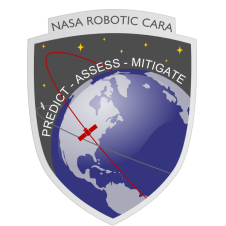


Software Development Kit: Orbit Determination (OD) Quality Assessment

CONJUNCTION ASSESSMENT AND RISK ANALYSIS (CARA) PROGRAM



*Astrorum, Inc*

*Waco, Tx*

*Omitron, Inc*

*Colorado Springs, CO*

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National Aeronautics and

Space Administration

Goddard Space Flight Center,

Greenbelt, MD 20771

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**Preface**

This document outlines the Orbit Determination (OD) Quality Assessment Routine and associated software 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 formatted 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 the Orbit Determination (OD) Quality Assessment routine, its associated inputs and outputs, the methodology used within and examples of usage.

## Required Software

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

* Matlab 2016b

# Risk Assessment Algorithm

## Orbit Determination Quality Assessment

The Orbit Determination Quality Assessment (ODQA) algorithm is intended to analyze an input Conjunction Data Message (CDM) and assess whether the controls and inputs used in the orbit determination process are sufficient to have general confidence in output data products, or if these inputs require further review. These quality assessment tests were developed by CARA drawing on the expertise of several subject matter experts and can be reviewed in a briefing given by Hedjuk[[1]](#endnote-1) the main contents of which will be restated here.

### Orbit Determination Quality Assessment – Thresholds and Calculations

The ODQA assessment for an individual object is broken down into four subsections relating to different qualities of the OD process. The number of violations within each subsection is consolidated into a single weighted score. An object with no violations would have an ODQA score of 1, while values less than unity reflect the level of concern the orbit determination process may engender. The weighting of ODQA subsections is as follows:

Table 1: ODQA Composite Score Weighting

|  |  |
| --- | --- |
| ODQA Subsection | Composite Weighting |
| Force Model Settings and Reasonability | 3 |
| OD Results Integrity | 2 |
| Covariance Integrity | 2 |
| Epoch Age | 1 |

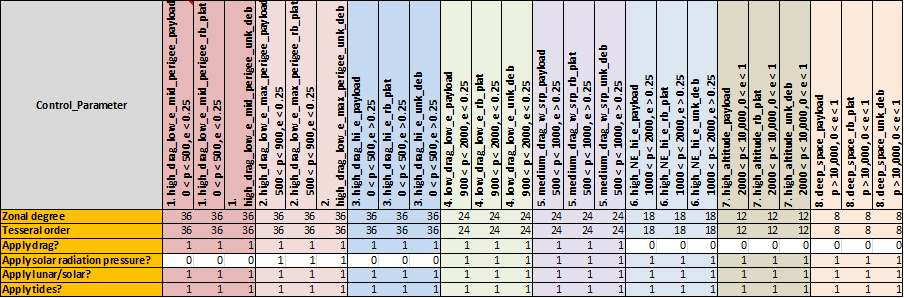
#### Force Model Settings and Reasonability

This subsection examines whether or not the force models implemented for a specific object are reasonable and consistent with recommended and reasonable levels. Specifically examining the following:

* Geopotential Degree and Order
* Atmospheric Drag
* Solar Radiation Pressure
* Lunar/Solar Perturbations
* Solid Earth Tides

Each of these force models has different prescribed levels and enablement flags based on the object’s orbit regime, and different reasonability values based on object type. The enabling of force models by orbit regime is summarized in the table below:

Table 2: Force Model Settings By Orbit Regime



Next, the absolute values of the ballistic coefficient (BC) and solar radiation pressure (SRP) coefficient are examined for reasonability. For any given satellite with these force models enabled, the minimum coefficient is **0.001 m2/kg**. The maximum reasonable values are given in the table below based on object type and EDR bin:

Table 3: Reasonable Maximum Coefficient Values Based on Object Type

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Object Type | Maximum BC EDR Bins 0 & 1 | Maximum BC EDR Bins >1 | Maximum SRP EDR Bins 0 & 1 | Maximum SRP EDR Bins >1 |
| Payload | 0.1 m2/kg | 0.1 m2/kg | 0.1 m2/kg | 0.1 m2/kg |
| Rocket Body | 0.2 m2/kg | 0.2 m2/kg | 0.2 m2/kg | 0.2 m2/kg |
| Debris | 1.0 m2/kg | 10 m2/kg | 1.0 m2/kg | 1.0 m2/kg |

#### OD Results Integrity

This subsection examines the OD span, residual acceptance and Weighted Root-Mean-Squared (WRMS) values for reasonability. This is to examine how well the batch process is determining an epoch state for a given object.

The batch process determines an appropriate OD update interval in order to accommodate a sufficient number of observations from which to derive an epoch state. Overly long OD intervals can increase an object’s prediction error, while overly short OD intervals can produce poor drag solutions. The OD algorithm used operationally at the CSpOC dynamically adjusts the Length of Update Interval (LUPI) to strike a balance between these two extremes by starting with an upper bound of the LUPI and attempting to shrink the span from there. Under certain conditions, the LUPI may expand as well, up to three times the initial, maximum LUPI. The calculation for the maximum and minimum LUPI spans for specific objects is re-hosted within the SDK software package and calculated as a function of an object’s EDR bin, eccentricity, and orbital period. This portion of the ODQA process throws violations if an object’s LUPI ratio to the minimum value is less than 1 or if the ratio to the maximum LUPI is greater than 1.5.

Table 4: LUPI Ratio Violation Ratios

|  |  |
| --- | --- |
| Maximum LUPI Ratio | 1.5 |
| Minimum LUPI Ratio | 1.0 |

This section also examines the residual acceptance rate of the OD process, which is the percentage of measurement residuals within the fit span that are retained in the final iteration of the OD process. A credible OD solution must include a reasonably large portion of available measurements. There are, however, situations in which low measurement residual rates are expected such as post-maneuver scenarios or when cross-tagging of satellites occur. The recommended threshold for residual acceptance before flagging a violation is **80%**.

The final check done as part of the OD results integrity analysis is a check on the WRMS. WRMS is the root mean square of the OD residuals, weighted by the expected error in the measurements themselves. Ideally, this will have a value of one, but may be either slightly above or below unity. A large WRMS score indicates a poor fit of the observational data while a small WRMS is less worrisome as it may arise when there are only a small number of observations used in determining the fit. Tolerable WRMS score ranges are based on object type and are as follows:

Table 5: ODQA WRMS Limits

|  |  |  |
| --- | --- | --- |
| Object Type | Minimum WRMS | Maximum WRMS |
| Payload | 0.8 | 1.5 |
| Rocket Body | 0.8 | 2.0 |
| Debris | 0.8 | 5.0 |

#### Covariance Integrity

This section examines the reported covariance matrix for an object contained within a given CDM and reports any untoward values that may cause analysis of said CDM to fail or give suspect results. Three checks are performed as part of this assessment; a default covariance check, a positive definiteness check, and an intrack position uncertainty check.

In some cases, the software at the CSpOC will be unable to form a correct covariance associated with a state estimate and in these cases, the conjunction is reported using a general perturbations scheme which lacks an associated covariance. To populate the covariance on the CDM for the object, the covariance is reported as a diagonal matrix with uncertainties set to a default value of **10 Earth radii**. In these cases, a CDM can be considered non-actionable. Hence a simple test is implemented to check for the presence of default covariance matrices.

On rare occasions the reported covariance matrices on a CDM may be non-positive definite (NPD). By definition, a covariance matrix must be positive definite in nature, and this property is required to accurately calculate the probability of collision. This may occur for a few reasons, but these instances are generally few and far between and can usually be attributed to either machine precision in reporting or the scale of the Eigen values of the covariance matrix. This is checked quite easily using Matlab’s built in Cholesky decomposition function (chol.m) which rapidly assesses of whether or not an object’s covariance matrix is positive definite. The Pc Omnibus tool suite contains a tool used to remediate these covariance matrices should they occur and is further detailed in the documentation for the “Two Dimensional Pc Calculation” SDK. Should an object have a non-positive definite covariance matrix, this is flagged as a violation.

The final check on the covariance matrix relates to the intrack uncertainty. The covariance matrices reported on a CDM are generally expressed in Cartesian coordinates. For most applications this is acceptable, and this is even required for the combined covariance matrix formulation required for two-dimensional probability of collision assessments. However, actual orbits are by definition ellipses, meaning that if the objects position uncertainty in the intrack direction is overly large, the uncertainty in the object state does not accurately follow the object’s orbital trajectory. In these cases, it makes more sense to compute probability of collision using a Monte Carlo methodology in the equinoctial frame.

When the intrack position uncertainty exceeds a certain percentage of the orbit circumference, a violation is indicated. Presently the threshold for this violation is set at 1/8th of an orbital period.

#### Epoch Age

The final section examines the age of a given object’s epoch state estimate and cites a violation if the difference between the object epoch and the TCA is overly large. This approach is largely dependent on the EDR of the object as the effects of drag are the largest source of force model uncertainty in low earth orbits. This makes sense as an object in a low EDR bin will likely have a more confident state estimate over a longer propagation period than objects in higher EDR bins.

Table 6: Epoch Age Threshold Table

|  |  |
| --- | --- |
| EDR Bin | Epoch Age Threshold (days) |
| 0 | 10 |
| 1 | 10 |
| 2 | 5 |
| 3 | 5 |
| 4 | 5 |
| 5 | 5 |
| 6 | 5 |
| 7 | 5 |
| 8 | 3 |
| 9 | 3 |
| 10 | 3 |

### Orbit Determination Quality Assessment – Source Code description

The primary function contained within the SDK used for assessing the OD quality of an object contained within a CDM is the:

CDM\_ODQualityAssessment.m

routine, which assesses the OD quality of an object using the thresholds given above.

As inputs, the routine accepts the following:

Table 7: ODQA Routine Input Parameters

|  |  |
| --- | --- |
| Input Variable | Definition |
| CDM | CDM Structure Object containing all information required for assessing the quality of the orbit determination process and object state reporting |
| Input\_Object\_Designator | Optional designator denoting which object contained within a CDM to assess the OD quality of. Defaults to secondary object. Allowable inputs:  - 1 '1' 'Primary'  - 2 ‘2’ ‘Secondary’ |
| ODQualityThresholds | Optional structure containing ODQA thresholds, defaults to recommended values defined above. |

The ODQA routine outputs the following:

Table 8: ODQA Routine Output Parameters

|  |  |
| --- | --- |
| Output Variable | Definition |
| CollectedScores | A 7X4 matrix that summarizes the results of all the binary tests administered. A “1” indicates a passed test, and a “0” indicates a failed test.  Column 1 contains results for the following model parameters tests: - Row 1: Geopotential Test - Row 2: Drag Effects Enabled Test - Row 3: SRP Effects Enabled Test - Row 4: Lunar/Solar Test - Row 5: Solid Earth Tides Test - Row 6: Reasonable BC Value Test - Row 7: Reasonable SRP Coefficient Test  Column 2 contains results for the following OD results tests: - Row 1: LUPI Ratio Test - Row 2: Residual Acceptance Test - Row 3: WRMS Test  Column 3 contains results for the following covariance integrity tests: - Row 1: Default Covariance Test - Row 2: Positive Definite Test - Row 3: Intrack Uncertainty Size Test  Column 4 contains results for the following epoch age tests: - Row 1: Epoch Age Test |
| CompositeScore | A single numerical value summary of the test results, which is a weighted average of the percent passing levels for each of the four ODQA testing subsections. |
| CurrentEval | A structure of binary results of the administered tests. |

Validation cases for this algorithm are contained within the unit test suite for the SDK at:

..\ODQualityAssessment\UnitTest\ODQAAnalysisCode\CDM\_ODQualityAssessment\_UnitTest.m

Table 9: ODQA Routine Unit Test Cases

|  |  |
| --- | --- |
| Test ID | Description |
| test01 | Test Debris Item OD Force Model Input Thresholds and Primary Object Analysis |
| test02 | Test Debris OD Span/statistics Thresholds |
| test03 | Test Debris OD Covariance Thresholds |
| test04 | Test Debris OD Epoch Age Thresholds |
| test05 | Test Rocket Body OD Force Model Input Thresholds and WRMS Limits |
| test06 | Test Payload OD Force Model Input Thresholds and WRMS Limits |

# Acronyms

|  |  |
| --- | --- |
| BC | Ballistic Coefficient |
| CA | Collision Avoidance |
| CARA | Conjunction Assessment Risk Analysis |
| CDM | Conjunction Data Message |
| CSpOC | Combined Space Operations Center |
| EDR | Energy Dissipation Rate |
| LUPI | Length of Update Interval |
| NPD | Non-Positive Definite |
| OD | Orbit Determination |
| ODQA | Orbit Determination Quality Assessment |
| Pc | Probability of Collision |
| SDK | Software Development Kit |
| SRP | Solar Radiation Pressure |
| TCA | Time of Close Approach |
| WRMS | Weighted Root-Mean-Squared |

# References

1. Hejduk, M. D. “*OD Quality Evaluation Approach*.” June 2016. Revised July 2019 by T. F. Lechtenberg. [↑](#endnote-ref-1)