Satellite Collision Avoidance
Supporting Ballistic Missile Flight Tests

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Threat of Orbital Objects on Missile Flight Tests

Objects in Low-Earth Orbit

Hyper-velocity impact of small object on Space Shuttle Endeavour’s radiator

https://orbitaldebris.jsc.nasa.gov/images/beehives/leo640.jpg

https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080010742.pdf
Satellite Collision Avoidance (COLA)

- Need to ensure that collisions do not occur in order to:
  - Protect missile from satellites and orbital debris
  - Protect active satellites from missile and missile debris
- Do not allow the missile to fire at times when it might collide with another object
- Define moving spheres (i.e. screening volumes) to encapsulate the missile objects
- A conjunction analysis is performed on the screening volumes vs. the satellite catalog to determine when it is safe to launch
COLA Analysis Timeline

- T-8 Months: Receive Trajectory Data
- T-6 Months: Screening Volume Development
- T-4 Hours: Post-Process Satellite Conjunctions
- T-2 Hours: Deliver Launch Window Reports
- T-0: Launch!
Monte Carlo Trajectory Set

Monte Carlo set of trajectories that account for expected dispersions due to variations in parameters such as vehicle performance and atmospheric conditions
COLA Analysis Timeline

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Deliver Launch Window Reports

T-0
Launch!
Satellite Altitude Distribution

• The satellite altitude distribution is used to define a weight function.
Screening Volume Calculation Overview

- Screening volume: sphere of constant radius following a trajectory
- Let \( f(x, y, z, t) = 1 \) if the space-time point is inside the net screening-volume region, and 0 otherwise
- The weight function based on satellite altitude distribution is \( W(alt) \)
- The net volume is
  - \( V(t) = \int f(x, y, z, t) \, dx \, dy \, dz \)
  - \( V_w(t) = \int f(x, y, z, t) \ast W(alt) \ast dx \, dy \, dz \)
- This can be further integrated over time to give the space-time-integral
  - \( VT = \int_{t_0}^{t_f} V(t) \, dt \)
  - \( VT_w = \int_{t_0}^{t_f} V_w(t) \, dt \)
Screening Volume Optimization - Overview

• Cost Function: Space-Time-Integral ($VT_w$)
  - Calculation time: ~1-10 seconds
  - Proportional to estimated launch window closure

• Constraint Function: All points bounded
  - At each time-step, all solid body objects must be inside the screening volumes
  - For debris represented as expanding spheres, the spheres must be completely inside the screening volumes

Adding $d_2$ to both screening volumes in this example is a simple (but over-conservative) way to ensure that the constraint is met.
Heuristic Estimation of Launch Window (LW) Closure

• Motivation
  - Best estimate of LW is to request 18th Space Control Squadron (18SPCS) to run a conjunction analysis (~days lead time)
  - Next best estimate is to run a conjunction analysis ourselves using Systems Tool Kit (STK) (~hours of setup + runtime)
  - Desire for fast estimation of LW closure (~seconds)

• Heuristic Estimation
  - Generated several sets of screening volumes
  - For each screening volume, $VT_w$ was calculated
  - Also, a conjunction analysis against the satellite catalog was run using STK to determine the percent of LW closed

\[
p_{Closed} = VT_w \times \left( \frac{100\%}{1.3 \times 10^{10} \text{ km}^3\text{s}} \right)
\] Screened against entire satellite catalog

\[
p_{Closed} = VT_w \times \left( \frac{100\%}{5.0 \times 10^{10} \text{ km}^3\text{s}} \right)
\] Screened against active satellites only

The heuristic estimation:
• Enables optimization algorithms for screening volume development
• Provides analysts with a fast, quantitative measure of the screening volume design
Trajectory and Screening Volume Animation Snapshots

$t_1$

$t_2$

$t_3$

$t_4$

$t_5$

$t_6$
COLA Analysis Timeline

T-8 Months
Receive Trajectory Data

T-6 Months
Screening Volume Development

T-4 Hours
Post-Process Satellite Conjunctions

T-2 Hours
Deliver Launch Window Reports

T-0
Launch!
Post-Processing Filters

- 18SPCS provides a conjunction report
- Filter conjunctions above the maximum altitude of the trajectory set
- Apply additional filters
COLA Analysis Timeline

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Sample Launch Exclusion Report

Header with delivery ID

Table of open launch times

Launch window graphic with closed launch times
Questions?

T-8 Months
Receive Trajectory Data

T-6 Months
Screening Volume Development

T-4 Hours
Post-Process Satellite Conjunctions

T-2 Hours
Deliver Launch Window Reports

T-0
Launch!
Backup
Procedures for Defining Spherical COLA Screening Volumes

• Solid Body Volume Definition
  - One or more spheres are defined to encompass a set of trajectories
  - Trajectories are considered from the time of the earliest 100 km altitude crossing to the time of latest
    100 km altitude descent crossing
  - An additional variation of $\pm \tau/2$ is considered, where $\tau$ is the interval between screened launch times

• Conjunction assessment for solid body objects are performed using standoff radii
  - Manned spacecraft: minimum radius + 200 km
  - Unmanned active spacecraft: minimum radius + 25 km
  - Inactive space objects: minimum radius + 2.5 km

• Inactive satellites and orbital debris are screened as needed to preclude interference with test execution

• Increasing use of covariance screens when applicable and required

• Post-Intercept Debris Fragments
  - Screening requirements defined for each satellite group (manned/Hubble/active) based on minimum fragment size, vulnerable object area, maximum allowable probability of collision
  - Debris fragmentation using the Kinetic Impact Debris Distribution (KIDD) computer model
  - Generate growing debris spheres, with radius defined by the required keep-out distance
Most eccentricities are small, so circular orbit approximation is reasonable

- Over 90% of satellites have an altitude > 600 km
- ~70% of satellites have an altitude between 600 and 1100 km
Satellite Distribution Comparison

- Similar distribution of satellites for entire catalog and active
- The Gaussian fit is better for the entire catalog
- Therefore, the fit for the entire catalog is used for the weight function
- Expect the number of satellites to increase in the future, especially low-altitude cubesats
STK Case Study Methodology

• 17 cases are considered
• For each case, one or several screening volumes are defined
• The screening volumes follow ballistic trajectories
• A conjunction analysis of the screening volumes vs. the satellite catalog is run using STK to calculate the percent of launch window closed ($p_{Closed}$)
• No post-processing is run to filter out conjunctions (such as maximum altitude)
STK Case Definitions

- Varying Radius
  - One screening volume for each case
  - The radius of the screening volume is varied between cases
  - Cases 1-5

- Varying Initial Speed
  - One screening volume for each case
  - Initial speed is varied between cases
  - Cases 6-8

- Two Screening Volumes: Leader/Follower
  - Two screening volumes for each case
  - The two volumes have the same trajectory, except the second volume is offset in launch time
  - The offset in launch time is varied between cases
  - Cases 9-12

- Two Screening Volumes: Side-By-Side
  - Two screening volumes for each case
  - The two volumes have the same trajectory, except the second volume is offset in cross-range at launch
  - The offset in cross-range is varied between cases
  - Cases 13-15

- Three Screening Volumes: Stair-Step in Time
  - Three screening volumes for each case
  - A single trajectory is split up in time, to form a stair-step of screening volumes with increasing radii
  - Case 17
Space-Time Integral Evaluation
Entire Satellite Catalog

- If \( p_{\text{Closed}} > 100\% \), the launch window is predicted to be fully closed

\[
p_{\text{Closed}} = VT_w \times \left( \frac{100\%}{1.3 \times 10^{10} \text{ km}^3\text{s}} \right)
\]
Space-Time Integral Evaluation
Active Satellites Only

\[ p_{\text{Closed}} = V T_w \times \left( \frac{100\%}{5.0 \times 10^{10} \text{ km}^3\text{s}} \right) \]

- If \( p_{\text{Closed}} \) > 80\%, the launch window is predicted to be mostly closed
Launch Window Closure vs. Active Satellite Catalog

LW closure for a single screening volume. Following a ballistic trajectory with 45° launch elevation, with initial speed varied.
Launch Window Closure vs. Entire Satellite Catalog

LW closure for a single screening volume. Following a ballistic trajectory with 45° launch elevation, with initial speed varied.
Optimization Algorithm: Best Screening Volume Trajectory

- **Object Trajectories**
  - Define a set of trajectories which need to be encapsulated by a screening volume
  - Trajectories can include solid bodies and intercept debris spheres
  - (Optional): Calculate maximum altitude

- **Screening Volume Candidate Trajectories**
  - Define a set of candidate trajectories to use for the screening volume
  - Typically, this is a subset of the object trajectories, but back/forward propagation is often required

- **Algorithm**
  - Calculate radius required for each screening volume candidate
  - Calculate heuristic for LW closure for each screening volume candidate
  - Pick candidate with minimum estimated LW closure

- **Split up in time (optional)**
  - Separation distance of object trajectories with respect to screening volume trajectory typically increases with time
  - Split up screening volume in time to form a stair-step of increasing radii
Optimization Algorithm: Vary Screening Volume Radii

- **Object Trajectories**
  - Define a set of trajectories which need to be encapsulated by a screening volume
  - Trajectories can include solid bodies and intercept debris spheres
  - (Optional): Calculate maximum altitude

- **Screening Volumes**
  - Manually select screening volume trajectories (typically 3-5)
  - Typically, this is selected from object trajectories, but back/forward propagation is often required
  - Define an initial guess for each radius

- **Algorithm**
  - Gradient descent, varying screening volume radii
  - Matlab fminsearch() (unconstrained optimizer)
  - If needed, the screening volumes are increased at the end of each iteration to ensure that they bound the object trajectories
  - Cost function: heuristic for estimated LW closure