
*EventRate*

# A Program to Estimate Expected Serious Conjunction Rates for CARA Missions

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# Program *EventRate*: Outline

- Introduction, summary, objectives and methodology
- Description of program inputs and outputs
- Usage instructions
- Analysis examples
- Installation and troubleshooting contact information

# Program *EventRate*: Introduction and Summary

- **The Matlab program *EventRate* estimates the rates that prospective CARA missions can expect to experience serious conjunctions, which are events that have last-update collision probability (Pc) values exceeding the specified threshold for risk mitigation maneuvers (RMMs)**
- **The program can also estimate cumulative Pc values* over the on-orbit lifetimes of prospective missions**
- ***EventRate* uses a semi-empirical simulation estimation algorithm, basing estimates on the extensive database of conjunction state and covariance data archived for previous and current CARA missions**
- **It allows trade-space analyses of several satellite and mission parameters:**

| | | |
|---|---|---|
| **Satellite HBR** | **On-orbit lifetime** | **Catastrophic events** |
| **RMM Pc threshold** | **RMM commit times** | **RMM type (trans. vs rot.)** |
| **Catalog growth factor** | **CARA orbital regime** | |

- **It also produces several graphical outputs illustrating the archived conjunction data used in the analysis, as well as the estimated event rates, cumulative Pc values, and associated estimation uncertainties**

*Perceived cumulative probabilities as measured by last-update Pc values

# Program *EventRate*: Objectives

- **Primary objective: Provide estimates of the occurrence rates of serious conjunction events expected for current or prospective CARA missions**
  - Serious events occur when the most recent available conjunction Pc estimate (i.e., the last-update Pc value) exceeds a risk-tolerance threshold
  - The risk-tolerance threshold is the Pc cutoff that a mission uses when deciding to perform or not perform a risk mitigation maneuver (RMM) — e.g., RMM Pc = 4.4e-4
  - The last-update Pc for a conjunction is the latest Pc estimate available before a mission's RMM "commit" time limit is reached, but that is also estimated after the mission's RMM "consider" time limit — e.g., commit at 1 day before TCA and consider at 3.5 days
- **Secondary objective: Provide associated estimates of perceived mission-cumulative Pc values, both with and without RMMs being performed**
  - The perceived mission-cumulative Pc represents an empirical estimate of the combined risk of all conjunctions experienced by a satellite throughout its active, on-orbit lifetime
  - For last-updates below the Pc threshold, no RMM is performed in the simulation, and the last-update Pc value itself provides a measure of the perceived risk of the event
  - For last-updates above the Pc threshold, however, an RMM is performed, and the estimated post-RMM Pc value provides a measure of the perceived risk of the event
  - The mission-cumulative Pc combines the perceived risks for all of the conjunctions experienced during an entire mission into one composite collision probability

# Program *EventRate*: Methodology

- **Perform a semi-empirical serious event rate and cumulative risk analysis**
  - For details of the formulation see Hall (2019) "Determining Appropriate Risk Remediation Thresholds From Empirical Conjunction Data Using Survival Probability Methods" AAS-631
  - Uses input OCMDB or OCMDB_PcTable.mat files for archived data (extracted from CARA database)
    - PcTable files for the examples outlined in this presentation are provided in the data/directory
    - For further analyses, a PcTable file containing conjunction information approved for release to the general public is provided in the data/ directory. Refer to the curated satellite list in the doc/ directory to select satellite IDs suitable for a given mission analysis.
- **Allow users to specify multiple parameters for prospective CARA missions**
  - Satellite parameters: Hard-body radius (HBR) and on-orbit mass
  - Mission parameters: Active on-orbit lifetime, orbital regime, flag to include vs exclude likely non-catastrophic collisions, and a secondary catalog population growth factor
  - Risk mitigation maneuver parameters: RMM Pc threshold, RMM commit and consider times, RMM type (translational vs rotational), and the RMM Pc reduction factor
- **Perform the following multi-step analysis using archived conjunction data:**
  - Calculate conjunction Pc values based on the prospective mission's HBR value
  - Determine last-update Pc values based on the mission's RMM commit/consider times
  - Use a sample with replacement methodology to simulate multiple realizations of the sequence of last-update Pc values experienced by the mission — see Hall (2019)
  - Estimate the expected rate that last-update Pc values exceed the RMM Pc threshold
  - Estimate the perceived mission-cumulative Pc value both with and without RMMs
  - Estimate 95% uncertainties based on the variations between multiple mission realizations

# Description of Program Inputs and Outputs

# Program *EventRate*: Example Input Parameter Specification File (for 'LEO22_HST_Example1')

```
%% Function EventRate parameter specification file
% for a prospective mission in an HST-like orbit

%% Emprical orbital conjunction data set parameters

% OCMDB file holding archived conjunction data
• params.PcTableFile = 'data\Test_C.mat';

% Set of CARA primaries to combine for the semi-empirical analysis
params.priset = 20580; % Only include HST itself for this example

% CARA orbital regime (optional) which contains the primaries
params.priorb = 'LEO2-2';

%% Mission parameters for the prospective satellite mission

% Basic mission parameters
params.mission_name = 'NewHST';
params.mission_HBR_meters = 10;
params.mission_duration_years = 15;
params.mission_on_orbit_mass_kg = 10800;
```

```
% Pc threshold for execution of risk mitigation maneuvers (RMMs)
params.EventRate_Pc_value = 1.0e-4;

% Mission RMM commit and consider times (days before TCA)
params.Tcommit_days   = 1.0;
params.Tconsider_days = params.Tcommit_days+2.5;

% Include or exclude likely non-catastrophic events for RMMs
params.exclude_noncatastrophic = false;

% Type of RMM: Translational (default, most common) or Rotational
(less common)
params.RemManeuver = 'Translational';
params.RemReduction = 0.03; % RMM reduction factor = Pc(post-
RMM)/Pc(pre-RMM)

% Secondary population growth factor for the mission
% (e.g., a factor of 1.3 indicates that the prospecive mission encounters
% a future secondary satellite population 30% larger than in the archived
% data set; default = 1)
params.SecondaryCatalogGrowth = 1.3;
```

# Program *EventRate*: Example Text Output and Function Output Variables

## Text output from executing EventRate('LEO22_HST_Example1')

**--- Summary of Semi-empirical Estimation Analysis ---**

**Orbit: 20580 (541km x 556km x 28deg in LEO2-2)**
**Interval: 2009-02-25 17:06 to 2019-01-27 18:31 (9.92 yr)**
**Commit/consider time limits: 1 to 3.5 day**
**Likely non-catastrophic events: Included**
**Unique events: 997 of 1600 within commit time limits**

**NewHST: duration = 15 years, HBR = 10 m, growth = 1.3**
**RMM threshold Pc = 1e-4 (RMM type = translational, RMM reduction = 0.03)**

**Mission average above-threshold event rate = 0.71 / year (95%: 0.27 to 1.33)***
**Mission cumulative Pc (with RMMs) = 2.1e-3 (95%: 1.6e-3 to 2.6e-3)***
**Mission cumulative Pc (no RMMs) = 8.1e-3 (95%: 3.2e-3 to 1.7e-2)***
***Quantities in red also output as Matlab function variables**

Note: Small numerical output differences from those presented in the proceeding slides may arise due to differences in hardware architecture or software

# Program *EventRate*: Plotted Cumulative Pc vs On-Orbit Duration

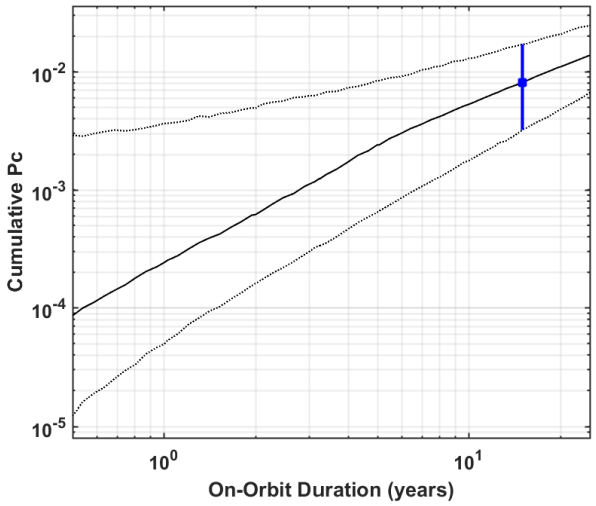
## LEO22_HST_Example1 Mission-cumulative Pc with no RMMs performed

*Semi-Empirical Cumulative Collision Probability*

*Orbit: 20580 (541km x 556km x 28deg in LEO2-2)*
*Interval: 2009-02-25 17:06 to 2019-01-29 02:12 (9.92 yr)*
*Commit/consider time limits: 1 to 3.5 day*
*Likely non-catastrophic events: Included*
*Unique events: 1014 of 1624 within commit time limits*

*NewHST: duration = 15 years, HBR = 10 m, growth = 1.3*
*No mission risk mitigation maneuvers (RMMs)*

*Mission Pc (no RMMs) = 8.1e-3 (95%: 3.2e-3 to 1.7e-2)*



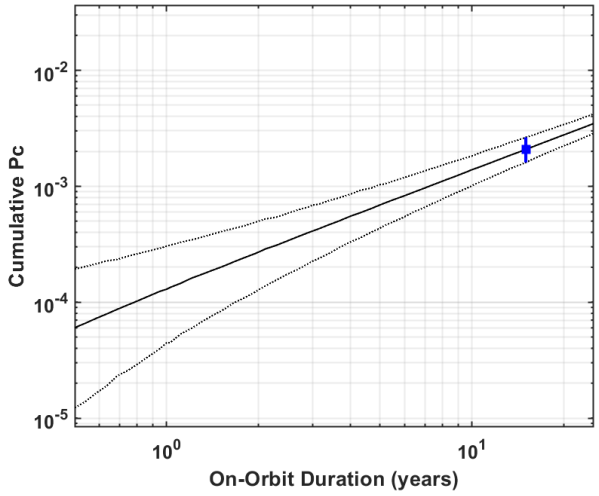

## LEO22_HST_Example1 Mission-cumulative Pc with RMMs performed

*Semi-Empirical Cumulative Collision Probability*

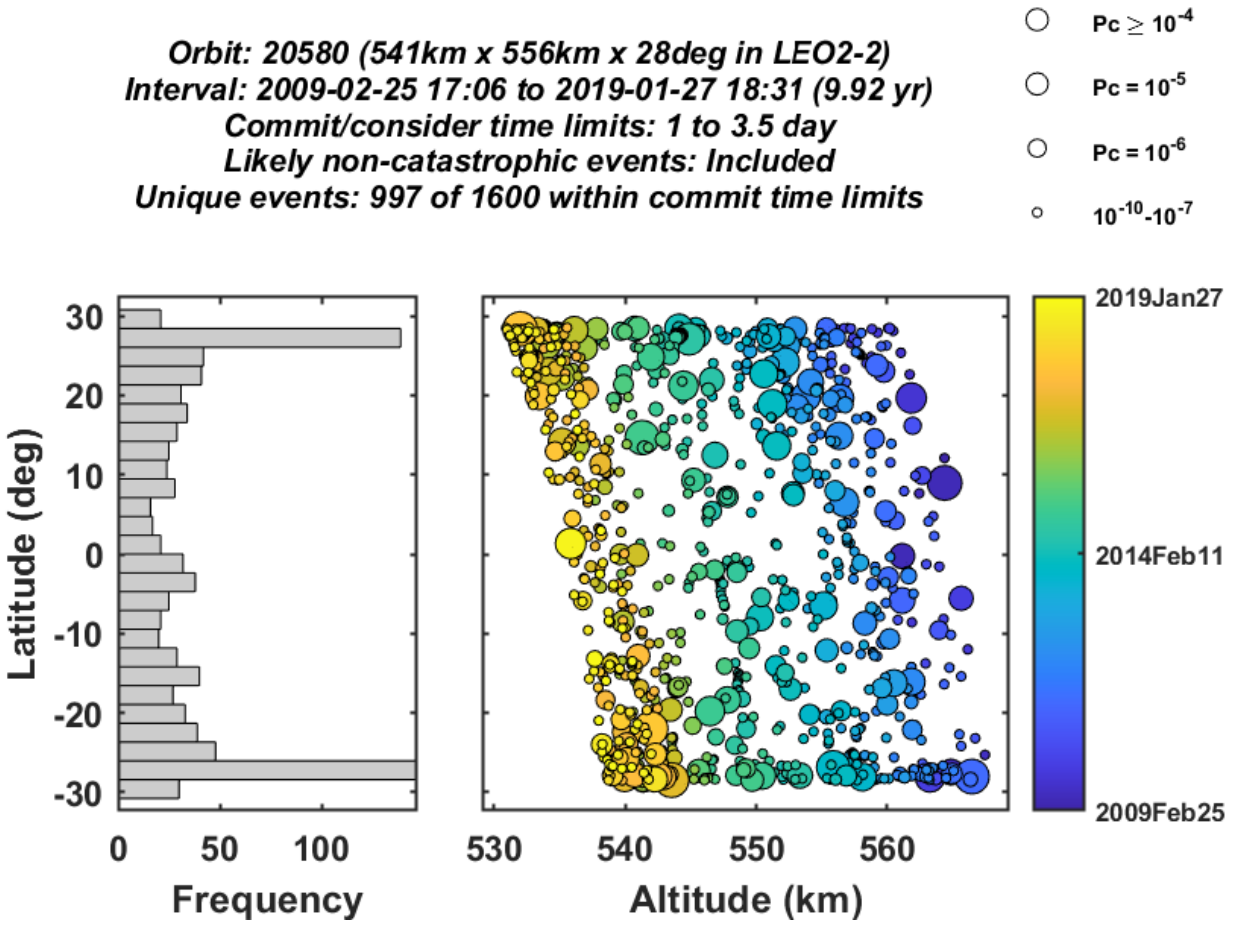
*Orbit: 20580 (541km x 556km x 28deg in LEO2-2)*
*Interval: 2009-02-25 17:06 to 2019-01-27 18:31 (9.92 yr)*
*Commit/consider time limits: 1 to 3.5 day*
*Likely non-catastrophic events: Included*
*Unique events: 997 of 1600 within commit time limits*

*NewHST: duration = 15 years, HBR = 10 m, growth = 1.3*
*RMM threshold Pc = 1e-4 (type = translational, $\rho$ = 0.03)*

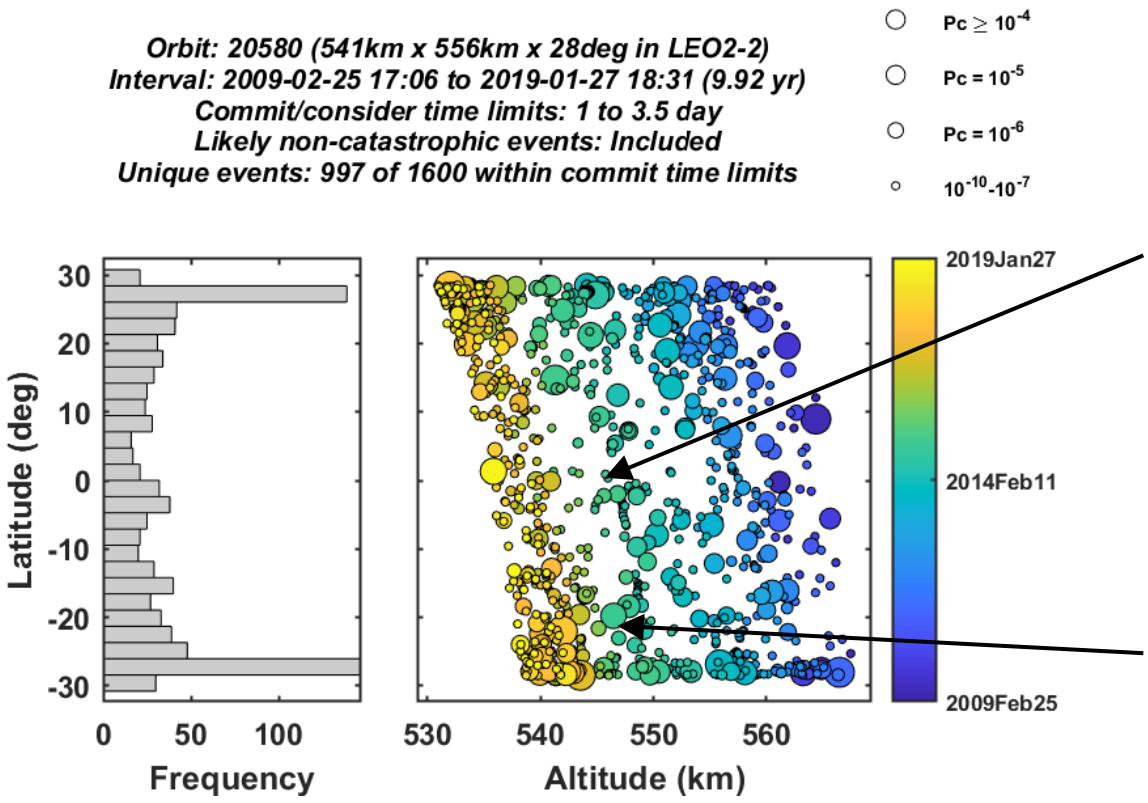
*Mission Pc (with RMMs) = 2.1e-3 (95%: 1.6e-3 to 2.6e-3)*

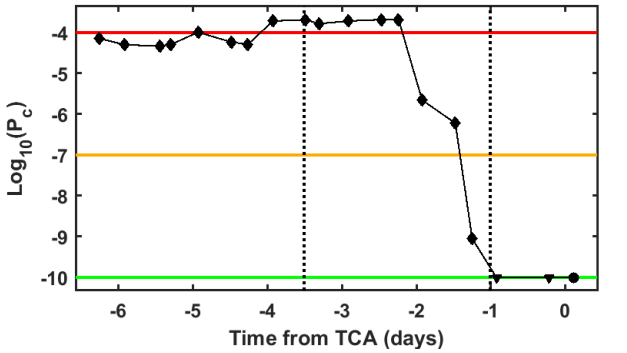


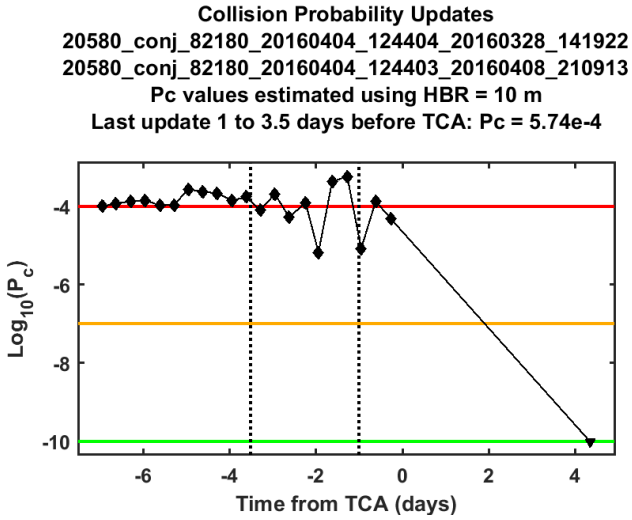
# Program *EventRate*: Plotted Spatial Distribution of the Analyzed Unique Conjunction Events



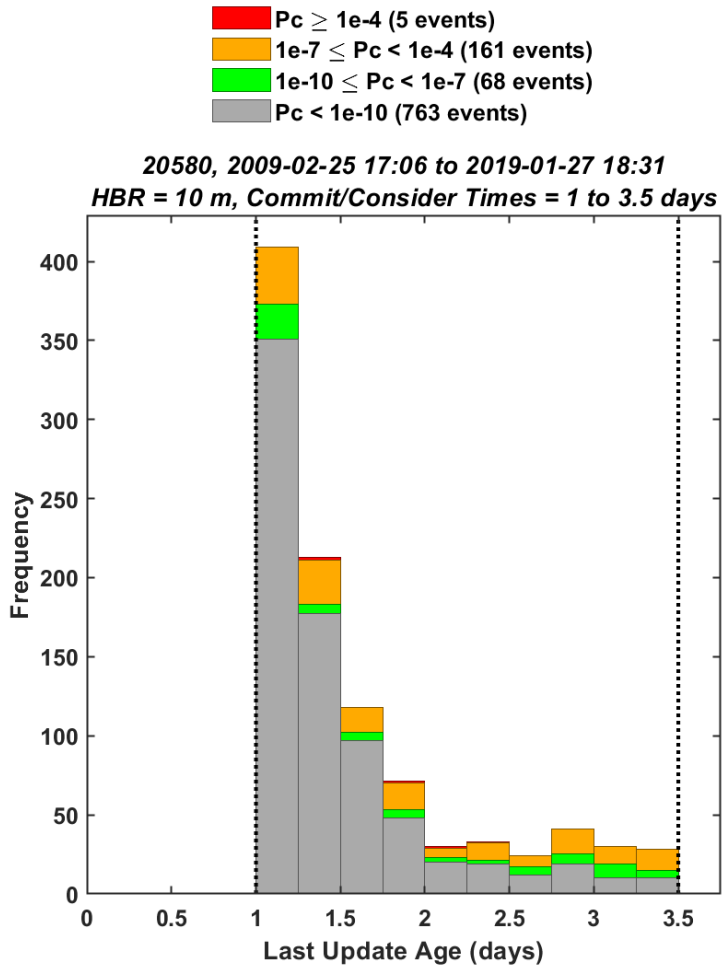
# Program *EventRate*: Plotted Pc Update Sequences for the Analyzed Unique Events

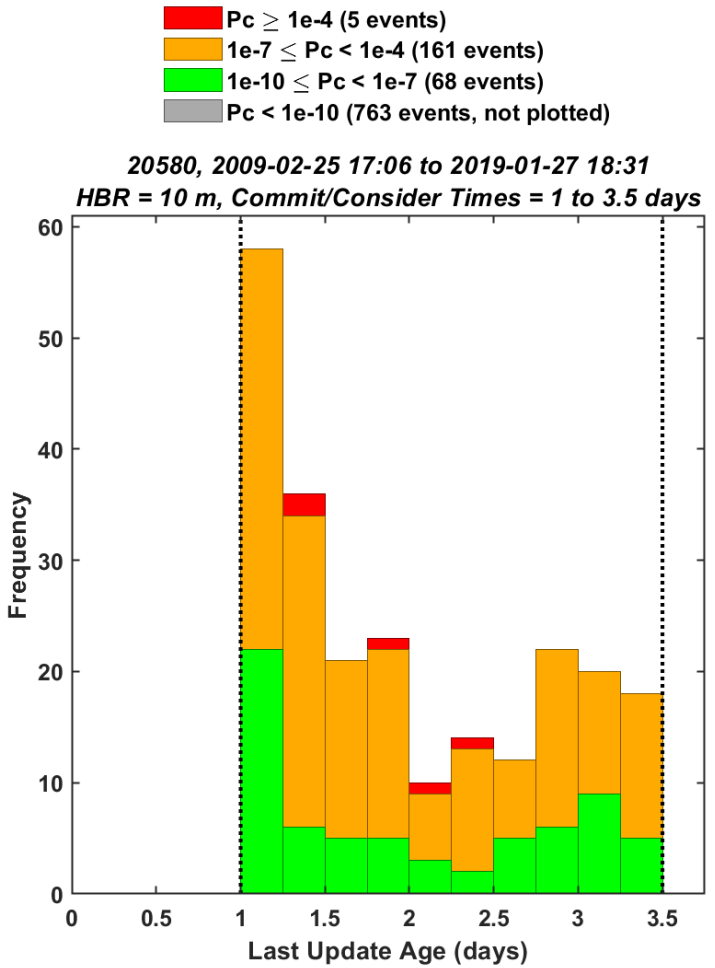


# Program *EventRate*: Plotted Distributions of Last-Update Pc Values for the Unique Events



# Usage Instructions

# Usage Instructions for Program *EventRate*
# Page 1

1. Program *EventRate* obtains required input parameters using a parameter specification file. Several example parameter specification files are provided in the "params" directory of the default distribution (such as LEO22_HST_Example1.m). These files can be used as templates for building new parameter files.
2. To estimate serious event rates for a prospective (or current) CARA mission, first find the CARA orbital regime that the mission plans to occupy (e.g., LEO2-3, LEO3-3, etc.).
3. Next, find a set of one or more current or past CARA missions within the CARA orbital regime that have orbital parameters most similar to that of the prospective mission. The archived conjunction data for this "selected" set of satellites will be used within the semi-empirical analysis algorithm.
   a. For example, in the pre-launch phase of a planned LEO2-2 mission with orbital parameters similar to those of the Hubble Spare Telescope (HST) mission, one would select HST itself (20580), as shown in the parameter file the LEO22_HST_Example1.m.
   b. Similarly, for a planned LEO3-2 mission with an orbital parameters similar to those of the A-train satellites, one could combine the archived conjunction data for the following four selected A-train members: 27424 (Aqua), 28376 (Aura), 38337 (GCOM-W1), 40059 (OCO-2), as shown in the parameter file LEO23_Atrain_Example1.m.
   c. All other mission parameters for the prospective mission (i.e., HBR, on-orbit lifetime, etc.) do not have to be similar to those of the selected CARA missions. So for the A-train example above, the prospective mission does not need to have an HBR that is the same as (or event similar to) any of the selected A-train satellites. The semi-empirical analysis algorithm only uses archived conjunction states and covariances, which do not depend on archived HBR values or other mission properties.

# Usage Instructions for Program *EventRate* Page 2

4. Build an OCMDB database .mat file that holds all of the conjunction data for the selected satellites, or a corresponding OCMDB PcTable file that holds precalculated Pc values.
   a. For LEO22_HST_Example1, the Test_C.mat file is provided in the distribution.
   b. For LEO23_Atrain_Example1, the Test_B.mat file is provided in the distribution
   c. An OCMDB PcTable file containing a curated set of missions is provided in the data directory and a list of curated satellites in this file is provided in the doc directory. Users desiring data from other missions or timeframes may reach out to the CARA team via an issue request on the GitHub site.
5. Copy one of the provided example parameter specification files to a file to be used for the prospective mission being analyzed. For example, for a new mission in an HST-like orbit, the file LEO22_HST_Example1.m could be copied to a file called New_Mission.m. This new file should be placed within the "params" subdirectory.
6. Edit the new parameters specification file to reflect the desired properties for the prospective mission, which should include the following satellite and mission properties:
   a. Short name of prospective mission: mission_name (recommended length: five characters or less)
   b. Satellite properties: mission_HBR_meters, mission_duration_years, and mission_on_orbit_mass_kg
   c. RMM execution threshold Pc value: EventRate_Pc_value
   d. RMM commit/consider times (days before TCA): Tcommit_days and Tconsider_days
   e. Type of RMM maneuver RemManeuver and associated Pc reduction factor RemReduction
   f. Flag to exclude likely non-catastrophic events for RMMs: exclude_noncatastrophic
   g. Secondary population growth factor for the mission: SecondaryCatalogGrowth

# Usage Instructions for Program *EventRate*
# Page 3

7. Execute the *EventRate* function from the main *EventRate* directory for the analysis, using the following calling syntax:

   EventRateOutput = EventRate('New_Mission');

8. Upon completion EventRateOutput will hold the quantitative estimates from the semi-empirical analysis, with the following fields
   a. MissionEventRate = 1x3 array holding the estimated mission-average RMM rate, and the associated 95% variation range for the multi-realization semi-empirical analysis: [median, 95%-low, 95%-high].
   b. CumulativePcNoRMMs = 1x3 array holding the estimated mission-cumulative Pc value for the mission if no RMMs were executed at all to mitigate the collision risk, and the associated 95% variation range for the multi-realization semi-empirical analysis: [median, 95%-low, 95%-high].
   c. CumulativePcWithRMMs = 1x3 array holding the estimated mission-cumulative Pc value for the mission if all threshold-level RMMs were executed to mitigate the collision risk, and the associated 95% variation range for the multi-realization semi-empirical analysis: [median, 95%-low, 95%-high].
   d. Details of the core ConjDist function analysis, only required for debugging and advanced analysis
9. Also upon completion, *EventRate* will create a new subdirectory in the "output" directory populated with the output plot files and a text log file with the details of the analysis.
10. If performing a trade-study of pre-launch prospective mission parameters, adjust one or more of the parameters in step 6, and rerun *EventRate* in order to see the quantitative effects of the adjustment(s) on the output numerical estimates MissionEventRate, CumulativePcNoRMMs and CumulativePcWithRMMs, as well as the corresponding changes in the associated analysis plots.

# Analysis Examples

## (all provided with the default *EventRate* distribution)

Note: Small numerical output differences from those presented in the proceeding slides may arise due to differences in hardware architecture or software

# Program *EventRate*: Serious Event Rate and Cumulative Risk Analysis Examples

- **A new mission in LEO2-2 with an orbit like that of the HST satellite**
  - Translational vs rotational risk mitigation maneuvers
- **A new mission in LEO3-2 with an orbit like that of the NOAA 18 & 19 satellites**
  - Changing the risk mitigation maneuver threshold Pc level
  - Changing the mission Hard Body Radius (HBR)
- **A new mission in LEO3-3 with an orbit like that of the METOP A & B satellites**
  - Short-duration vs long-duration active on-orbit mission lifetime
- **A new mission in LEO1-1 with an orbit like that of the GPM satellite**
  - Very low collision risk mission scenario
- **A new mission in LEO2-3 with an orbit like that of the A-train satellites**
  - Changing the RMM commit and consider times
- **A new mission in LEO3-2 with an orbit like that of the DMSP satellites**
  - Changing the secondary catalog growth factor
- **A new mission in HEO with an orbit like that of the Van Allen satellites**
  - A very large (HBR = 50 m) satellite in a high eccentricity orbit

Note: Orbit regime definitions may be found in the file “EventRate Orbit Regime Definitions.xlsx” in the doc directory

*Note: Non-catastrophic analysis is only available using complete OCMDB files. The default distribution only contains OCMDB PcTable files, which do not have enough information for this analysis mode.

# *EventRate* Cumulative Pc vs Duration
## Translational vs Rotational Risk Mitigation Maneuvers

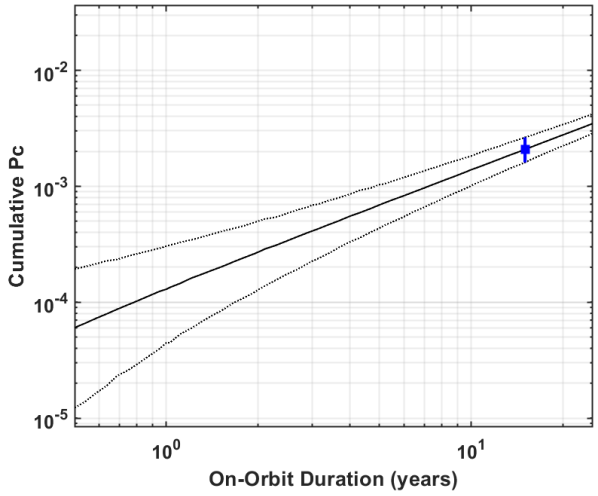
### LEO22_HST_Example1
### Translational RMMs (ρ = 0.03)
### 15-year Cumulative Pc* ≈ 2.1e-3

*Semi-Empirical Cumulative Collision Probability*

*Orbit: 20580 (541km x 556km x 28deg in LEO2-2)*
*Interval: 2009-02-25 17:06 to 2019-01-27 18:31 (9.92 yr)*
*Commit/consider time limits: 1 to 3.5 day*
*Likely non-catastrophic events: Included*
*Unique events: 997 of 1600 within commit time limits*

*NewHST: duration = 15 years, HBR = 10 m, growth = 1.3*
*RMM threshold Pc = 1e-4 (type = translational, $\rho$ = 0.03)*

*Mission Pc (with RMMs) = 2.1e-3 (95%: 1.6e-3 to 2.6e-3)*



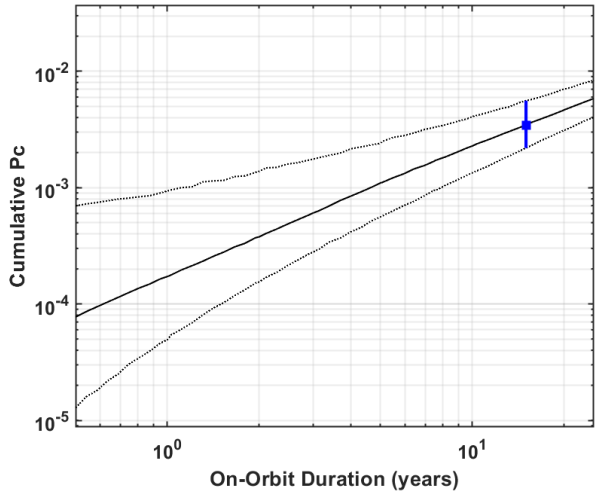

### LEO22_HST_Example2
### Rotational RMMs (ρ = 0.23)
### 15-year Cumulative Pc* ≈ 3.5e-3

*Semi-Empirical Cumulative Collision Probability*

*Orbit: 20580 (541km x 556km x 28deg in LEO2-2)*
*Interval: 2009-02-25 17:06 to 2019-01-27 18:31 (9.92 yr)*
*Commit/consider time limits: 1 to 3.5 day*
*Likely non-catastrophic events: Included*
*Unique events: 997 of 1600 within commit time limits*

*NewHST: duration = 15 years, HBR = 10 m, growth = 1.3*
*RMM threshold Pc = 1e-4 (type = rotational, $\rho$ = 0.23)*

*Mission Pc (with RMMs) = 3.5e-3 (95%: 2.2e-3 to 5.6e-3)*




***Cumulative 15-year mission Pc with no RMMs ≈ 8.1e-3**

# *EventRate* RMM Rate vs Threshold Pc

## Changing Risk Mitigation Maneuver Threshold Pc Level

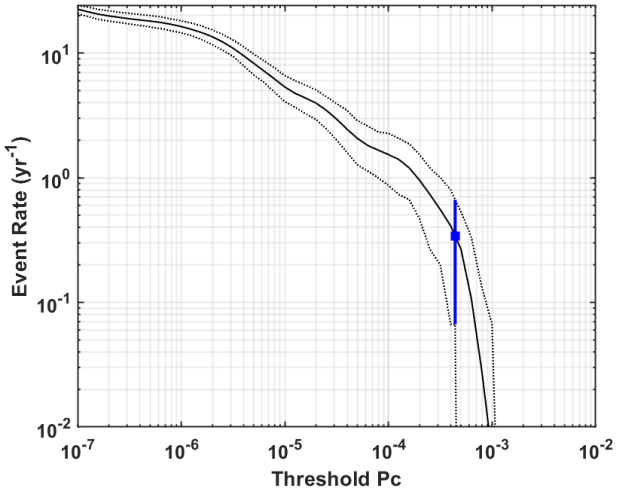
### LEO32_NOAA1819_Example1
### RMM threshold Pc = 4.4e-4
### RMM Rate ≈ 0.34 / year

*Semi-Empirical Threshold Pc Event Rates*

*Orbit: NOAA1819 (841km x 870km x 99deg in LEO3-2)*
*Interval: 2016-09-21 12:53 to 2019-01-29 08:34 (2.35 yr)*
*Commit/consider time limits: 1 to 3.5 day*
*Likely non-catastrophic events: Included*
*Unique events: 1973 of 2251 within commit time limits*

*NewNOAA: duration = 15 years, HBR = 6 m, growth = 1.3*
*Serious event threshold Pc = 4.4e-4*

*Estimated event rate = 0.34 / year (95%: 0.07 to 0.67)*



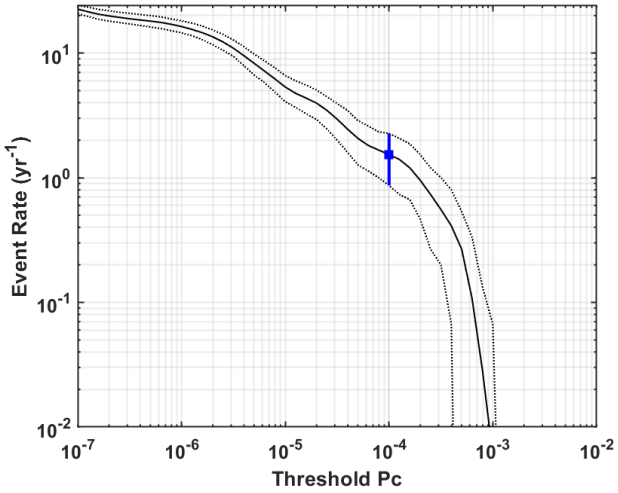

### LEO32_NOAA1819_Example2
### RMM threshold Pc = 1.0e-4
### RMM Rate ≈ 1.53 / year

*Semi-Empirical Threshold Pc Event Rates*

*Orbit: NOAA1819 (841km x 870km x 99deg in LEO3-2)*
*Interval: 2016-09-21 12:53 to 2019-01-29 08:34 (2.35 yr)*
*Commit/consider time limits: 1 to 3.5 day*
*Likely non-catastrophic events: Included*
*Unique events: 1973 of 2251 within commit time limits*

*NewNOAA: duration = 15 years, HBR = 6 m, growth = 1.3*
*Serious event threshold Pc = 1e-4*

*Estimated event rate = 1.53 / year (95%: 0.87 to 2.27)*



# *EventRate* RMM Rate vs Threshold Pc
## Changing the Mission Hard Body Radius

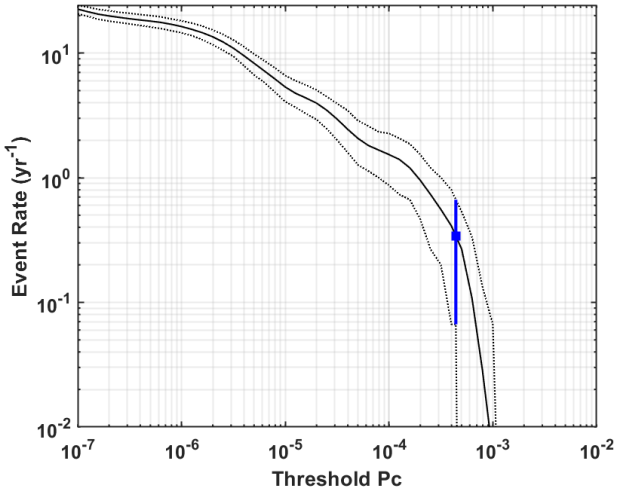
## LEO32_NOAA1819_Example1
## Mission HBR = 6 m
## RMM Rate ≈ 0.34 / year

***Semi-Empirical Threshold Pc Event Rates***

***Orbit: NOAA1819 (841km x 870km x 99deg in LEO3-2)***
***Interval: 2016-09-21 12:53 to 2019-01-29 08:34 (2.35 yr)***
***Commit/consider time limits: 1 to 3.5 day***
***Likely non-catastrophic events: Included***
***Unique events: 1973 of 2251 within commit time limits***

***NewNOAA: duration = 15 years, HBR = 6 m, growth = 1.3***
***Serious event threshold Pc = 4.4e-4***

***Estimated event rate = 0.34 / year (95%: 0.07 to 0.67)***



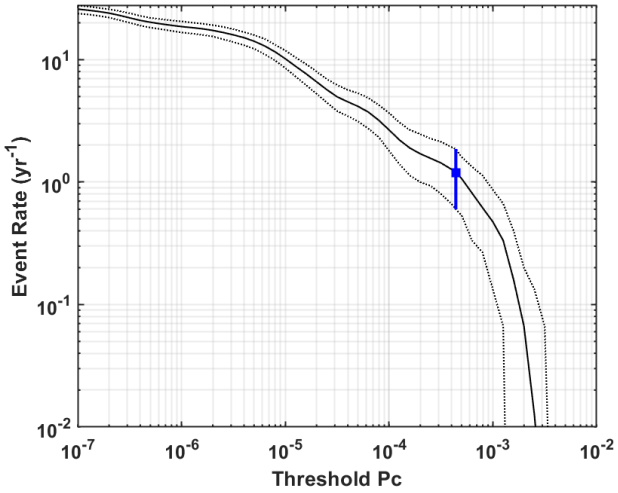

## LEO32_NOAA1819_Example3
## Mission HBR = 10 m
## RMM Rate ≈ 1.2 / year

***Semi-Empirical Threshold Pc Event Rates***

***Orbit: NOAA1819 (841km x 870km x 99deg in LEO3-2)***
***Interval: 2016-09-21 12:53 to 2019-01-29 08:34 (2.35 yr)***
***Commit/consider time limits: 1 to 3.5 day***
***Likely non-catastrophic events: Included***
***Unique events: 1973 of 2251 within commit time limits***

***NewNOAA: duration = 15 years, HBR = 10 m, growth = 1.3***
***Serious event threshold Pc = 4.4e-4***

***Estimated event rate = 1.20 / year (95%: 0.60 to 1.87)***



# *EventRate* Cumulative Pc vs Duration

## Short- vs Long-Duration Active On-orbit Mission Lifetime

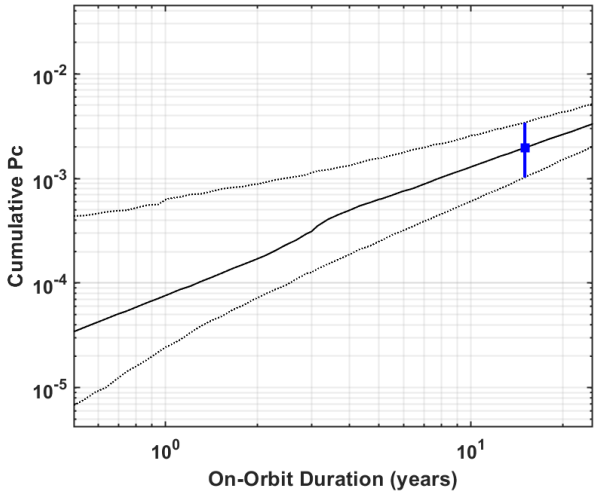
### LEO33_METOPAB_Example1
### Mission Duration = 15 years
### Mission Cumulative Pc ≈ 2.0e-3

***Semi-Empirical Cumulative Collision Probability***

***Orbit: 29499 38771 (813km x 846km x 99deg in LEO3-3)***
***Interval: 2016-10-01 07:30 to 2019-01-29 16:34 (2.33 yr)***
***Commit/consider time limits: 1 to 3.5 day***
***Likely non-catastrophic events: Included***
***Unique events: 1787 of 2076 within commit time limits***

***NewMetop: duration = 15 years, HBR = 5 m, growth = 1***
***RMM threshold Pc = 4.4e-4 (type = translational, $\rho$ = 0.03)***

***Mission Pc (with RMMs) = 2.0e-3 (95%: 1.0e-3 to 3.4e-3)***



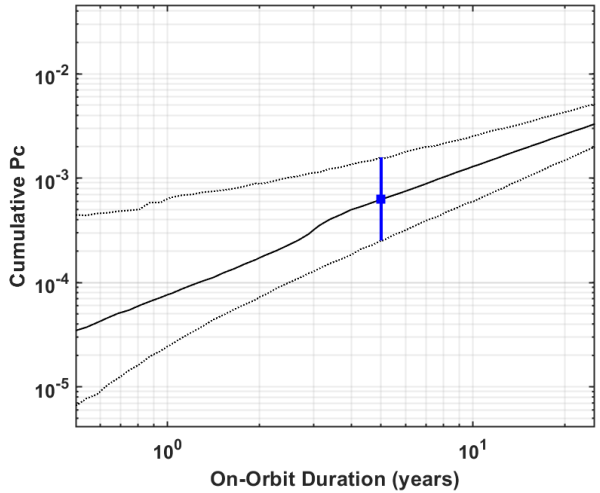

### LEO33_METOPAB_Example2
### Mission Duration = 5 years
### Mission Cumulative Pc ≈ 6.3e-4

***Semi-Empirical Cumulative Collision Probability***

***Orbit: 29499 38771 (813km x 846km x 99deg in LEO3-3)***
***Interval: 2016-10-01 07:30 to 2019-01-29 16:34 (2.33 yr)***
***Commit/consider time limits: 1 to 3.5 day***
***Likely non-catastrophic events: Included***
***Unique events: 1787 of 2076 within commit time limits***

***NewMetop: duration = 5 years, HBR = 5 m, growth = 1***
***RMM threshold Pc = 4.4e-4 (type = translational, $\rho$ = 0.03)***

***Mission Pc (with RMMs) = 6.3e-4 (95%: 2.5e-4 to 1.6e-3)***



# *EventRate* Event Rate & Cumulative Pc
## Very Low Collision Risk Mission Scenario

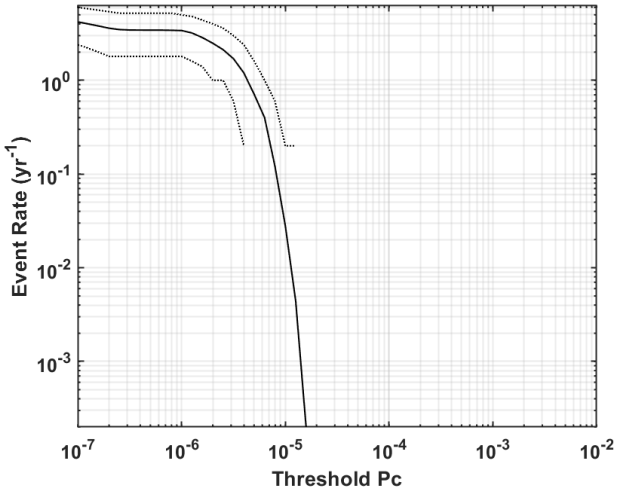
## LEO11_GPM_Example
## HBR = 5 m and Duration = 5 years
## Mission RMM Rate ≈ 0.0 / year

***Semi-Empirical Threshold Pc Event Rates***

***Orbit: 39574 (400km x 414km x 65deg in LEO1-3)***
***Interval: 2017-05-05 14:00 to 2019-08-18 21:02 (2.29 yr)***
***Commit/consider time limits: 1 to 3.5 day***
***Likely non-catastrophic events: Included***
***Unique events: 681 of 998 within commit time limits***

***NewGPM: duration = 5 years, HBR = 5 m, growth = 1.3***
***Serious event threshold Pc = 4.4e-4***

***Estimated event rate = 0.00 / year (95%: 0.00 to 0.00)***



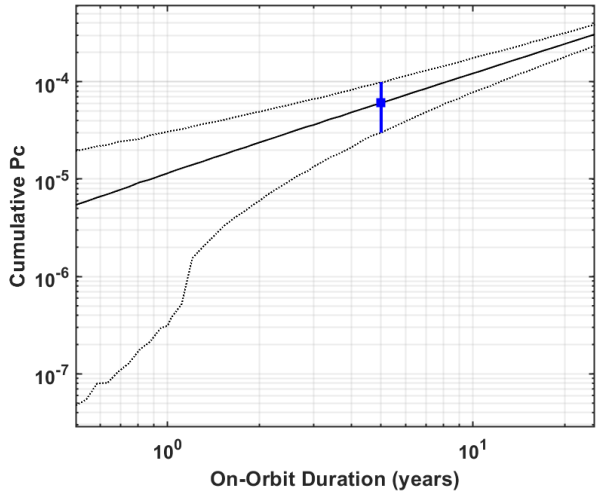

## LEO11_GPM_Example
## HBR = 5 m and Duration = 5 years
## Mission Cumulative Pc ≈ 6.1e-5

***Semi-Empirical Cumulative Collision Probability***

***Orbit: 39574 (400km x 414km x 65deg in LEO1-3)***
***Interval: 2017-05-05 14:00 to 2019-08-18 21:02 (2.29 yr)***
***Commit/consider time limits: 1 to 3.5 day***
***Likely non-catastrophic events: Included***
***Unique events: 681 of 998 within commit time limits***

***NewGPM: duration = 5 years, HBR = 5 m, growth = 1.3***
***RMM threshold Pc = 4.4e-4 (type = translational, $\rho$ = 0.03)***

***Mission Pc (with RMMs) = 6.1e-5 (95%: 3.0e-5 to 9.9e-5)***



# *EventRate* RMM Rate vs Threshold Pc
## Changing the RMM Commit and Consider Times

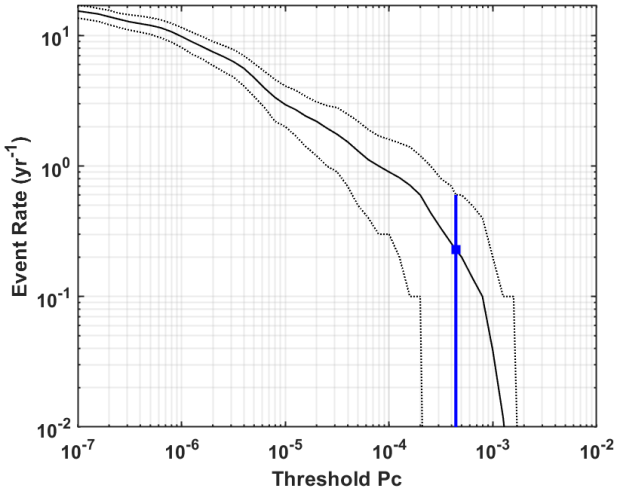
### LEO23_Atrain_Example1
### Commit-Consider = 0.5-3.0 days
### RMM Rate ≈ 0.23 / year

*Semi-Empirical Threshold Pc Event Rates*

*Orbit: 4ATRs (695km x 728km x 98deg in LEO2-3)*
*Interval: 2017-04-28 17:27 to 2019-08-22 21:47 (2.32 yr)*
*Commit/consider time limits: 0.5 to 3 day*
*Likely non-catastrophic events: Included*
*Unique events: 5108 of 6100 within commit time limits*

*NewAtrain: duration = 10 years, HBR = 8 m, growth = 1.3*
*Serious event threshold Pc = 4.4e-4*

*Estimated event rate = 0.23 / year (95%: 0.00 to 0.60)*



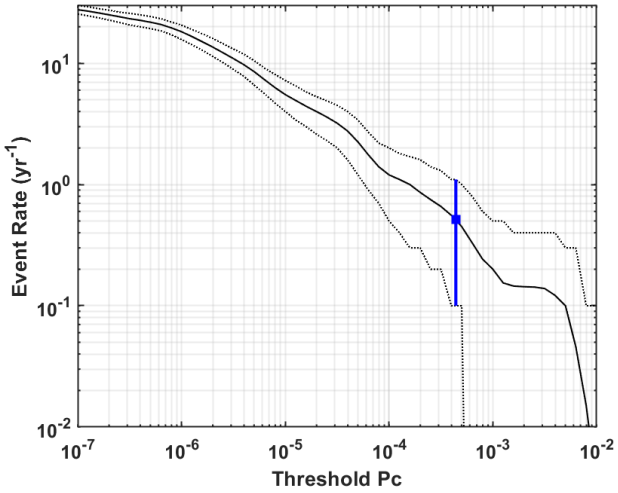

### LEO23_Atrain_Example2
### Commit-Consider = 1.5-4.0 days
### RMM Rate ≈ 0.51 / year

*Semi-Empirical Threshold Pc Event Rates*

*Orbit: 4ATRs (695km x 728km x 98deg in LEO2-3)*
*Interval: 2017-04-28 17:27 to 2019-08-22 21:47 (2.32 yr)*
*Commit/consider time limits: 1.5 to 4 day*
*Likely non-catastrophic events: Included*
*Unique events: 5245 of 6100 within commit time limits*

*NewAtrain: duration = 10 years, HBR = 8 m, growth = 1.3*
*Serious event threshold Pc = 4.4e-4*

*Estimated event rate = 0.51 / year (95%: 0.10 to 1.10)*



# *EventRate* RMM Rate vs Threshold Pc
## Changing the Secondary Catalog Growth Factor

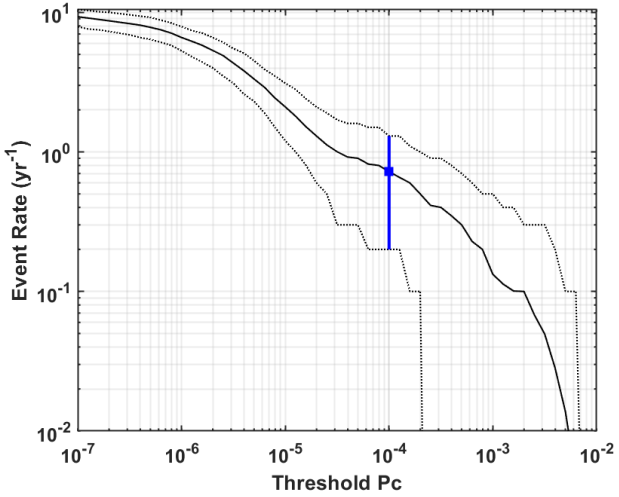
### LEO32_DMSP_Example1
### Secondary Catalog Growth = 1.0
### RMM Rate ≈ 0.72 / year

*Semi-Empirical Threshold Pc Event Rates*

*Orbit: 7DMSPs (836km x 863km x 99deg in LEO3-2)*
*Interval: 2017-05-01 06:48 to 2019-08-22 16:48 (2.31 yr)*
*Commit/consider time limits: 0.5 to 3 day*
*Likely non-catastrophic events: Included*
*Unique events: 5597 of 6467 within commit time limits*

*NewDMSP: duration = 10 years, HBR = 6 m, growth = 1*
*Serious event threshold Pc = 1e-4*

*Estimated event rate = 0.72 / year (95%: 0.20 to 1.30)*



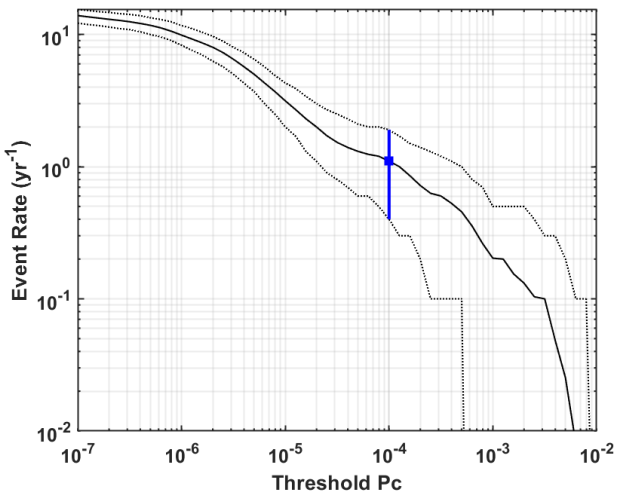

### LEO32_DMSP_Example2
### Secondary Catalog Growth = 1.5
### RMM Rate ≈ 1.10 / year

*Semi-Empirical Threshold Pc Event Rates*

*Orbit: 7DMSPs (836km x 863km x 99deg in LEO3-2)*
*Interval: 2017-05-01 06:48 to 2019-08-22 16:48 (2.31 yr)*
*Commit/consider time limits: 0.5 to 3 day*
*Likely non-catastrophic events: Included*
*Unique events: 5597 of 6467 within commit time limits*

*NewDMSP: duration = 10 years, HBR = 6 m, growth = 1.5*
*Serious event threshold Pc = 1e-4*

*Estimated event rate = 1.10 / year (95%: 0.40 to 1.90)*



# *EventRate* Event Rate & Cumulative Pc
## Very Large Satellite in High Eccentricity Orbit

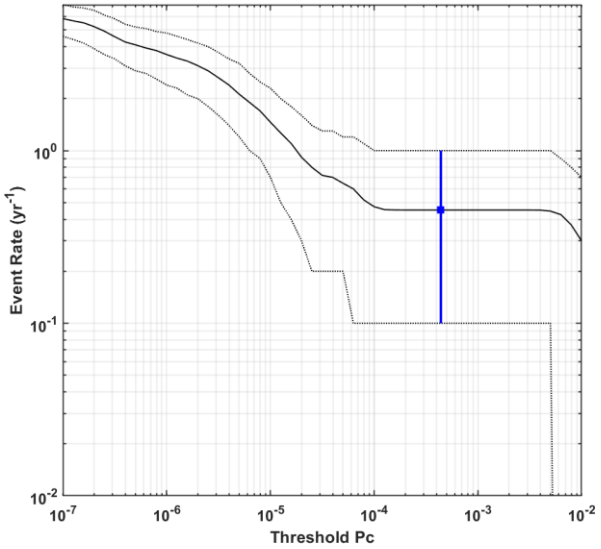
**HEO_VanAllen_Example**
**HBR = 50 m & Duration = 10 years**
**Mission RMM Rate ≈ 0.45 / year**

*Semi-Empirical Threshold Pc Event Rates*

*Orbit: VAAB (593km x 30585km x 10deg in HEO)*
*Interval: 2017-05-01 14:40 to 2019-08-25 18:46 (2.32 yr)*
*Commit/consider time limits: 0.75 to 3.25 day*
*Likely non-catastrophic events: Included*
*Unique events: 11926 of 15843 within commit time limits*

*NewHEO: duration = 10 years, HBR = 50 m, growth = 1.05*
*Serious event threshold Pc = 4.4e-4*

*Estimated event rate = 0.45 / year (95%: 0.10 to 1.00)*



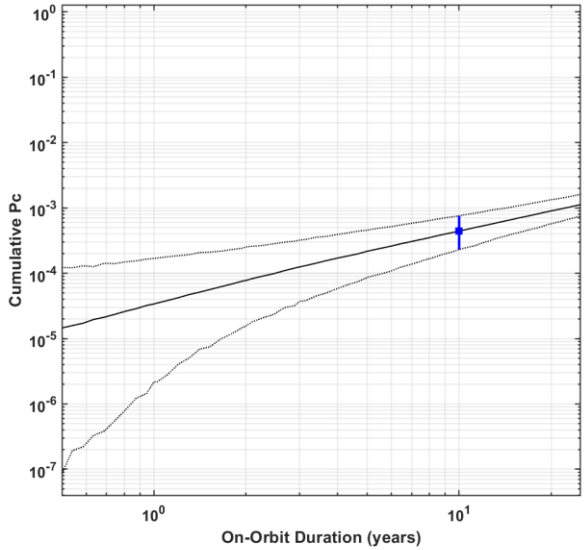

**HEO_VanAllen_Example**
**HBR = 50 m & Duration = 10 years**
**Mission Cumulative Pc* ≈ 4.4e-4**

*Semi-Empirical Cumulative Collision Probability*

*Orbit: VAAB (593km x 30585km x 10deg in HEO)*
*Interval: 2017-05-01 14:40 to 2019-08-25 18:46 (2.32 yr)*
*Commit/consider time limits: 0.75 to 3.25 day*
*Likely non-catastrophic events: Included*
*Unique events: 11926 of 15843 within commit time limits*

*NewHEO: duration = 10 years, HBR = 50 m, growth = 1.05*
*RMM threshold Pc = 4.4e-4 (type = translational, $\rho$ = 0.03)*

*Mission Pc (with RMMs) = 4.4e-4 (95%: 2.3e-4 to 7.6e-4)*




***Cumulative mission Pc with no RMMs ≈ 0.15**