Recommended methods for setting mission conjunction analysis hard body radii

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Agenda and Overview

- **Introduction**
  - Motivation and objectives
  - Primary satellite area projection methods
  - Projected-area variational effects to Hard Body Radius (HBR)
- **Analysis Approach and Results**
  - HBR profiles investigated
  - Dataset used
  - 2D-Pc profile range analysis
- **Conclusions and Recommendations**

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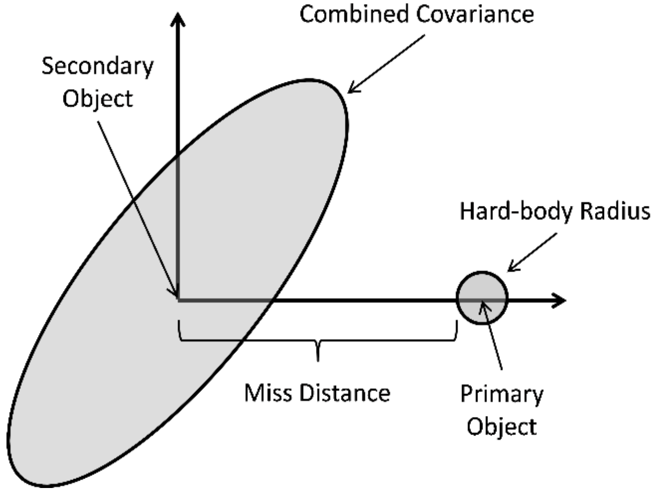
Motivation and Objectives

Motivation

- The probability of collision (Pc) calculation takes into account the entire circular area on the conjunction plane and thus the Pc values may at times be over-estimated, especially for non-symmetrical spacecraft whose center of mass is not the center of the object



Hard-body Radius and Covariance schematic for Probability of Collision (Pc) calculations

- The over-estimation of Pc can be shown to be an especially important factor when attempting to meet certain long-term collision risk goals for a particular mission.

Motivation and Objectives

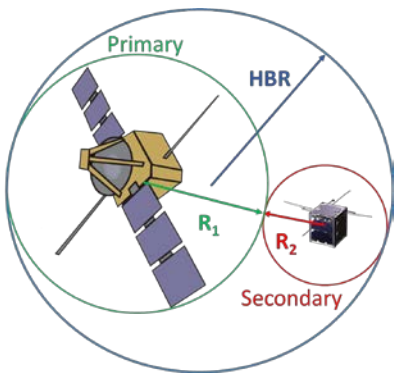
Objective

- Various approaches exist in literature on determining the HBR but few technical analysis has been done to:
  - Develop and validate an accurate approach and representation in defining the HBR
  - Assess the sensitivity of the HBR to the probability of collision

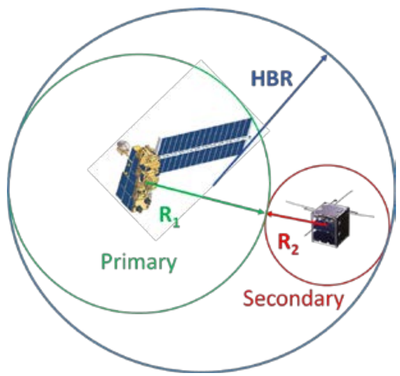
- The present study attempts both the *a priori* assessment and conjunction reprocessing of historical conjunction database by redefining the HBR definition profiles
- The final objective is to provide operational recommendations for setting the HBR value for a specific mission

Primary satellite area projection methods

- Collision risk assessments employ the use of a 2D Pc which is evaluated on a 2D encounter plane whose normal vector is the relative velocity vector of the primary and secondary objects.
- When projecting a spacecraft unto the encounter plane, a symmetrical spacecraft may have a same HBR capture compared to an asymmetric spacecraft, assuming the center of mass is defined as the center of figure for the circumscribing circle; This is not an accurate representation.



Symmetric Primary Satellite



Asymmetric Primary Satellite

- So, we propose an approach that focuses on the projected area of the spacecraft onto the encounter plane to define the HBR.

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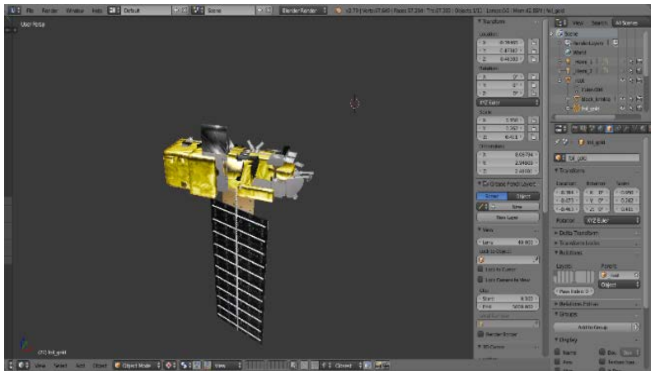
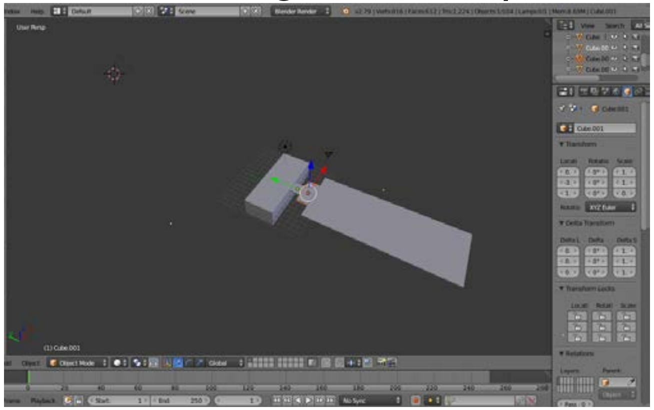
Primary satellite area projection methods

Method 1: 3D-CAD Model using Blender Software exported the vertices based on the attitude (if known) of the spacecraft on the conjunction plane.

1. 3D CAD Model into the software



2. Constructing a 3D simplified model



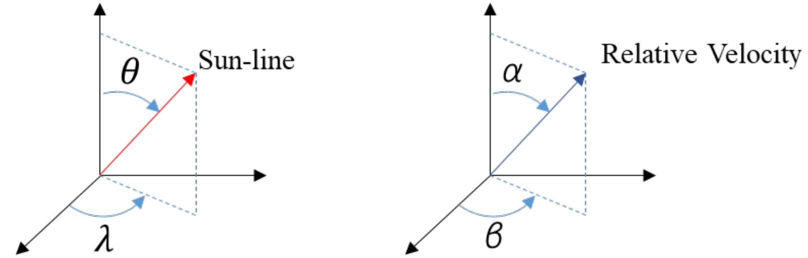
- This method relied on using Ray Tracing techniques and Spherical Harmonics:
  - Combination of orthonormal functions over a unit sphere to calculate the projected cross-sectional area.

$$f(\theta,\lambda) = \sum_{n=0}^{\infty} \sum_{m=0}^{n} [A_{nm} \cos m\lambda + B_{nm} \sin m\lambda] \bar{P}_{nm} (\cos\theta)$$

A_{nm}, B_{nm} are the analogs of Fourier coefficients

$\bar{P}_{nm}$ are the normalized associated Legendre Polynomials

  - Adapted from applications for Solar Radiation Pressure perturbation on a spacecraft*.



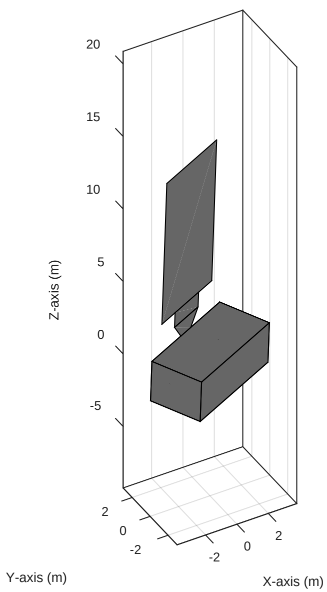
  - Effective for a static spacecraft (can be run only once), can be computationally complex with rotating solar panels (*revisit for future work*).

*A. Farrés, D. Folta and C. Webster, "Using spherical harmonics to model solar radiation pressure accelerations." *2017 AAS/AIAA Astrodynamics Specialist Conference*, (Preprint) AAS 17-780

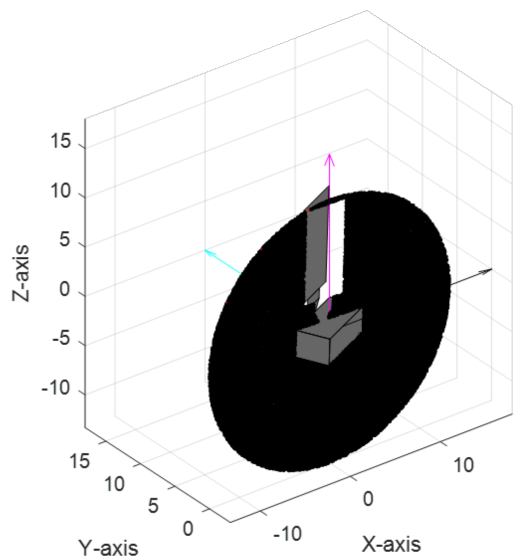
Primary satellite area projection methods

Method 2: Construct an N-Plate Polygon to capture the spacecraft in the conjunction plane using MATLAB.

	Projected Cross-Sectional Area	Defined Circumscribing Circle	Ratio
HST Area *(m^2)*	67.1	150.7	2.25
AURA Area *(m^2)*	145.7	555.7	3.81

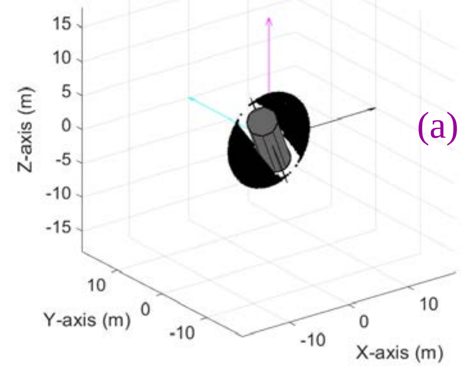


(1) Sample 3D spacecraft model in MATLAB

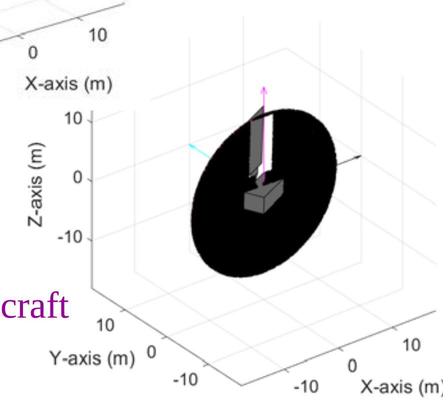


(2) Projected cross sectional area on conjunction plane (XZ-plane)

Cross-Sectional Areas vs Circumscribing Circles HBR comparisons



(a) Symmetric Spacecraft



(b) Asymmetric Spacecraft

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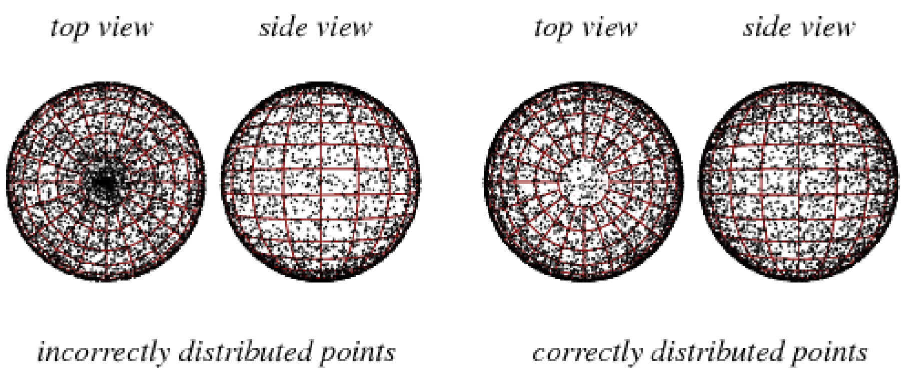
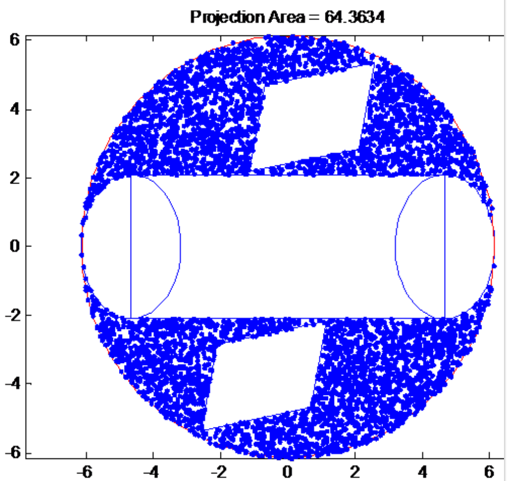
Projected-area variational effects to Hard Body Radius (HBR)

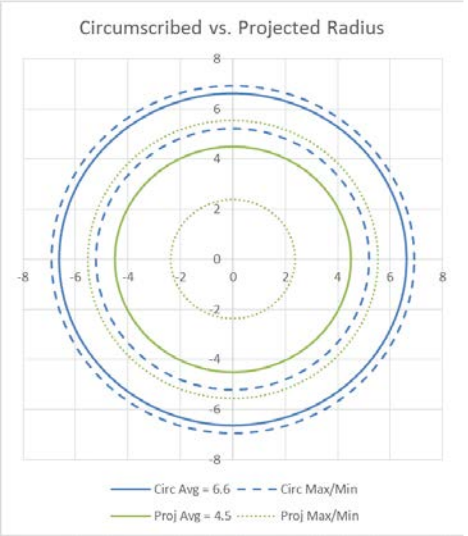
- **Generate a sample of points in a circle to determine the projected area on the encounter plane.**
- **Uniform distributions of $\theta: \{0, 2\pi\}, \phi: \{0, \pi\}$ result in a concentrated distribution near the poles**
- **Uniform sphere distribution equations obtain the correctly distributed points:**

$$\theta = 2\pi u$$
$$\phi = sin^{-1}(2v - 1)$$
$$v = 2\pi w$$





(a) Projected area polygon on conjunction plane using the uniformly distributed points



(b)Projected-area-equivalent and circumscribing circles

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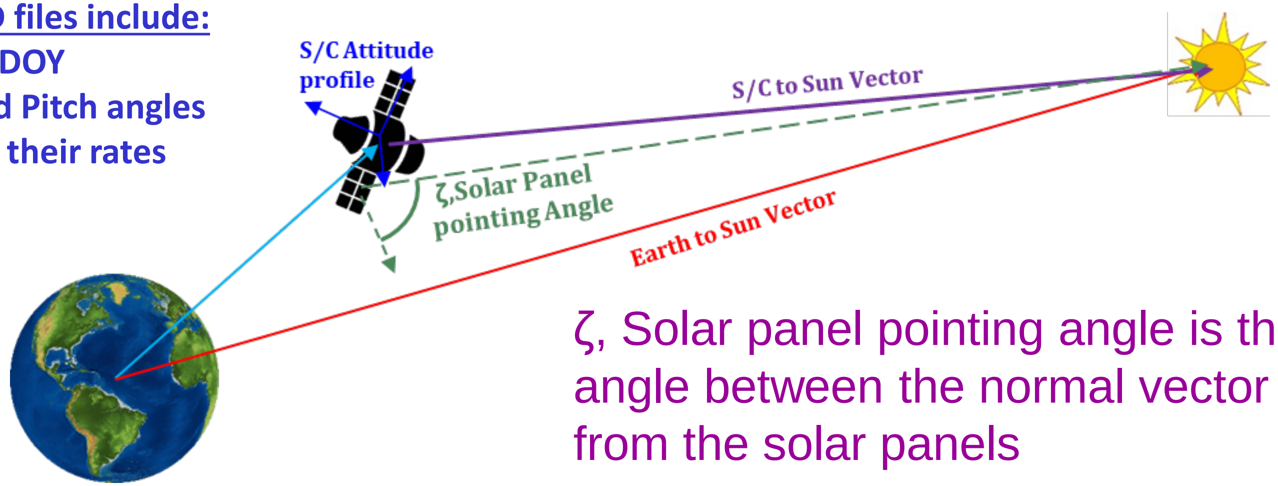
Analysis Approach and Results

- **Given that we can project the spacecraft onto the conjunction plane, it is important that the projected areas are correct.**
- **We can achieve that by:**
  - Incorporating the spacecraft attitude information (.FDD files) at the time of closest approach (TCA) to capture the rotations of the spacecraft bus
  - Use SPICE kernels to calculate the solar pointing vector from the spacecraft for the solar panels' attitude incorporation (maximize exposure to the sun*)

Attitude .FDD files include:
-Epoch YYYY-DOY
-Roll, Yaw and Pitch angles (radians) and their rates (radians/sec)



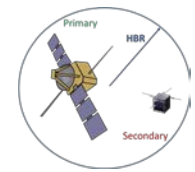
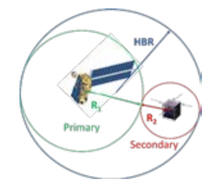
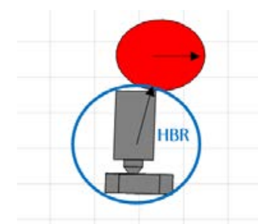
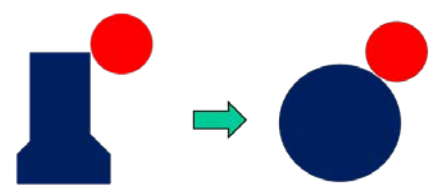
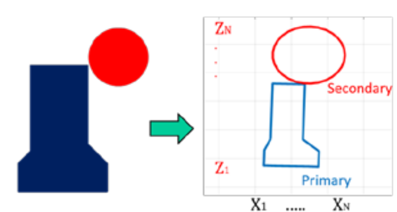
ζ, Solar panel pointing angle is the angle between the normal vector from the solar panels

*** In this analysis we assume the solar panels have 3-axis rotational capability**

HBR profiles investigated

- We investigate 5 different profiles that can be used to define the HBR.
- For each profile, a unique Pc calculation method may be required.
- We compare Profiles 2-4 with Profile 1, and Profiles 1, 3-4 with Profile 2.
- Profile 2 is referred as the current approach missions typically use when defining the HBR.

HBR Profiles: Pc method and considerations

	Pc Method	Description	Schematic
1	A fixed Hard Body Radius (HBR)	20 m or 15 m total HBR	
2	Circumscribing circle with secondary	1.5 m added for secondary object	
3	Event-Specific projected area with circumscribing circle	Incorporated attitude profile for spacecraft bus and solar panels, 1.5 m added for secondary object	
4	Primary spacecraft projected area realized as a circle	Primary spacecraft's projected area realized as a circle and a secondary object with a 1.5m radius	
5	Event projected polygon area	Incorporated attitude profile and calculated Pc using polygon indices.	

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Dataset Used

- **We examine a six month's history of conjunction information for Three NASA payloads in near-circular 700km orbits, extracting conjunction information that:**
  - Exceeds a Pc of 1e-5
  - HBR of 20m for AQUA and AURA and a HBR of 15m for TERRA

- **We incorporate sample attitude files for a week's worth of data from April 21st, 2018. If the epoch at TCA fell outside the attitude files, a nominal Nadir-pointing attitude profile was considered.**

- **The following SPICE kernels were furnished:**
  - pck00010.tpc : Orientation constants for the Sun/Planets
  - de421.bsp : Planetary ephemerides
  - naif0010.tls : Leap seconds file*

*Make sure the accurate .tls file is used. For post Jan 2017 it is naif0012.tls
https://naif.jpl.nasa.gov/naif/

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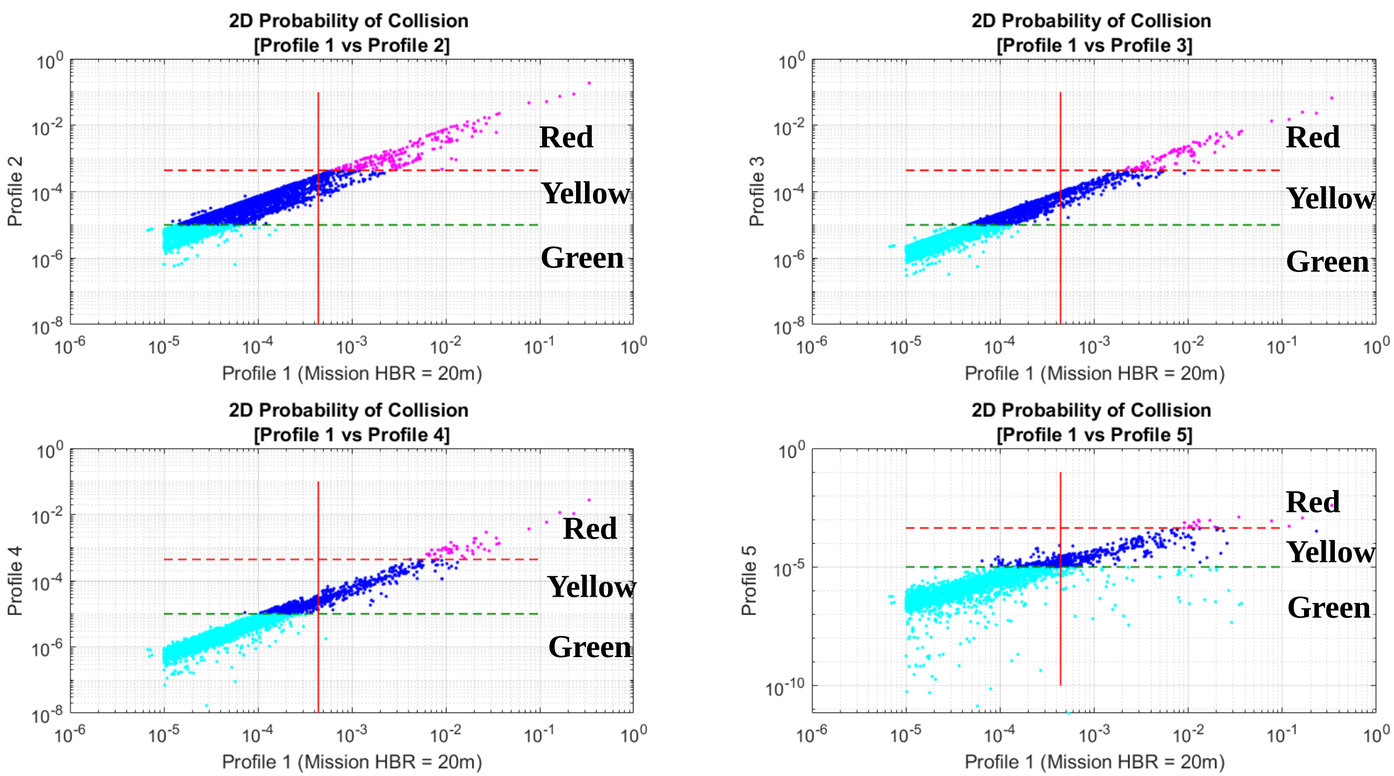
2D-Pc profile range analysis

- **All 3 Spacecraft: 3771 CDMs were considered (not unique events)**
- **We compare the computed Pc for Profile 1 with Profiles 2-5**

% of Red Category Decremented	Profile 2	Profile 3	Profile 4	Profile 5
Profile 1	43.97%	73.05%	87.49%	95.98%

Percentage of Profile 1 that decremented from a Red Category (Pc > 4.4e-4) to a Yellow Category (4.4e-4 < Pc < 1e-5) for the HBR Profiles 2-5



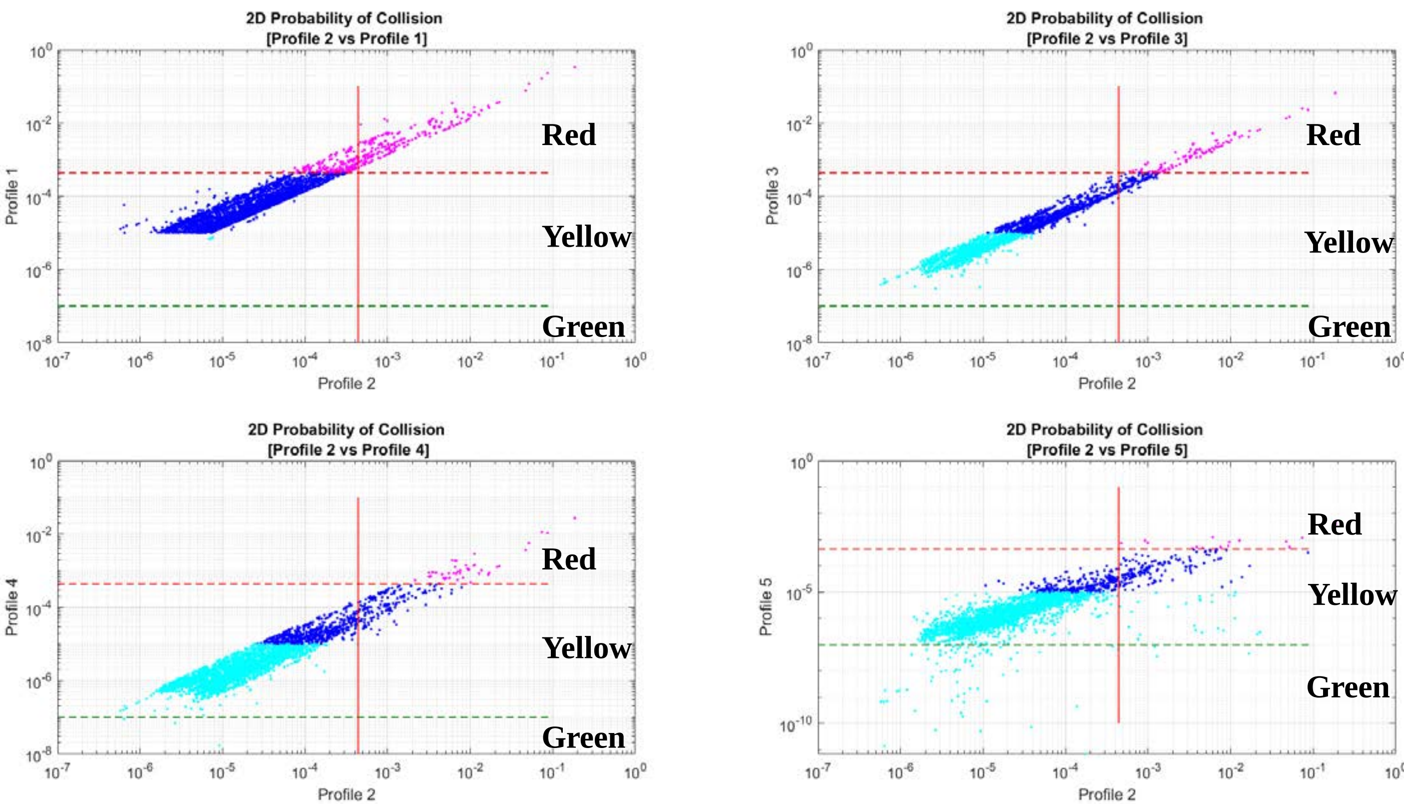
Spacecraft Pc values at TCA for the various HBR profiles on the conjunction plane

2D-Pc profile range analysis

- **All 3 Spacecraft: 3771 CDMs were considered (not unique events)**
- **We compare the computed Pc for Profile 2 with Profiles 1,3-5**

% of Red Category Decremented	Profile 1	Profile 3	Profile 4	Profile 5
Profile 2	0%	51.90%	78.48%	92.83%

Percentage of Profile 2 that decremented from a Red Category (Pc > 4.4e-4) to a Yellow Category (4.4e-4 < Pc < 1e-5) for the HBR Profiles 1, 3-5



Spacecraft Pc values at TCA for the various HBR profiles on the conjunction plane

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Conclusions and Recommendations

- This analysis has shown the advantages of employing any one of many different HBR definitions/constructions in calculating the Pc

- In the event that a mission's attitude information is readily available with reasonable accuracy levels, incorporating a variable HBR would be extremely beneficial in collision avoidance decision making

- It is obvious that the attitude profile for a spacecraft is not deterministic and undergoes various non-conservative perturbations that affect the accuracies of the attitude information.

- However, the objective of this work was to demonstrate the benefits of using the best representative HBR value possible in order to avert unnecessary risk mitigation maneuvers and over-head costs for risk mitigation planning.

ACKNOWLEDGEMENTS

We acknowledge with gratitude the contributions of former Omitron employee, Lauren Johnson on an earlier version of this study.

THANK YOU

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