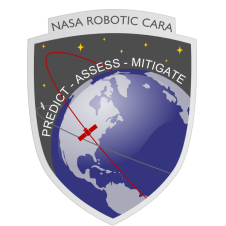


Software Development Kit: Conjunction Consequence Assessment

CONJUNCTION ASSESSMENT AND RISK ANALYSIS (CARA) PROGRAM



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**December 2019Preface**

This document outlines the Conjunction Consequence (also referred to as Collision Consequence) Assessment Algorithms submitted as part of the Software Development Kit (SDK). The SDK is intended to provide both industry and government customers with a code base with which to perform standard calculations inherent to the Collision Avoidance (CA) problem and as outlined in the CA Standard.

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# Introduction

The CARA Software Development Kit (SDK) contains entries and artifacts for each major algorithm needed to perform the required Collision Avoidance (CA) calculations outlined in the CA Standard. For a typical algorithm, the SDK will include a version of the algorithm, a driver program to take information from a text format CDM and execute the algorithm, producing the needed calculation or output, and a series of test cases that exercise the algorithm and produce validated results.

This document describes a specific algorithm, its associated inputs and outputs, the methodology used within the algorithm and examples of usage.

## Required Software

The following list is of software and hardware requirements for use of this SDK:

* Matlab 2016b

# Risk Assessment Algorithms

## Conjunction Consequence Assessment

Risk is properly considered as the combination of likelihood and consequence; but conjunction assessment has usually limited itself to the consideration of only collision likelihood. When considered from an orbital regime protection perspective, the focus shifts to the question of the amount of debris that a collision might produce (the “consequence”). An operational algorithm for determining the expected amount of debris production should a conjunction result in a collision, has been proposed and previously validated.[[1]](#endnote-1),[[2]](#endnote-2)

### Collision Consequence – Mathematical Formulas

#### Debris Generation Methodology

The NASA Orbital Debris Program Office (ODPO) has been studying the subject of collision and explosion fragmentation debris for several decades. Based on known satellite collisions and staged hyperkinetic collisions, the ODPO has developed methods to estimate the size and number of debris pieces generated by a hyperkinetic impact, as included in the EVOLVE 4 satellite break-up model[[3]](#endnote-3).

The initial consequence-based assessment of a conjunction is whether the event could result in a “catastrophic” collision that produces widespread fragmentation of both the primary and secondary objects; or “non-catastrophic” in which only the secondary object is likely to fragment. This determination is made through a relationship based on the relative momentum of the two objects; a collision may be considered “catastrophic” if the relative kinetic energy exceeds 40,000 J/kg.

Once the “catastrophic” or “non-catastrophic” nature of the event has been determined, an additional relation is used to estimate the possible number of debris objects that may be generated

In the above equation, *Lc* refers to the characteristic length of the debris piece size threshold above which the operator is concerned*, i.e.,* how many pieces will be generated with a characteristic length larger than *Lc*. A reasonable limiting value for this variable would be the minimum characteristic length for which an operator might expect tracking data, such as 5 cm for the published tracking fidelity of the Space Fence.

The previous equations are relatively straightforward to evaluate if all terms are known. However, for prospective conjunctions, the secondary mass values are often not known, predominantly because the secondary objects involved in conjunctions are often fragmentation debris, such as those from the Fengyun or Iridium-COSMOS events. There are also many other possible reasons why the secondary object characteristics may be unknown; this is simply the most dominant one. The relative velocity of the two objects is generally well known due to orbit determination processes for the two objects, as is the primary object’s mass which is known from the spacecraft’s operator, but the mass of the secondary object is still unknown.

#### Unknown Satellite Mass Estimation Process

The mass of a secondary object orbiting at a low altitude can be estimated using parameters contained within the atmospheric drag equation:

Estimation of an object’s drag characteristics is of significant import in the orbit determination process, as this is the primary non-conservative force acting on objects in low earth orbit, where large numbers of spacecraft missions operate. As such, the collective terms for satellite drag can be determined as part of the orbit determination process and collected via a term known as the ballistic coefficient and is typically included in reported spacecraft states.

(4)

Knowledge of the ballistic coefficient allows for estimation of the object mass, but this requires that the drag coefficient (*Cd*) and frontal area (*A*) also be estimated or known. Secondary object frontal area estimation is described in further detail in Section: 2.1.1.3. There are numerous methods to estimate *Cd*, but due to a desire for conservatism (overestimation of secondary object mass), a relatively large *Cd* is recommended for mass estimation of unknown satellites.

* Recommended *Cd* for Mass Estimation: **2.7**

Variations in the drag coefficient estimates are often small compared to frontal area variations and atmospheric density variations, particularly for satellites orbiting at lower altitudes as shown in analysis by Pilinski et al.[[4]](#endnote-4), which estimated that Cd variations are typically about 2% except in extremely low altitude cases. The mass estimation process uses a sampling methodology to affect *Cd* uncertainty on the evaluation of collision consequence. Specifically, for each estimate of the drag coefficient, a number of samples are drawn from a normal distribution with a specified standard deviation, for conservatism, it is recommended to use a relatively high relative uncertainty.

* Recommended Relative *Cd* Uncertainty: **5%**

The mass estimates are given as a distribution of estimated satellite masses, which may be used either to determine a distribution of collision consequence results, or on a quantile basis to determine a conservative estimate of collision consequence. It is recommended to use the following mass estimation quantile:

* Recommended Mass Estimation Quantile: **99.9%**

#### Unknown Satellite Frontal Area Estimation Process

The frontal area of the secondary object may be estimated using a relationship between the projected area of the satellite and the object’s radar cross section (RCS). RCS characterizes the intensity of radar energy reflected during tracking observations and is a solved-for variable in the radar range equation if the signal-to-noise ratio and range are known. Typically this is reported as the median RCS value, as the RCS distribution does not conform to a normal distribution.

Although the RCS value has units of area, it is not a direct estimate of a satellite’s cross sectional area, but can be used to estimate the distribution of an object’s characteristic size. This is accomplished using the ODPO’s size estimation model (SEM), which was developed by fragmenting a satellite in a vacuum, measuring the characteristic dimensions of the resulting fragments, and correlating those to radar returns when illuminated in all possible configurations.iii Radar theory allows a dimensionless relationship to be established between an object’s characteristic length (normalized by the radar wavelength) and the object’s RCS (normalized by the square of the radar wavelength).

If the wavelength of the observing radar is known, the characteristic length, *Lc*, of the object may be roughly estimated using the median RCS (a value that is made available from the 18th Space Control Squadron at the Combined Space Operations Center (CSpOC), for example). The uncertainty distribution for *Lc* can be characterized using the NASA ODPO size estimation model (SEM)[[5]](#endnote-5), which uses a distribution of RCS values to produce a corresponding distribution of characteristic lengths. The distribution of RCS values may be approximated as a Swerling III distribution, grounded by a single shape parameter that can be derived from the RCS median value. While this methodology is not an ideal characterization of RCS distributions, it outperforms most other choices, as presented by Hejduk and DePalma[[6]](#endnote-6). Using this Swerling III distribution, a large set of samples representing the secondary object RCS are generated for use in the mass estimation process, which are then used in conjunction with the SEM to estimate object characteristic length.

This process provides a method by which the characteristic length may be determined if the RCS and the tracking radar’s wavelength or frequency is known; if not, a good approximation of a generic radar may be established using radar frequencies of either UHF (~430MHz) or L-Band (~1200MHz), depending on object RCS value. The characteristic length distribution of the secondary object is then used to approximate a distribution of estimates of the satellite frontal area:

### Collision Consequence – Source Code Description

There are two primary functions contained within the SDK used for estimating the secondary object mass and debris production respectively:

* EstimateObjectMassQuantiles.m
* CollisionConsequenceNumPieces.m

#### Mass Estimation Routine (EstimateObjectMassQuantiles.m)

Table 1: Mass Estimation Routine Input Parameters

|  |  |
| --- | --- |
| Input Variable | Definition |
| RCS | Radar Cross Section of Secondary Object (m2) |
| B | Ballistic Coefficient of Secondary Object (m2/kg) |
| BVar | Ballistic Coefficient Variance of Secondary Object (m4/kg2) |
| Cd | Drag Coefficient Estimate of Secondary Object (dimensionless) |
| CdVar | Drag Coefficient Variance of Secondary Object (dimensionless) |
| QuantileVector | 1XN Vector of desired mass quantile estimates (optional, defaults to 0.999 (99.9%)) |
| NumOfSamples | INTEGER number of samples to generate (optional, Default = 10000, or a minimum number to accurately describe highest input quantile) |

Table 2: Mass Estimation Routine Output Parameters

|  |  |
| --- | --- |
| Output Variable | Definition |
| massVec | [NumOfSamplesX1] array of the secondary object mass estimates for each individual sample |
| QuantileArray | [NX2] Structure array of Mass Quantile Estimates |

#### Collision Consequence Routine (CollisionConsequenceNumPieces.m)

Table 3: Collision Consequence Routine Input Parameters

|  |  |
| --- | --- |
| Input Variable | Definition |
| PrimaryMass | Mass of Primary Object (kg) |
| VRel | 1x1, 3X1, or 1X3 vector of the relative velocity the primary and secondary objects (m/s) |
| SecondaryMass | NX1 Matrix of Secondary Mass Values for Examination (kg) |

Table 4: Collision Consequence Routine Output Parameters

|  |  |
| --- | --- |
| Output Variable | Definition |
| Catastrophic | [NX1] logical array indicating whether the sampled collision is catastrophic |
| NumOfPieces | [NX1] array of the number of pieces expected to be generated from a collision for each sample |

#### Validation Cases

Validation cases for these algorithms are contained within the unit test suites for the SDK at:

..\ConjunctionConsequence\UnitTest\CollisionConsequenceCode\  
EstimateObjectMassQuantiles\_UnitTest.m

..\ConjunctionConsequence\UnitTest\CollisionConsequenceCode\  
CollisionConsequenceNumPieces\_UnitTest.m

These test cases were developed using NaK sphere validation cases, and limiting cases for collision consequence assessment.

Table 5: Mass Estimation Validation Cases

|  |  |
| --- | --- |
| Test ID | Description |
| test01 | NaK sphere used as part of process validation efforts with available RCS, Ballistic Coefficient, and Ballistic Coefficient Variance data. |
| test02 | NaK sphere used as part of process validation efforts with available RCS, Ballistic Coefficient, and Ballistic Coefficient Variance data. |
| test03 | NaK sphere used as part of process validation efforts with available RCS, and Ballistic Coefficient. Available Ballistic Coefficient variance information is delivered as zero/empty. |
| test04 | 6U NanoSat used as part of process validation efforts with available RCS, Ballistic Coefficient, and Ballistic Coefficient Variance data. |
| test05 | 1U NanoSat used as part of process validation efforts with available RCS, and Ballistic Coefficient. Available Ballistic Coefficient variance information is delivered as zero/empty. |
| test06 | GNB Satellite used as part of process validation efforts with available RCS, Ballistic Coefficient, and Ballistic Coefficient Variance data. |

Table 6: Collision Consequence Validation Cases

|  |  |
| --- | --- |
| Test ID | Description |
| test01 | An array of secondary object masses were chosen to meet all boundary cases for collision consequence assessment:   * 0 input for secondary mass * Definitively non-catastrophic * Boundary case catastrophic (reported as non-catastrophic) * Definitively catastrophic * Secondary mass exceeds primary mass |

# Acronyms

|  |  |
| --- | --- |
| CARA | Conjunction Assessment Risk Analysis |
| CDM | Conjunction Data Message |
| ECI | Earth Centered Inertial |
| HBR | Hard Body Radius |
| Pc | Probability of Collision |
| SDK | Software Development Kit |

# References

1. Lechtenberg, T. F., “An Operational Algorithm for Evaluating Collision Consequence,” AAS Astrodynamics Specialist Conference, 2019, Portland, ME, AAS 19-669. [↑](#endnote-ref-1)
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3. Johnson, N.L., Krisko, P.H., Liou, J.-C., and Anz-Meador, P.D.: “NASA’s New Breakup Model of EVOLVE 4.0.” *Advances in Space Research,* Vol. 28 No. 9 (2001), pp. 1377-1384. [↑](#endnote-ref-3)
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5. C. L. Stokely et al., "Haystack and HAX Radar Measurements of the Orbital Debris Environment; 2003", JSC-62815, Nov 2006. [↑](#endnote-ref-5)
6. Hejduk, M., DePalma, D., “Comprehensive Radar Cross-Section “Target Typing” Investigation for Spacecraft”, *Advances in the Astronautical Sciences*, Vol. 135, 2010, AAS 09-301. [↑](#endnote-ref-6)