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CONJUNCTION ASSESSMENT SCREENING VOLUME SIZING AND EVENT FILTERING IN LIGHT OF NATURAL CONJUNCTION EVENT DEVELOPMENT BEHAVIORS

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Conjunction Assessment screening volumes used in the protection of NASA satellites are constructed as geometric volumes about these satellites, of a size expected to capture a certain percentage of the serious conjunction events by a certain time before closest approach. However, the analyses that established these sizes were grounded on covariance-based projections rather than empirical screening results, did not tailor the volume sizes to ensure operational actionability of those results, and did not consider the adjunct ability to produce data that could provide prevenient assistance for maneuver planning. The present study effort seeks to reconsider these questions based on a six-month dataset of empirical screening results using an extremely large screening volume. The results, pursued here for a highly-populated orbit regime near 700km altitude, identify theoretical limits of screening volume performance, explore volume configuration to facilitate both maneuver remediation planning as well as basic asset protection, and recommend sizing principles that maximize volume performance while minimizing the capture of "chaff" conjunctions that are unlikely ever to become serious events.

INTRODUCTION

Satellite Conjunction Assessment (CA) activities can be divided into three parts: conjunction screenings, which identify satellites that in the near future will pass within close proximity of a protected space asset; conjunction risk assessment, which determines the actual risk of collision posed by these close passings; and conjunction remediation, which examines for high-risk conjunctions how to modify the primary object's orbit most efficiently to reduce the conjunction risk while at the same time not creating new risky conjunctions with other objects. The conjunction screening process, while more algorithmically straightforward than the latter two parts, is foundational as the gatekeeper function that flags potentially serious conjunctions for further analysis. If the screening approach falls short in some way, then the entire CA process becomes unreliable. Even though much of the current CA research focuses on the more algorithmically-compelling latter two portions of the process, it is extremely important that the CA screening process function properly and efficiently in order to ensure the integrity of the entire CA enterprise.

Historically, CA screenings have been performed geometrically, through the use of a defined three-dimensional physical volume called a "screening volume." The basic conceptual operation

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of the screening algorithm using a screening volume is as follows. First, the orbital parameters for the protected space asset, called the primary object, and those of all of the other objects in the catalogue are compared through a series of filtering techniques to eliminate satellite pairs whose orbits differ sufficiently that, even with large orbital element uncertainties, they cannot be considered to be collision candidates.[1] Next, ephemerides for the primary object and the remaining objects that survive the filtering process (called secondary objects) are propagated forward some number of days, in present practice at the Joint Space Operations Center (JSpOC) 7 days forward for LEO and 10 days forward for all other regimes. The geometric screening volume is then constructed, and it is usually either a rectangular prism or ellipsoid, with relative dimensions appropriate to the expected componentized position error distribution of the primary satellite's orbit regime. This volume is placed on the primary's ephemeris and then "flown" forward the requisite number of days. Any secondary satellites that find themselves within this screening volume are considered conjunctors and made the subject of a Conjunction Data Message (CDM), which is sent to the owner/operator of the primary satellite and provides the data necessary to begin performing in-depth risk assessment for the conjunction. If the screening volume is sized appropriately and the screening process executed sufficiently frequently (current JSpOC practice is every eight hours), then all potentially serious conjunctions should be identified.

While this statement certainly seems reasonable at the conceptual level, in developing the implementation details a number of problems arise. First, determining the proper size of a screening volume is actually a complex process that involves both philosophical as well as technical considerations. In the past, screening volume sizes have been generated by examining large histories of conjunction joint covariances[*] for the conjunctions that took place within a particular orbit regime and sizing each screening volume dimension based on an upper-percentile point of the one-sigma component error variances. One such study, for example, used the 95th percentile values of these variances considered individually by component.[2] While not an unreasonable procedure for an earlier period in the development of the CA discipline, this approach suffers from certain shortcomings. Because each axis of the covariance components was considered independently, the composite result of formulating a screening volume from the three 95th percentile component values did not produce a screening volume with a 95th percentile capture performance, and analysis performed as part of the present investigation demonstrates that the capture percentage is rather less than that value. Additionally, using the covariance components in this way makes the presumption that the covariance values are independent of the conjunction miss distances, since these distances are artificially reduced to zero to make this concept viable. It is not at all clear that that is a reasonable presumption, and exploratory analysis by the authors has suggested that this approach can tend to leave the covariances oversized. A more robust procedure is needed, especially in light of the immanent deployment of the USAF Space Fence radar, which is expected to increase the space catalogue size substantially and thus force a reassessment of screening volume size.

Before considering alternative methodologies, however, it is prudent to pause to consider the question more philosophically, to wit: what is the actual goal of the conjunction screening process? In posing the question to CA risk assessment practitioners, their testimony is that they wish to be able to identify, several days in advance of the conjunction time, "all" encounters that will

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[*] Most analytic approaches to calculating the Pc employ a joint position uncertainty covariance matrix, which is the combination of state uncertainties for the primary and secondary objects to formulate a covariance matrix describing their relative uncertainty. If the individual covariance matrices are uncorrelated, the joint covariance can be obtained by a simple summation of the two individual matrices.

eventually become serious conjunctions. This advance warning is very helpful in allowing the risk assessment process to examine the quality of the secondary objects' orbit determinations and tweak if necessary and, if the objects' sensor tracking is sparse, to request tracking increases. If instrumented conjunction screening data using an extremely large screening volume can be obtained, it is a straightforward exercise to identify ranges of screening volume sizes that will capture nearly all events that eventually will become serious. Such volumes are likely to be extremely large and thus will include a substantial number of conjunctions that are not serious and will never become so, but some practitioners would consider this a disadvantage that should be borne in order to achieve the desired capture completeness.

Before moving too quickly to honor such a request, it must be asked what one truly will be able to do with results of this type. If, some notable number of days before conjunction time, events that will become high risk distinguish themselves in some way, through an elevated probability of collision (Pc) or some other identifying metric, then indeed the future high-risk events can be anticipatorily identified and analyzed. However, if many days before the conjunction time these events look essentially like all of the other low-risk events, then it can be questioned whether having included them this early in screening results accomplishes any operational objective. If the number of conjunctions produced by the screening process is large and there is no way to distinguish among these results which conjunctions are likely to become high risk and which are likely to remain low, then what is the operational action that can be taken with such a results set? The number of identified conjunctions is too large to allow each item to be treated as a potential high-risk conjunction and analyzed deeply, and it unlikely to be acceptable to submit tracking increase requests for the entire screening output. It seems, therefore, that it is preferable to size screening volumes to allow positive identification of as many potential high-risk conjunctions as possible. A current operational practice is to treat any conjunction with a Pc greater than 1E-07 as an event with the potential to become serious. By using this criterion, one could propose sizing the screening volume so as to identify as many events as possible that both will become serious events and have a Pc of at least 1E-07 at the time of screening, thus identifying themselves as candidates for careful orbit determination examination and potential tracking increase requests. Other severity criteria can and should be investigated as well; but the principle advanced here is that the capture by a screening volume of future serious events needs to be considered in terms of the ability actually positively to identify such events at the time of screening, not merely to include them in a large, amorphous set of screening results that fail to distinguish between potentially high-risk and low-risk conjunctions.

In the main, screening volume sizing has been conducted in a manner that attempts to make the volumes as small as possible yet meet the screening objective; this impetus certainly seems sensible in that it reduces the amount of extraneous data obtained, as this both adds confusion to risk assessment and increases the data processing and transfer demands. There is, however, an advantage to somewhat "oversized" volumes that is not at first obvious, and it relates to efficiency in planning satellite conjunction risk mitigation maneuvers (and other maneuvers as well) when they are needed. When a satellite maneuver is planned in order to reduce the risk of a particular conjunction, the proposed maneuver is evaluated both against the conjunction that is prompting the maneuver in the first place, to ensure that the maneuver bring the risk down to an acceptable level; and additionally, against any other known conjunctions, to make sure that a fresh serious event is not generated by this mitigation maneuver. Sometimes maneuvers are explicitly chosen in order to reduce the risk among several known upcoming conjunctions. Once a particular maneuver is chosen, it is part of the usual procedure to submit the planned maneuver ephemeris to the JSpOC for an explicit screening run; and from this screening activity any potentially serious conjunctions generated by this proposed maneuver will be identified. It is inefficient, and in some cases operationally dangerous, to depend on this screening activity as the sole method to identify maneuver-induced conjunction problems. Because of the delays between submitting a maneuver for screening and receiving results, a many-iteration sequence of submitting a maneuver ephemeris, finding a new conjunction-related problem, revising and resubmitting the ephemeris, finding a new problem with this revised maneuver plan, &c. can rapidly use up all of the pre-maneuver planning time, leaving the owner/operator in a position in which there is no certified maneuver plan in hand at the point at which the maneuver commands must be uploaded to the spacecraft. If, however, a largish screening volume has been used, then the owner/operator is generally in possession of precision state and covariance information for most objects in broad proximity of the protected asset. This information can be used to perform a prudent and informed selection of the initial proposed maneuver (by determining whether candidate maneuvers would create potentially dangerous conjunctions with these other objects), thus greatly reducing the possibility of rejection due to a newly-discovered conjunction upon maneuver screening at the JSpOC. Since excessive iteration of proposed maneuver ephemerides both adds a safety-of-flight risk and imposes additional workload on the JSpOC, it may well be beneficial to consider larger screening volumes. While creating a larger data processing demand, such volumes nonetheless will produce an overall more advantageous situation for both the owner/operator and the JSpOC in allowing improved maneuver planning by reducing necessary iterations.

STUDY DATASET

Due to a special arrangement between NASA and the US DoD, NASA CA screenings are performed by NASA personnel who sit on the JSpOC ops floor and have access to the operational system; this arrangement allows for helpful analysis opportunities performed on a non-interference basis with other JSpOC activities. To support the present analysis, for a six-month period (1 OCT 2016 – 31 MAR 2017) for the ~65 primary spacecraft that NASA protects, initial screenings were performed once daily with an extremely large screening volume with dimensions of 50 km radial x 250 km in-track x 250 km cross-track, looking forward 7 days for LEO objects and 10 days for other orbit regimes. Risk assessment parameters, such as the Pc, were not calculated as part of this large screening at the time of initial execution in order to keep the runs from becoming overly computationally demanding. Such a large screening volume should include, ideally from the first discovery opportunity, nearly all events that eventually will become serious. As such, it should constitute an excellent test set from which to experiment further to determine the expected performance of smaller and differently-configured screening volumes.

For the purposes of the present analysis, the examination is confined to the results for twelve protected primaries that are all in near-circular orbits at approximately 700km altitude; this allows a quite large dataset for the initial exploration of a number of different screening-related questions. This satellite group presently uses a screening volume that is 0.5 km radial x 17 km in-track x 20 km cross-track ellipsoid (each of these dimensions is one of the semi-axes of the ellipsoid), so results from a screening volume of these dimensions can be used as a point of comparison against which to evaluate the performance of other possibilities. Based on that which is learned from this more expansive investigation, endorsed procedures can be repeated for the other orbit regimes to examine continuity of results, which can then be presented to decision-makers to determine whether CA screening procedures for NASA-protected payloads should be modified in some way.

GEOMETRIC SCREENING VOLUME PERFORMANCE

With the dataset described in the previous section, it is a straightforward exercise to evaluate the relative performance of different screening volumes that have dimensions smaller than the extremely large test volume; changes in both overall volume and ratio of the three ellipsoid axes (and therefore aspect ratio of the ellipsoid) can be explored. Before beginning such an exercise, however, it is important to establish success criteria for the experiment, namely how the "performance" of different screening volumes will be evaluated. The most important performance index is the number of conjunction events that will eventually become serious that the screening volume will capture by a certain TCA. For example, one might want a screening volume to be sized so as to capture, by five days until TCA, 95% of conjunction events that will eventually become serious. This criterion immediately prompts the question of the definition of a serious conjunction event. Sensitivity analyses on this criterion (and even the way it is measured) should, in principle, be conducted; but the CA discipline has largely converged on a "red event" criterion of a Pc in the neighborhood of 1E-04 – 5E-04. For the purposes of this analysis the value 1E-04 will be used to define the serious event for which the screening volume should be sized to capture. Screening volume sizes for different capture percentages at different capture times should also be evaluated. Capture times refer to the time before TCA at which the serious event is discovered. Ideally, in LEO all such events would be captured at the 7 days to TCA point—the most temporally distant point at which the capture could take place, given the present screening cadence If this is not possible, captures at the 6 and 5 day points are also early enough to allow non-frenetic exercise of the early-event activities, such as review of the OD and requests for additional tracking. It would seem that a first capture at seven days would always imply an additional capture at 6 days, at 5 days, &c., but there is in fact some chatter for events at the outer limits of the screening volume boundary, so it is better to construe the temporal aspect as "found in the 7 day screening," "found in either the 7 or 6 day screening," "found in the 7, 6, and/or 5 day screening," *usw*. Capture percentages refer to the percent of serious events that are captured by a screening at a particular time (or array of subsequent screenings over a set number of days, as explained above). While a number of different capture percentages could be examined, three nominal levels were chosen for explicit reporting: 80% capture (4 out of 5 events), 90% capture (9 out of 10 events), and 95% capture (19 out of 20 events). The 80% level is shown more as an anchor point, as this level of capture is too small to satisfy most owner/operators. The 90% level is probably the smallest that would be considered operationally acceptable, and the 95% level, especially when formulated as "capturing 19 out of 20 serious events" usually resonates with decision-makers. This last level is the level at which most other space situational awareness (SSA) requirements typically are levied (*i.e.,* at the 95th percentile).

One final consideration is the presence or absence of some criterion to indicate which of the captured events are likely to develop into serious events, with such a criterion construed as a necessary but not sufficient condition for an event developing in this manner. There are a number of possibilities for this criterion, ranging from an elevated Pc value at the time of screening (the vast majority of conjunctions identified through volumetric screening have a Pc value of 0) to some other conjunction severity parameter, such as the Mahalanobis distance. There are further filtering techniques that could be applied to the conjunctions identified by the volumetric screening to try to reduce the "chaff" effect of including conjunctions that will never develop into serious events. For the initial presentation of these results, no such secondary criterion is applied—what is displayed is merely the percentage of serious events captured by the screening volume.

All of the details of this methodology make more sense when applied to a concrete example, so at this point it is appropriate to consider Figure 1. The presentation is somewhat complicated to read and interpret, so the following steps through the process in prose form. Each column of graphs corresponds to a certain serious event capture percentage: the first column is for an 80% capture, the second for 90%, and the third for 95%. In each such case, a serious event is defined as one for which the maximum Pc over the course of the entire event exceeds 1E-04.

Each row of graphs corresponds to a particular time to TCA: the bottom row is for 7 days before TCA, the penultimate row for by at least 6 days to TCA (shown as 7-6 days in the row title), the antepenultimate row for by at least 5 days to TCA (shown as 7-5 days in the row title), and the first row for by at least 4 days to TCA (shown as 7-4 days in the row title); this first row (7-4 days) is given for context, but notification of events this close to TCA gives very little opportunity for anticipatory preparation and is not operationally recommended. Within each of the twelve contour plots contained in the graph set, the x-axis corresponds to the screening volume cross-track dimension, the y-axis to the screening volume radial dimension, and the color to the in-track dimension. Both regular axes (x and y) and the colormap are logarithmically scaled—the former by a logarithmic arrangement of grid lines and the latter by the reporting of the logarithmic rather than linear value of the in-track dimension. The color (and thus the in-track dimension) for every radial/cross-track ordered pair in the graph is determined so as to make the capture percentage equal the level to be represented by the graph It is the dependent variable of sorts in the analysis. White space on the graph indicates regions in which no reasonable in-track dimension (up to 100km) will allow the capture percentage to be met. The leading-edge of the colored region is not conceptually dissimilar to an "efficient frontier" in an optimization plot, but there are important differences. In a true optimization plot, the plotted line represents the boundary of the region within which the optimization objective is met, so there is never any reason to choose a point past the line, in the interior portion of the curve—that area represents similar performance but at higher cost. In the graphs shown here, the colored space represents the region of radial, in-track, and cross-track dimensions that allow the capture percentage to be met (one optimization criterion), but there is also a second such criterion: the number of conjunctions, and thus data load, produced by using a screening volume of the particular combination of radial, in-track, and cross-track dimensions. As one proceeds along the y=x diagonal within the colored space, the performance in terms of capture percentage may not be improving much, but the number of conjunctions generated by the use of the larger volume is most likely increasing; this increase is additional "chaff" that will not become serious events but will result in additional data processing and distraction. Fully to evaluate the propriety of any given screening volume dimension requires the pairing of one of these contour plots with a similar plot that shows for each dimension set the total number of conjunctions captured, and indeed these will be provided shortly; but first it is helpful to observe some general performance principles from this first graph type alone. Finally, as a point of reference, the colored dot shown in each of the graphs represents (by placement and color) the size of the screening volume currently used operationally for this particular orbit regime. As a narrated example of reading these plots, consider the graph in the second row and third column (7-5 days from TCA, 95% capture). Here the current screening volume size (shown by the dot) is right at the quasi-"efficient frontier," so it is very close to achieving the performance level indicated (*i.e.,* 95% capture). It appears that the cross-track dimension could be reduced slightly by moving the dot to the left to continue to maintain the same stated performance yet decrease the screening volume size slightly. One could reduce the required in-track size by moving to the green interior, but with the current graph set it is not known how much that would increase the data production rate from each screening.

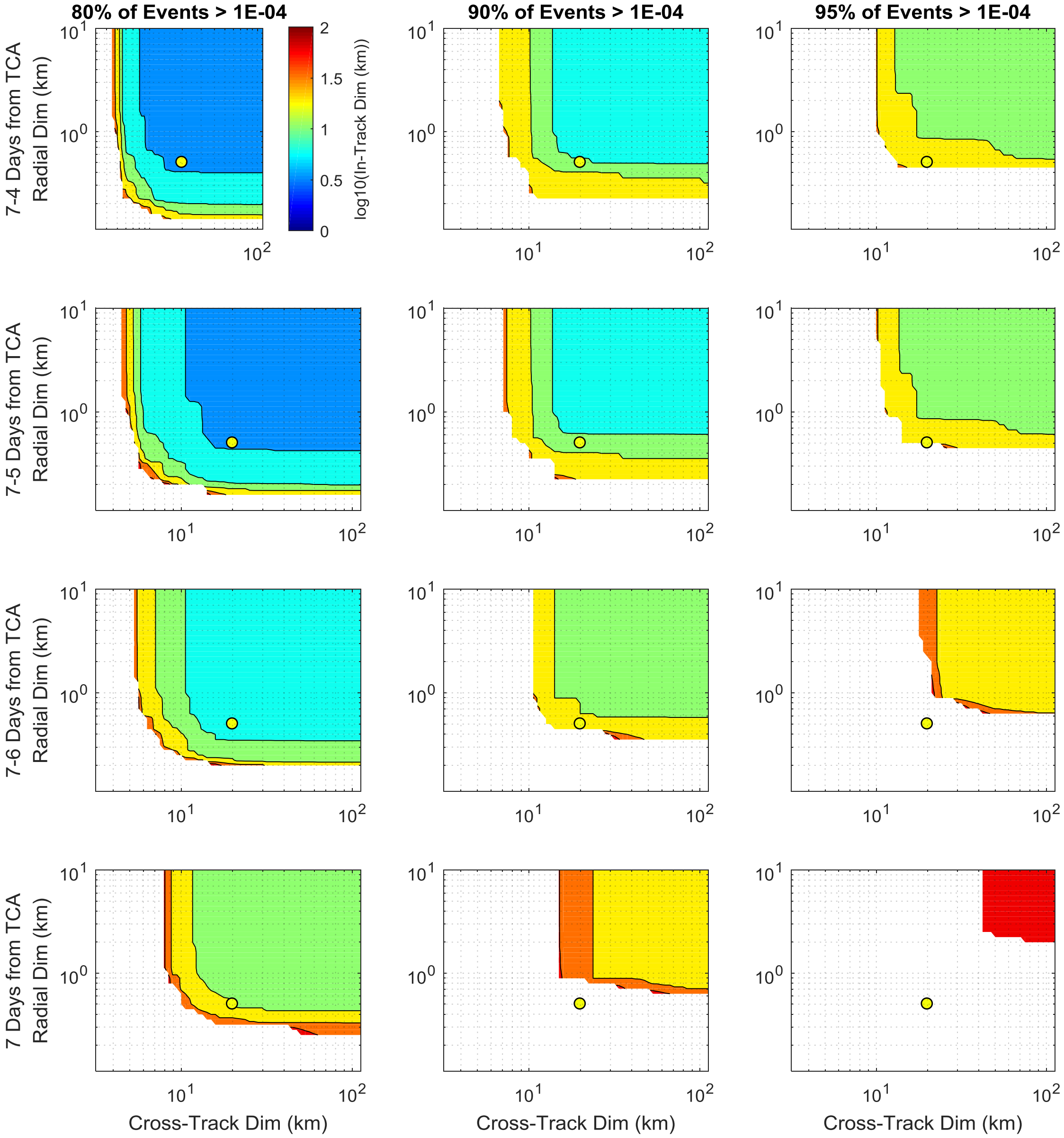


Figure 1. Screening Volume Capture Percentages by Time to TCA, without Provision for Identification of Possible Serious Events.

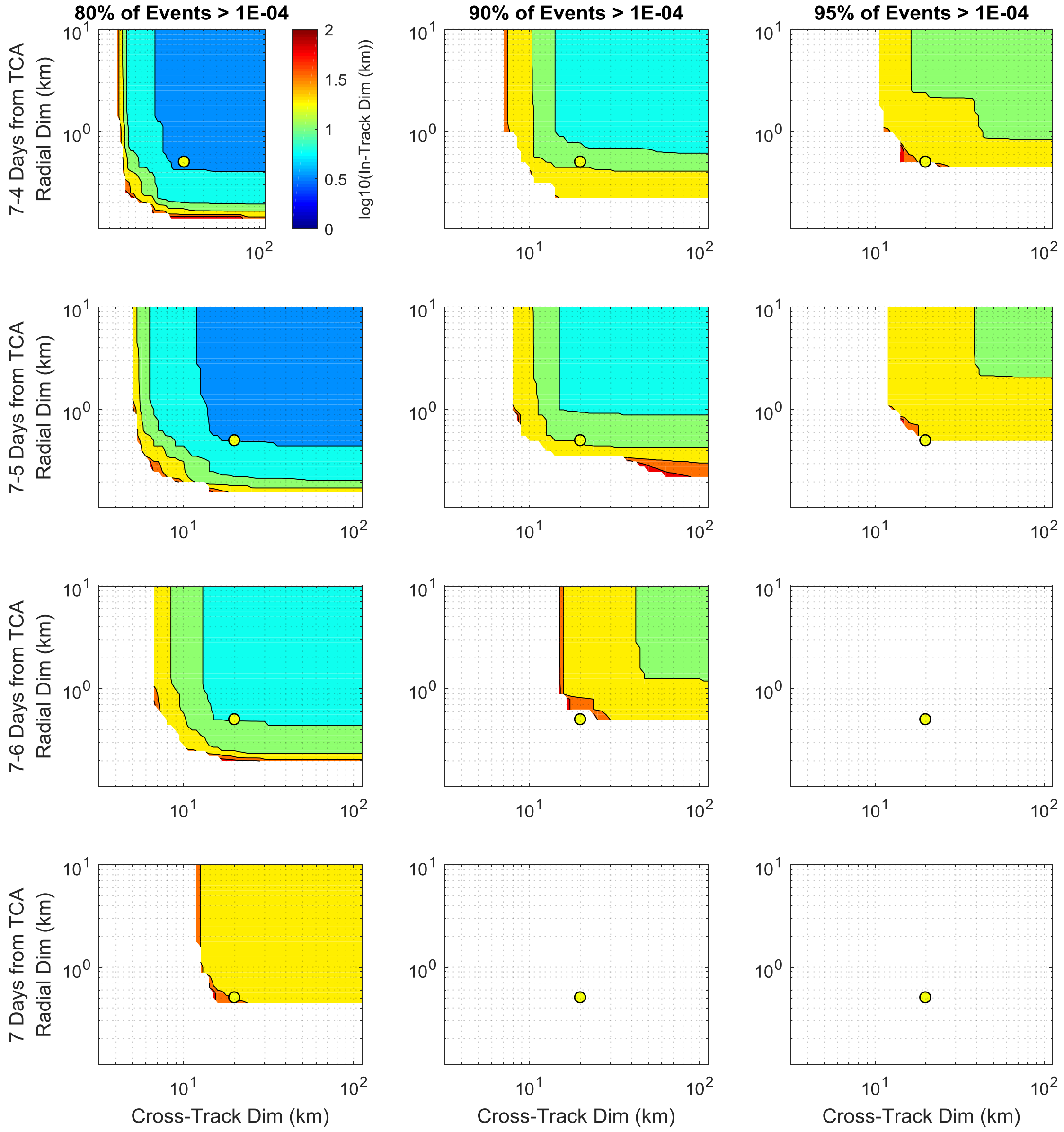


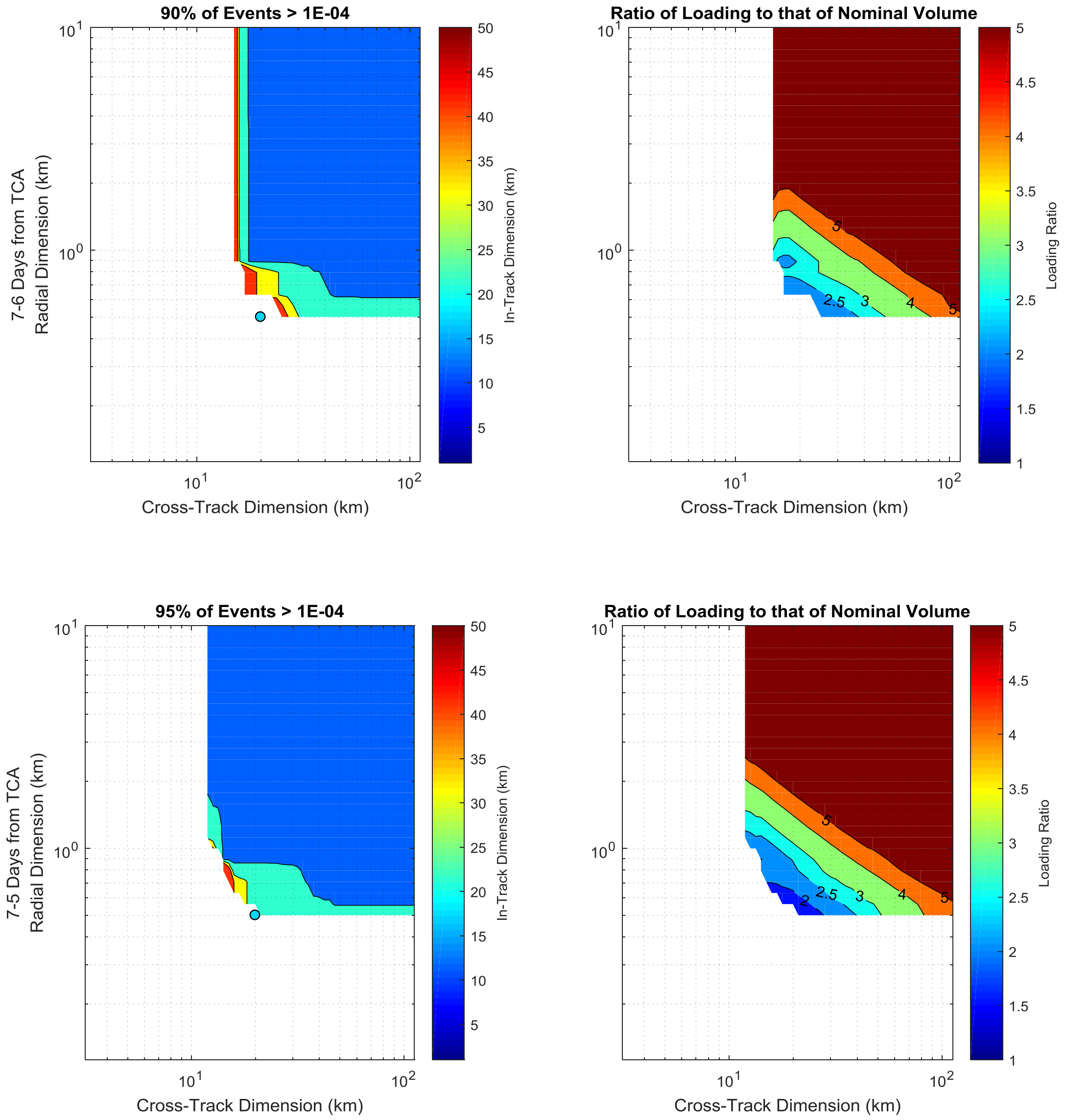
Figure 2. Screening Volume Capture Percentages by Time to TCA, with Pc Threshold Provision for Identification of Possible Serious Events.

Ideally, of course, one would like the highest level of capture percentage to be achieved at the furthest time from TCA, as this would render the greatest operational benefit. Such performance is reflected in the bottom right graph. As can be seen, the current screening volume sizing (represented by the dot) is quite far from the colored region, whose color is dark red; so a substantial increase in the screening volume size would be necessary to create compliance with the 95% capture percentage. The situation is more sanguine if six rather than seven days' warning is acceptable; here an apparently more manageable increase could bring the dot into the colored region and thus produce 95% compliance. If one is happy with 90% at 7-6 days or 95% at 7-5 days, then current sizing is essentially adequate. However, it should be reiterated that these graphs give values for simply capturing the given number of events that will eventually become serious. They do not consider whether there would be any way to identify these particular events within the screening results and act positively on them.

Figure 2 attempts to do this by recasting the capture percentage as the percentage of serious events captured but additionally requires that they be positively identified within the screening results by having a Pc value > 1E-07. While the appearance of some of the plots is essentially unchanged, others show important differences, especially in the bottom-right portion of the collection. The three plots that constitute the bottom-right corner do not contain a colored region at all—at least within the reasonability bounds of 10km in radial and 100km in in-track and cross-track dimensions. It is thus not possible to achieve the desired capture percentage at the stated times before TCA. It is quite likely that growing the screening volume to an essentially unbounded size will not improve the situation: it is simply not possible, for example, until five days to TCA to reach a 95% capture percentage in a way that also identifies the potentially significant events to allow subsequent action on them. Of course, sensitivity analyses on the 1E-04 "red" threshold and the 1E-07 "yellow" threshold should be completed thoroughly to ensure that this result not be an artifact of this particular combination of red and yellow thresholds, but informal sensitivity analyses by the authors produced extremely similar results. There seems to be a class of significant events, composing 5-10% of the group depending on time to TCA, that due to environmental or orbit maintenance reasons do not manifest themselves as serious until less than five days to TCA. Modifying screening volume sizes and approaches to try to improve the situation will probably not be able to alter this circumstance much, if at all. If one wishes screening volumes that both capture incipient serious events and identify them in some way, one must acclimate himself to a 90% capture percentage at 7-6 days and a 95% capture percentage at 7-5 days, at which points, interestingly, the current screening volume size is reasonably close to achieving this level of performance.

These results naturally lead to the question of what the additional screening data production would be if the current screening volume size were to be increased to push the volume size into the colored area for these two situations. The plots in Figures 3a and 3b attempt to represent this in a binary display: the left graph is a reproduction of the plot from Figure 2 (3a gives the 90% capture level for 7-6 days and 3b the 95% capture level for 7-5 days), although with a linear rather than logarithmic scaling of in-track screening volume size; and the right plot gives the number of conjunctions produced by the screening volume as a scale factor of the loading induced by the current screening volume size. It is evident that, as one pushes deep into the interior of the colored region, the loading can increase substantially (it is not difficult to exceed a scale factor of 5). At the edge of the colored region closest to the dot, however, the situation is not nearly so frightful: the contours are a bit difficult to read here, but in Figure 3a this edge would seem to represent an approximate doubling of the loading and in 3b approximately a scale factor of 1.5. There are binning and interpolation uncertainties with reading contour plots, so in the next section a table with exact values for these (and other) calculations is given. The takeaway here is that the

90%/95% performance levels (at 7-6 and 7-5 days) can be met with what is probably a tolerable increase in conjunction production. One can refrain from examining these formal calculations at present because there is a competing set of considerations that will help to shape screening volume sizes, namely the ability to identify conjunctions that may become serious as part of maneuver planning.



Figures 3a (top) and 3b (bottom). Screening Volume Capture Percentages for Particular Times to TCA, Paired with Statements of Ratio of Data Production to that of Nominal Screening Volume.

GEOMETRIC VOLUME SCREENING FOR MANEUVER PLANNING SUPPORT

It was discussed earlier in this paper that larger screening volumes can aid the maneuver planning process by providing situational awareness of the objects that are in proximity of a protected asset, even if based on the asset's current trajectory these objects will never present serious conjunction events. If state information about these objects is known, during maneuver planning proposed new trajectories for the primary asset can be assessed against these objects to determine whether they are likely to cause a post-maneuver serious conjunction event. If so, such trajectories can be eliminated early from consideration and therefore not consume unneeded iterations (and therefore use up important time in the operational cadence) of ephemeris screenings. If one wishes routine screenings to accommodate this particular application, then it must be determined what screening volume sizing would best accomplish this goal in a manner that also minimizes the capture of additional "chaff" conjunctions.

The best method to perform this sizing is to profile actual satellite maneuvers to determine how much positional change these maneuvers introduce as a function of time. The extent of the componentized positional change determines how large a screening volume would need to be to capture a conjunction event at the maneuvering satellite's new position. To this end, drag make-up maneuver (DMU) histories for the last several years were obtained for three NASA satellites (the Aqua, Aura, and Terra spacecraft) in near-circular, near-700km orbits, yielding intended radial, in-track, and cross-track maneuver delta-V values. For these satellites, most of the propulsive thrust for their DMUs was expended in the in-track direction, although there was radial and cross-track thrusting that was also considered in the analysis. For each maneuver, both unperturbed and perturbed high-precision trajectories for the satellite were generated, and these ephemerides were compared at and around time points of interest to generate radial, in-track, and cross-track position differences. With this dataset of position differences, one can then determine what percentage of these position difference ordered triples are captured by a particular screening volume size. Of course, actual maneuver sizes will depend on space weather conditions at the time of the maneuver (and therefore the amount of atmospheric drag acceleration that is expected) and the particular DMU strategy that each satellite owner/operator adopts (*e.g.*, does one wish to place the satellite in the middle or at the leading edge of its "control box"). Nonetheless, examining extensive past maneuver histories is the best way to get a general sense of the size of the capture percentages that different screening volume sizes will generate.

Figure 4 presents the results of this investigation. While these plots may at first look similar to those given earlier in Figures 1 and 2, they are actually rather different in construction. Because the cross-track component error for this DMU type is extremely small (never more than 20m over the four-day propagation interval examined), it can essentially be neglected in the analysis. As such, the x- and y-axes for the graphs become the in-track and radial components, respectively; and the color can now represent the overall capture percentage (so all capture percentages can be represented within a single graph). Each of the four plots presented gives a different propagation state post-maneuver. The 1 to 4 day window used here is a critical time-frame for maneuver planning because a mission may not be able to respond at all to a high-risk event that is discovered less than two days after a maneuver, and responding within three to four days after a maneuver, while perhaps possible, is still highly undesirable. The size of the current screening volume for this orbit regime is indicated by the white dot.

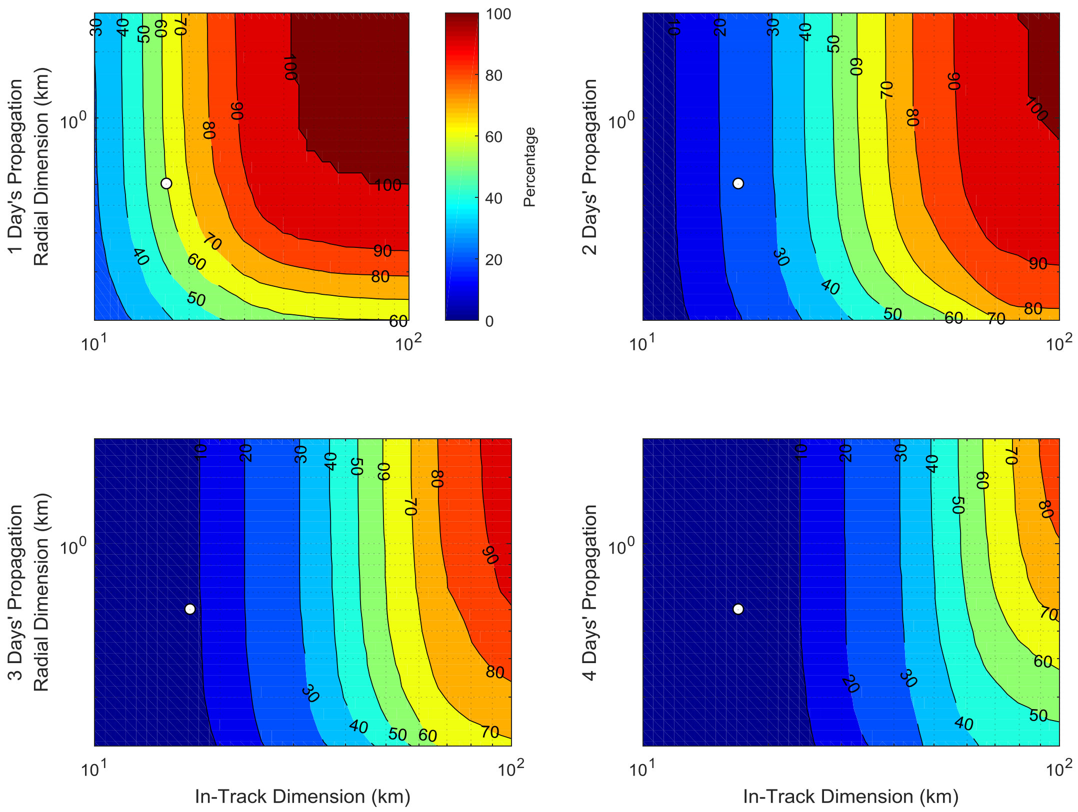


Figure 4. Capture Percentages of Conjunctions Induced by Primary Satellite Maneuvers, as a Function of Radial and In-Track Screening Volume Dimensions.

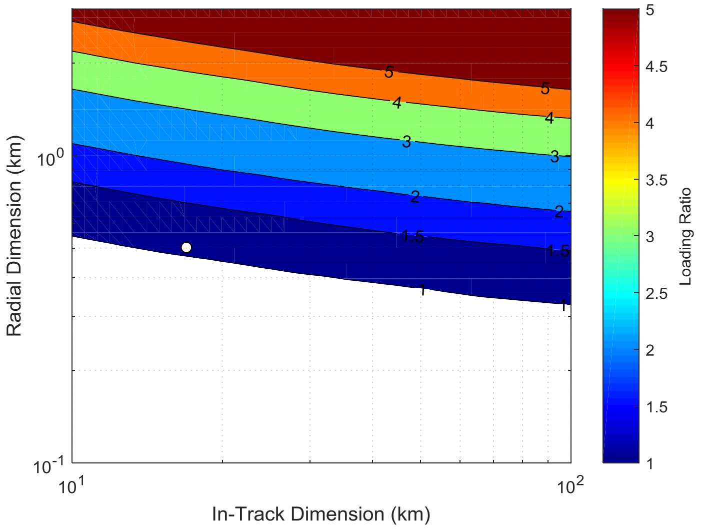


Figure 5. Data Production Increase Ratio, as a Function of Radial and In-Track Screening Volume Dimensions.

One notices immediately the near-vertical alignment of the contours, at least in the neighborhood of the current screening volume size--this indicates that changing the radial dimension of the screening volume will have a relatively small effect on the capture of conjunctions lurking at maneuver-induced future positions, whereas an increase in the in-track volume size will have a substantial effect. This overall trend is hardly a surprise, since for this DMU type nearly all of the maneuver impulse is provided in-track. It is also to be expected that larger in-track screening volume increases will be necessary at larger propagation times to meet a desired capture percentage, and the differences here are significant: an increase of the in-track screening volume dimension from 17 to 30 km is adequate at one day's propagation time to achieve a 90% capture level, but an increase to a full 100km in-track dimension at four days' propagation time (the full right edge of the graph) can barely achieve a 70% capture level. Of course, these statements are not particularly meaningful without the accompanying "chaff event" capture levels in order to understand the level of loading imputed by such a screening volume change. Figure 5 provides this information in a plot is similar to the right-hand plots of Figure 3 but with the axes changed to in-track and radial screening volume dimensions. One notices immediately that the contours here are close to horizontal, meaning that the loading increases only slightly as the in-track dimension is increased. In fact, one can increase the in-track size of the current screening volume from 17km to 100km and realize an increase over the current loading of only a factor of ~1.5. Exact calculations for scenarios in the previous and present sections are presented in Table 1 below:

Table 1. Performance Indices for Screening Volumes of Different Sizes.

R (km)	I (km)	C (km)	% Capture at 7-6 Days	% Capture at 7-5 Days	Loading Scale Factor	Comment
0.5	17	20	85	90	1.00	Nominal volume size
0.6	30	25	90	95	1.65	Small change to meet reqt
0.5	100	20	88	94	1.48	Change I to 100km only
0.6	100	25	90	96	2.14	Both small changes (row two) and I set to 100km

The first row in this table gives the performance for the unaltered, "nominal" screening volume size. One sees that it falls below the desired performance by five percentage points at both the 7-6 and 7-5 day points. The second row reflects the relatively small changes to the screening volume dimensions to bring performance to the desired 90% and 95% levels. This creates an increase in data generation by a factor of about 1.5. If one leaves the nominal radial and cross-track dimensions unaltered but increases the in-track dimension to 100km, then performance very near the desired levels (88% and 94%) can be achieved with, again, a data generation increase of about a factor of 1.5. Finally, if the small adjustments to the screening volume size are left in place but the in-track component grown to 100km, then performance only slightly exceeding the desired levels is realized but the data generation increases more than a factor of two.

The purpose here is not to advance a firm recommendation to increase the screening volume size for this orbit regime to any of the improved levels shown in the table; at the least, one would wish a broader survey of maneuver types to ensure that the recapture performance will actually occur as stated. Rather, it is to demonstrate that carefully-tailored screening volume sizes appear to be able to obtain serious event capture percentages close to their practical maxima and at the same time capture events that, while not presently serious, could well become so after a typical maneuver. Both of these can be achieved with relatively bounded increases in the production of "chaff" events that serve neither purpose but increase workload. This conclusion can motivate a broader operational analysis to obtain precise screening volume sizes to meet these objectives.

ADVANCED SCREENING FILTERING TECHNIQUES

Filtering techniques to reduce the screening results down to a smaller group of conjunctions that hold a real possibility of becoming serious events constitutes an area of some research. As discussed previously, Hoots *et al.* proposed a set of simple filters to eliminate pairs of objects for which it was concluded that collision was simply not possible; and such filtering techniques have been implemented in the current operational system. The effect of these filters in eliminating conjunction pairs that could become significant after a primary satellite maneuver has not been studied; but given the relative coarseness of these filters, the effect is not expected here to be great. More elaborate filtering techniques have been studied in some depth, appear in the general literature, and have been recommended for operational implementation at third-party CA establishments. The approach described by Alfano,[3] for example, considers for a given miss distance the maximum Pc that can be expected for the conjunction by either allowing the covariance to assume any size and orientation possible or by assuming a restricted set of sizes/orientations based on catalogue profiling. Conjunctions for which this maximum Pc falls below the red threshold can be ignored as not serious. George and Chan[4] take a different approach by setting the conjunction's miss distance to zero and combining the primary and secondary covariances so as to maximize the covariance size. If even in this scenario the Pc is below a threshold, it is concluded that the event could not possibly become serious because the covariance will only shrink (rather than expand) as the time to TCA is lessened and the propagation interval thus decreases. Both of these approaches could be applied to the results of a volumetric screening in order to identify and eliminate "chaff" conjunctions.

To do this, however, would be either to sacrifice the secondary benefit of allowing non-serious additional conjunctions to assist in maneuver planning efficiency or to make only a relatively minor difference in the number of "chaff" conjunctions eliminated. The Alfano method is predicated upon presuming that the two objects' current miss distance will remain the same. This clearly will not be the case should a maneuver be executed, so this method will eliminate conjunctions that are not serious against the current primary trajectory but could become serious were a maneuver to alter it. The George and Chan approach is perhaps better suited as a filtering mechanism under these circumstances because it proceeds from the assumption of a zero-miss distance, which is much closer to the eventuality of a maneuver's bringing the primary close to a secondary object that is at present not threatening. However, with the present precision of the SP catalogue, this filtering technique removes relatively few conjunctions. Figure 6 below gives a CDF plot of the George-Chan max Pc calculation for all of the events identified in the experimental dataset, and only about 5% would be eliminated using a red threshold of 1E-04—not enough of a reduction to transform the situation appreciably. So if one wishes to maintain the virtue of an expanded screening volume in order to enable efficient maneuver planning, filtering techniques to try to reduce the "chaff" events do not appear to be particularly helpful.

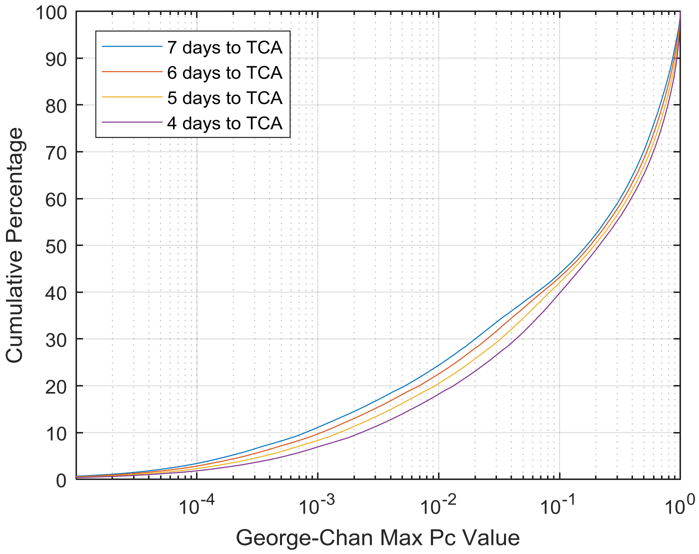


Figure 6. Cumulative Distribution Function (CDF) plot of George-Chan Maximum Pc Calculation for Analysis Dataset.

CONCLUSIONS AND FUTURE WORK

Screening volumes have historically been sized to attempt to capture a certain percentage of the events that will eventually become serious, but this sizing has been conducted both speculatively from covariances and without any parallel analysis that certified that the serious events are identifiable and thus can be acted upon in some way. The availability of six months of extremely large screening data for a heavily-populated orbit regime (altitude between 500 and 750 km, low eccentricity) has allowed this sizing to be performed empirically and to take cognizance of serious event recognition at the time of screening. It was determined that certain capture percentages are not possible regardless of the screening volume size because some potentially serious events do not identify themselves as such until very close to TCA (within only a few days). For the orbit regime analyzed, levels of 90% at 7-6 days from TCA and 95% at 7-5 days from TCA were achievable, and that with only relatively small size increases from the volume that is presently in use. This screening volume size augmentation increases the overall loading (in terms of number of conjunctions produced per screening) to about one and one-half times its present level.

A competing virtue to event capture percentages is providing conjunction "situational awareness" for a larger region about the primary so that these conjunctions, not serious given the primary's current trajectory, can be considered as part of maneuver planning and thus reduce maneuver screenings to trajectories that have already been pre-certified as viable. Analyzing the drag make-up maneuver histories for three NASA satellites in this orbit regime revealed that an increase in the in-track component of the screening volume to what by historical standards is a very large value (100km) would allow the capture of nearly 70% of the conjunctions that could become serious under typical maneuver conditions. The increase in this dimension would impute a loading increase of a little more than 1.5 times the current loading level if the other two screening volume dimensions are kept at their nominal levels. If these other two dimensions are grown so as to achieve the 90%/95% capture levels at 6 and 5 days (respectively), then the loading slightly more than doubles. JSpOC and NASA staff will need to decide whether the virtues of the additional performance on both fronts would merit the increased data processing and workload, especially in the context of expected additional increases due to the incipient deployment of the US Air Force's Space Fence radar.

Once this decision is taken, future work will include making similar calculations for the other orbit regimes used in conjunction assessment (presently GEO, MEO, two HEO, and three other LEO) and rendering the associated decisions for those regimes based on analysis results. Additionally, it is advisable to examine the use of other proxy metrics for conjunction severity, such as the Mahalanobis distance. Initial and informal explorations of the use of the Mahalanobis distance metric by the authors were disappointing in that both the predictive power of conjunction severity was reduced and the "chaff" effect increased over that of volumetric screening volume approaches, but these investigations should be formalized and published.

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