JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Satellite Collision Avoidance Supporting Ballistic Missile Flight Tests

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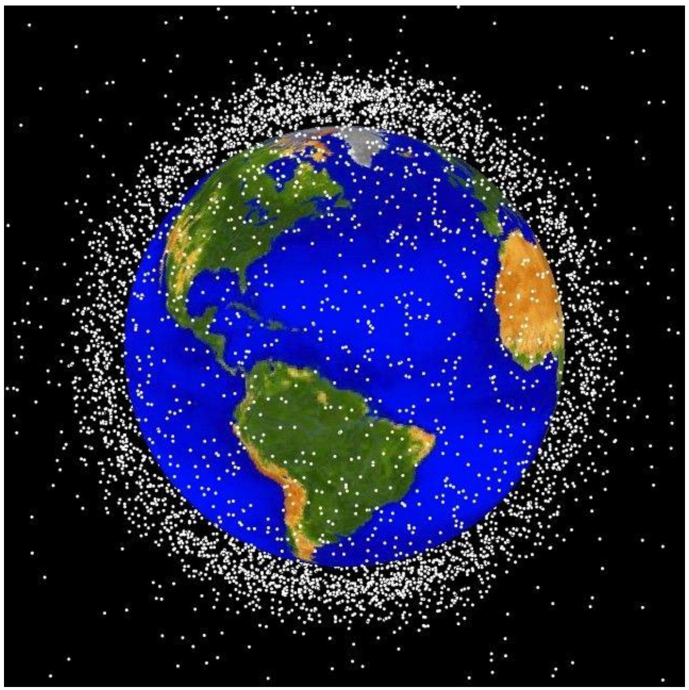
Threat of Orbital Objects on Missile Flight Tests

Objects in Low-Earth Orbit



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

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

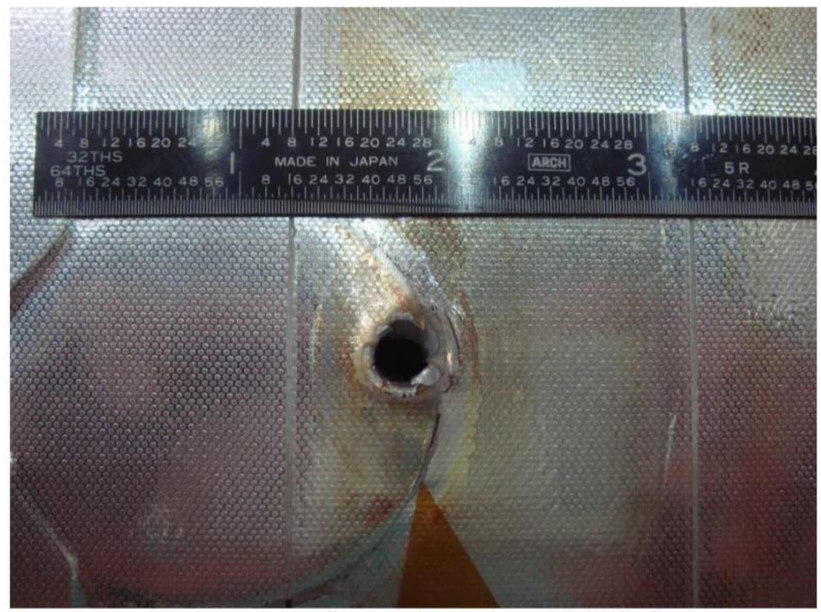
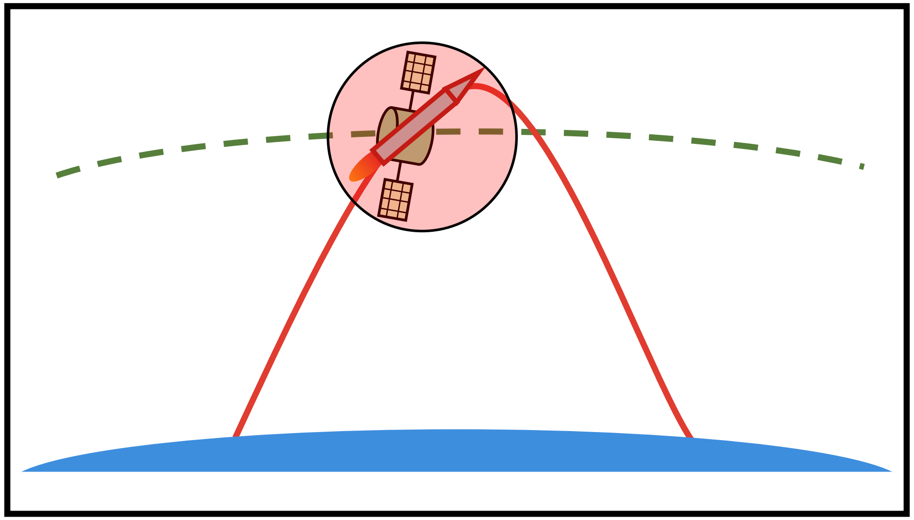


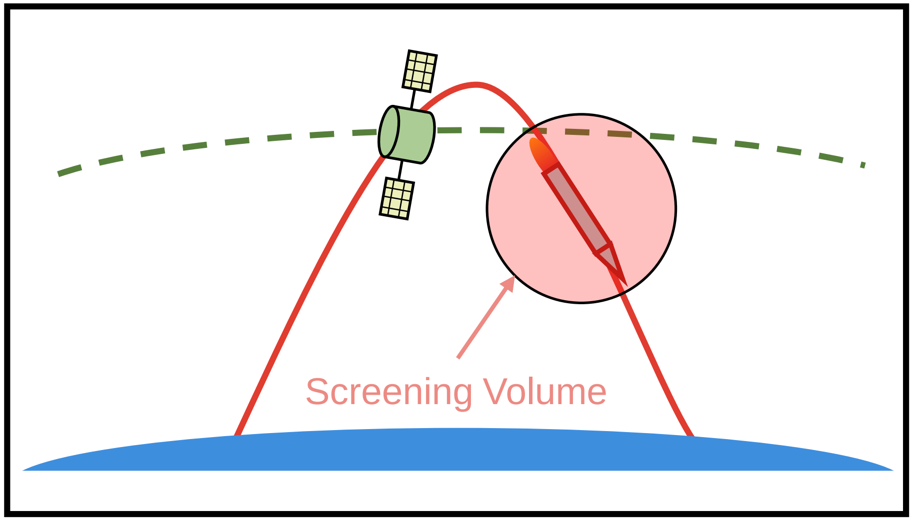
Figure 1: Entry-hole damage (5.5mm diameter hole) to Endeavour’s left-side aft-most radiator panel observed during post-flight inspection.

https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080010742.pdf

Satellite Collision Avoidance (COLA)



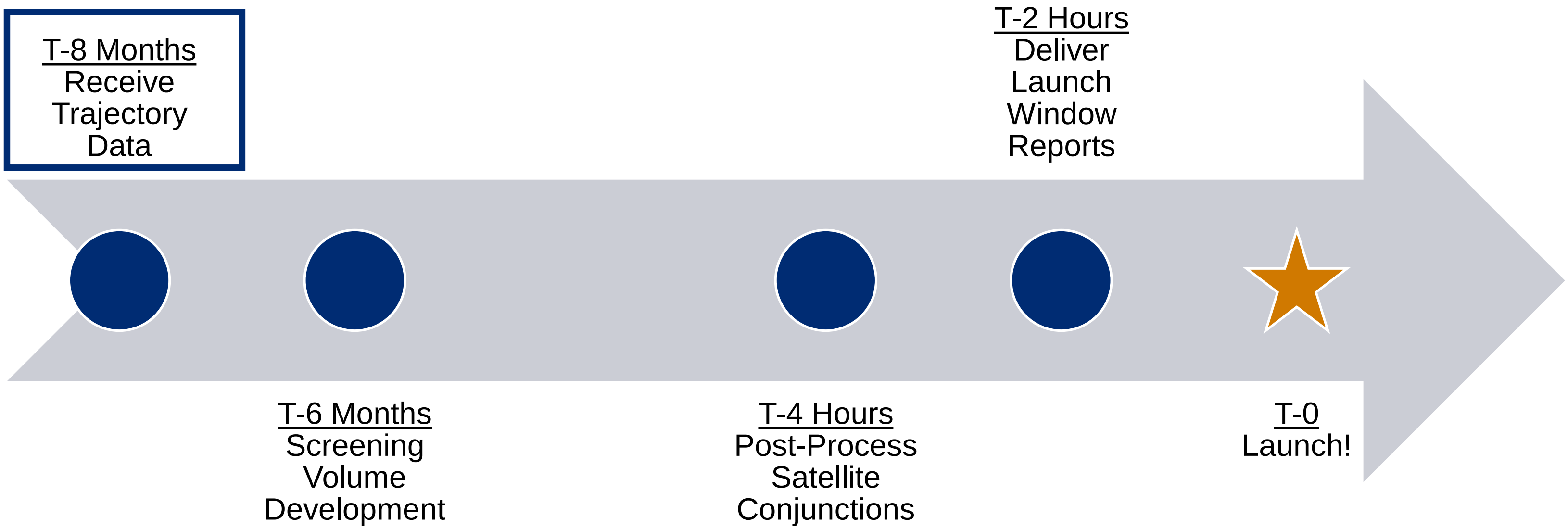
Unsafe missile launch time



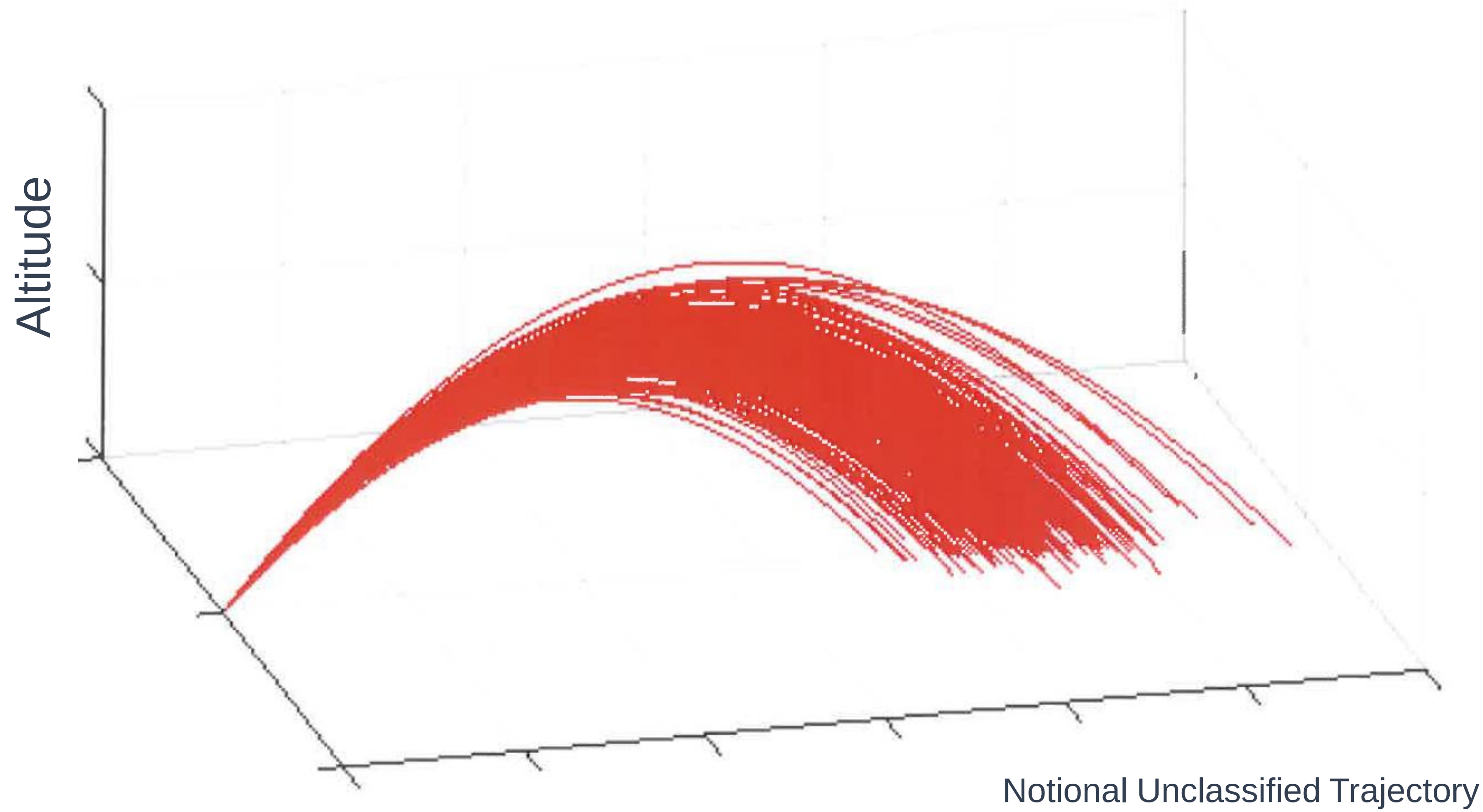
Safe missile launch time

- 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

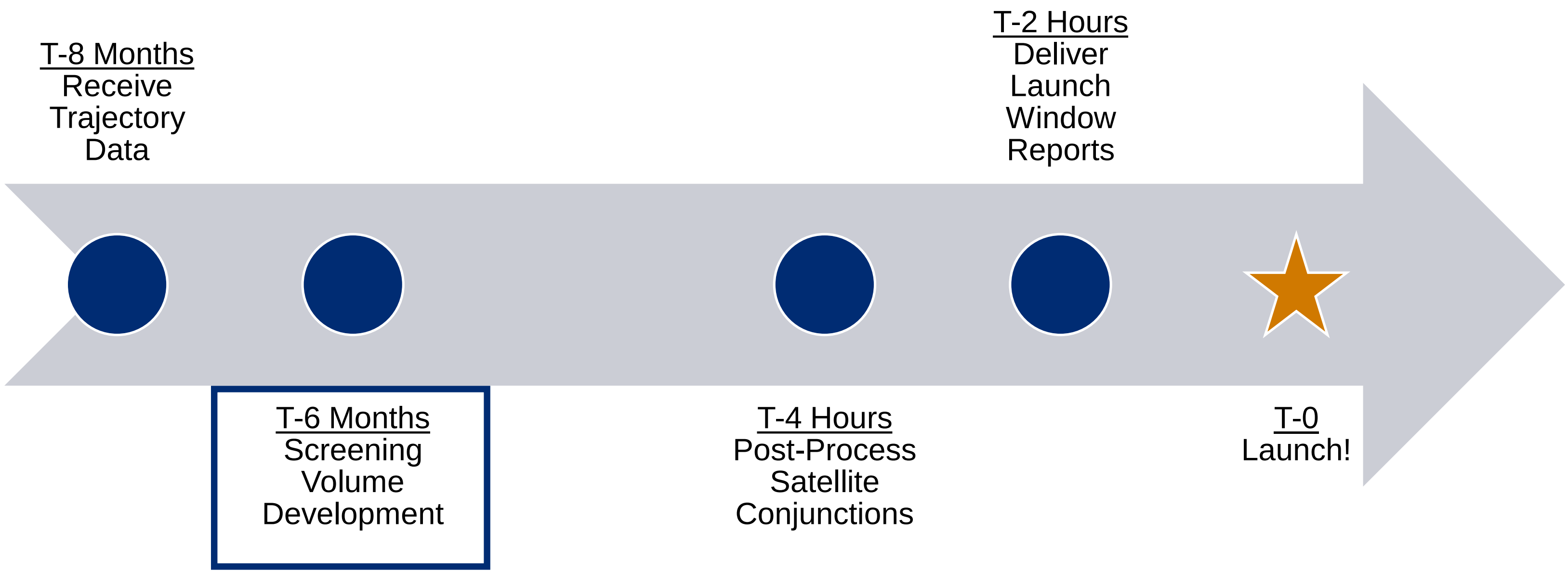


Monte Carlo Trajectory Set



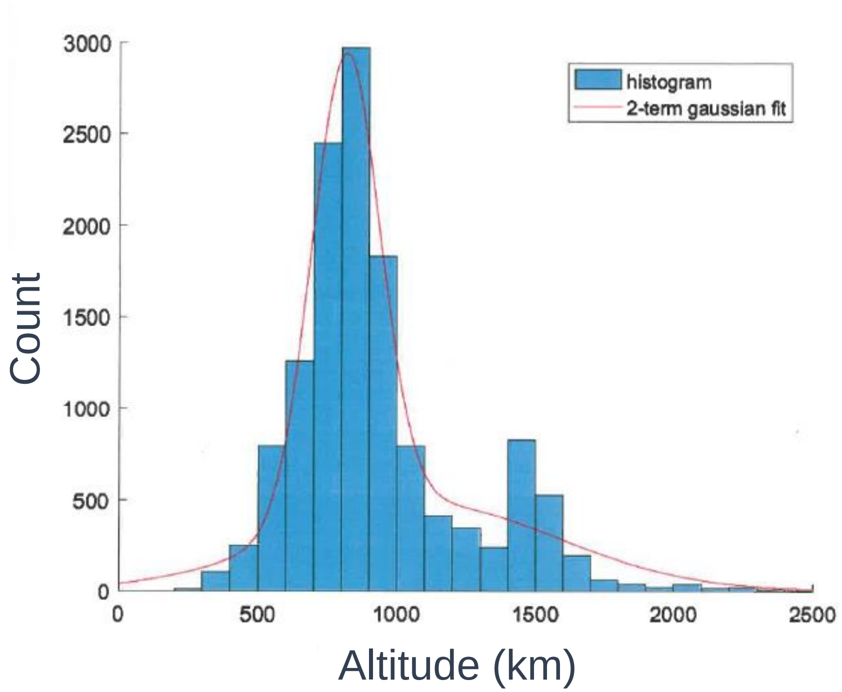
Monte Carlo set of trajectories that account for expected dispersions due to variations in parameters such as vehicle performance and atmospheric conditions

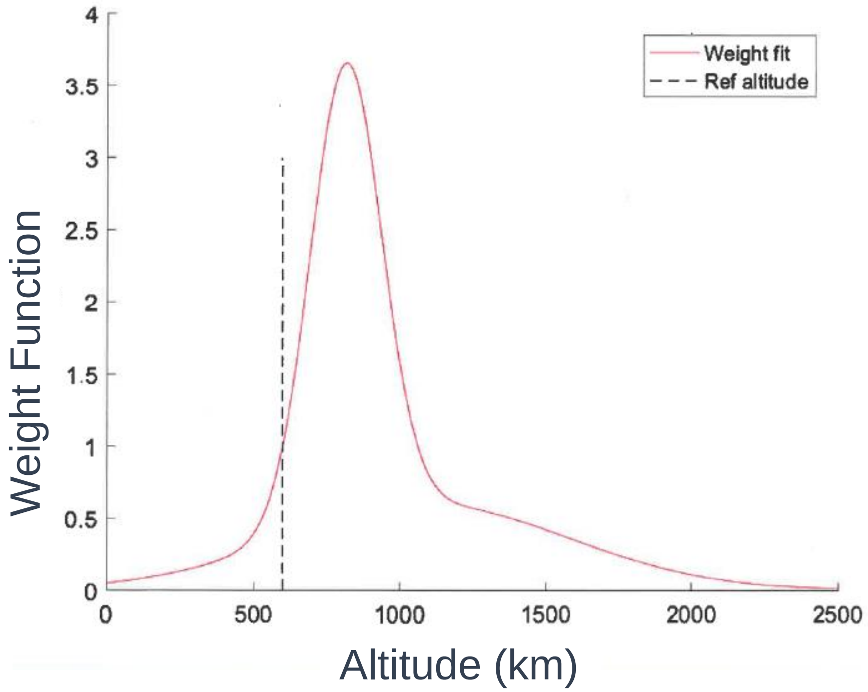
COLA Analysis Timeline



Satellite Altitude Distribution

- The satellite altitude distribution is used to define a weight function



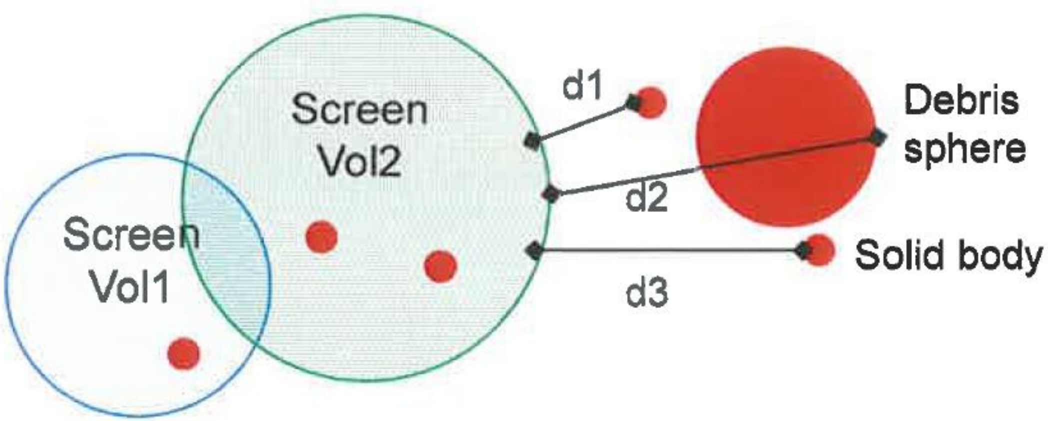


Screening Volume Calculation Overview

- 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
  - $V(t) = \int f(x, y, z, t)\, dx\, dy\, dz$
  - $V_w(t) = \int f(x, y, z, t) * W(alt) * dx\, dy\, dz$
- 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 d2 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

$$pClosed = VT_w * \left(\frac{100\%}{1.3 * 10^{10}\ km^3 s}\right)$$

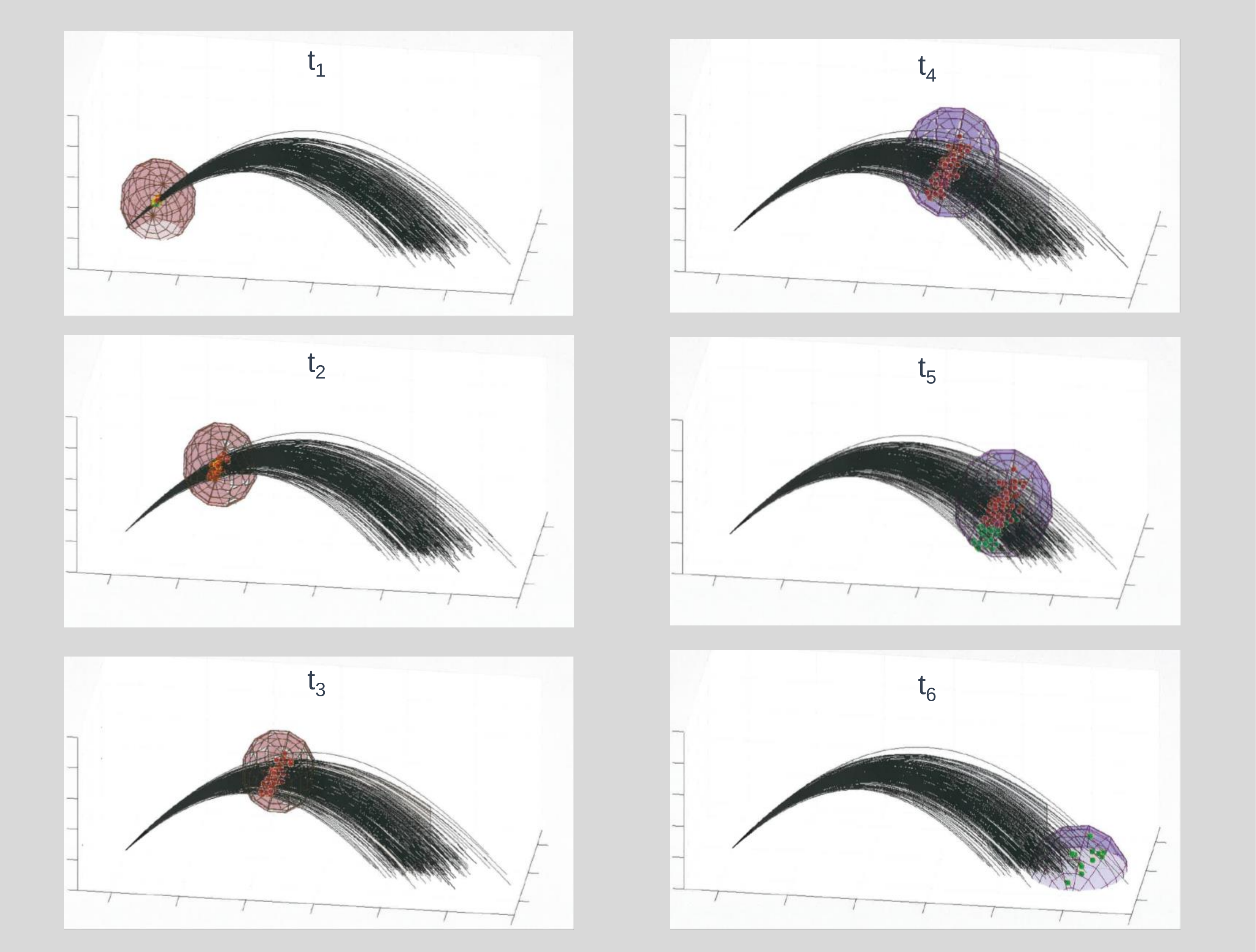
Screened against entire satellite catalog

$$pClosed = VT_w * \left(\frac{100\%}{5.0 * 10^{10}\ km^3 s}\right)$$

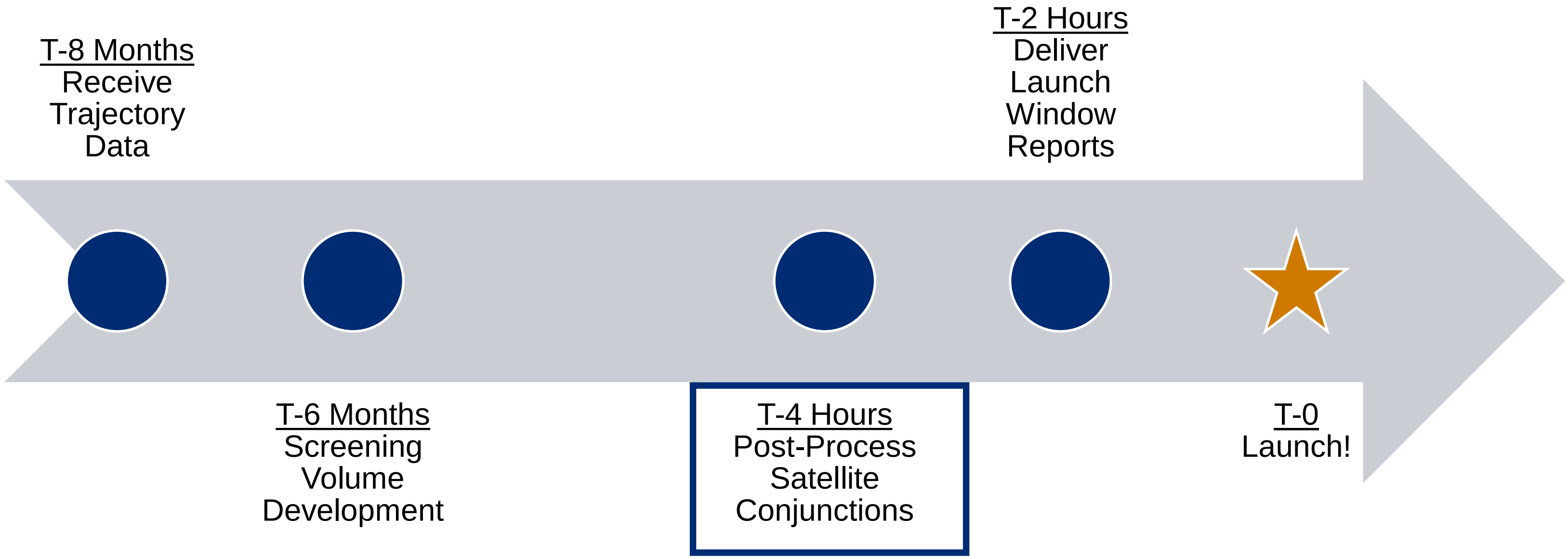
Screened against active satellites only

The heuristic estimation:
- Enables optimization algorithms for screening volume development
- Provides analysts with a fast, quantitative measure of the screening volume design

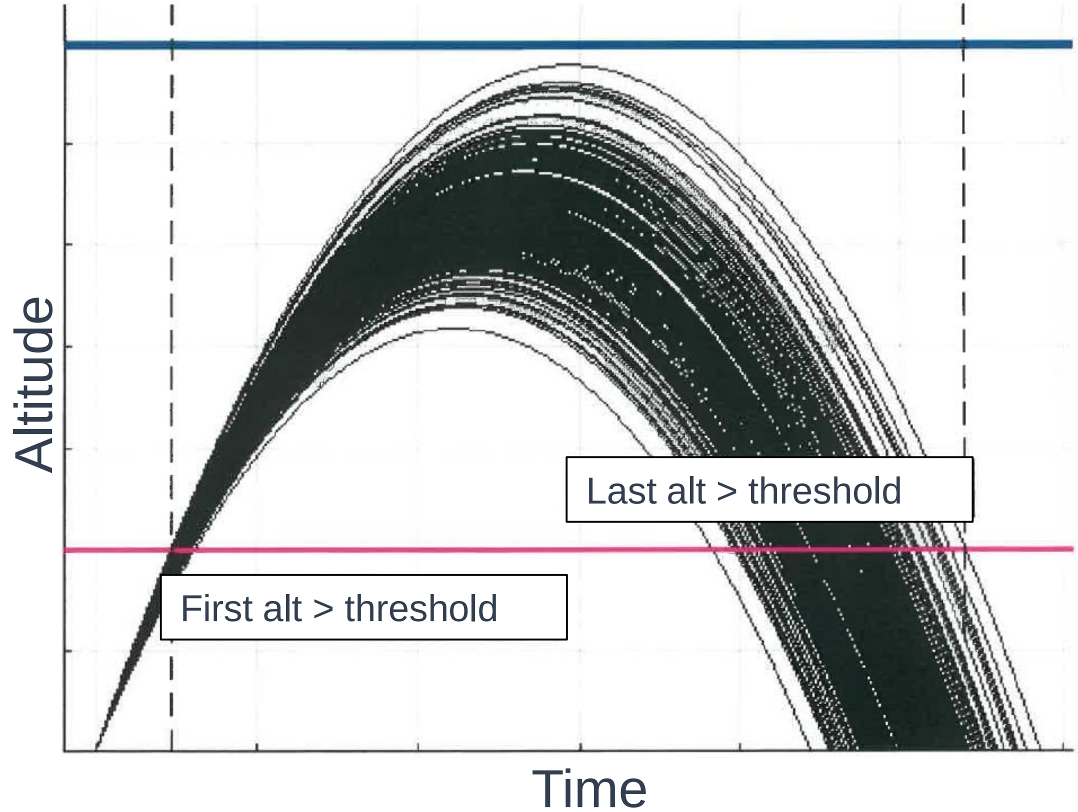
Trajectory and Screening Volume Animation Snapshots



COLA Analysis Timeline

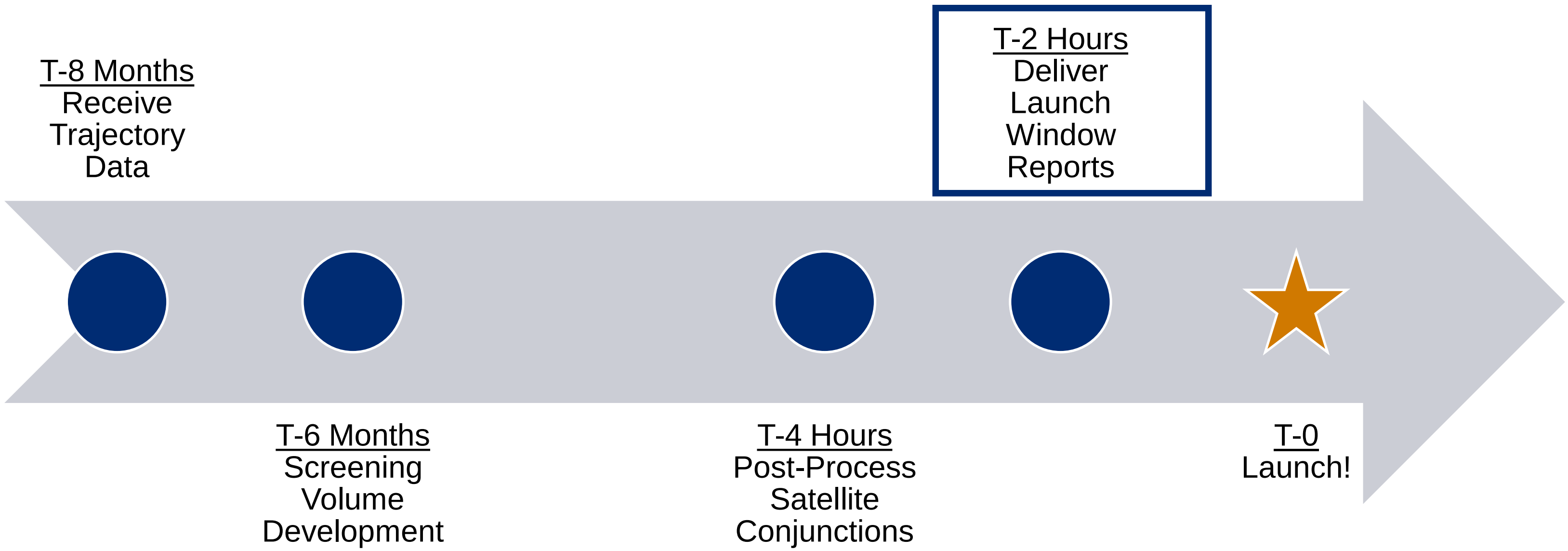


Post-Processing Filters



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

COLA Analysis Timeline



Sample Launch Exclusion Report

Header with delivery ID

Table of open launch times

Launch window graphic with closed launch times

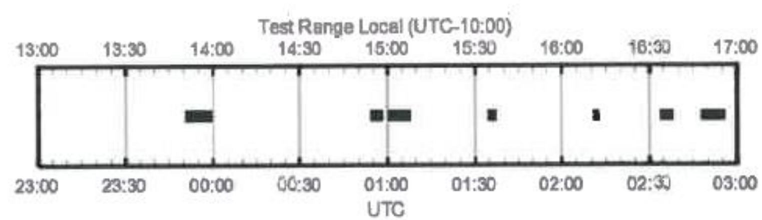
L-2 hours L-2 hours

Launch Window Openings:

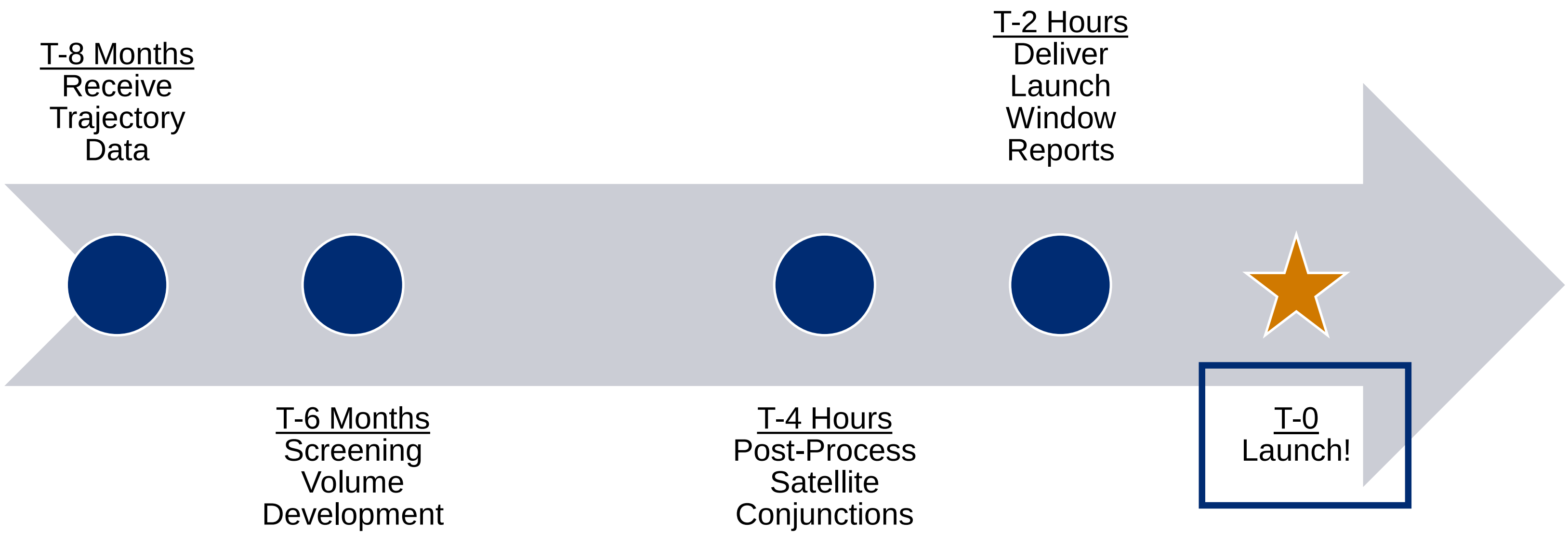
Start ZULU day:hr:mn:ss	End ZULU day:hr:mn:ss	Start, WHSKY day:hr:mn:ss	End, WHSKY day:hr:mn:ss	Duration hh:mm:ss
180:23:00:00	180:23:50:30	180:13:00:00	180:13:50:30	00:50:30
180:23:59:30	181:00:54:00	180:13:59:30	180:14:54:00	00:54:30
181:00:58:40	181:01:00:10	180:14:58:40	180:15:00:10	00:01:30
181:01:07:50	181:01:34:20	180:15:07:50	180:15:34:20	00:26:30
181:01:37:40	181:02:10:50	180:15:37:40	180:16:10:50	00:33:10
181:02:13:00	181:02:33:30	180:16:13:00	180:16:33:30	00:20:30
181:02:38:00	181:02:47:40	180:16:38:00	180:16:47:40	00:09:40
181:02:56:10	181:03:00:00	180:16:56:10	180:17:00:00	00:03:50

Total closed time: 00:39:50
Total open time: 03:20:10

Launch Window Blackout Periods
(Note: minor grid interval is 5 min)



Questions?



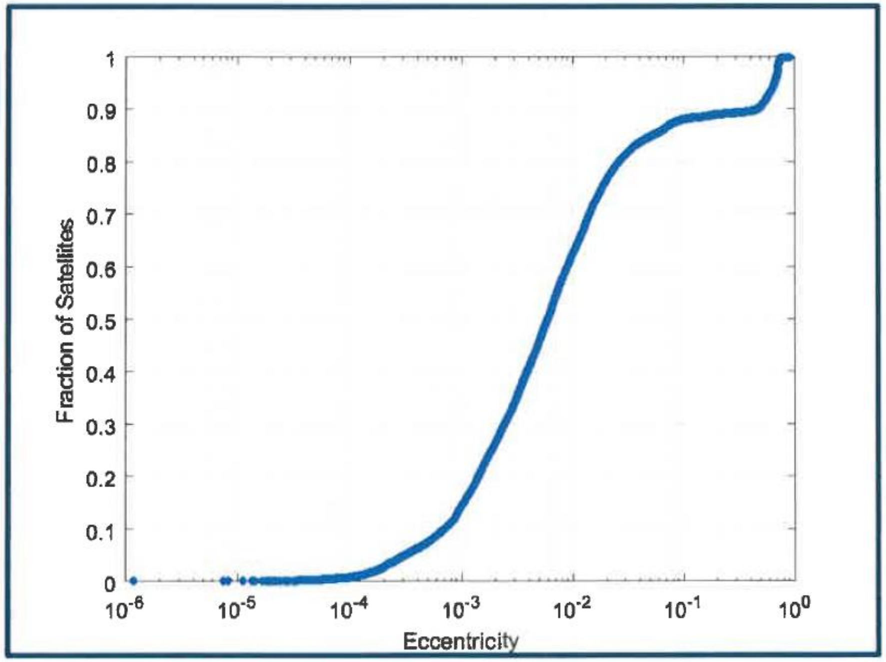
T-8 Months
Receive Trajectory Data
T-2 Hours
Deliver Launch Window Reports
T-6 Months
Screening Volume Development
T-4 Hours
Post-Process Satellite Conjunctions
T-0
Launch!

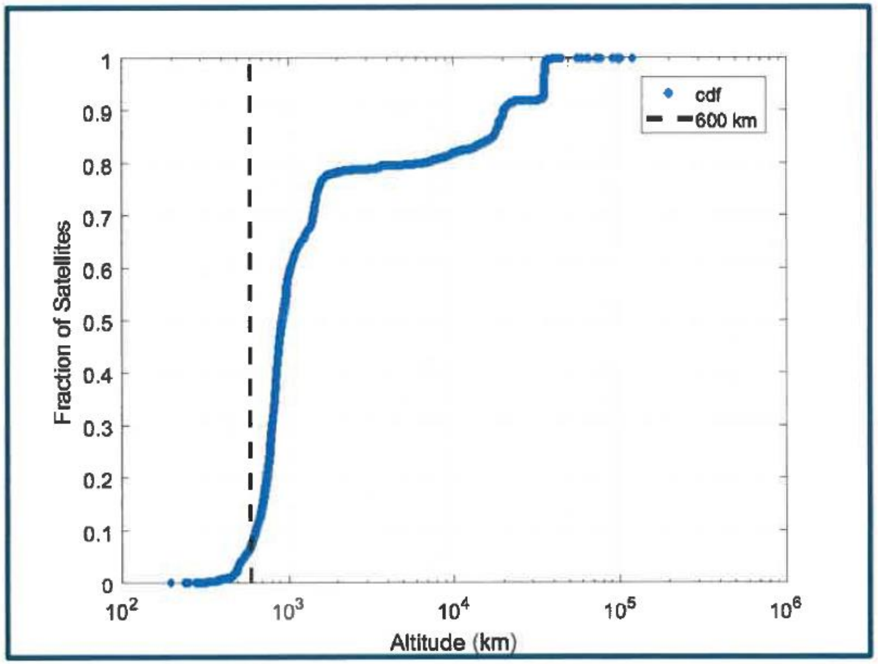
Backup

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 τ 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

Satellite Cumulative Distribution Functions



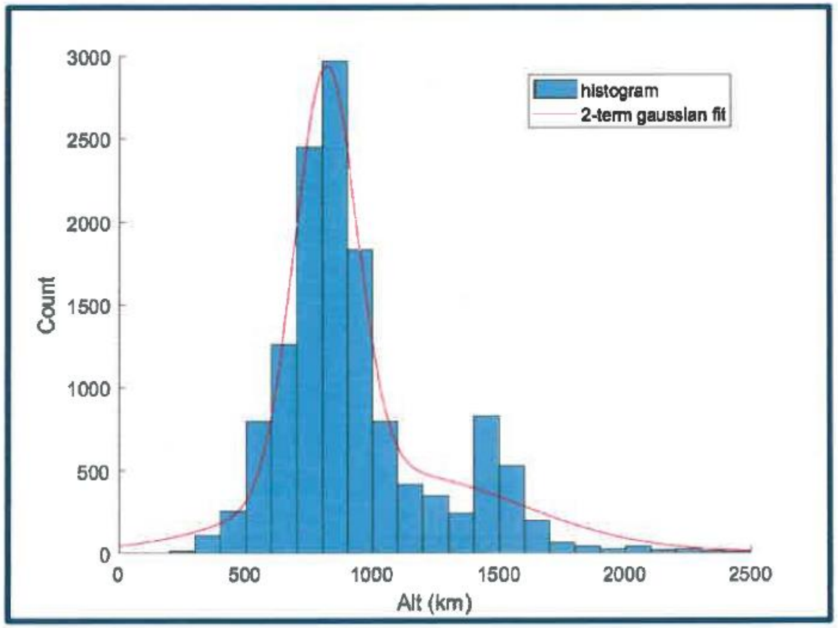


Most eccentricities are small, so circular orbit approximation is reasonable

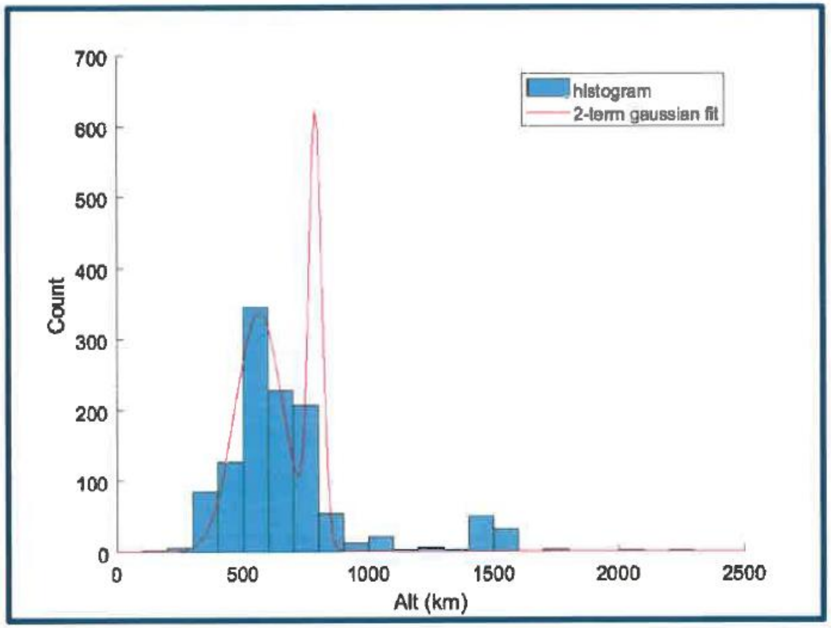
- Over 90% of satellites have an altitude > 600 km
- ~70% of satellites have an altitude between 600 and 1100 km

Satellite Distribution Comparison

Entire Satellite Catalog



Active Satellites Only



- 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

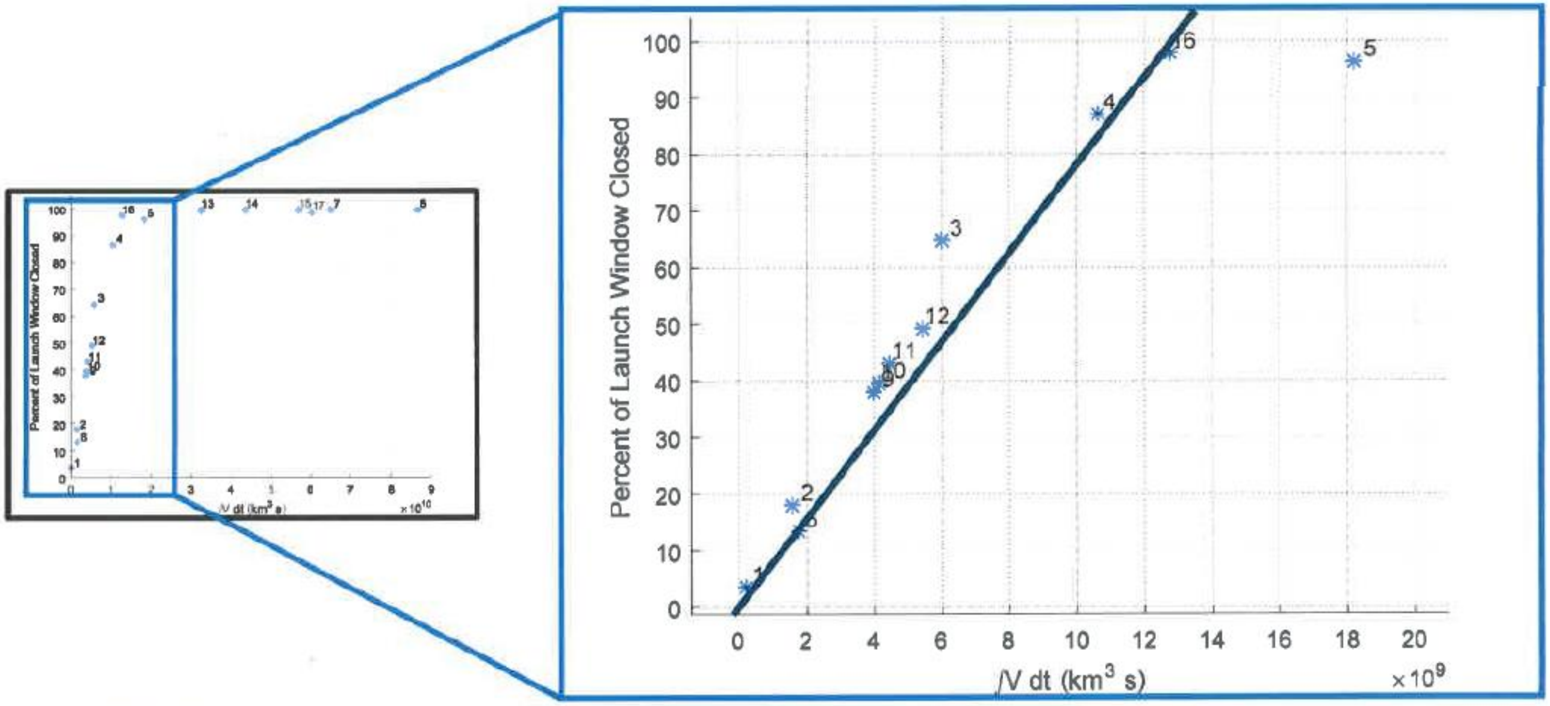
STK Case Study Methodology

- 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 (pClosed)
- 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

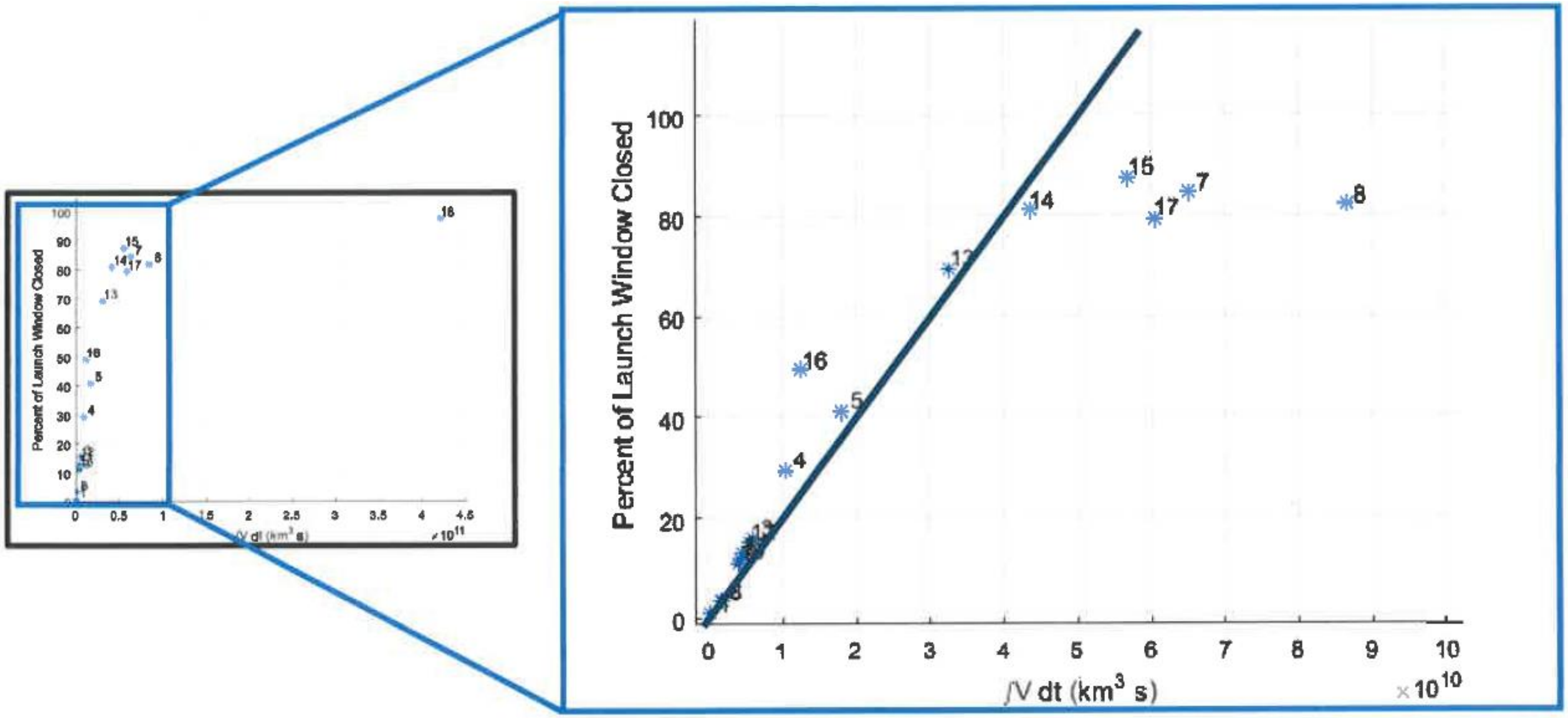
Space-Time Integral Evaluation
Entire Satellite Catalog



$$pClosed = VT_w * \left(\frac{100\%}{1.3 * 10^{10}\ km^3 s} \right)$$

- If $pClosed > 100\%$, the launch window is predicted to be fully closed

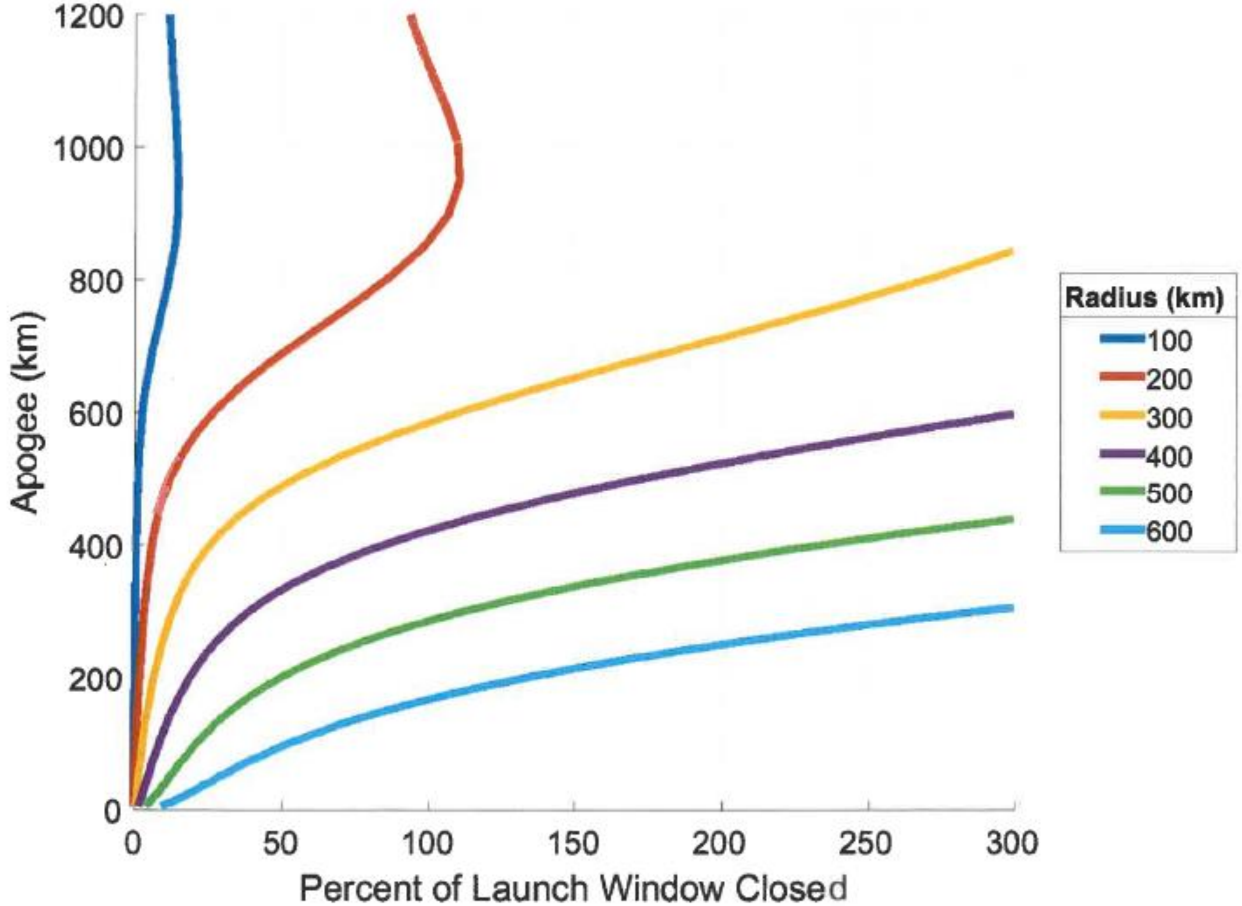
Space-Time Integral Evaluation
Active Satellites Only



$$pClosed = VT_w * \left(\frac{100\%}{5.0 * 10^{10}\ km^3 s}\right)$$

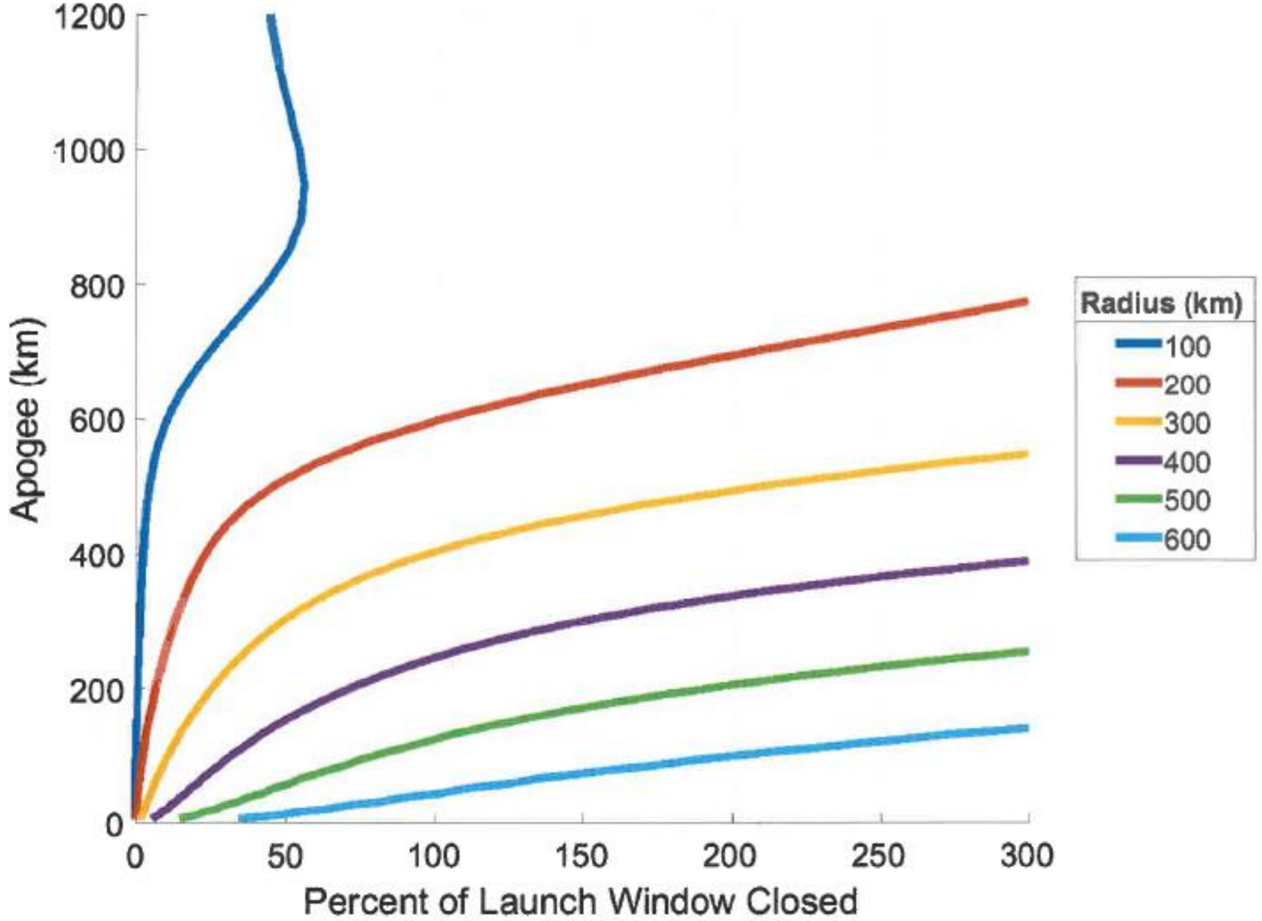
- If $pClosed > 80\%$, the launch window is predicted to be mostly closed

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

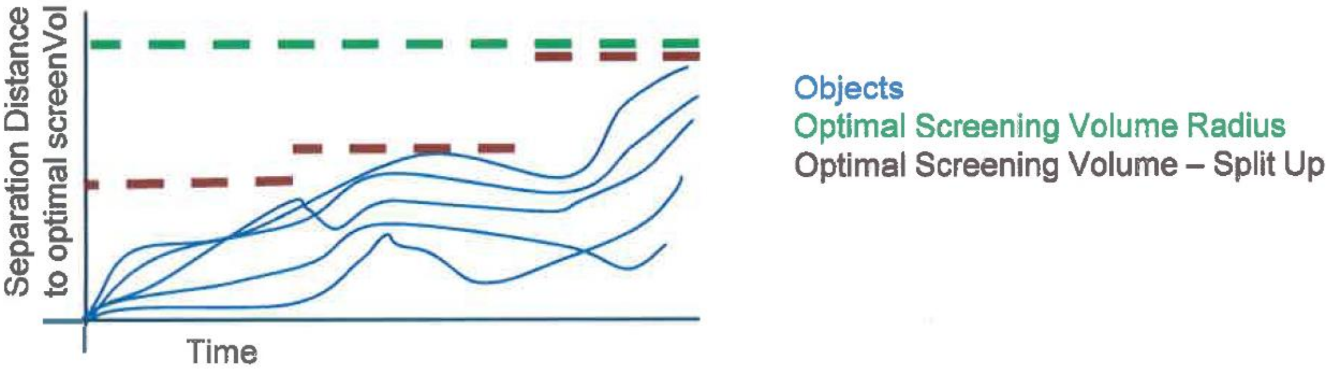
Launch Window Closure vs. Entire Satellite Catalog



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

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