Unified 4D Trajectory Approach for Integrated Management of Commercial Air and Space Traffic

Federal Aviation Administration

FAA CoE for CST Technical Meeting

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Overview

- Team members
- Purpose of Task
- Research Methodology
- Results
- Next Steps
- Contact Information

Team Members

- PI: Juan J. Alonso, Department of Aeronautics & Astronautics, Stanford University
- Thomas J. Colvin, Graduate Student, Department of Aeronautics and Astronautics, Stanford University
- Collaborations/discussions with:
  - Banavar Sridhar, NASA Ames
  - Karl Billimoria, NASA Ames

Purpose of Task

- Projected growth in demand will make it increasingly hard to accommodate launches on a SUA basis
- Looking for a more rational approach that:
  - can adapt to fluctuating frequency of launches
  - can accommodate uncertainties in trajectories
  - ensures proper separation at all times
  - can be integrated with FAA's NextGen system

Research Objectives

1. Develop plausible architectures for an Integrated Airspace Management System (IAMS)
2. Research and develop the foundation of such a tool based on time-space probabilistic trajectories
3. Create a prototype implementation for a proof-of-concept system

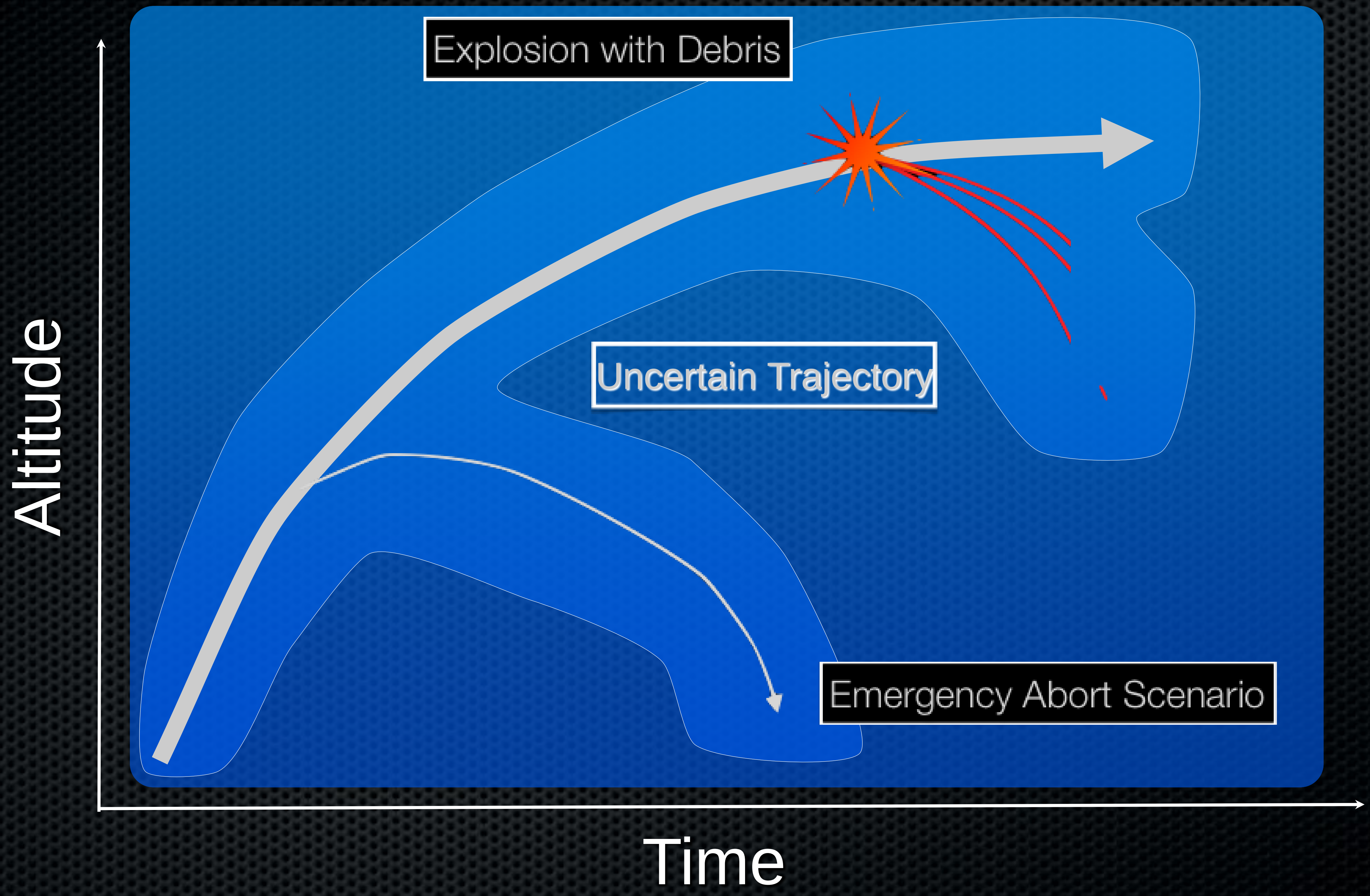
- During first few months, we are focusing on item 2

Methodology & Results

- Problem:
  - Need Special Use Airspace (SUA) for rocket launch
  - Current method for creating SUA may be overly conservative
  - Fairness issues: are we favoring one industry over another?
  - No quantitative framework for creating SUAs

- Proposed Solution:
  - Create a probabilistic framework for creating SUAs to a specified level of safety

Conceptual Framework

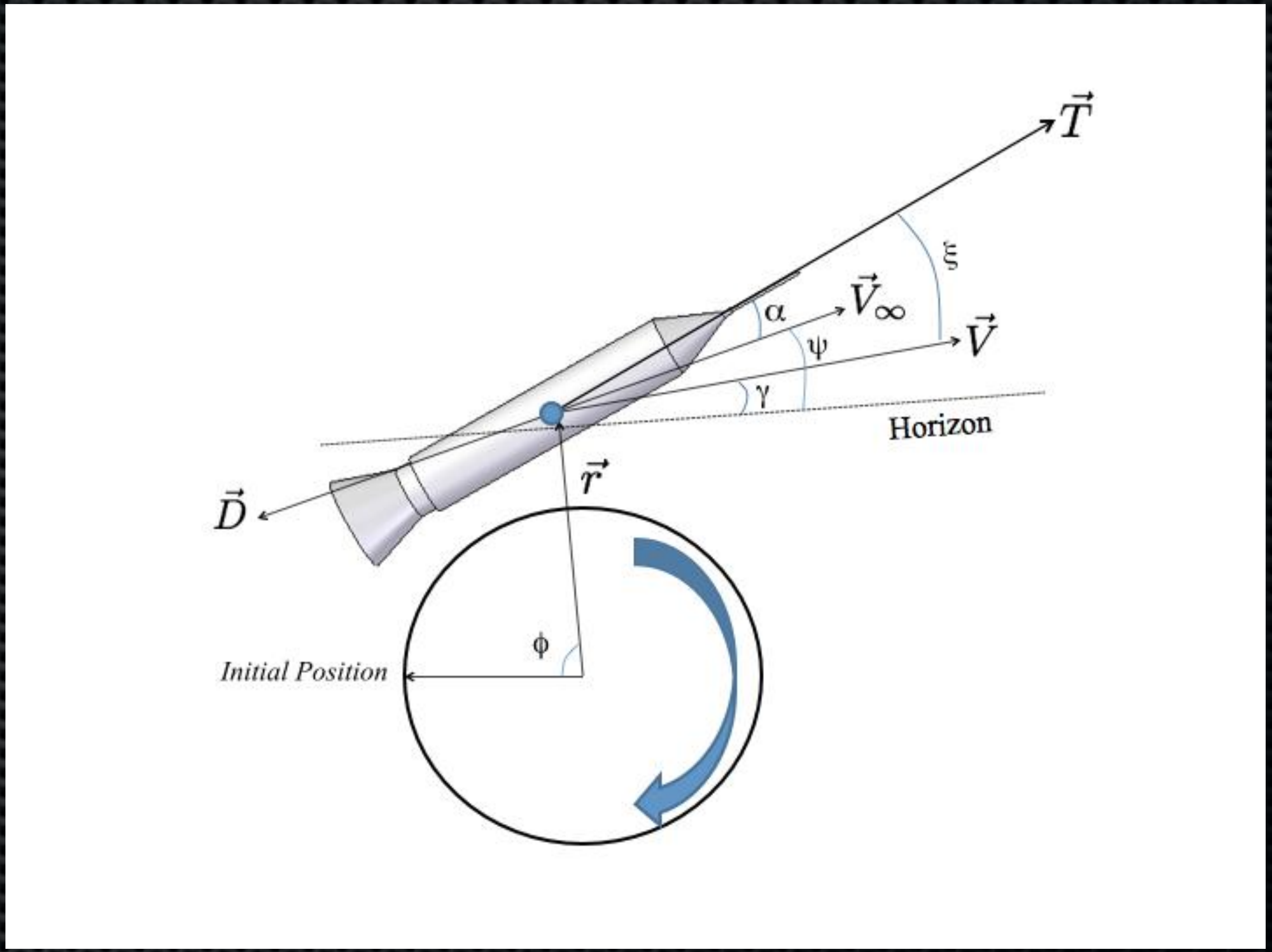


Initial Research Goals

- Focus on:
  - ✓ Investigate ways in which a compact 4-D envelope can be created and specified
  - ✓ Demonstrate the 4-D envelope concept in 3-D (x,y,t)
  - ✓ Begin creating a software architecture that generates 4-D envelopes for specific launch profiles
  - ✓ Use Monte Carlo simulation to <u>approximate</u> the rocket location PDF, sampled at many points, to a given level of safety
- Provide hooks for, but do not spend significant time on (refined later):
  - − Accurate characterization of weather profiles, failure modes and probabilities, debris model

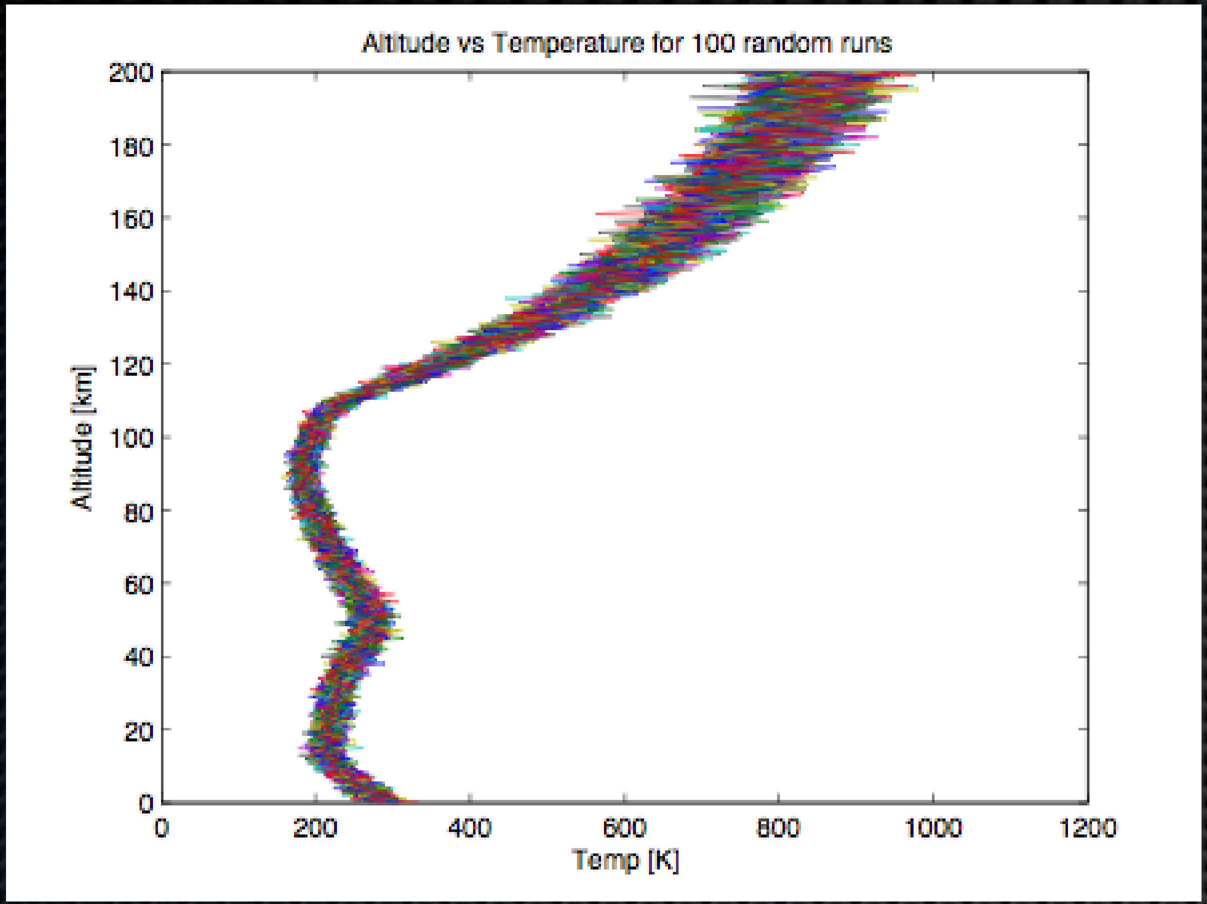
Nominal Trajectory

- 2-D round rotating Earth
  - Propagate r, V, φ, γ
- SSTO launch vehicle
- Optimal trajectory has thrust vectoring (T, ξ)
- Aerodynamic effects are roughly modeled

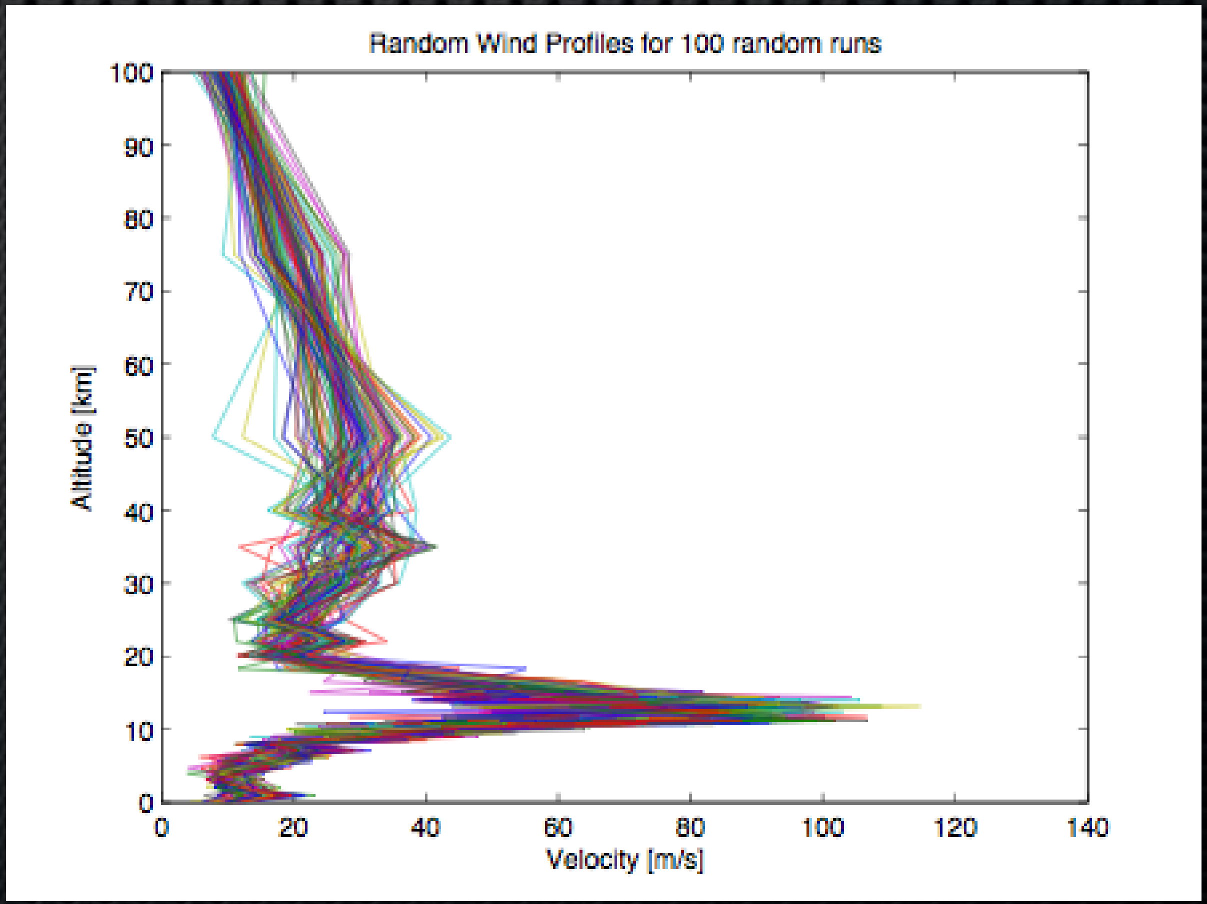


Source: Capristan, F. "Aerodynamic Effects in Launch Vehicle Optimal Trajectories"

Weather Uncertainty



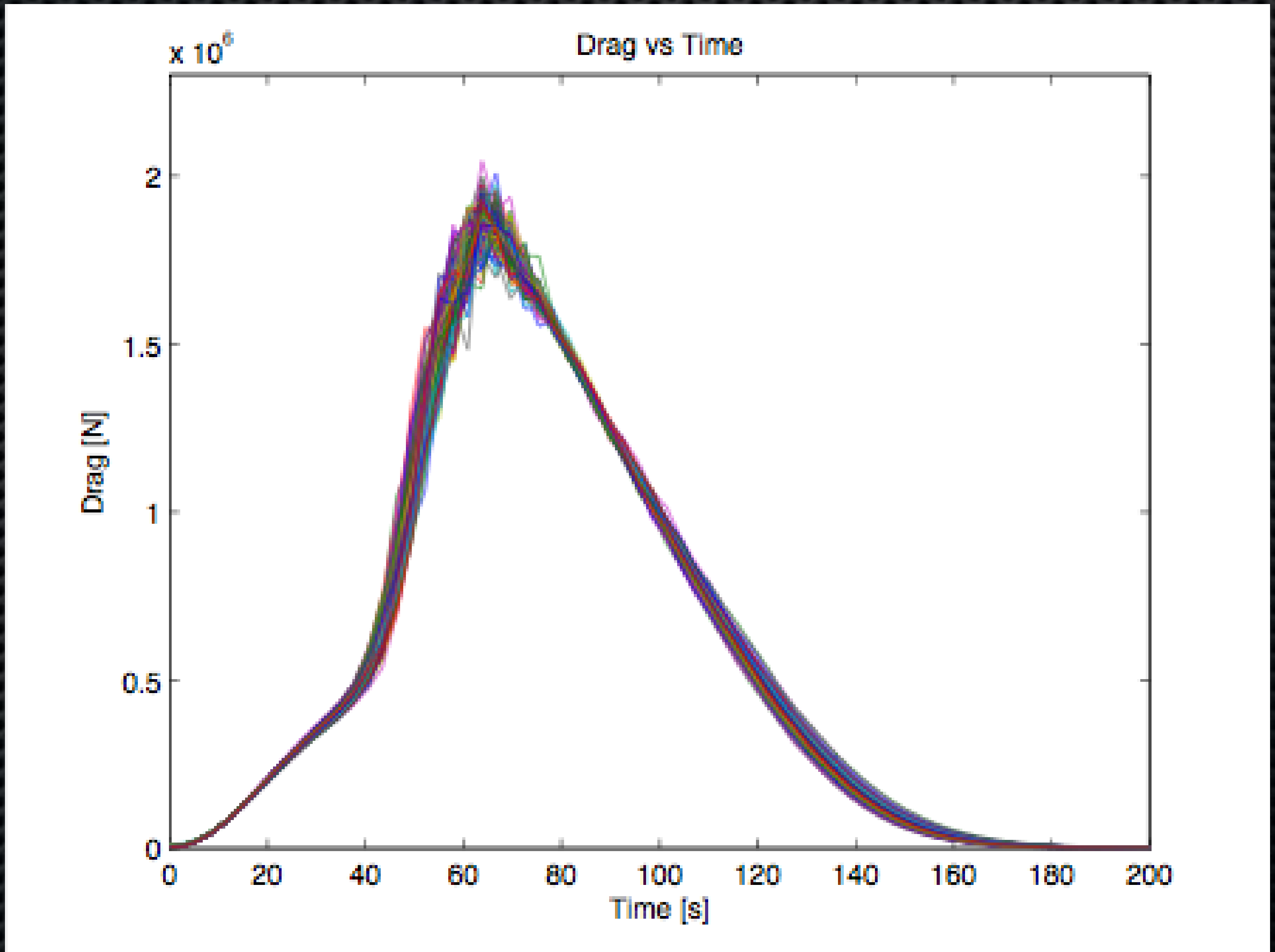
5% Uncertainty
in Temperature



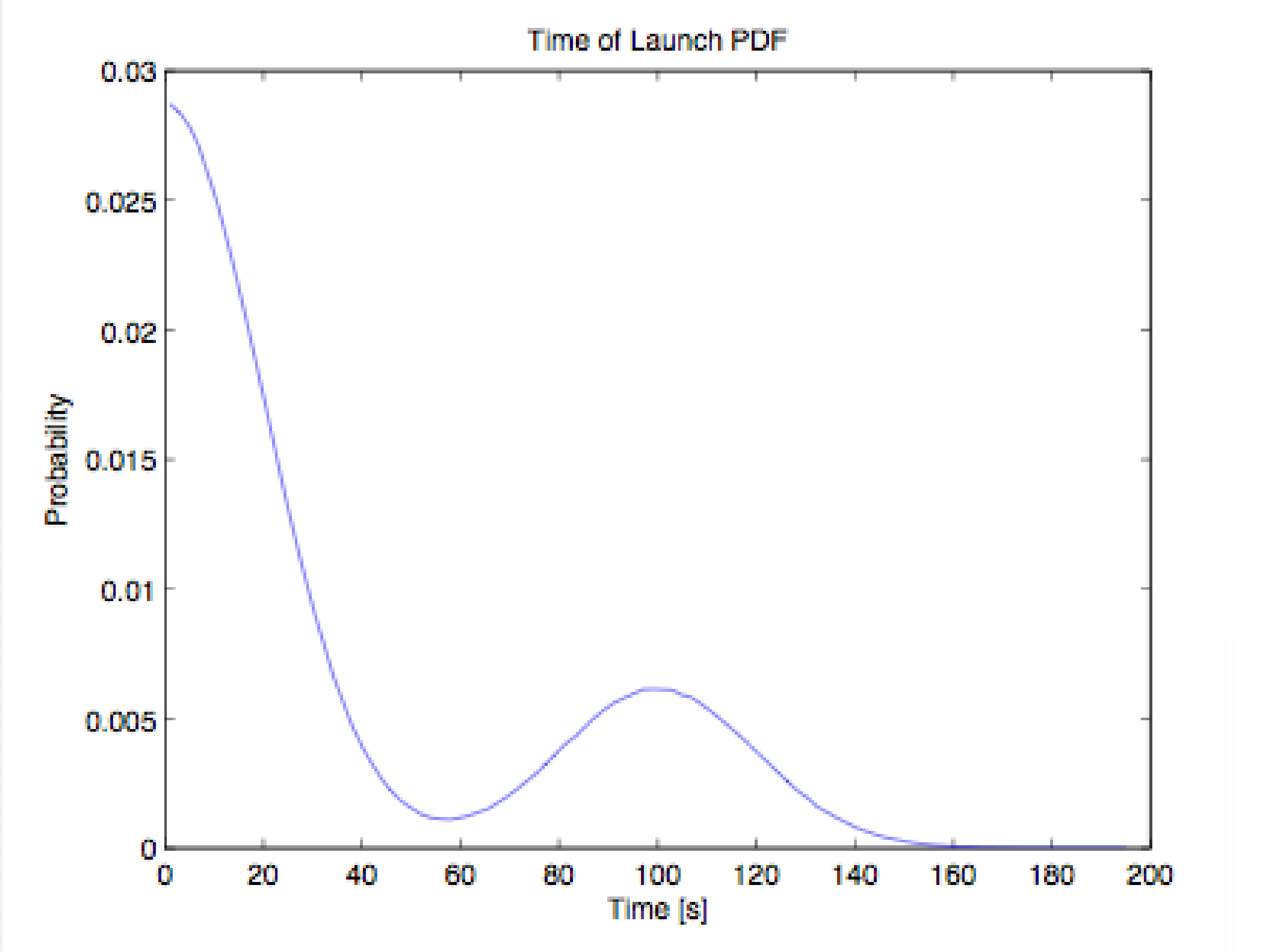
20% Uncertainty
in Wind Velocity

Creates Drag Uncertainty

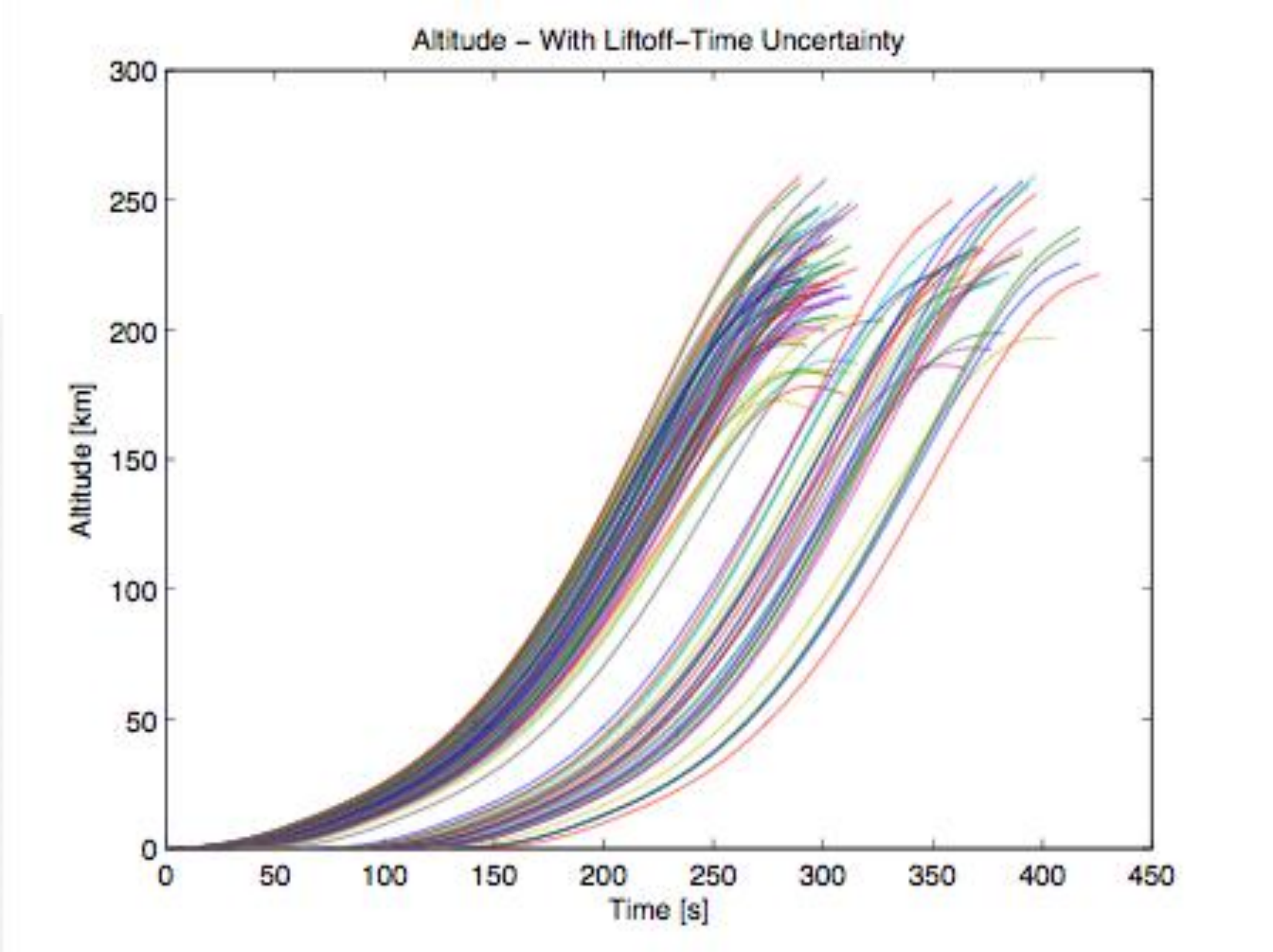
$$C_D = (2 - \cos\alpha)\frac{0.4750M_\infty^2 - 0.7127M_\infty + 0.3049}{M_\infty^2 - 1.914M_\infty + 1.042}$$



Uncertain Lift-off Time

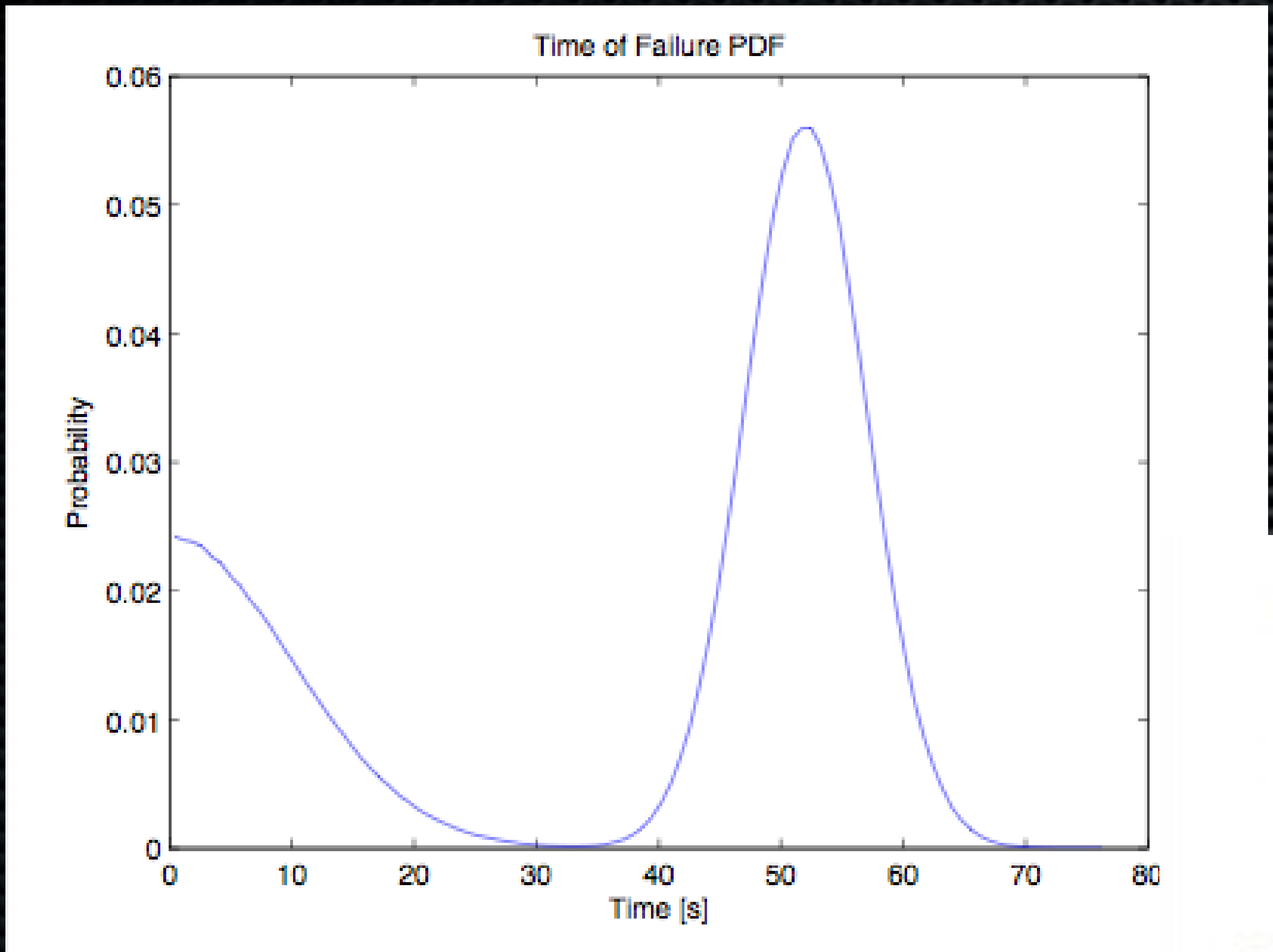


- Rockets do not always launch on time

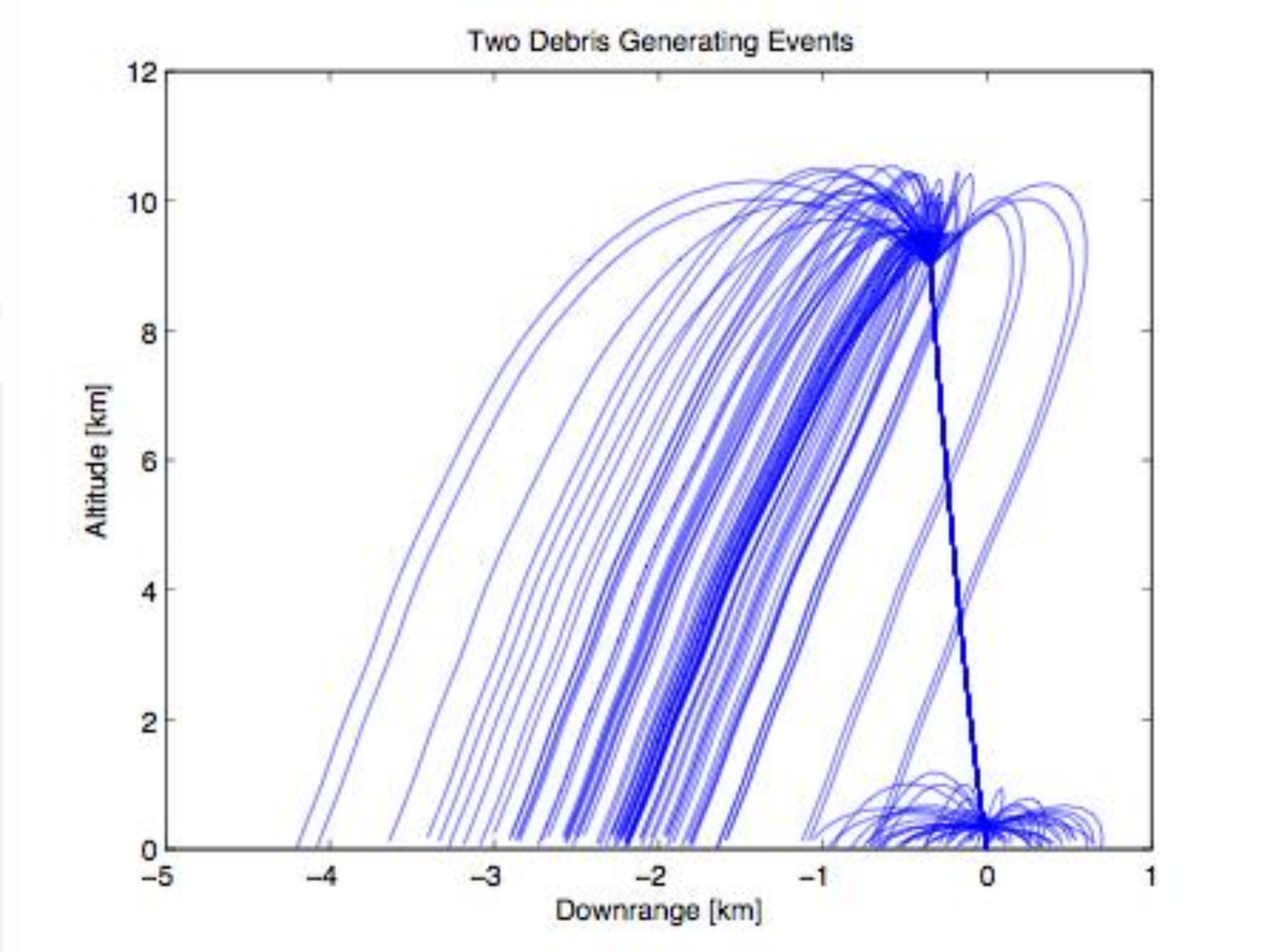


One-sided, multi-modal pdf

Failure Uncertainty



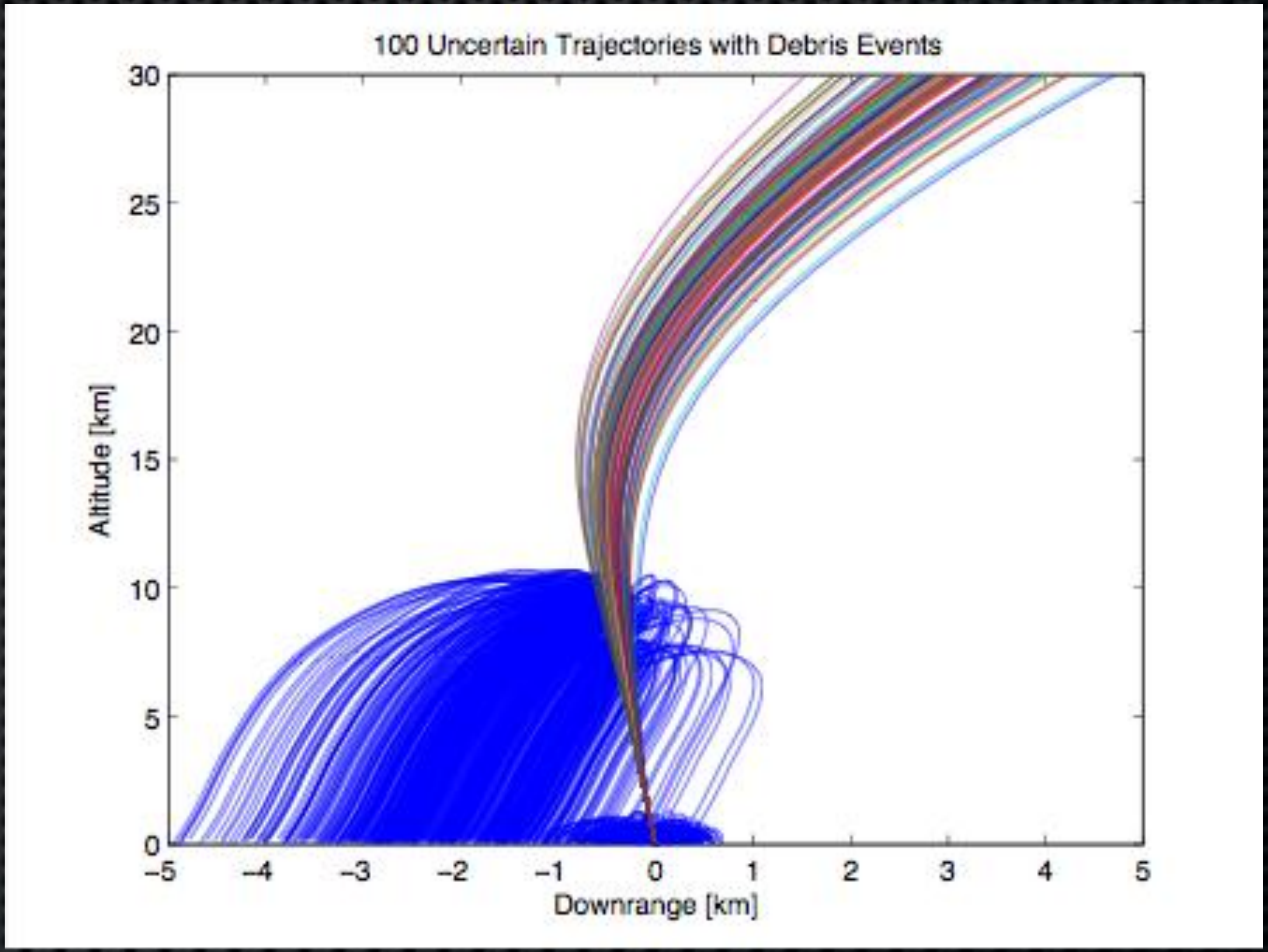
Assume 1% of all launches fail



Failure occurs near pad or at max q

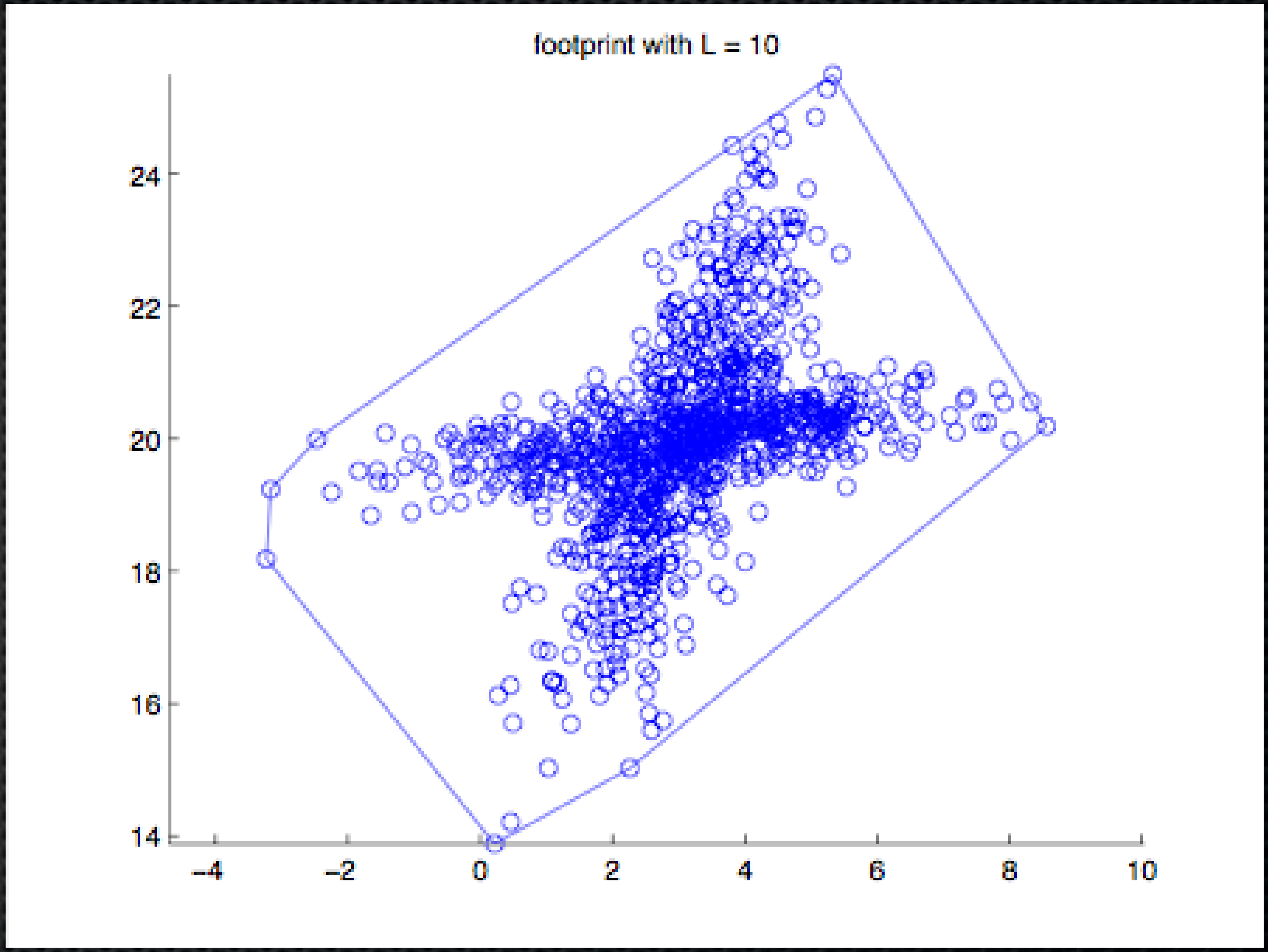
What We've Got So Far

- Software framework that accepts arbitrary:
  - Thrust profiles (TVC, etc)
  - Weather profiles for wind and temperature, with uncertainty parameters for each
  - Failure parameters and distributions
  - Debris model
- Outputs:
  - Collection of uncertain trajectories with debris-generating failure events from a MC simulation



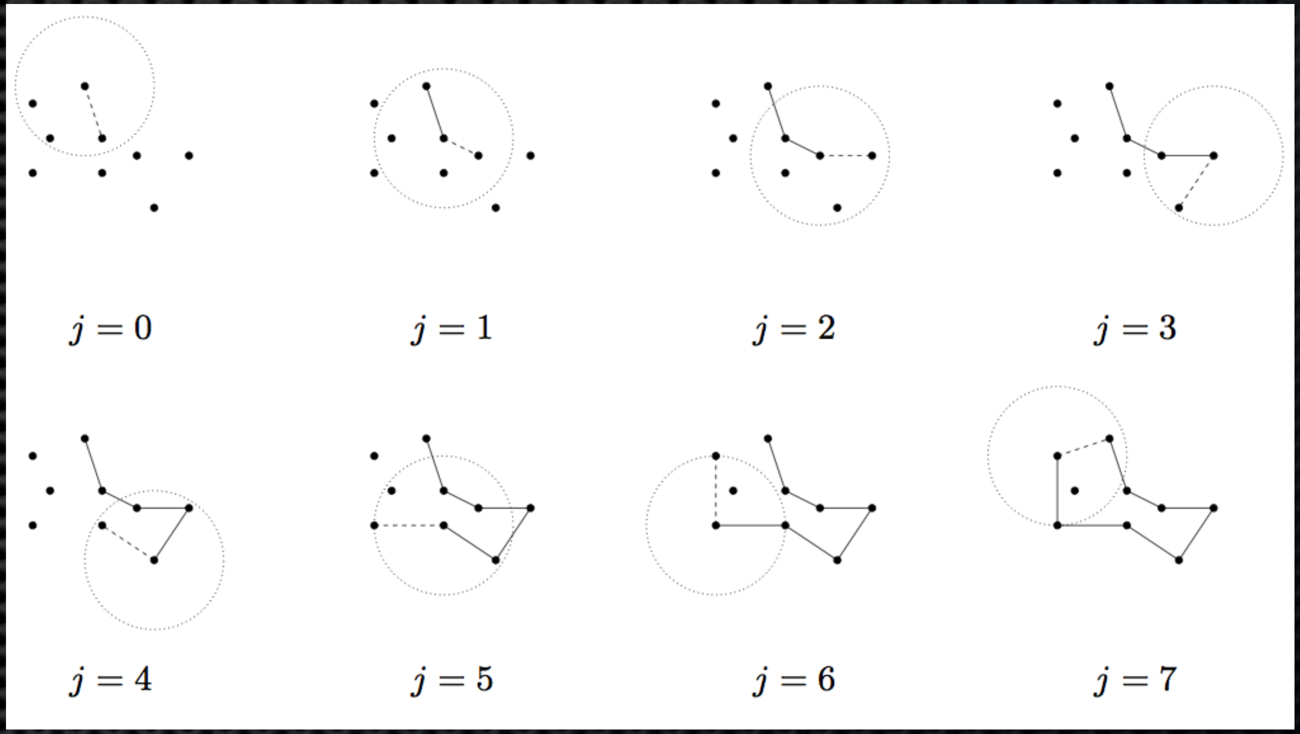
4D Probabilistic Trajectories and Envelopes

- Trajectories as points in space and time
- Risk level of 10^-10, approximated with MC
- How do we turn this set of trajectories into something useful?
- Methods Available
  - Level Sets
  - Delauney Triangulation
  - Convex Hulls
  - Non-convex Footprints



Swinging Arm

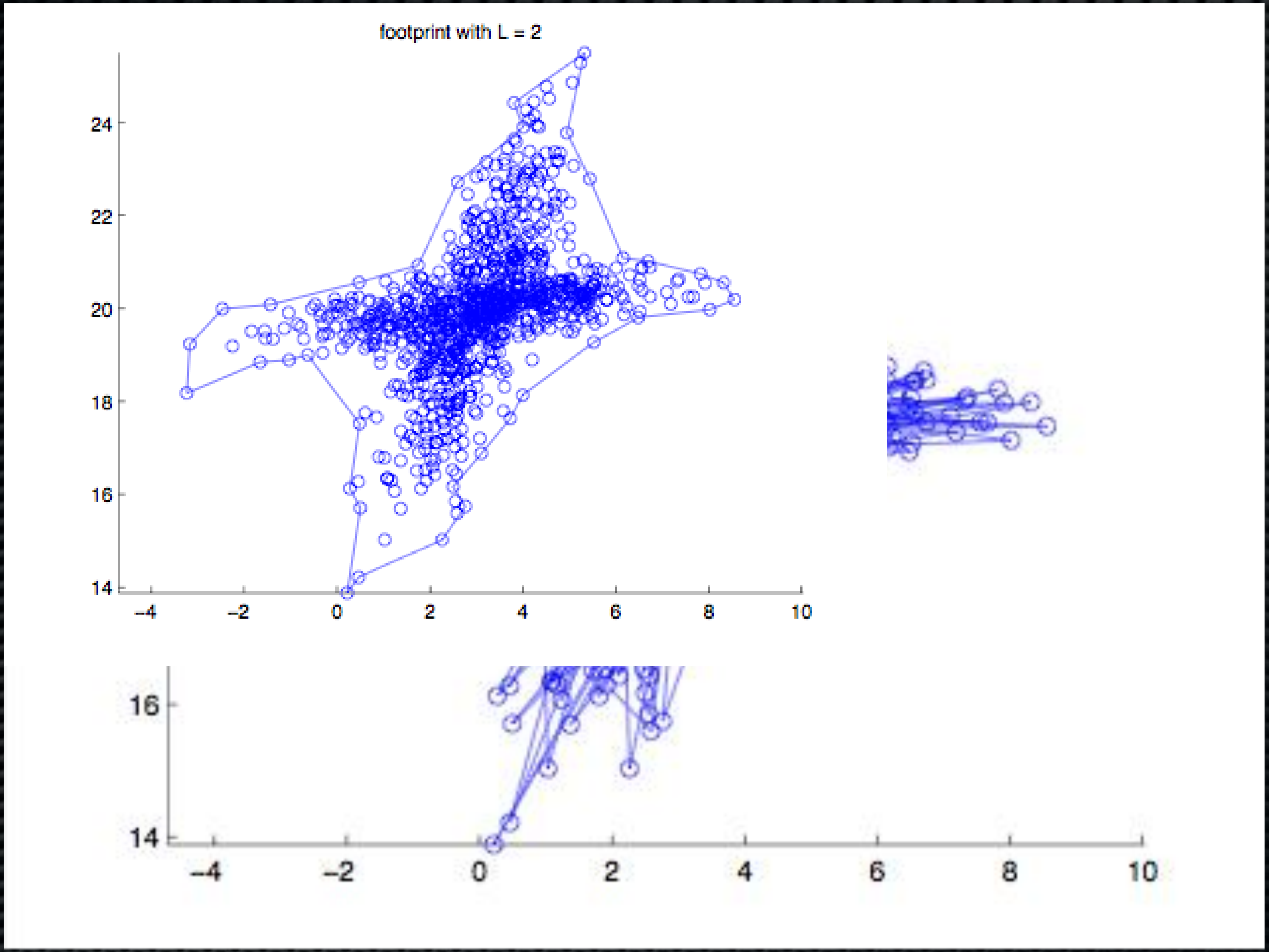
- Generates multiple disconnected "footprints"
  - Non-convex, non-regular polygon
- Creates groupings that visually appear more accurate
- Generalizes up to 3D
- Arm short enough, multiple footprints



Source: Galton, A. "What is the region occupied by a set of points?"

- Cons:
  - Non-regular polygons

Footprint Example



Footprint Example

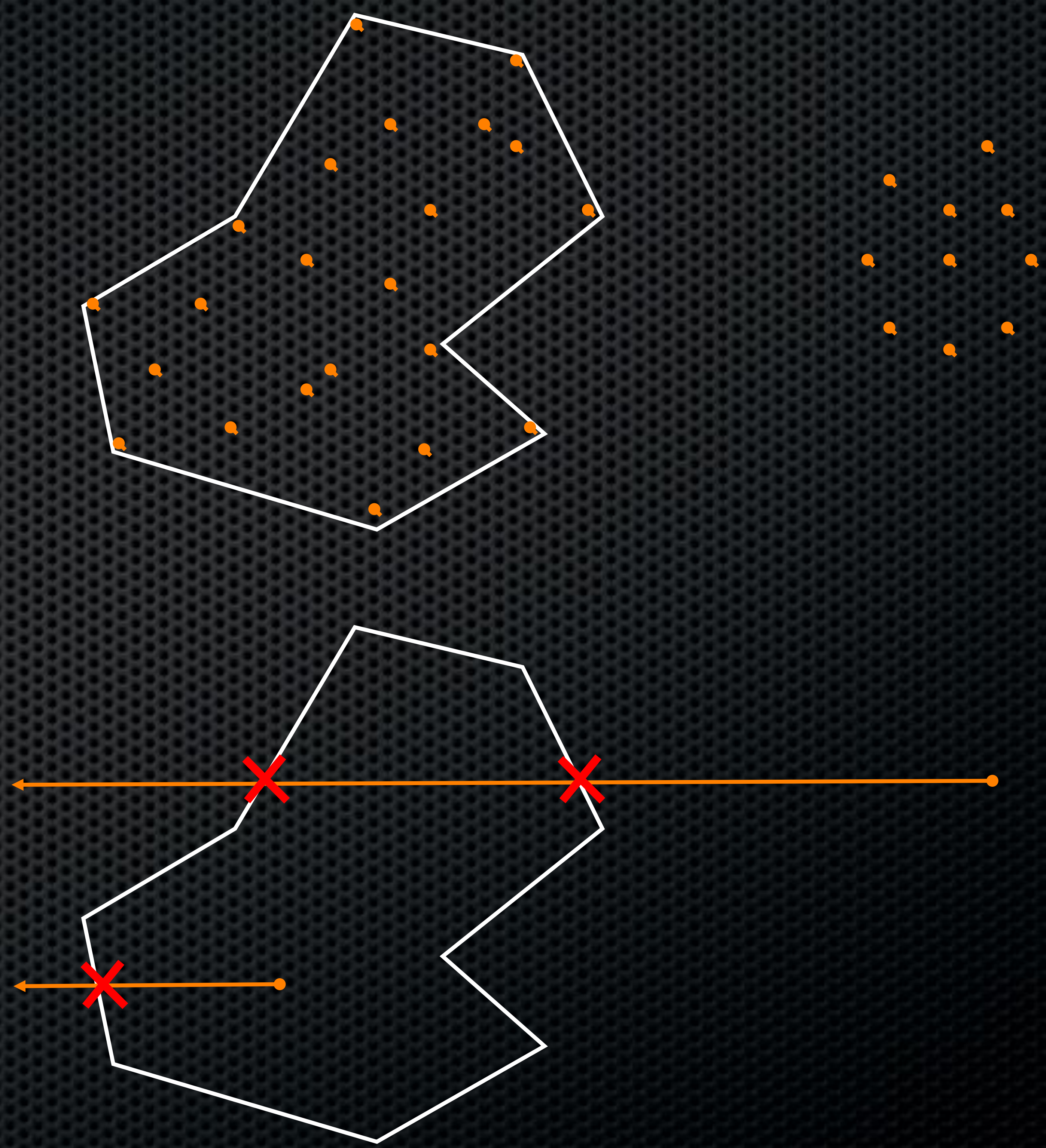
QuickTime™ and a
decompressor
are needed to see this picture.

Making the next footprint

- Arm length short enough, get multiple footprints

- Remove interior and boundary points

- Crossings:
  - Odd is in
  - Even is out



An Early Footprint

QuickTime™ and a
decompressor
are needed to see this picture.

Footprint Through NAS (L=40km)

QuickTime™ and a
decompressor
are needed to see this picture.

Footprint Through NAS (L=4km)

QuickTime™ and a
decompressor
are needed to see this picture.

Footprint Through NAS (L=2km)

QuickTime™ and a
decompressor
are needed to see this picture.

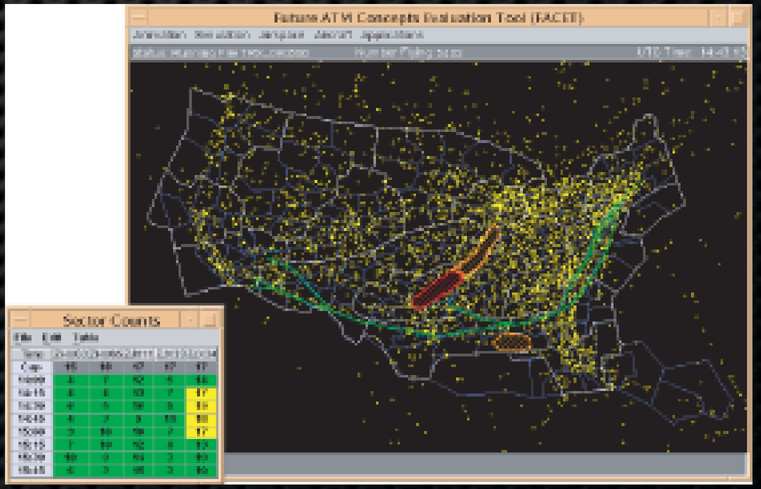
Volume Savings

- Tube: 51,400 km2 sec
  - Conservative. No safety factors.
- Convex: 15,300 km2 sec
  - 30% of the original volume
- Footprint 2km arm: 6,500 km2 sec
  - Only 13% of the original volume!

QuickTime™ and a
decompressor
are needed to see this picture.

Conclusions & Future Work

- Conclusions:
  - Code accepts arbitrary thrust, weather, and failure profiles for Monte Carlo simulation of uncertain trajectories
  - Creates multiple polygonal envelopes around the trajectories (and debris) that represent a no-fly zone
  - Demonstrates the possibility of significant volume (area*sec) savings over conventional tube approach



- Future Work:
  - Full 4-D (Swinging Slab)
  - Accurate weather and debris models with uncertainty
  - Active control in rocket during ascent and staging
  - Integration with NASA's FACET tool for scenarios with various launch sites, frequencies + typical day in the NAS

References

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- Galton, A., Duckham, M. “What is the region occupied by a set of points?” GIScience 2006, LNCS 4197, pp. 81-98, 2006
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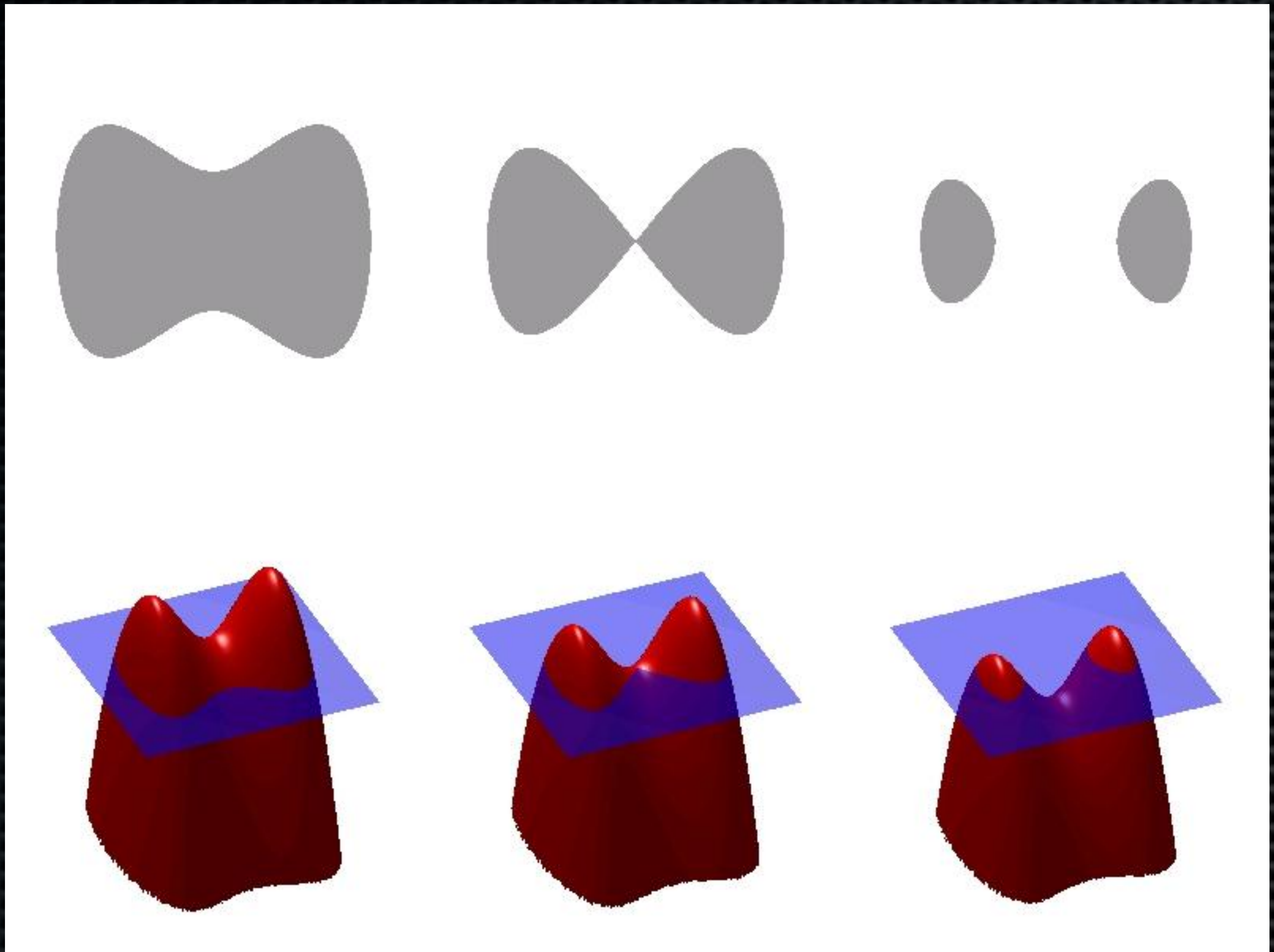
Backup Slides

Level Sets



Source: http://en.wikipedia.org/wiki/Level_set_method

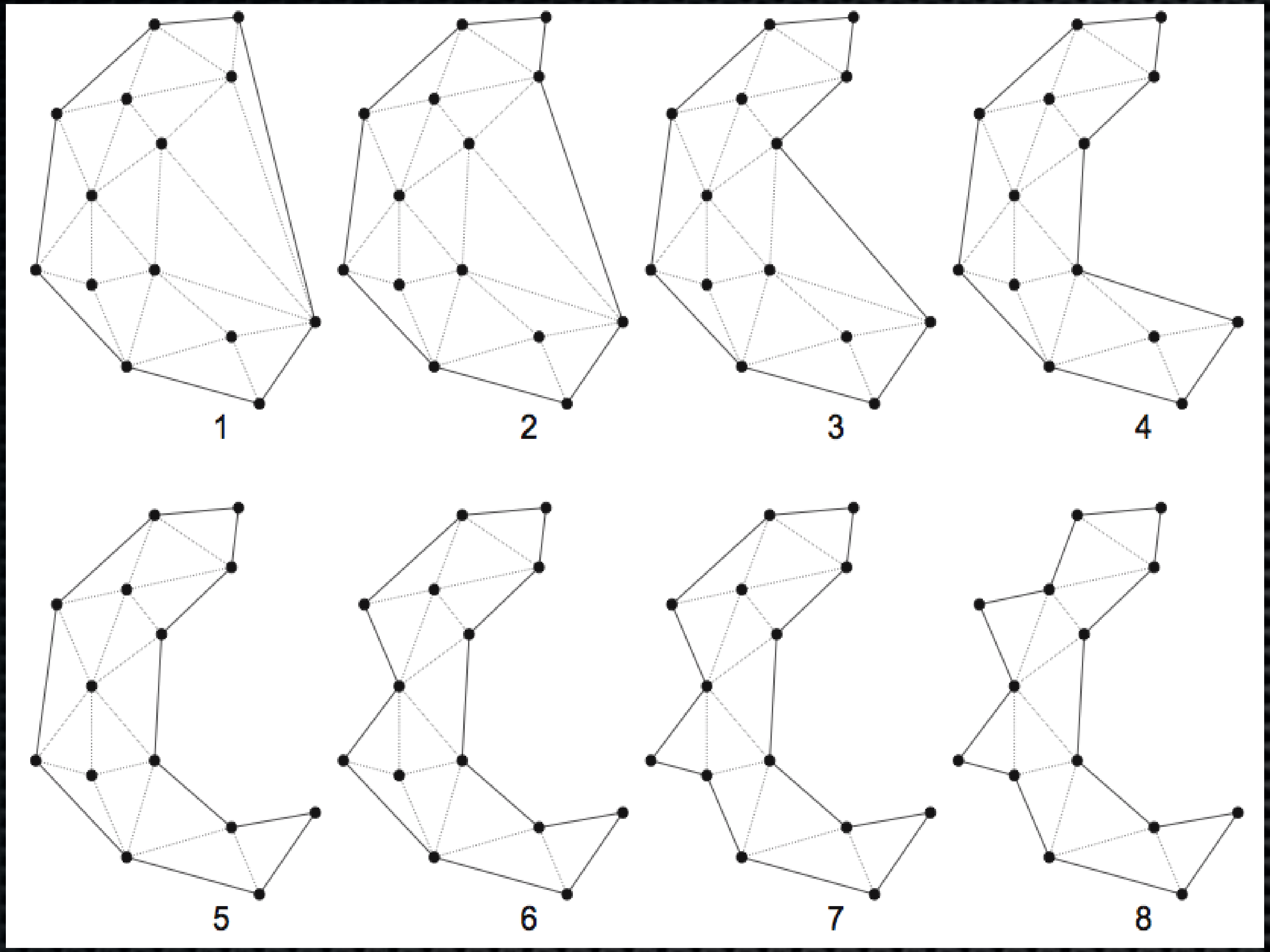
- Useful for visualizing dynamic interfaces
- N-Dimensional surface is slice of an (N+1)D function
- Easily handles pinching and merging interfaces
- Set operations are easy

Level Set Example

- Hard to create the distance function
- Finding the area enclosed is not straightforward
- Allows holes within the boundary
- Slow

QuickTime™ and a
decompressor
are needed to see this picture.

Delauney Triangulation

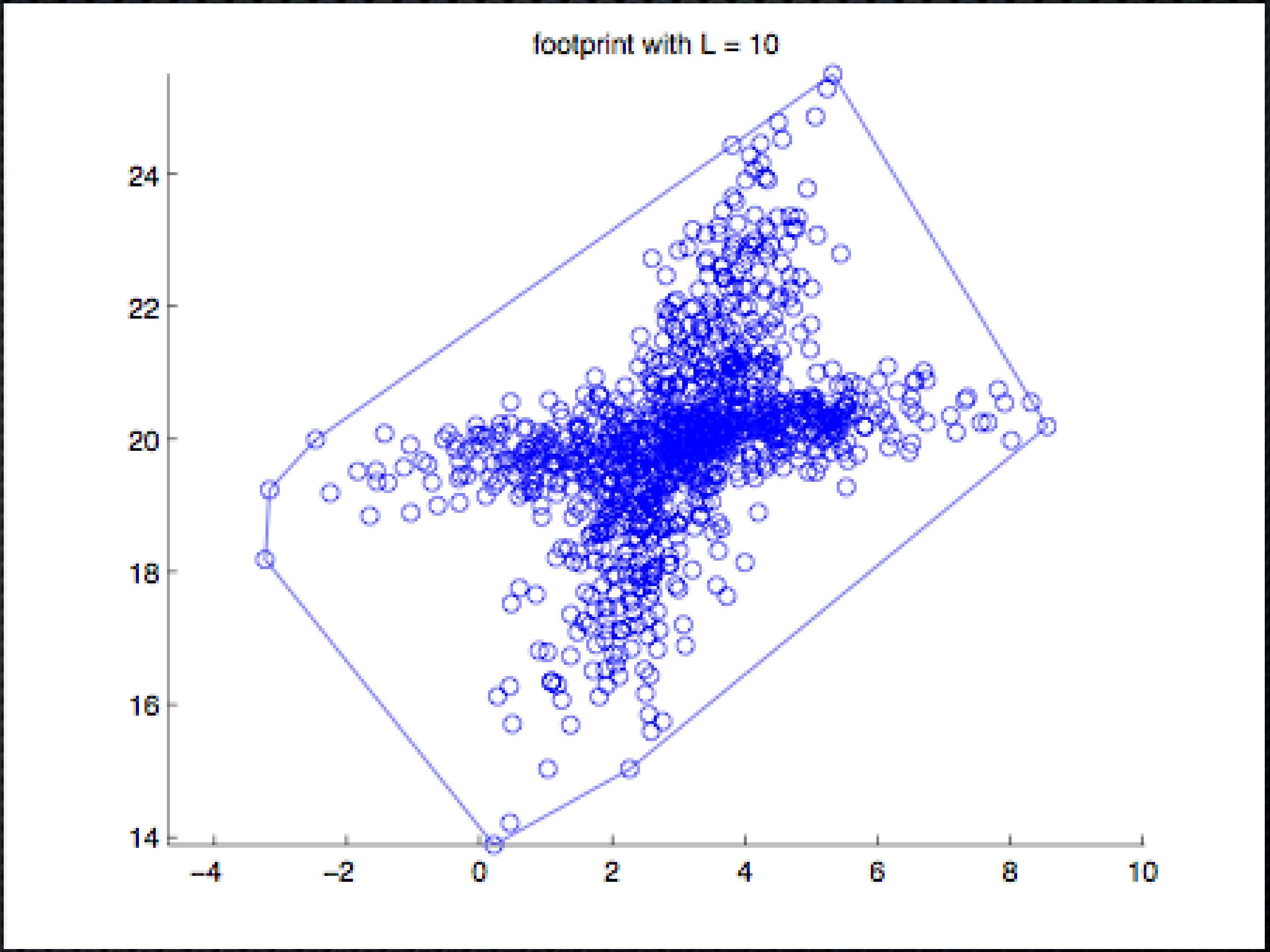


Source: Galton, A. “What is the region occupied by a set of points?”

- Overview
- Connect all dots with series of triangles
- Remove boundary edges
    - Generates single connected regular polygon
- Cons:
- Want to eliminate most points! Worth it?
- Creates a single shape

Convex Hulls

- Easy to generate
- Wastes a lot of space
- Only get one shape
- Can get these with footprint methods



Swinging Arm Algorithm

- Order all points from top to bottom, right to left.
- Set all points as ‘available’ and pick an arm length
  - Store top-right available point in footprint and set it as current point:
    - Swing the arm clockwise from current point until it hits another point
    - Store this point as being in the footprint and set it as the new current point
    - Repeat until current point == starting point
  - Set all points that form or are interior to the footprint as ‘unavailable’
  - Repeat until all points are unavailable
- xxxx