

NASA CONJUNCTION ASSESSMENT RISK ANALYSIS UPDATED REQUIREMENTS ARCHITECTURE

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The NASA Conjunction Assessment Risk Analysis (CARA) program has been performing routine on-orbit satellite conjunction risk analysis for unmanned NASA spacecraft since 2005, and has developed a robust operations procedure and set of recommended best practices for operational conjunction assessment. However, a number of recent developments in Space Situational Awareness and commercial space operations conduct, such as the imminent deployment of much more sensitive space sensing systems and the launching of much larger satellite constellations, have begun to challenge these standard collision risk parameters and calculations. In response CARA has pursued a multi-year evaluation initiative to re-examine risk assessment algorithms and techniques, to develop needed improvements, and to assemble analysis-based operational requirements. This paper gives an overview of the principal parts of the Conjunction Assessment (CA) risk assessment process used at CARA, outlines the technical challenges that each part presents, surveys the possible solutions, and then indicates which particular solution is being recommended for NASA.

INTRODUCTION

The NASA Conjunction Assessment Risk Analysis (CARA) program was initiated in January of 2005 to protect the Agency's unmanned missions from collision with on-orbit objects. The NASA Human Spaceflight (HSF) program, historically supporting missions such as the Space Shuttle, the International Space Station (ISS), and ISS visiting vehicles, had worked with the Department of Defense in the 1980s to develop the high accuracy space object catalog and CA screening products that would eventually develop into the Conjunction Data Message (CDM) and other standard formats in use today. In 2004, CARA was created and, using the basis of the HSF CA process and modifying it to apply to a wider range of orbit regimes and types of vehicles, developed a process that is now required for all non-HSF operational Agency assets. CARA currently supports about 70 spacecraft using the institutional risk assessment process described herein.

However, a number of recent developments in Space Situational Awareness (SSA) and commercial space operations conduct have begun to challenge these standard collision risk parameters and calculations. These developments include the imminent deployment to operations of the Space Fence Radar, an Air Force sensor that is expected to change the sensitivity of the Space Surveillance Network (SSN) from the current detection capability of 10 cm in LEO to 5 cm, as well as the launch of many large constellations (100s to 1000s of members each) to various low Earth altitudes. Both of these developments will increase the workload of

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analyzing and mitigating close approach events, making improvements to the existing process necessary. Improvements such as decreasing the uncertainty in the relevant computations and the inclusion of more automated processes are necessary to adapt CARA to handle the evolving space environment. Therefore, CARA has pursued a multi-year evaluation initiative to re-examine risk assessment algorithms and techniques, to develop needed improvements, and to assemble analysis-based operational requirements. This paper gives an overview of the CA risk assessment process used at CARA, outlines the technical challenges being encountered, surveys the possible solutions, and then indicates which particular solution is being recommended for NASA. The paper concludes with an inventory of remaining important open research questions as well as statements of the operational utility that would be engendered by their solutions.

CURRENT CARA OPERATIONS PROCESS OVERVIEW

Conjunction assessment is a three-step process. First, trajectory data for a protected asset is screened against the catalog of on-orbit objects to predict close approaches. This catalog is maintained at the 18th Space Control Squadron (18 SPCS) at Vandenberg Air Force Base (VAFB) in California, and screenings for NASA non-HSF assets are performed by the NASA CARA Orbital Safety Analysts (COSAs) co-located with 18 SPCS at VAFB. This step is performed two times per day for spacecraft in highly eccentric orbits (HEO) and geosynchronous (GEO) orbit regimes, and 3 times per day for spacecraft in low earth orbit (LEO). Second, risk assessment is performed on the screening results. CARA has an operations team located at NASA Goddard Space Flight Center (GSFC) who perform this function for NASA non-HSF protected assets. CARA has an automated process to ingest the screening data results and parse them into reports sent out to customers along with analysis of the results. CARA Operators also use offline tools to manually evaluate and perform additional analysis on close approaches that are deemed risky, dubbed “High Interest Events” (HIEs), or have characteristics that require further scrutiny. In step three, mitigation actions are taken by the mission owner/operator (O/O) for events that are deemed risky. CARA works closely with the O/O, whose job it is to weigh the close approach risk analysis and recommendation from CARA against other mission risks and constraints to choose a mitigation approach. The remaining sections of this paper describe step 2, the CARA risk assessment process, in more detail, including the inputs and outputs, the software tools used, analysis performed by the COSAs and the CARA Operators, as well as proposed improvements to various steps in the process. An overview of the full operations processes is shown in Figure 1, and is further described in the sections that follow.

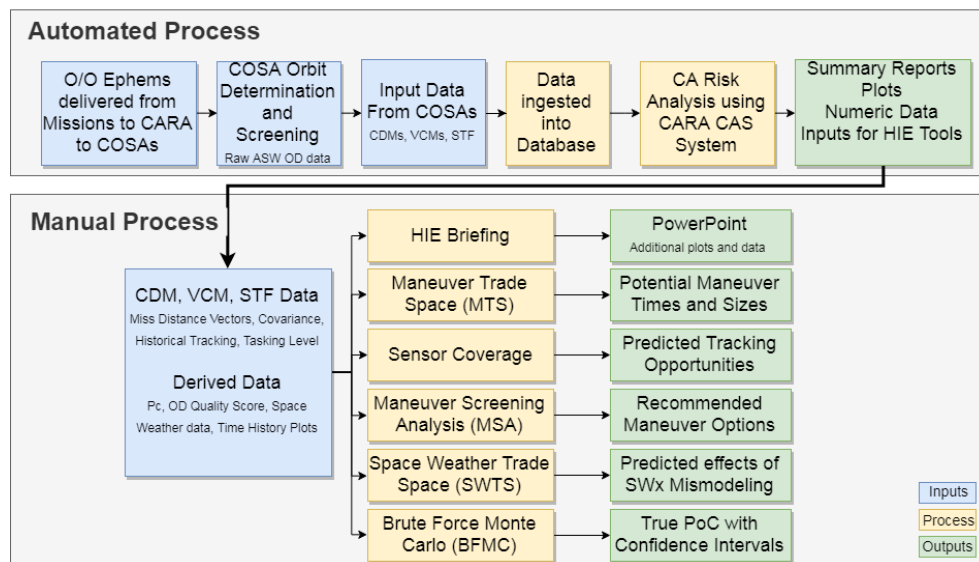


Figure 1: CARA Operations Processes

Input Data

There are two sets of screening data produced at the 18 SPCS by the COSAs for CARA. One set uses the Owner/Operator (O/O)-provided ephemeris data sent by CARA to VAFB. The other uses the 18 SPCS in-house Astrodynamics Support Workstation (ASW) solution for the protected assets. The ASW orbit determination (OD) solution is derived from non-cooperative tracking data collected by the Air Force Space Surveillance Network (SSN) and does not model maneuvers planned by an O/O. The O/O solution is generated from tracking data collected by the operator responsible for flying the asset and includes modeled maneuvers planned to occur within the ephemeris timespan as well as tuned covariance data. Providing ephemerides that include planned maneuvers is critical to ensure mission and orbit regime safety, because it enables the ephemerides to be screened against those of other assets that may also be maneuvering, preventing a situation in which two assets maneuver into each other. Identifying potential collisions due to planned maneuvers in advance through the screening process allows operators to communicate with each other to avoid these close approaches. It is especially critical for missions using electrical propulsion, differential drag, or other methods of continuous thrusting to provide ephemeris files to 18 SPCS, as otherwise other operators would not be screened against the true trajectory but only the non-maneuver one from the ASW, which would not match the as-flown trajectory.

Based on screening each of these input sources, the COSAs send various routine data products to CARA for further processing and calculation at the CARA Operations Center, including Conjunction Data Messages (CDMs), Vector Covariance Messages (VCMs), raw ASW OD data, and object tasking and tracking information. The majority of CARA calculations and data analysis use the CDM data, which includes the primary and secondary satellite identification numbers (SatIDs) and common names, the event relative miss distance, miss components, and velocity. For each object, the ephemeris file name used is provided as well as the individual object covariance, Radar Cross Section (RCS), the Energy Dissipation Rate (EDR) and Ballistic Coefficient (Bc), and other OD data. CDM files contain state and covariance information for both objects involved in a predicted close approach encounter at the time of closest approach (TCA). CDM data is considered of much greater accuracy than Two Line Element (TLE) data as it uses higher resolution modeling of orbital perturbations. Also, TLEs do not contain covariance data, so a probability of collision (Pc) cannot be calculated for the encounter. Therefore, TLEs are not recommended for performing CA and are not used by CARA. VCM data contains state and covariance information for a single object at the OD Epoch generated by the ASW. CARA calculations and analysis performed using this data are discussed later in the paper.

While the CDM provides more accurate data than the TLE, the data produced is not without issues of which users should be aware. CARA has investigated two of these issues related to the individual object covariance: the potential for non-Gaussian covariance in the Cartesian coordinate frame and/or potential cross-correlation error in the primary and secondary covariance. Both of these covariance issues violate assumptions necessary for the standard 2D Pc algorithm used by NASA and most other operators to be valid. CARA has investigated the effects of these issues on the CARA process and results. The potential solutions are explored below in the “PROCESS UPDATES” sections *Gaussianity of Cartesian-Framed Covariances*, and *Cross-correlation of Error in Pc Computation*, respectively.

Beyond data contained within the CDM and VCM products, the CARA process also utilizes as input the raw ASW output data. After completing the daily screenings, the COSAs analyze OD data as solved for by the ASW such as the OD arc length, the weighted root mean square (WRMS), the ballistic coefficient (Bc), or other solved-for parameters to identify problems and take action to manually improve the OD solution. Additionally, they review the OD solution for erroneous data or to identify tracking observations in the database that had not been automatically associated with the secondary object in question.

Further, the CARA process uses tasking and tracking data on the secondary (non-protected) object. The DoD has a tasking process to request that SSN sensors task objects and send resulting tracking data back to 18 SPCS to feed the orbit determination process that allows maintenance of the space object catalog. The process is based on placing objects in categories that determine how much tracking will be collected and the priority with which the sensor will attempt to track them. The CARA Team receives a daily Sensor and Tasking File (STF) from the COSAs that provides sensor tracking and tasking information for objects identified in the daily screening including the current tracking priority level for an object, and whether a request has been made by the COSAs to increase the tasking level. Data from the STF is also used to identify potential

future tracking opportunities. While no tracking can be guaranteed for an object, tracking predictions can be useful to determine a potential Go/No Go time for a planned maneuver such that decision-makers know when new tracking data and thus an updated OD solution for a secondary object could be received, hence the best time to set the latest possible decision point.

Finally, primary and secondary object Hard Body Radius (HBR) values are also used as input for an accurate Pc calculation. CARA currently adds O/O HBR values to a static secondary value chosen to reflect the size of 95% of secondary objects encountered. The analysis section *Removing Uncertainty from Pc Calculation* discusses improving the primary object contribution. Further system updates are expected to change the secondary contribution on an event basis depending on the object type (debris, rocket body, or payload) or known object dimensions, if available.

Automated Data Processing

Once the daily screening data, namely the CDMs and STF file, are received from the COSAs, the CARA Conjunction Assessment System (CAS) automatically begins its processing and calculations in order to produce output reports containing event information. The Probability of Collision (Pc) is calculated and the events are assigned a category. Events with a Pc greater than 4.4×10^{-4} are considered “Red” events. These are events that are actively worked by the Operators to ensure the risk is understood and appropriate action taken. Events having a Pc of 1×10^{-7} or less are considered “Green”, meaning that they don’t pose a threat to the protected asset. The only Green events actively worked by CARA Operators are those in which the secondary object is another operational payload. In those cases, CARA reaches out to the other operator to ensure that no maneuvers are planned that could affect the conjunction evolution. Events having a Pc that falls between red and green levels are labelled as “yellow” and are monitored for changes in status. For yellow events an additional criteria is examined, that of the quality of the orbit determination. If the secondary is determined to have a low-quality OD solution, the risk may change if the OD is improved. CARA works with the COSAs to ensure that all possible actions are taken to improve the OD solution. In some edge cases the 2D Pc algorithm cannot be used because the underlying assumptions do not apply. CARA has developed a test to determine which close approaches do not permit the use of the standard 2D PC calculation, and examines several possible approaches to address the issue as discussed in *2D Pc Limitations* section below.

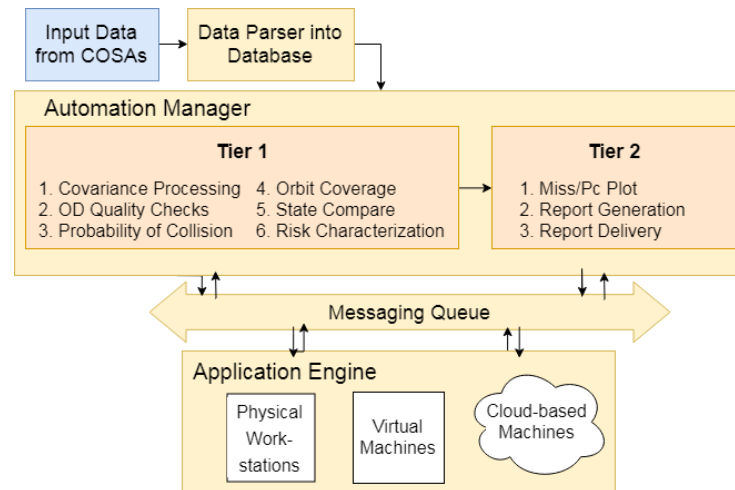


Figure 2: CAS Automation Process Flow

There are many other parameters computed during the automated CAS execution. CAS contains four main pieces: a Data Parser, the Automation Manager, a Messaging Queue, and Application Engines. The interaction of these pieces can be found in Figure 2 below. Automation begins when new data is received from the COSAs and the Data Parser parses and writes the data to a relational database. Once parsed, the Automation Manager follows a predefined set of services needed to generate reports and other output data.

A service is considered a specific calculation like probability of collision, or action such as report generation or distribution. In this way, CAS uses a Service-Oriented Architecture (SOA) giving the system modularity to add, update, or remove services independently of the other software pieces. Further, the Automation Manager is split into tiers which order the services to ensure that any dependencies for a calculation on a previous service are met prior to running. Currently, Tier 1 completes all data calculations and Tier 2 uses the resulting data to generate plots, make reports, and distribute the final output. The services are run in a specific order within the Tiers as described in Figure 2. Services include OD Quality, Probability of Collision, State Compare, Risk Characterization, Report Generation, and Report Distribution.

Each service is called from the Automation Manager via the messaging queue and routed to a workstation that is either **physical, virtual, or on the cloud** to complete the task. Scaling the number of workstations used can decrease the overall time needed to run automation.

Some of the algorithms utilized by the CAS system, such as the 2D Pc algorithm, are being released for public use as Software Development Kits (SDKs). SDKs include the source code along with a number of test cases.

Automated Processing: Output Data

CAS automation produces three main output products. The Risk Characterization Report is used internally by the CARA Team to analyze close approaches to determine which may require further examination or improvements to the OD solution for the secondary. A COSA Worklist report is also produced that rank orders the predicted close approaches by red/yellow/green category, and within those by quality of the OD solution. This report is sent back to the COSAs at VAFB to enable them to focus limited resources on improving those OD solutions that could be most helpful for events that are of high concern. Finally, CA Summary Reports are sent to missions with the latest information on close approaches that the missions are currently considering mitigation for. This report both displays data taken directly from the input files as well as shows results of calculations performed as part of the CAS services. Figure 3a shows the summary data included in the report. Note that screening data is provided for both the ASW and O/O solutions, and that the Pc for each many differ based on whether a maneuver is present in the O/O ephemeris. Figure 3b shows an excerpt from the Summary Report details section that is described further in the following paragraphs.

| Days to TCA | TCA (GMT) | Secondary Object | Primary Ephem Source | Secondary Ephem Source | Screening Epoch (GMT) | Miss [m] | R [m] | I [m] | C [m] | Tracked Since Previous OCM? | Pc |
|-------------|---|------------------|----------------------|------------------------|-----------------------|----------|-------|--------|--------|-----------------------------|------------------|
| 5.8 | 16 Jul 2019 12:14:50 Details | METEOR-M (35865) | ASW | ASW | 10 Jul 2019 15:11:53 | 817.1 | -5.3 | -703.5 | -415.5 | Y | 8.66e-6 (1:115K) |
| 5.8 | 16 Jul 2019 12:14:50 Details | METEOR-M (35865) | O/O + ASW Cov. | ASW | 10 Jul 2019 15:11:53 | 566.0 | 2.6 | -488.0 | -286.7 | Y | 5.04e-4 (1:2K) |

Figure 3a: Sample CA Summary Report Data Note that the ASW solution is yellow while the O/O is red. This is due to propagation and covariance differences in the ASW and O/O solutions.

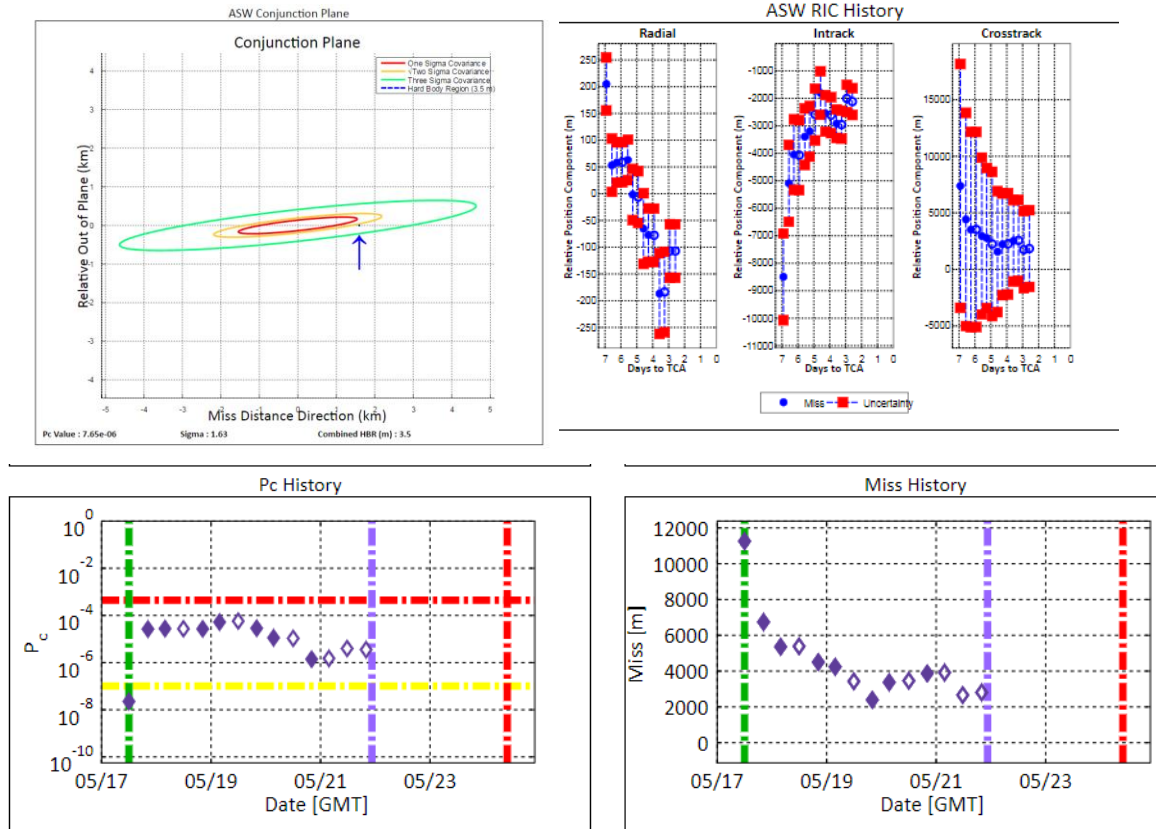


Figure 4b: Sample Report Plots Top Left: 2D Conjunction Plane Plot; Top Right: Radial, In-Track, Cross-Track (RIC) Miss Component and 1-Sigma Uncertainty Time History Plot; Bottom left: P_c Time History Plot; Bottom right: Miss Distance Time History Plot.

The 2D Conjunction Plane shows the relationship between the miss distance, uncertainties, and P_c for an event. The X-axis is the relative position vector and the Y-axis is the relative out-of-plane component. The velocity direction for the event would be the Z-axis for a 3D plot of the event. Additionally, the 1, $\sqrt{2}$, and 3-sigma covariance ellipses are displayed as projected into the 2D plane with the HBR encapsulating the primary and secondary objects placed at the miss distance and identified by the blue arrow. As TCA approaches and new tracking is received for the two objects, the covariance ellipse tends to contract moving the HBR outside of the 3-sigma ellipse. At this point, the P_c for an event usually begins to drop off rapidly. For some events, if no new tracking is received, or the estimated miss distance is particularly small, the P_c may remain static until close to or through TCA. Contraction of the 2D projected covariance for an event at 6- and 1-day to TCA is shown in Figure 4.

The RIC Miss Component Plot with 1-sigma uncertainties in Figure 3b reveals how the Radial, In-Track, and Cross-Track (RIC) components have evolved throughout the event history. An analyst can use this plot to compare the RIC component changes to the 1-sigma component uncertainty to identify unexpectedly large changes. If the covariance for an event is large, due to poor secondary OD for a small debris object or if the primary object recently maneuvered, it is not unreasonable to see kilometers of in-track position change. On the other hand, if both objects are well-tracked, a large change outside of the 1 or 2-sigma uncertainties for the radial component could be a sign of erroneous data and warrants further investigation by the COSAs.

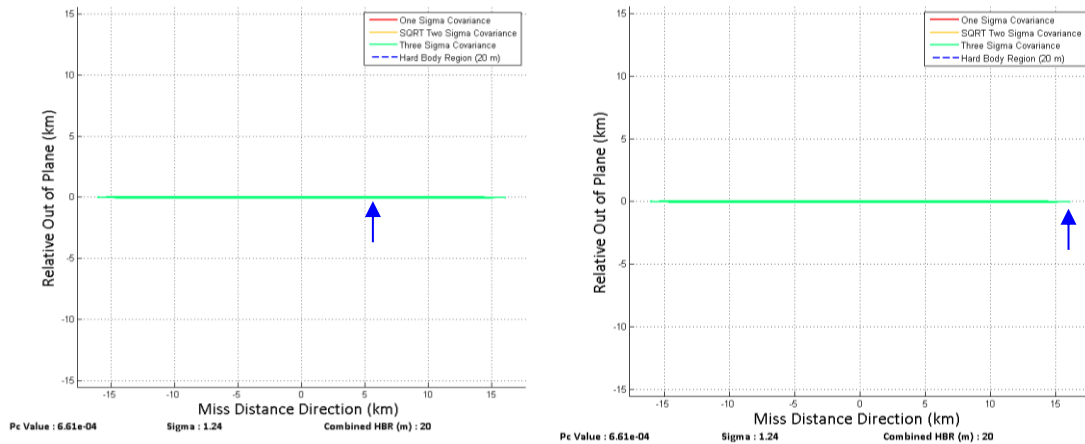


Figure 5: 2D Conjunction Plane Evolution The left plot at 6 days to TCA shows the HBR completely within the 3-sigma ellipse while at 1 day to TCA in the right plot shows uncertainty contraction and an HBR well outside of the 3-sigma ellipse. Over this time period the Pc decreased from high to low Pc.

Last, the Pc and Overall Miss Distance Time History plots are straightforward, showing the evolution over time of these values. The Pc Time History Plot indicates the CARA High and Moderate Risk thresholds in Red and Yellow horizontal lines, respectively. Along the vertical axis, planned maneuvers will be indicated if reported by the O/O. This can be useful to see how a planned maneuver may affect a particular event by increasing or decreasing the Pc.

In addition to plots, a large amount of data either taken directly from the CDM or derived during the automation run is included on the report. This includes individual object information, OD information, and event information. All of this information is reviewed by the CARA Operator to understand an event and make recommendations to mission O/Os. Examples of the data is shown below in Figure 5 below.

| Event Information | | |
|-----------------------------|------------------|------------------|
| | ASW | OO |
| 2D Probability Of Collision | 2.78e-06 | 2.86e-06 |
| 3D Probability Of Collision | 2.78e-06 | 2.86e-06 |
| Radial Miss (Sigma) [m] | -399.5 (312.3) | -400.9 (312.3) |
| Intrack Miss (Sigma) [m] | -1180.0 (8303.0) | -1174.3 (8301.7) |
| Crosstrack Miss (Sigma) [m] | 5696.0 (3619.9) | 5676.8 (3619.9) |

| | | |
|---------------------------|---------------|-------------|
| Apogee [km] | 537.0890227 | 557.6536104 |
| Perigee [km] | 526.1881279 | 532.7129632 |
| Inclination [deg] | 34.97484371 | 97.78200566 |
| RCS [m^2] | 0.2164 | 0.032 |
| HBR | 2.5 | N/A |
| EDR [W/kg] | 8.02e-5 | 2.46e-2 |
| Ballistic Coeff. [m^2/kg] | 0.01305206335 | 5.19061118 |
| Planned Maneuver | N | N/A |
| OD Score | 1.0 | 0.9 |

| Flags | |
|---|--|
| Event | Object |
| <ul style="list-style-type: none"> repeating conjunction event | <ul style="list-style-type: none"> potential active secondary secondary increased tasking requested secondary rcs > 1 sq. m. |

Figure 6: Examples of Event Information, Object Information, and Flags

Event information such as the latest Pc value, individual object components, 1-sigma uncertainties, relative velocity, and approach angle are used to understand the current event behavior and identify further analysis that may be needed. For example, if a low relative velocity is identified, the CARA Operator will know to run the Monte Carlo tool, described in the next section.

The latest Pc value is one of the most important pieces of data that is evaluated by the CARA Operators. Currently, three Pc categories exist: Red or High Risk, Yellow or Moderate Risk, and Green or Low Risk. Most, but not all additional analysis is dictated by the Pc being in the High Risk category. Moderate and Low risk events as determined by the Pc value may require additional analysis based on the flags identified for the primary, secondary, or overall event. New Pc threshold analysis explores the collision consequence for an event particularly if a collision between the primary and secondary is predicted to create a high or low number of debris objects. This new analysis is further described in the *Collision Consequence* section below.

Individual object information such as the apogee, perigee, inclination, RCS, EDR, and Bc provide further insight into any event. For example, a high EDR (such as 2.46×10^{-2}), indicates that the object is more likely to have changes in its predicted state due to atmospheric drag predictions, and so may be subject to large changes in predictions between updates. Objects with a high Bc (more sheet-like) and/or at low orbit regimes are more likely to have a high EDR. Further, these objects require shorter OD solutions that require a higher density of tracking. Understanding this relationship and comparing to the OD information provided, allows CARA Operators to make decision as to whether a definitive OD solution or its future propagation, can serve as the basis for CA, or if the event is inactionable due to a poor OD solution or other event parameters.

Also shown are some of the many event and object flags that are identified through the automated process. Event flags could indicate that there is a repeating conjunction event where a primary has multiple close approaches with the same secondary object. Object flags are specific to a primary or secondary including many flags about the OD information; such as the suitability of the OD arc length or if the OD Weighted Root Mean Square (WRMS) value is too high, if there are upcoming or recent maneuvers, or if the object is tracked by a single station. These flags are evaluated by the CARA team after each screening both by the CARA Operators and the COSAs. The COSAs receive the object and event flags via the COSA Worklist that

is delivered with each automation run. They will focus on the OD-related flags as well as other OD information provided in the Worklist described further below. Similarly, the CARA Operators will use the flags to identify additional tools that need to be run as described in the *Manual Data Processing* section.

The COSAs review the event and object data via the COSA Worklist that prioritizes events for manual OD checks by Pc and their OD Score. The OD score is calculated based on some of the flags described previously, and a score less than one indicates that deficiencies in the OD have been identified. Depending on the object and its characteristics updates to the OD may or may not be feasible. Nevertheless, the effort of the COSAs to improve the object's OD solutions help improve accuracy and reduce the covariance size for an object's definitive state and orbit prediction. In some cases, these OD checks can lead to changes to the overall event solution including significant increases or decreases in Pc. While the automated OD process works for a majority of objects, having the COSAs perform manual OD updates is a critical part of the CARA Operations process and directly tied to information calculated by the CAS system.

The data and plots shown here, plus additional information are evaluated for HIEs at each update, nominally 2-3 times per day. From here, the CARA operator will decide the necessary next steps including which manual tools need to be run and when to contact a mission O/O about an event. The manual tools and their output are described in the following section.

Manual Data Processing: Tools and Output

Using the output report, the CARA Operator will determine which events are considered high interest and will need further analysis. The CARA Operator recommendation for a mission to perform a maneuver for an HIE is largely based on the event Pc. The use of the Pc and other event data as a basis for CA recommendations was analyzed on a philosophical level as described in the *Collision Probability, Possibility, and Plausibility* section below. Ultimately the mission O/O is responsible for the final maneuver decision as operational risks must be considered alongside the conjunction risk.

Multiple tools can be run for additional information and to determine recommendations including the HIE Briefing, Pc vs. HBR, Maneuver Trade Space (MTS), Sensor Coverage, Maneuver Screening Analysis (MSA), Space Weather Trade Space (SWTS), and Monte Carlo Pc Calculation. Descriptions of each tool and their output can be found below.

HIE Briefing

Once the CARA Operator has analyzed the event, he will work with the Owner/Operator to determine the best course of action. One tool that CARA uses to communicate with the O/O is the HIE Briefing is generated by a CARA Operator to provide the mission O/O with more details about an event. A portion of the briefing is shown in Figure 6 below. The starting output from the automated HIE Briefing Tool is a PowerPoint with default slides and data that are then updated manually to include CARA recommendations and supporting offline analysis results. In addition to the plots described in the automated output section above, the HIE Briefing will generally also include output from many of the manual tools such as MTS, MSA, and SWTS. These are run separately by the analyst and input into the briefing. Any information, plots, or data deemed relevant to decision-making for an event will be included in the briefing in addition to anything requested specifically by the mission.



Primary vs. Secondary HIE Briefing

TCA: 11 Nov 2016 at 14:11:26 UTC
Briefing number 1

NASA Robotic CARA Team

Briefing Creation Time: 10 November 2016 18:24 UTC

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Executive Summary

- Executive Summary
- Primary Object Information
- Secondary Object Information
- Conjunction Geometry
- Conjunction Event History
- Space Weather
- Sensor Coverage
- Maneuver Planning
- Summary & Recommendations
- Backup

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Summary & Recommendations

Event Summary
Primary vs. Secondary

TCA: 11-Nov-2016 14:11 UTC
Time to TCA: 0.8
ASW CDVs Received: 19
O/O CDVs Received: 16
Last CDV Received: 10-Nov-2016 15:58 UTC
Next Delivery: 11-Nov-2016 00:00 UTC

| Current Risk Summary | | |
|--------------------------|----------|----------|
| | ASW | O/O |
| Probability of Collision | 1.70e-04 | 1.66e-04 |
| Miss Distance (m) | 3601.1 | 3568.0 |
| Radial (m) | 114.9 | 120.7 |
| In-Track (m) | -2590.9 | -2568.7 |
| Cross-Track (m) | -2498.4 | -2473.4 |
| HBR (m) | 20.00 | 20.00 |

The CARA team is confident in our risk assessment analysis because:

- We have confidence in the secondary object's epoch state solution.
- We have confidence in the secondary object's state and state uncertainty predictions.

Recommended Course of Action:
- Monitor through TCA

- **Summary**
 - Secondary is poorly tracked
 - Low probability of detection for opportunities prior to TCA
 - Due to uncertainties large maneuver is required to mitigate risk
- **CARA Team Recommends**
 - Monitor event

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Figure 7: Sample HIE Briefing Output. The sample output includes the title page, agenda, executive summary and the final summary and recommendation slide. Most of the manual tool output is included.

One of the most important parts of the HIE Briefing is the CARA Operator Recommendation. In the example, the recommendation was to monitor the event only. In other cases, it may be to plan and screen a maneuver based on the times and sizes provided or to execute a maneuver that has already been screened and deemed safe. As stated previously, the decision to maneuver is made by the mission O/O with the CARA Operator providing a recommendation based on the latest CA data available. Other operations conflicts or constraints may preclude a mission from maneuvering or drive a more conservative maneuver decision than what is recommended by CARA.

Pc vs. HBR

The Pc vs. HBR tool allows the CARA Operator to evaluate a more accurate Pc value for an event based on the size of the secondary object. Because the CAS automation uses a static secondary object contribution, some events may have a Pc calculated with an oversized or undersized HBR. This is particularly the case when the secondary object is a large payload or rocket body.

When a mis-sized HBR is identified, generally due to a large secondary object, the CARA Operator will run the Pc vs. HBR tool to calculate a series of Pc values based on varying the HBR. Sample output from the tool is shown in Figure 7 below. Whether the Pc is higher, lower, or substantially the same as compared to the nominal Pc is communicated to the mission O/O. Any new recommendations based on the adjusted Pc are also provided. Using variable HBR estimates in the software to more accurately reflect the object size and thus minimize inaccuracies in the initially computed Pc would be preferable. Presently, there are complex challenges for implementation due to the wide array of data formats used by mission that would have to be ingested and utilized. CARA has investigated a number of alternatives and is currently considering making software and process updates in this area in anticipation of the higher workload anticipated once Space Fence comes online. Efforts are described in the *Removing Uncertainty from the Pc Calculation* section.

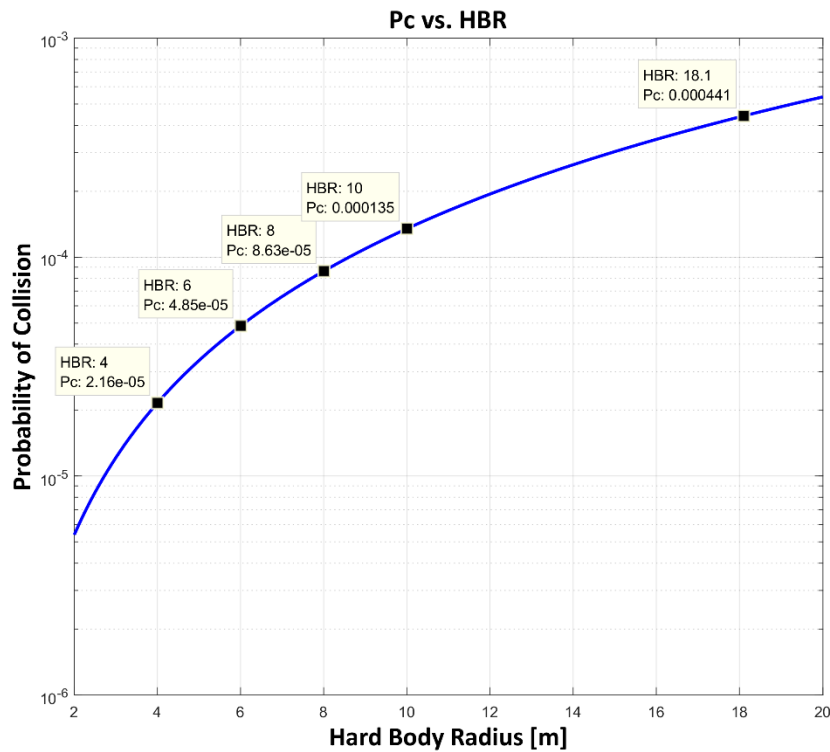


Figure 8: Pc vs. HBR Plot This plot shows that the Pc for the event can vary from 4.4×10^{-4} which is considered high risk for a 18.1 m HBR to 2.16×10^{-5} which is considered moderate risk for a 4 m HBR. The more accurate 4 m HBR changes the CARA recommendation from maneuver to monitor.

Maneuver Trade Space (MTS)

For almost every HIE, the CARA Operator will generate Maneuver Trade Space (MTS) plots for the O/O. These plots are a valuable tool in enabling the operator to choose a target mitigation maneuver time that meets mission requirements and constraints while sufficiently mitigating the maneuver. Without this tool, missions would choose a maneuver time that was convenient, have the COSAs screen it, then potentially find that the chosen maneuver did not fully mitigate the risk and/or caused new conjunctions with other objects. Having this tool allows missions to choose a feasible maneuver that they know will mitigate the conjunction without wasting valuable time before TCA to iteratively screen multiple maneuver options. The larger the delta-v of the predicted maneuver, the more likely new events will be identified post-maneuver. CARA operators recommend leaving enough time during maneuver planning for at least two iterations of maneuver development and screening, although generally one is sufficient.

For missions with chemical propulsion, an MTS plot will look like the output in Figure 8 below. The Y-Axis gives a range of maneuver start times and the X-Axis a range of maneuver delta-vs. For each pair of maneuver time and delta-v, a new event Pc is calculated by applying those maneuver parameters to the no-burn solution of the primary. The plot contour coloring corresponds to the resulting post-maneuver Pc value using a log scale ranging from a Pc of 1×10^{-10} to 1. Pcs below 1×10^{-10} are considered to be 0 for the purposes of risk mitigation. The nominal no-burn Pc can be found along the y-axis because that is where the delta-v magnitude is 0. CARA has historically made a conservative post-maneuver remediation Pc recommendation of 1×10^{-10} based on previous analysis. This value has been known to be overly conservative, so new remediation thresholds have been developed through recent analysis as described in the *Remediation Threshold* section below.

In the example in Figure 8, a delta-v of 3 cm/s is predicted to fully mitigate for a series of maneuver times from 12 hours to TCA through TCA. These ideal maneuvers occur about once per orbit at TCA – $(N + \frac{1}{2})$

orbit, a location that enables a maximum radial separation at TCA. Additional in-track separation is accumulated, but this will occur over many hours to days, rather than nearly instantaneously for the radial separation increase.

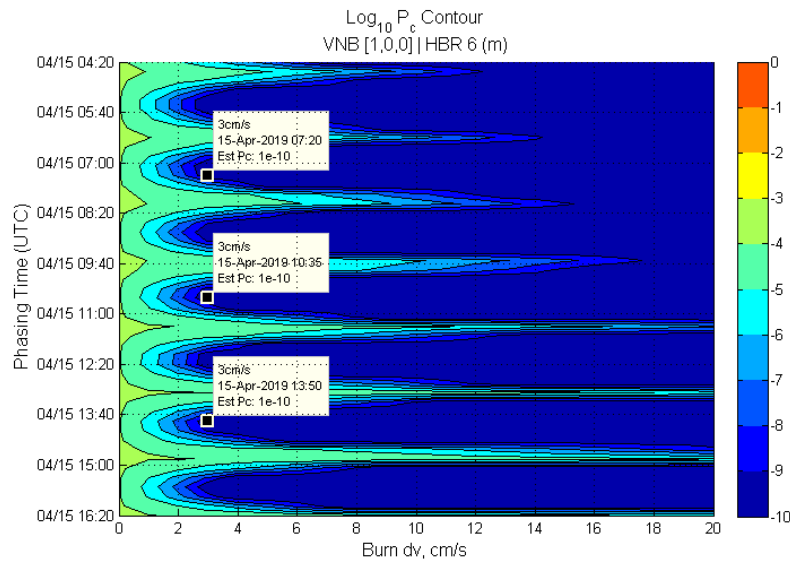


Figure 9: MTS Output. Recommended maneuvers are highlighted manually by the CARA Operator.

Each mission supported by CARA has different maximum, minimum, and average delta-v values, as well as the ability to perform maneuvers in different directions. This information is taken into consideration by the CARA Operators when running MTS so as to provide the most useful output to the mission. The tool can also be run to look at maneuver sensitivity for a planned Station Keeping or Orbit Raise maneuver. In this mode, the Operator can see if a change in the time or size of a nominally planned maneuver can mitigate an upcoming event. Screening a planned maneuver prior to its execution is always required to ensure no new high risk events outside of the current screening volume are identified.

In addition to considering maneuvers that mitigate the HIE, all other events received within the screening volume are analyzed. This allows the recommended maneuver to be adjusted as needed based on the effects of other events. In some cases, the ideal maneuver for the HIE will introduce a new high risk event, as shown in Figure 9. The numerical values are not important, but the Pc contours clearly show an example of this issue. The plot on the left shows that for the primary event of concern, a maneuver size of about 4.5 cm/s provides sufficient mitigation, however the plot on the top right shows that this maneuver significantly increases the Pc with another event post-maneuver. The bottom plot shows the overall effect of increasing the maneuver size to about 9 cm/s to avoid both objects.

The MTS plot can be generated for differential drag or electric propulsion missions given a known change in the Bc or the amount of constant thrust, respectively. Maneuvers of this type generally require more time for full mitigation and will need to be performed early in order to accumulate in-track separation over time. In general, chemical propulsion, particularly if available in the retrograde and posigrade directions is the most flexible for CA risk mitigation.

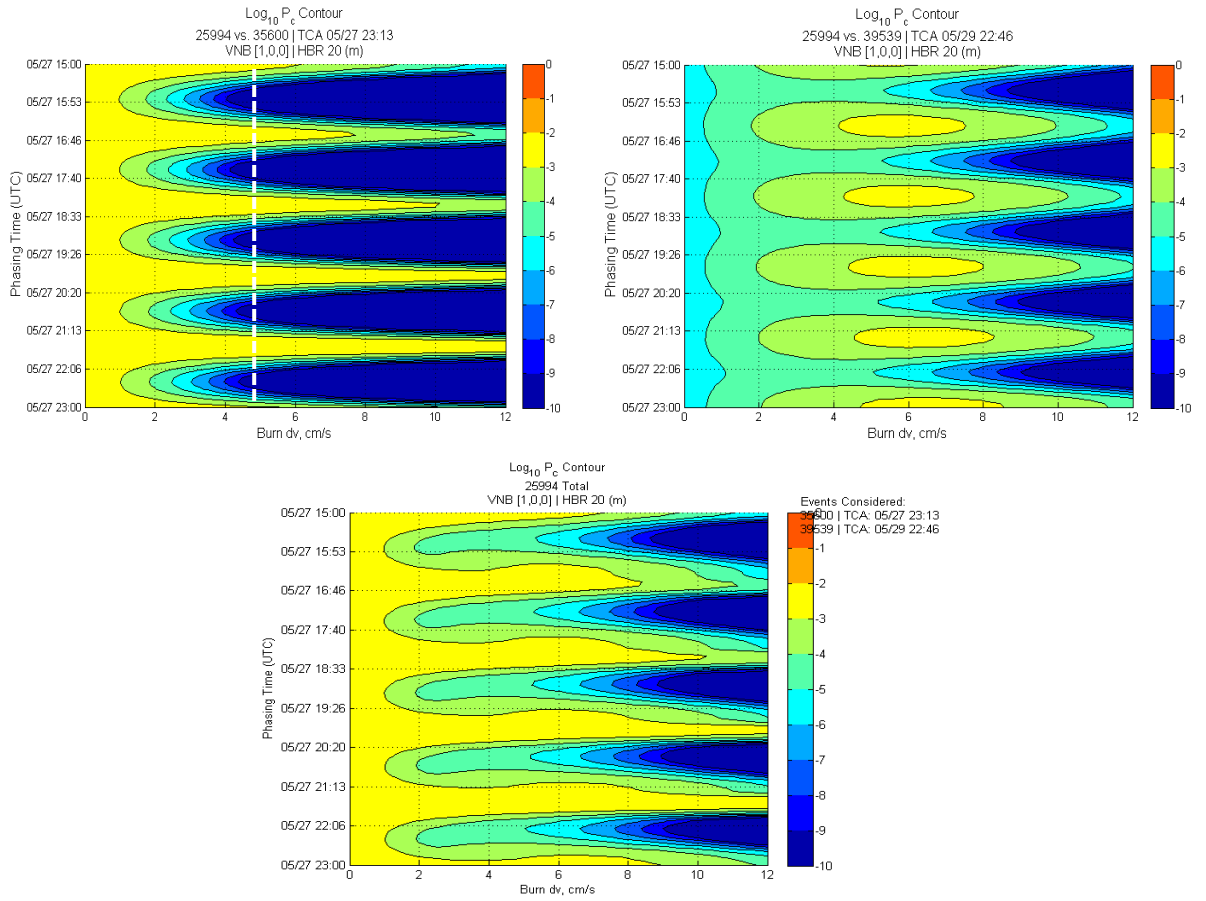


Figure 9: MTS Output for multiple events.

Once a mission plans a Risk Mitigation Maneuver (RMM) based on the MTS times and sizes recommended by CARA, they will produce one or more ephemerides modeling the planned maneuver. Often multiple times and sizes are analyzed to improve the likelihood that one of the screened maneuvers is safe, and/or to analyze possible hot or cold burns. If all screened maneuvers show post-maneuver events of concern or do not fully mitigate the primary event, the mission will attempt to re-plan and rescreen a new set of maneuvers.

The effects of newly introduced events on the maneuver recommendation is based on their P_c, post-maneuver time to TCA, and OD Quality. In some cases, there is a risk of needing to perform multiple RMMs in close succession if there are limited mitigation options presented. In some cases, a high or moderate risk secondary event will decrease in P_c before a subsequent maneuver is needed.

The example MSA output below in Figure 10 shows the comparison of three maneuvers planned by a mission to mitigate an event with the secondary object. The maneuver modeled in the first ephemeris only mitigates the P_c for the event to 4.86×10^{-5} and would not be recommended as it is still too high of a risk and may require a second maneuver too soon after the first. Either of the other maneuvers mitigates to 0 and given no other post-maneuver events, either would be recommended.

| Secondary | Ephemeris Name | Covariance Source | TCA (GMT) | Miss Distance (m) | Radial Miss (m) | InTrack Miss (m) | CrossTrack Miss (m) | Pc |
|-----------|--------------------|-------------------|----------------------|-------------------|-----------------|------------------|---------------------|----------|
| 00000 | ManeuverEphemeris1 | O/O CCSDS | 21 Feb 2019 11:35:16 | 1589.9 | 58.54 | 1187.15 | -1057.47 | 4.86e-05 |
| 00000 | ManeuverEphemeris2 | O/O CCSDS | 21 Feb 2019 11:35:16 | 987.5 | 124.46 | 729.59 | -653.79 | 0 |
| 00000 | ManeuverEphemeris3 | O/O CCSDS | 21 Feb 2019 11:35:16 | 793.3 | 163.09 | 578.38 | -517.82 | 0 |

Figure 10: MSA Output. *Three maneuver options were screened with the latter two mitigating to a 0 Pc*

Sensor Coverage

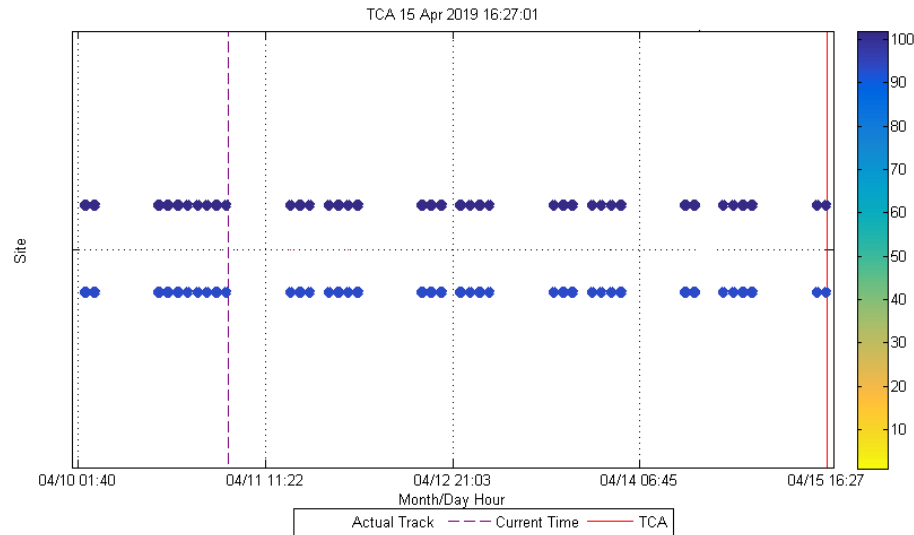


Figure 11: Sensor Coverage Output. *Tracking opportunities from one site is predicted.*

The Sensor Coverage tool is used to identify potential tracking opportunities for a secondary object. Knowing when tracking passes might be available enables operators to determine what the latest time is that should be used as a decision point for maneuver execution to include the most recent data. Figure 11 shows an output example from the tool. In this example, there is one sensor that is predicted to track the secondary object with multiple opportunities prior to TCA. In this example, the last set of predicted tracking occurs right before TCA (the red vertical line), and would not be received at 18 SPCS prior to TCA, so a decision point after the previous pass would have the latest possible data and waiting is not beneficial.

It is important to note that these are predicted tracking opportunities only, and there is no way to guarantee that an object will receive new tracking. There are many barriers to tracking such as sensor visibility, planned and unplanned sensor outages, higher priority objects, incorrect sensor radar strength or pointing position for acquisition, or in rare cases, miss-tagged observations. When new tracking is received on a secondary, the COSAs will receive an Automatic Observation Notification (AON) message. This is a cue for the COSA to generate a 1v1, an update that is for a single event primary vs. secondary. In some cases, the new tracking can lead to significant changes to the OD solution and event Pc and change the final remediation decision.

Space Weather Trade Space (SWTS)

Space Weather events such as Coronal Mass Ejections (CMEs) are still poorly understood and hard to predict at intervals greater than 3 days. However, atmospheric drag is the largest uncertainty factor in predicting future trajectories for low earth space objects, so it is important that the modelling used in those trajectories is as accurate as possible. The 18 SPCS uses the High Accuracy Satellite Drag Model (HASDM) with Jacchia-Bowman 2009 modelling, which applies coefficients to model the atmosphere based on tracking behavior of calibration satellites and modelling space weather phenomenon^{1, 2, 3}. CARA has developed a Space Weather Trade Space (SWTS) tool to assist operators with understanding how the Pc for a conjunction

event could be affected by any mis-modelling present in the trajectory prediction due to the poorly understood phenomena.

The tool runs a series of Pc calculations after varying the primary and secondary Bc values and propagating to TCA. The Bc value acts as a proxy to the atmospheric density as they are multiplicative in their effects on an object's acceleration. This produces a trade space of values around the nominal Pc. If there is high sensitivity to atmospheric changes and on-going solar activity is identified, confidence may be decreased in the current Pc. Alternatively, if there is low sensitivity during solar activity, a greater confidence can be placed in the Pc.

SWTS plots are classified as “At Peak”, “Off Peak”, and “Flat”. An “At Peak” plot will have atmospheric miss-modeling that is predicted to decrease the Pc from the nominal value. “Off Peak” events have the potential for increased risk with a higher Pc predicted due to miss-modeling. Both “At Peak” and “Off Peak” outputs represent sensitivity to miss-modeling. On the other hand, “Flat” output for an event indicates that miss-modeling is not expected to significantly change the Pc and thus sensitivity is low. Examples of varying event sensitivity to changing atmospheric drag can be seen in the various plots in Figure 12.

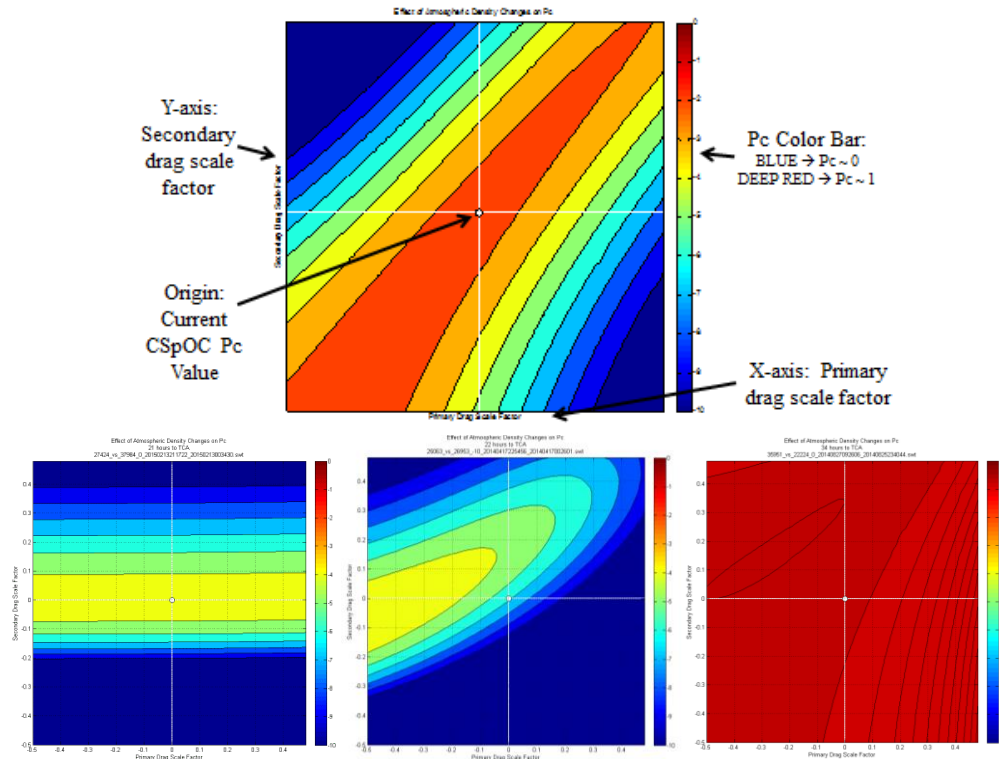


Figure 2: SWTS Output Examples. The top plot described the SWTS plot for event where the primary and secondary are about equally sensitive to changes in drag and the current Pc is “At Peak”. Below from left to right you have a highly sensitive secondary object and “At Peak” Pc, a sensitive primary and secondary “Off Peak”, and insensitive primary and secondary “Flat” plot.

Monte Carlo Pc Calculation

The Monte Carlo Pc Calculation is needed to produce an accurate Pc when the underlying 2D Pc assumptions fail. These assumptions are identified in the *2D Pc Limitations* section below. A common reason to run Monte Carlo is when an event has low relative velocity. In these cases, the assumption that the event occurs nearly instantaneously fails. Another reason to run Monte Carlo is for repeating conjunction events where a primary has many close approach events with the same secondary over a short time period. This situation is further described in the *Repeating Conjunctions* section below.

Once identified, there are two types of the Monte Carlo Pc Calculation can be used. First, based on the analysis described in the *Faster Monte Carlo* section below, a Monte Carlo Pc calculated beginning at TCA using the CDM data provides the needed accuracy for the vast majority of CA risk assessment. This “CDM-mode” Monte Carlo can produce a result in minutes, with faster output the higher the nominal Pc value. This is a significant improvement in CPU time over the Brute Force Monte Carlo (BFMC) tool further described below.

For the minority of events that require a more robust calculation, the BFMC tool was developed. The main difference in the BFMC tool is the use of the VCM rather than the CDM for the event input data. Propagating the initial OD state from epoch provides greater accuracy than performing multiple instances of propagation on a CDM, both backwards and forwards in time. To increase the speed of the BFMC, which can take hours for high Pc events to days for low Pc or long propagation time events, deploying in a parallelized fashion to the cloud is being explored.

Output plots, which are similar for both versions of the Monte Carlo Tool, are shown in Figure 13. The output shows the nominal Monte Carlo Pc, confidence intervals for the Pc (orange band centered on nominal solution as defined in Hall⁴), and a comparison to the 2D Pc. The confidence interval indicates the likelihood that the true Pc value lies within the interval provided. More trials are needed to increase the confidence level and shrink the confidence interval band. The example in Figure 13 uses more trials to reduce the 99% confidence interval. Typical confidence levels used are 95% or 99%.

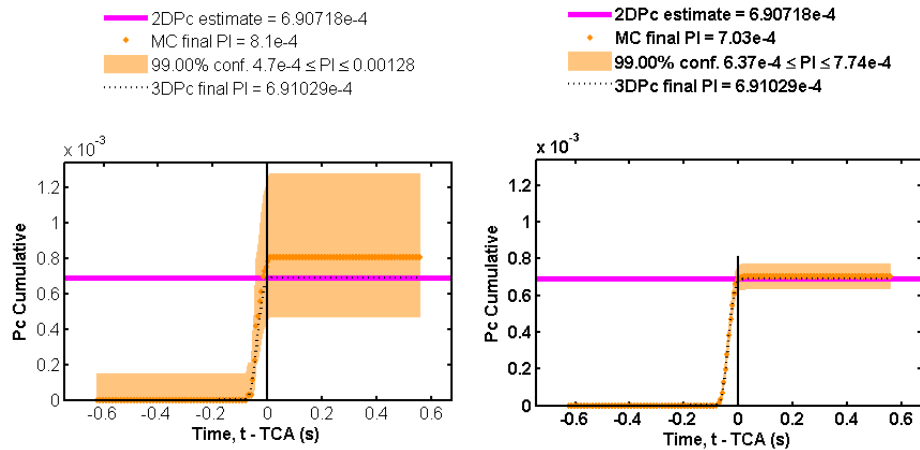


Figure 13: Monte Carlo Output. Two output plots are shown here using different numbers of trials. The left plot used 3.4E6 trials compared to 1.01E6 trials on the right. The increased number of trials reduced the 99% confidence interval. Both show the nominal 2D Pc within the confidence interval.

PROCESS UPDATES AND SUPPORTING ANALYSIS

While the existing CARA process is very robust and has served the Agency well for the past 15 years, the rapidly evolving space environment is driving the need for improvements in the process to meet evolving needs. Over the past 1-2 years, CARA has embarked on a rigorous set of analyses to develop solutions to aspects of the process that offered opportunities for improvement. This section describes each of the identified areas and the chosen solution. Each area highlighted herein is described fully in a referenced standalone paper.

Removing Uncertainty from Pc Calculation

In order to ensure that the number of events is limited to only those that are true threats as much as possible, the amount of uncertainty inherent in the Pc computation needs to be well understood, and minimized to the extent reasonable. One way to do this is to appropriately size the Hard Body Radius (HBR), the combined frontal area of the objects involved in the encounter. Historically, NASA missions have typically chosen their HBR in an extremely conservative manner, thus artificially increasing the probability of collision and assessed risk of the event. A recent analysis was performed by Mashiku⁵ that develops an array of

different HBR options (stab in dark, circumscribing sphere, maximum projected area into any plane, actual projected area into conjunction plane) and characterizes the differences that these varied approaches visit upon the Pc. NASA plans to implement this range of different HBR approaches into its regular processing chain so that, especially for high-interest events, the differences in resultant Pc values driven by different HBR choices can be made manifest and help to inform the decision process. Since Pc varies with the square of hard-body radius, changes in the employed HBR can have a substantial impact on the resultant Pc and thus overall expected level of conjunction likelihood.

2D Pc Limitations

The 2-D Pc computation relies on a number of assumptions, but it is often not clear in any given situation whether these assumptions are honored. An analysis performed by Hall⁶ developed a test to evaluate the reasonability of one of these assumptions: whether the covariance is sufficiently static over the encounter interval that it can be considered essentially constant. CARA will implement the test to be applied automatically to each predicted close approach to determine whether the assumption inheres for any particular case. If it does not, the system will notify a CARA operator that a Monte Carlo Pc calculation will need to be run for this particular case.

Gaussianity of Cartesian-Framed Covariances

The limitations of the ability of a Cartesian covariance to represent the “true” state uncertainty volume can cause misrepresentation and, in some cases, incorrect Pc computations. An analysis undertaken by Lechtenberg⁷ develops and implements a particular test for the ability of the Cartesian covariance adequately to represent a state estimate’s error volume, producing test thresholds for concluding adequate Gaussian behavior in Cartesian space and profiling past conjunction histories to establish the severity of the problem. CARA will implement these thresholds operationally to test each close approach to ensure that a Cartesian-based 2-D Pc calculation can be used; if not, the system will notify a CARA operator that a Monte Carlo Pc calculation will need to be run for this particular case.

Faster Monte Carlo

Because it is dependent on certain assumptions, the 2-D Pc cannot be used ubiquitously; but the main alternative, Monte Carlo approaches, can be computationally prohibitive. An analysis by Hall⁴ demonstrates that for most classes of conjunctions that encounter difficulties with the analytic 2-D Pc calculation, the correct Pc can be calculated with Monte Carlo techniques that proceed from the TCA states and covariances, rather than the much more computationally demanding approach of proceeding from epoch. This strain of Monte Carlo calculation, which works with the TCA states and covariances but with the state uncertainty sampling performed in equinoctial elements, is being integrated with the NASA automated conjunction assessment system so that it can be automatically invoked in those situations in which the 2-D Pc is judged to be inadequate and for which Monte Carlo from epoch is not necessary.

Repeating Conjunctions

Conjunctions that exhibit low relative velocity often do not have a well-defined TCA and therefore cannot be evaluated by the 2-D Pc or Monte Carlo at TCA formularies. An analysis by Baars⁸ develops a mode of from-epoch Monte Carlo that spans a stated temporal duration (rather than encounter boundaries) and reports the accumulated risk. Profiling of conjunction histories with this capability has helped to establish guidance for determining in which situations time-span-based, rather than TCA-based, Monte Carlo Pc calculations are advisable.

Collision Consequence

Even though risk evaluation is generally conducted as the combination of likelihood and consequence, CA operations has nearly entirely focused on the likelihood portion and not the consequence, at least in terms of a conjunction’s debris production potential. This analysis by Lechtenberg⁹ deploys fragmentation algorithms developed by the NASA ODPO to assess the debris production potential of any given conjunction. Such information can be used for triaging multiple conjunctions or setting different remediation requirement levels based on the debris production consequence. NASA is still considering how best to make use of this capability; however the analysis was undertaken with the assumption that the additional workload caused by

Space Fence and large constellations may make it difficult to analyze each predicted close approach, so the consideration of consequence is an additional way that the mitigation options can be narrowed. CARA intends to provide as part of each conjunction's analysis an estimate of the expected debris production should it result in a collision as a consideration when making risk assessment and mitigation decisions.

Cross-correlation of Error in Pc Computation

Most CA risk assessment activities proceed presuming that the errors in the primary and secondary state estimates are independent and thus that their two covariances are uncorrelated; combination of covariances can thus be accomplished by simple addition. However, it is known that these covariances actually do contain shared errors, especially if these covariances were initially adjusted to compensate for errors expected to be encountered in prediction. An analysis by Casali¹⁰ develops a method to identify the shared error and represent its presentation at TCA, so that the shared elements can be identified and the shared error removed when forming the joint covariance. The USAF plans to place in the remarks field of the CDM primary and secondary object drag sensitivity vectors to allow a decorrelated joint covariance to be formed, which can then be used to calculate a more reliable 2-D Pc.

Remediation Thresholds

It is necessary to establish risk assessment parameter thresholds in order to identify high-interest events, but these values are often chosen somewhat arbitrarily and cannot point to an analytical basis. An analysis by Hall¹¹ uses a large historical conjunction database to establish relationships among lifetime risk postures and individual event remediation thresholds, further considering the role of HBR, satellite orbital lifetime, and post-remediation risk level. These analytical results will be provided to interested owners/operators as an aid in setting appropriate high-interest event thresholds for their particular spacecraft.

Collision Probability, Possibility, Plausibility

While CA risk assessment has proceeded for years with a well-established set of practices, the formalisms that govern these practices have been implicit and not laid out in a philosophical context. An analysis by Hejduk¹² establishes the governing principles, fundamental question, and null hypotheses that provide the foundation for the NASA CARA risk assessment enterprise. This supporting philosophical structure aids in the proper selection of risk assessment parameters and illuminates proper, defensible, and consistent action in response to varied risk assessment situations.

OPERATIONS DEVOLUTION

NASA is currently considering instituting a paradigm called "devolution" under which the operations portion of CARA could be pushed out to the mission flight operations teams to handle along with their other operations work. CARA would retain the CA technical authority under the Office of the Chief Engineer continuing to provide analytical research and development as well as operations support to non-devolved missions. A new NASA Standard will be created that will govern the CA process for the Agency's unmanned missions, providing a framework within which the devolution can occur. The Agency is currently conducting two Pilot Programs over the course of the next two years. All the necessary requirements and supporting processes will be developed and implemented for a few missions during the Pilots. Upon completion, results will be presented to Agency management, who will weigh any additional risk and/or cost against potential flexibility/automation offered by the devolution paradigm, and a decision will be made whether to allow additional mission to use the devolution framework in the future.

In support of devolution, CARA will evaluate 3rd party tools to determine whether they meet the Agency's CA needs. A tool certification plan has been developed that identifies the critical features that must be present for a CA tool used by NASA. These features are listed in Table 1. Test cases are available for each item, and the list is expected to evolve over time as the industry changes.

| Item | Tool Feature | Topical Area | Non-Maneuverable Spacecraft Requirement | Maneuverable Spacecraft Requirement |
|------|--------------|--------------|---|-------------------------------------|
|------|--------------|--------------|---|-------------------------------------|

| | | | | |
|---------------------------------------|--------|--|---|--------------------------------------|
| Point Estimate of Risk | T-1.1 | Miss-Distance Reporting | <input type="checkbox"/> | <input type="checkbox"/> |
| | T-1.2 | 2-D Pc Calculation from ASW data | <input type="checkbox"/> | <input type="checkbox"/> |
| | T-1.3 | Identify and flag when 2-D Pc Calculation from ASW data is Non-Positive Definite | <input type="checkbox"/> | <input type="checkbox"/> |
| | T-1.4 | 2-D Pc Calculation from ASW data with Covariance Cross-Correlation | <input type="checkbox"/> | <input type="checkbox"/> |
| | T-1.5 | Indication of 2-D assumption inadequacy | <input type="checkbox"/> | <input type="checkbox"/> |
| | T-1.6 | Owner/Operator Ephemeris/Pc Calculation | <input type="checkbox"/> (HEO,GEO), <input type="checkbox"/> (LEO) | <input type="checkbox"/> |
| | T-1.7 | Identify and flag Missing Covariance for Pc Calculation | <input type="checkbox"/> (or T-1.8) | <input type="checkbox"/> (or T-1.8) |
| | T-1.8 | Covariance Synthesis Capability | <input type="checkbox"/> (or T-1.7) | <input type="checkbox"/> (or T-1.7) |
| | T-1.9 | Monte Carlo from TCA: equinoctial frame | <input type="checkbox"/> (or T-1.10) | <input type="checkbox"/> (or T-1.10) |
| | T-1.10 | Position Monte Carlo from Epoch | <input type="checkbox"/> (GEO) | <input type="checkbox"/> (GEO) |
| | T-1.11 | Collision Consequence | <input type="checkbox"/> | <input type="checkbox"/> |
| Pc Error Analysis | T-2.1 | Covariance mis-sizing sensitivity | <input type="checkbox"/> (or T-2.2) | <input type="checkbox"/> (or T-2.2) |
| | T-2.2 | Pc Uncertainty: Full consideration of all error sources | <input type="checkbox"/> | <input type="checkbox"/> |
| Predicted Situation at Decision Point | T-3.1 | Historical Pc Trending (Event Histories) | <input type="checkbox"/> | <input type="checkbox"/> |
| | T-3.2 | Space Weather Sensitivity | <input type="checkbox"/> | <input type="checkbox"/> |
| | T-3.3 | Tracking Prediction | <input type="checkbox"/> | <input type="checkbox"/> |
| | T-3.4 | Predictive Pc Trending | <input type="checkbox"/> | <input type="checkbox"/> |
| Maneuver Planning Aids | T-4.1 | MTS: Single Conjunction | N/A | <input type="checkbox"/> |
| | T-4.2 | MTS: Multiple Conjunctions | N/A | <input type="checkbox"/> |
| | T-4.3 | Maneuver Trade-Space: Execution Error | N/A | <input type="checkbox"/> |
| Stress Loading | T-5.1 | Loading Performance Test | <input type="checkbox"/> | <input type="checkbox"/> |

Table 1: Identified Tool Features for CA, Both Required ☐ and Optional ☐

CONCLUSIONS AND FUTURE WORK

The CARA program follows the life cycle of a spacecraft, from providing analysis during the design phase, simulating support in preparation for operations, supporting routine on-orbit operations including ascent and descent maneuvers, and assisting with anomaly resolution. During the on-orbit phase, Operational activities are accomplished by a combination of the CARA COSAs and the CARA Operators located at VAFB.

The space environment is changing rapidly. Operators are becoming less traditional, to include even elementary schools, so it is important to share lessons learned from those operators who have many years of

experience in the field to ensure safety of flight and preserve the space environment for future generations. The United States, especially the Department of Commerce, is working to develop a Space Traffic Management (STM) architecture that is expected to change the CA offerings that are available to spacecraft operators. NASA plans to continue to operate using the existing partnership with DoD during this time of change; however CARA will continue to evaluate changes to the state of the art and incorporate updates as they are determined to meet the Agency needs.

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