Assessing GEO and LEO Repeating Conjunctions Using High Fidelity Brute Force Monte Carlo Simulations

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The 2019 AAS/AIAA Astrodynamics Specialist Conference
Portland, Maine, August 11-15, 2019
Paper AAS 19-612

Agenda and Overview

- **Introduction**
  - Motivation and objectives
  - Review previous *Brute Force Monte Carlo* (BFMC) implementation
  - Updates made to BFMC implementation
- **Analysis**
  - Identification of repeating conjunctions
  - Sample GEO repeating conjunctions
  - Sample LEO repeating conjunctions
- **Conclusions and Future Work**

Motivation and Objectives

- **Motivation** The probability of collision (Pc) between two Earth-orbiting satellites using the semi-analytical "2D-Pc" formulation[1,2] and the previous implementation of BFMC may fail to provide accurate results for repeating encounters[3,4]
- **Objective** Develop a method for identifying and assessing repeating conjunctions using high-fidelity BFMC[3] Pc simulations

[1]J.L. Foster and H.S. Estes, "A Parametric Analysis of Orbital Debris Collision Probability and Maneuver Rate for Space Vehicles," NASA/JSC-25898, Aug. 1992

[2]M.R. Akella and K.T. Alfriend, "The Probability of Collision Between Space Objects," *Journal of Guidance, Control, and Dynamics*, Vol. 23, No. 5, pp. 769-772, 2000

[3]D. Hall *et al*, "High-Fidelity Collision Probabilities Estimated Using Brute Force Monte Carlo Simulations" AAS 18-244, Aug. 2018

[4]K. Chan, *Spacecraft Collision Probability*, El Segundo, CA, The AeroSpace Corporation, 2008

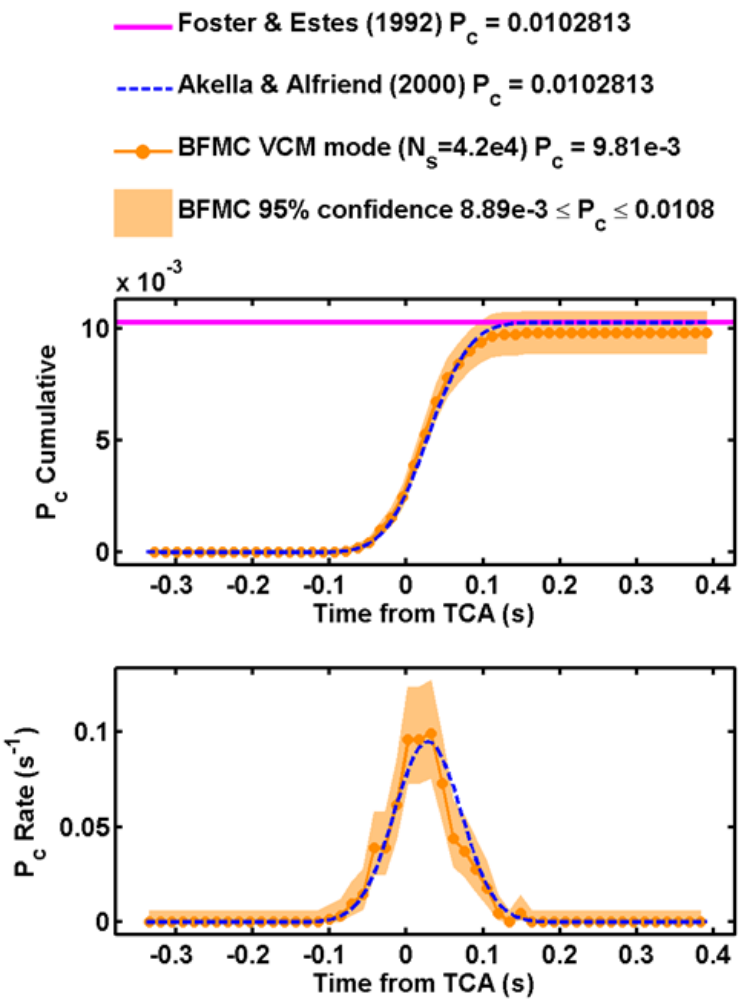
Review of BFMC-Pc Estimation

- **BFMC is an advanced implementation of a method developed in 2011 by Chris Sabol and co-authors[1,2]**
  - Estimates Pc values using Monte Carlo simulations
  - Uses high fidelity special perturbations (SP) orbital propagation
  - Uses SP orbital states comprised of the six equinoctial orbital elements plus a ballistic coefficient and a solar radiation pressure parameter
- **VCM mode "from-epoch" simulations[2]**
  1. Sample SP orbital states from uncertainty probability distribution functions (PDFs) for the primary and secondary satellites at their orbital determination (OD) epoch times
  2. Propagate the sampled SP states forward in time through a collision risk assessment period
     - Explicitly check if the intervening distance ever becomes less than the combined hard-body radii (HBR)
  3. Register a collision at the time of first contact within the risk assessment period

[1]C. Sabol *et al*, "Probability of Collisions with Special Perturbations using the Monte Carlo Method" AAS 11-435, 2011
[2]D.Hall *et al*, "High-Fidelity Collision Probabilities Estimated Using Brute Force Monte Carlo Simulations" AAS 18-244, 2018

Review of BFMC-Pc Estimation (cont.)

- **Risk assessment interval for short-duration encounters closely brackets the time of closest approach (TCA)[1]**
  - Based on the short-term encounter validity interval defined by Coppola[2]
  - Hits in BFMC are counted only if they occur within the defined risk assessment interval
- **Long-duration and/or repeating conjunctions require an expansion of the risk assessment interval**



[1]D.Hall *et al*, "High-Fidelity Collision Probabilities Estimated Using Brute Force Monte Carlo Simulations" AAS 18-244, 2018
[2]V.Coppola, "Evaluating the Short Encounter Assumption of the Probability of Collision Formula" AAS 12-248, 2012

Updates to BFMC-Pc Estimation

- **Expand the risk assessment interval**
  - Starts at the time of the last OD epoch and ends 7 days later
  - Called the BFMC long duration VCM (LD-VCM) mode
- **Add method for identifying possible repeating conjunctions**
  - Only run the resource intensive BFMC LD-VCM mode when needed
- **Modify the focus of BFMC LD-VCM mode away from TCA**
  - Select a Pc value above which a mitigation needs to occur (i.e. a “red” event threshold of 1e-04) called the maximum-risk threshold
  - Identify the time when the repeating conjunction exceeds the maximum-risk threshold
  - Report maximum-risk threshold crossing time and confidence interval in addition to the cumulative Pc value
- **Implement a “burst” detection algorithm**
  - Identifies when individual close approach events effectively blend together in time

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Identifying Repeating Conjunctions

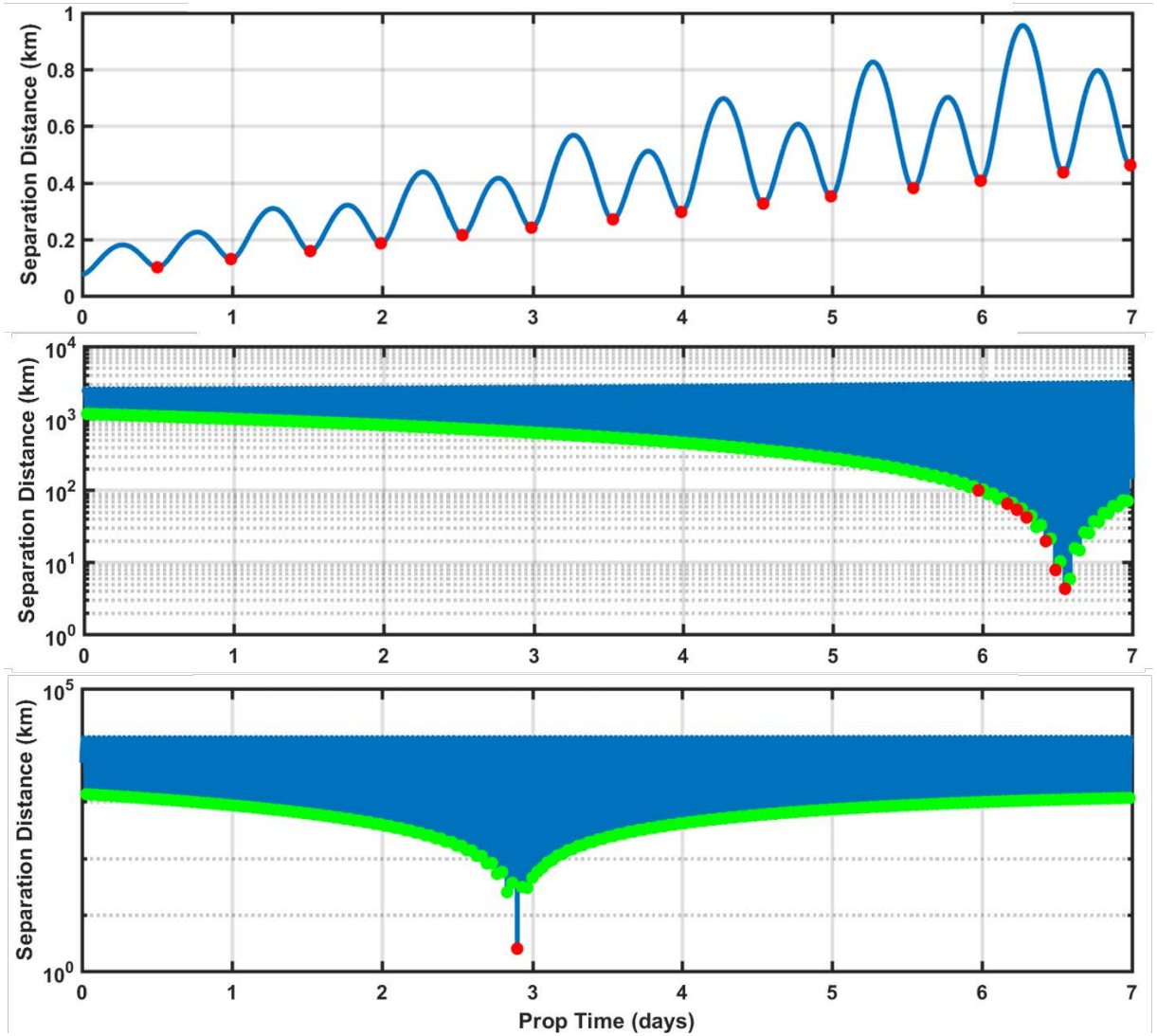
- **Algorithm Description**
  1. **Propagate SP states and covariances of primary and secondary from OD epochs to 7 days after the time of the last OD epoch**
  2. **Convert SP states to ECI position vectors and calculate the distance between the vectors throughout the propagation interval**
  3. **Determine the local minima of the distances and calculate the 2D-Pc at each minimum**
  4. **If more than 1 2D-Pc exceeds 1e-10, the conjunction is a possible repeating conjunction**
- **Tested against a set of 90 CARA high-Pc test cases**
  - Correctly identified all 6 repeating conjunctions of the 90 sample conjunctions

Identifying Repeating Conjunctions (cont.)

GEO Repeating

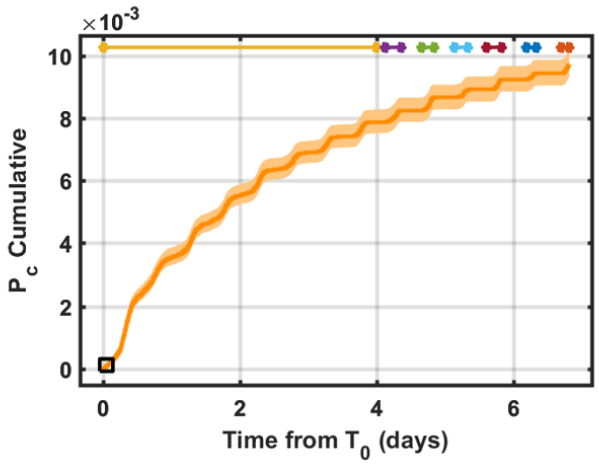
LEO Repeating

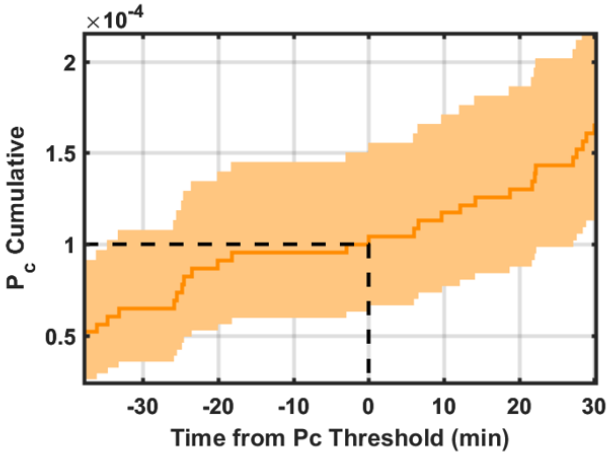
LEO Temporally Isolated



Blue line = separation distance, Red circles = local minima exceeding 1e-10 Pc threshold, Green circles = all other local minima

GEO Repeating Conjunction





Pattern indicative of two closely-spaced objects which do not separate appreciably throughout their orbits.

BFMC VCM mode (N_s=230016) P_c = 9.73e-3

BFMC 95% confidence 9.34e-3 $\leq P_c \leq$ 0.01014

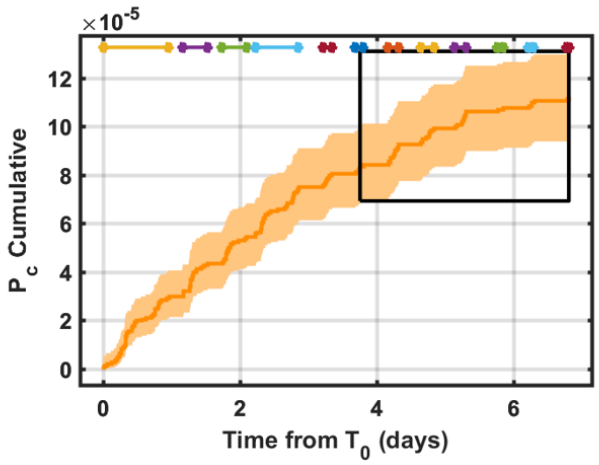
T_0 = 2017-11-07 23:50:42.666

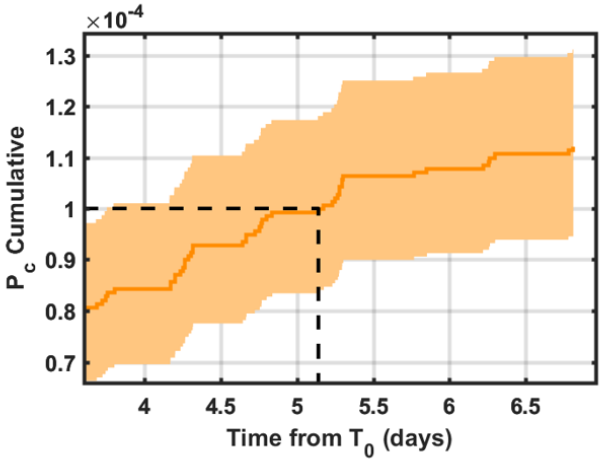
Pc Threshold Crossings ($P_c \geq$ 1e-4):

Earliest (95% conf): 2017-11-08 00:29:43.319
Nominal: 2017-11-08 01:04:25.943
Latest (95% conf): 2017-11-08 01:31:34.384

Corresponds to the top graph in slide 9.

GEO Repeating Conjunction





Same orbits as the last conjunction, except the HBR has been reduced to illustrate the detection of more bursts.

BFMC VCM mode (N_s=1.4e6) P_c = 1.12e-4

BFMC 95% confidence 9.5e-5 $\leq P_c \leq$ 1.31e-4

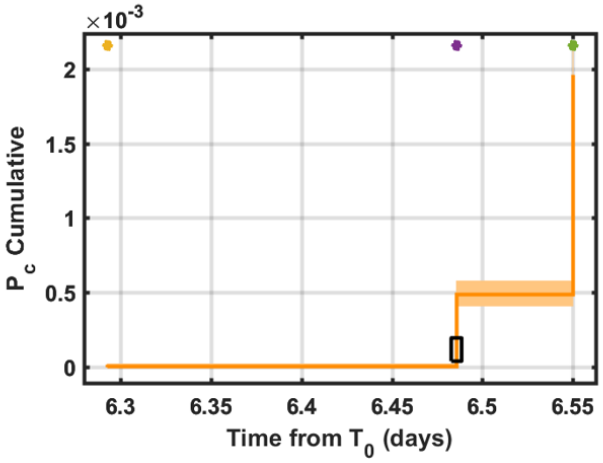
T_0 = 2017-11-07 23:50:42.666

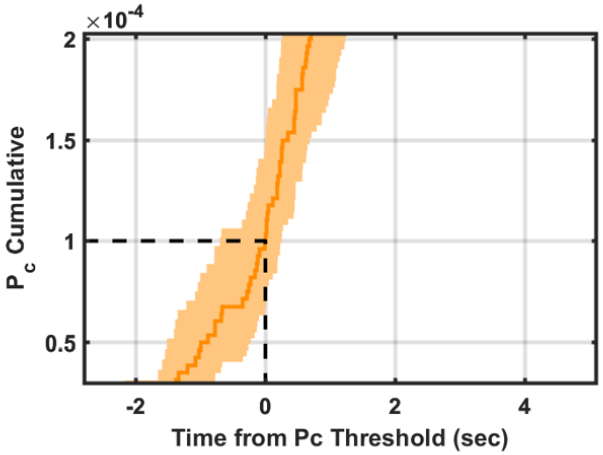
Pc Threshold Crossings ($P_c \geq$ 1e-4):

Earliest (95% conf): 2017-11-11 18:00:59.169
Nominal: 2017-11-13 03:12:25.550
Latest (95% conf): Not Found

Corresponds to the top graph in slide 9.

LEO Repeating Conjunction





Pattern indicative of two objects that are not coplanar but have similar periods.

BFMC VCM mode (N_s=2.8e5) P_c = 1.96e-3

BFMC 95% confidence 1.8e-3 $\leq P_c \leq$ 2.14e-3

T_0 = 2017-09-10 13:51:22.974

Pc Threshold Crossings ($P_c \geq$ 1e-4):

Earliest (95% conf): 2017-09-17 01:30:38.884
Nominal: 2017-09-17 01:30:39.577
Latest (95% conf): 2017-09-17 01:30:39.822

Corresponds to the middle graph in slide 9.

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Conclusions and Future Work

- **BFMC LD-VCM mode should be used to assess the Pc risk of long-duration and/or repeating conjunctions**
- **Initial method has been developed to identify repeating conjunctions**
- **In addition to cumulative Pc, the maximum-risk Pc threshold crossing time should be used for evaluating repeating conjunctions**

- **Future Work**
  - Further testing is needed to verify the Pc threshold level used to identify repeating conjunctions is valid
  - BFMC LD-VCM mode Pc estimates need to be tested against a larger data set to rigorously test the robustness of the overall algorithm
    - Focus on GEO conjunctions