COE CST Fourth Annual Technical Meeting

# Analysis Environment for Safety Assessment of Launch and Re-Entry Vehicles

## Task 258

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COE CST
Center of Excellence for
Commercial Space Transportation

# Overview

- Team Members
- Purpose of Task
- Research Methodology
  - -Range Safety Assessment Tool (RSAT)
  - -Surrogate Modeling for Uncertainty Quantification (UQ) and Optimization
- Results / Progress to Date
- Conclusions / Future Work

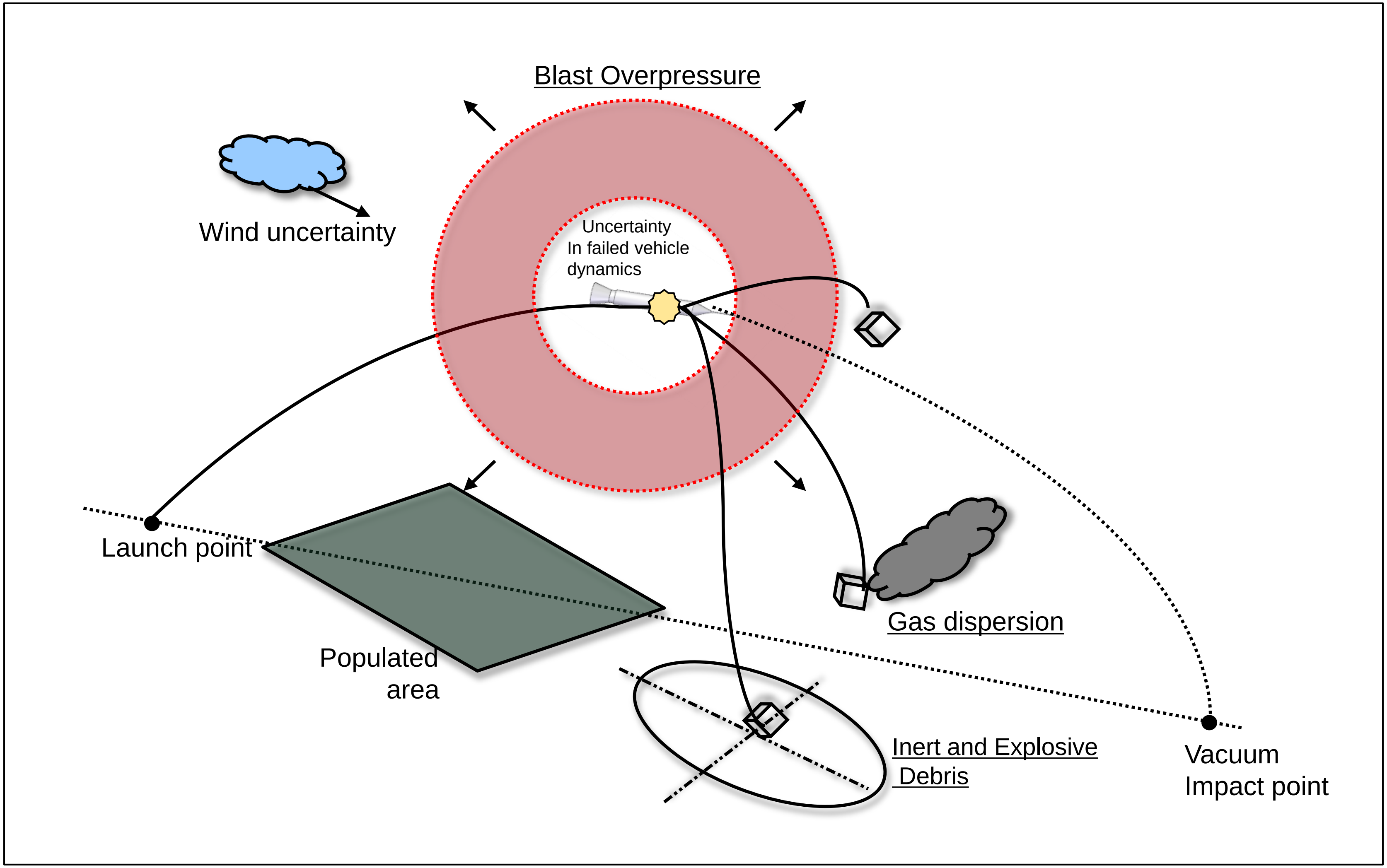
# Team Members

- PI: Juan J. Alonso, Aero & Astro, SU
- Francisco Capristan, Aero & Astro, Graduate Student, SU
- Paul Wilde, FAA
- Program Manager: Ken Davidian

# Purpose of Task/Goals

- To provide the FAA and the community with an independent analysis tool capable of quantifying the safety of the uninvolved public due to launch and re-entry vehicle malfunctions.
- To study uncertainty effects on the current safety metrics and evaluate if they are appropriate for a variety of commercial space transportation vehicles.
- To validate the resulting tool with existing and proposed vehicles so that the resulting tool/environment can be confidently used.
- To increase the transparency of the safety assessment of future vehicles via a common analysis tool that is entirely open source and, thus, streamline the licensing process for a variety of vehicle types.

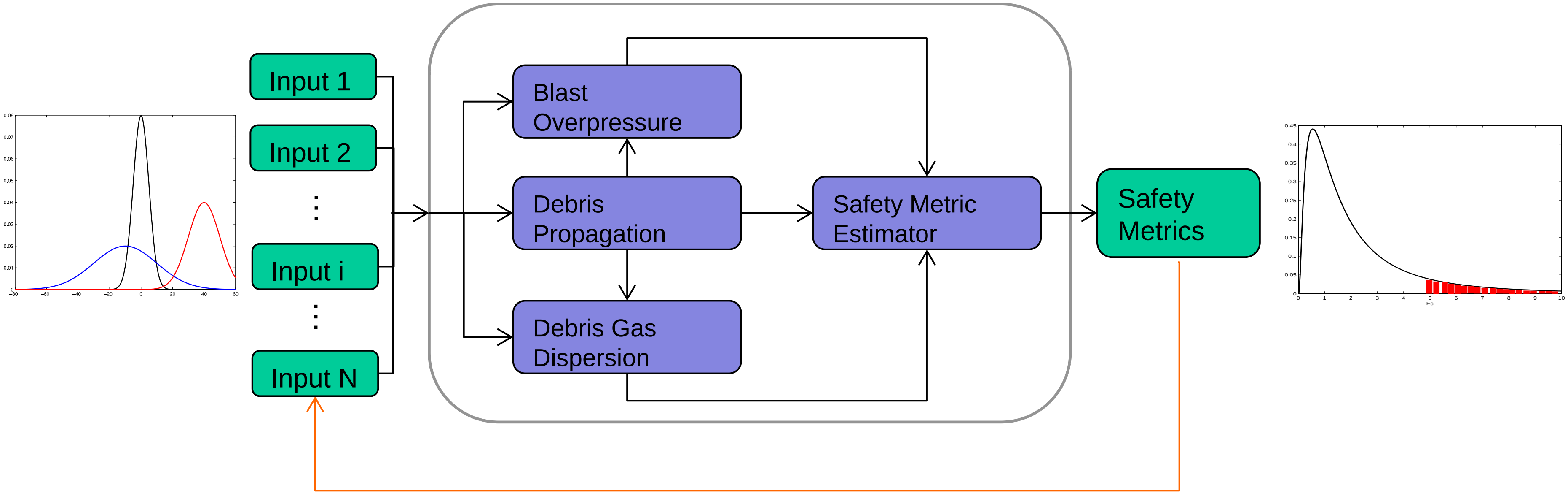
# Range Safety Assessment Tool (RSAT)



Safety Analysis Environment Schematic

# RSAT

- Main focus is on safety to the uninvolved public (expected casualties).
- There are 3 main modeling modules.



Input 1
Input 2
⋮
Input i
⋮
Input N

Blast Overpressure
Debris Propagation
Debris Gas Dispersion
Safety Metric Estimator

Safety Metrics

Inverse Problem

- Results obtained by solving the inverse problem could be used to inform licensing restrictions or influence design.

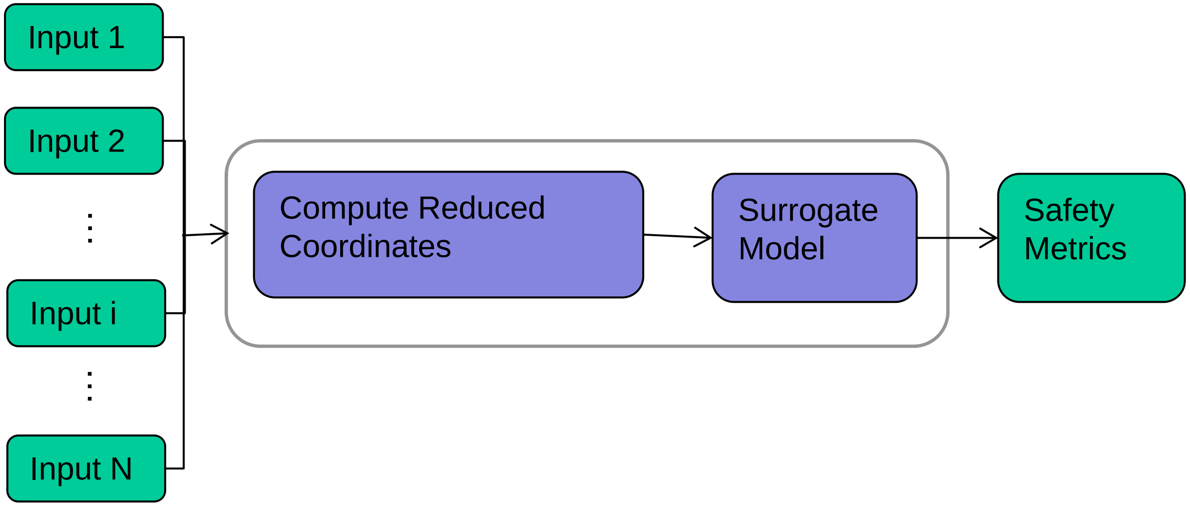
*Details in “Range Safety Assessment Tool (RSAT): An analysis environment for safety assessment of launch and reentry vehicles (AIAA 2014-0304), Francisco M. Capristan, Juan J. Alonso, 52nd Aerospace Sciences Meeting, 2014, 10.2514/6.2014-0304”

# UQ and Optimization

Some of the challenges include:

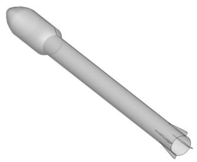
- The cost for each evaluation, coupled with the large number of samples required for UQ demand large computational resources.
- The value of interest tends to be noisy due to the stochastic nature of the problem.
- Most methods suffer from the curse of dimensionality.

We are proposing the use of Active Subspaces to decrease the dimensionality of the problem and apply Gaussian Process Regression (GPR) as the surrogate to decrease the computational cost.

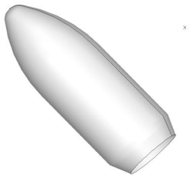


# Results

- Generic ELV vehicle launching towards ISS orbit.
- Aerodynamic data obtained from Missile Datcom.
- SPOT was used to generate optimal trajectories.
- Wind variations obtained from Earth GRAM.
- Performed Ec calculation due to inert and explosive debris.



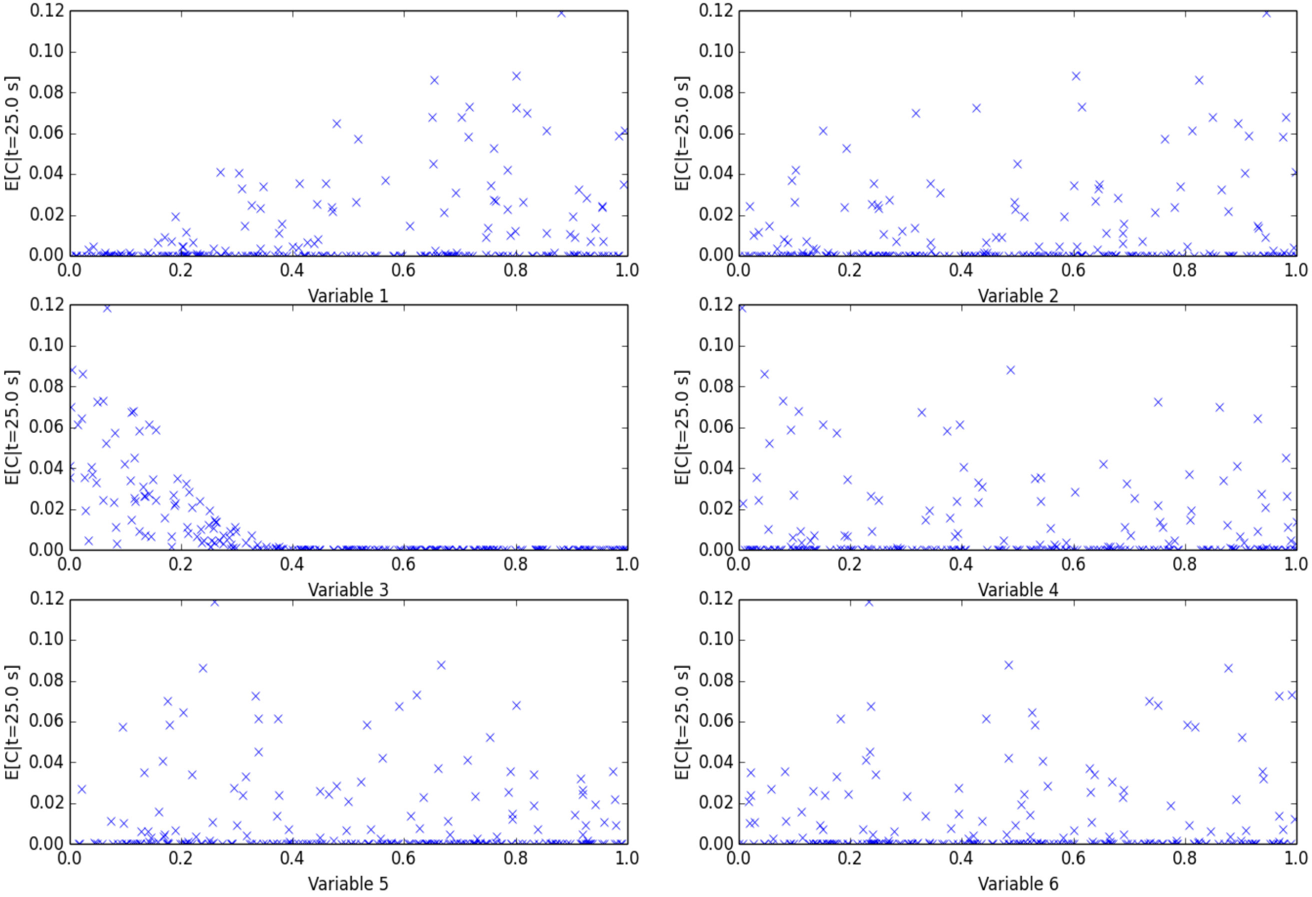
First Stage



Second Stage

# Results

- Uncertainty effects on E(C|t=25 sec)

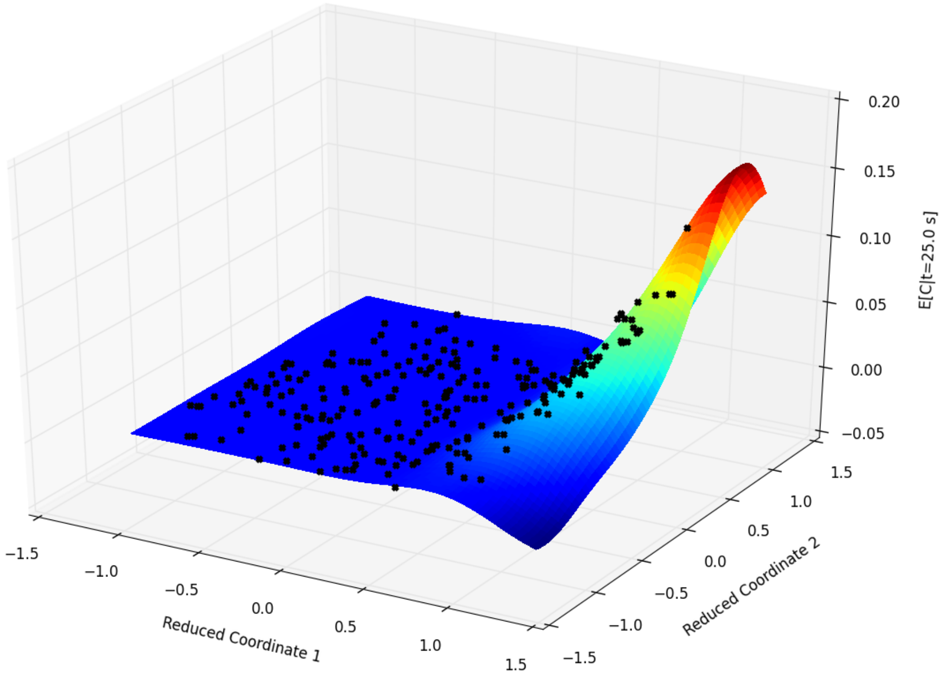


Only 6 variables shown from a total of 47.

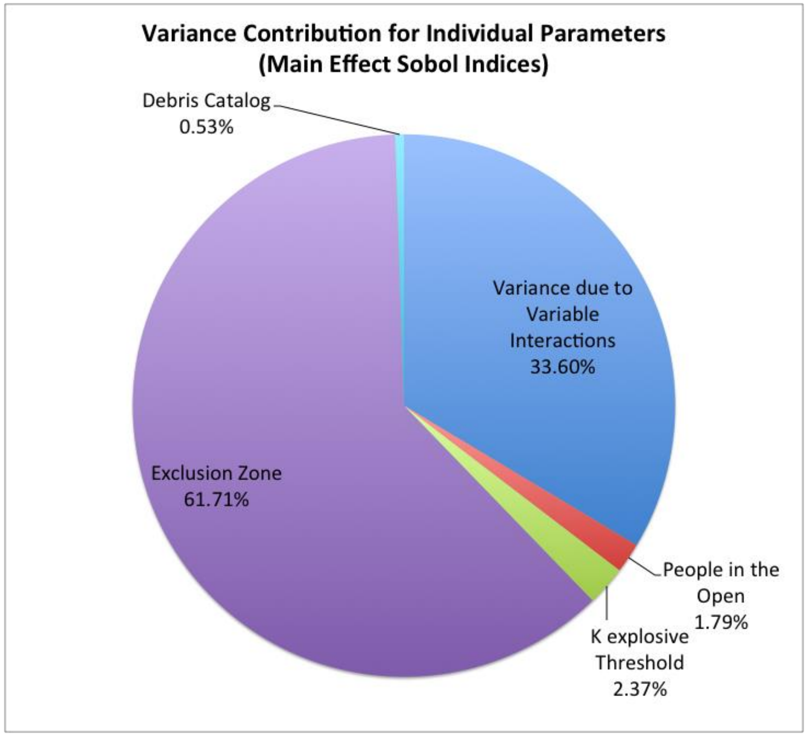
Can we do anything with this data?

# Results

E(C|t=25 sec) can be approximated by two reduced coordinates. The surrogate model does a good job capturing the location of the test points.

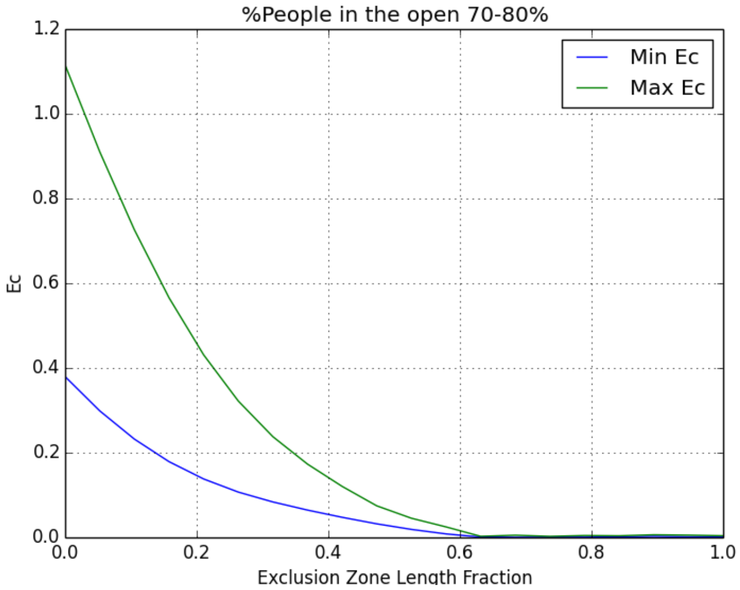


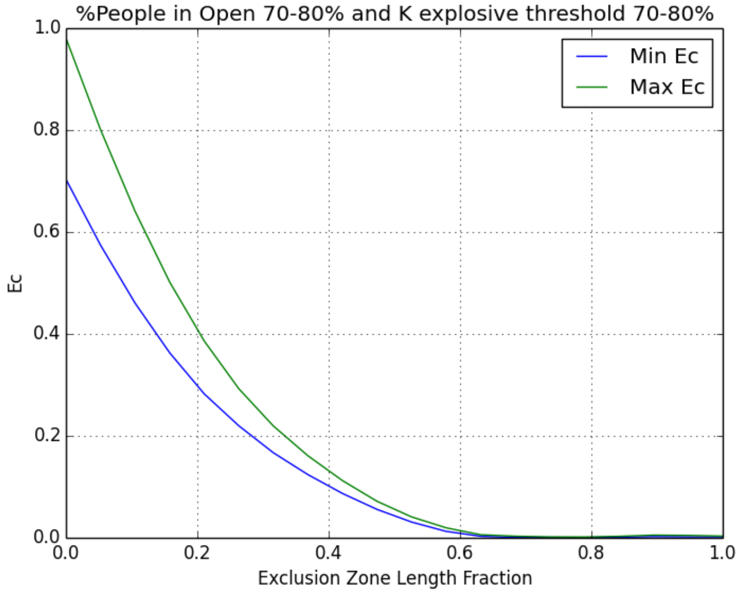
Surrogate Model with Reduced Coordinates

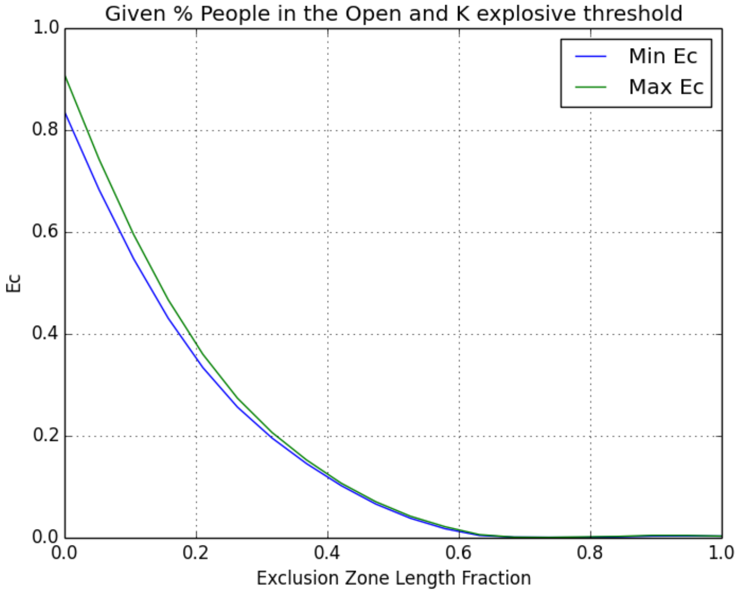


# Results

- Consider the best and worst possible E(C) scenarios given different exclusion zones sizes.
- The surrogate model is used to do the optimization.
- The low cost of evaluating the surrogate allows the creation of histograms for E(C|params).







# Conclusions

- The Range Safety Assessment Tool (RSAT) considers:
  - Nominal and off-nominal trajectories
  - Failure Probabilities
  - Wind variations
  - Population density
  - Sheltering (roof types)
  - Debris Catalogs
  - Exclusion zones
- Active subspaces coupled with GPR help provide surrogate models that can be used to perform UQ and optimization.
- RSAT can compute global sensitivity analysis for an entire trajectory.
- Initial optimization runs suggests that the current methodology could help identify inputs that could lead to worst case scenarios.

# Ongoing and Future Work

- Further investigate how input uncertainties affect E(C) calculations.
- Use RSAT to analyze other vehicle configurations (e.g. suborbital vehicles).
- Identify parameters of interest to solve the inverse problem.
- Demonstrate how inverse solutions can be used in the context of licensing or setting mission requirements.

# Contact Information

| | |
|---|---|
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| Francisco M. Capristan | fcaprist@stanford.edu |

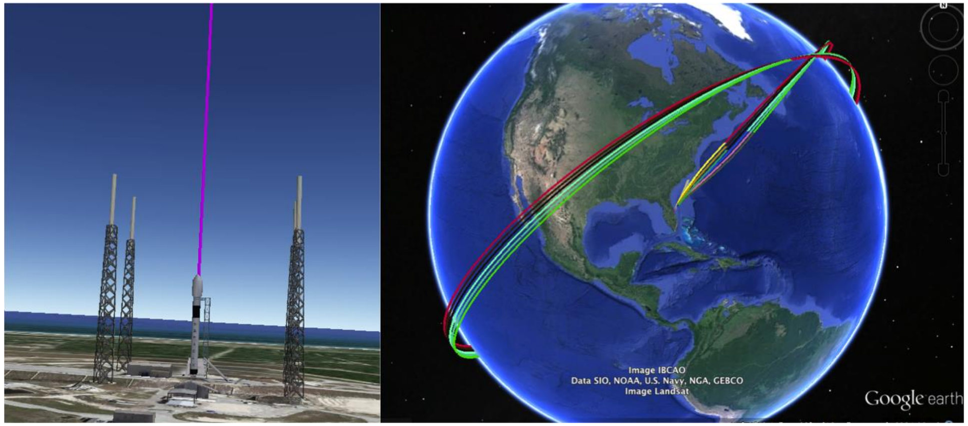
# Backup Slides

# Trajectory Development

Stanford Program to Optimize Trajectories (SPOT)

- In house 3-DOF trajectory code that uses a pseudospectral collocation method.
- Python code with a few fortran modules.
- Available optimizers:
    - SNOPT (commercial)
    - IPOPT (open source)
- Aerodynamics : CD as a function of Mach number
- MISSILE DATCOM used to obtain aerodynamic data

Trajectory perturbation (Thrust offset, wind, etc) performed with SPOT’s trajectory propagation capabilities



Sample Trajectory

# Safety Assessment Tool

- Inputs
    - Nominal and off-nominal trajectories
    - Failure Probabilities
    - Wind variations
    - Population density
    - Sheltering (roof types)
    - Debris Catalogs:
        - Size/number of pieces
        - Aerodynamic characteristics
- Outputs
    - Monte-Carlo-like debris locations
    - Expected Casualties

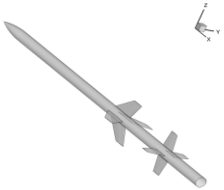
# Sample Trajectories

Falcon 9 type vehicle to the ISS orbit

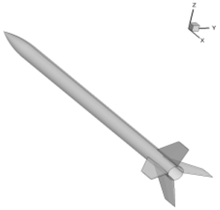
First Stage

Second Stage

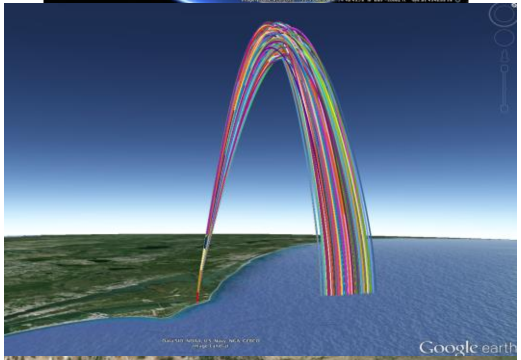
Stratos II Sounding Rocket.
~60 km Altitude



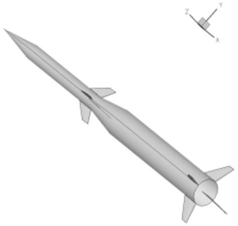
First Stage



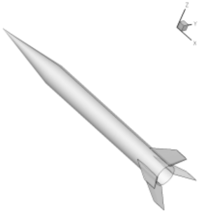
Second Stage



SONDA III Sounding Rocket.
~600 km altitude

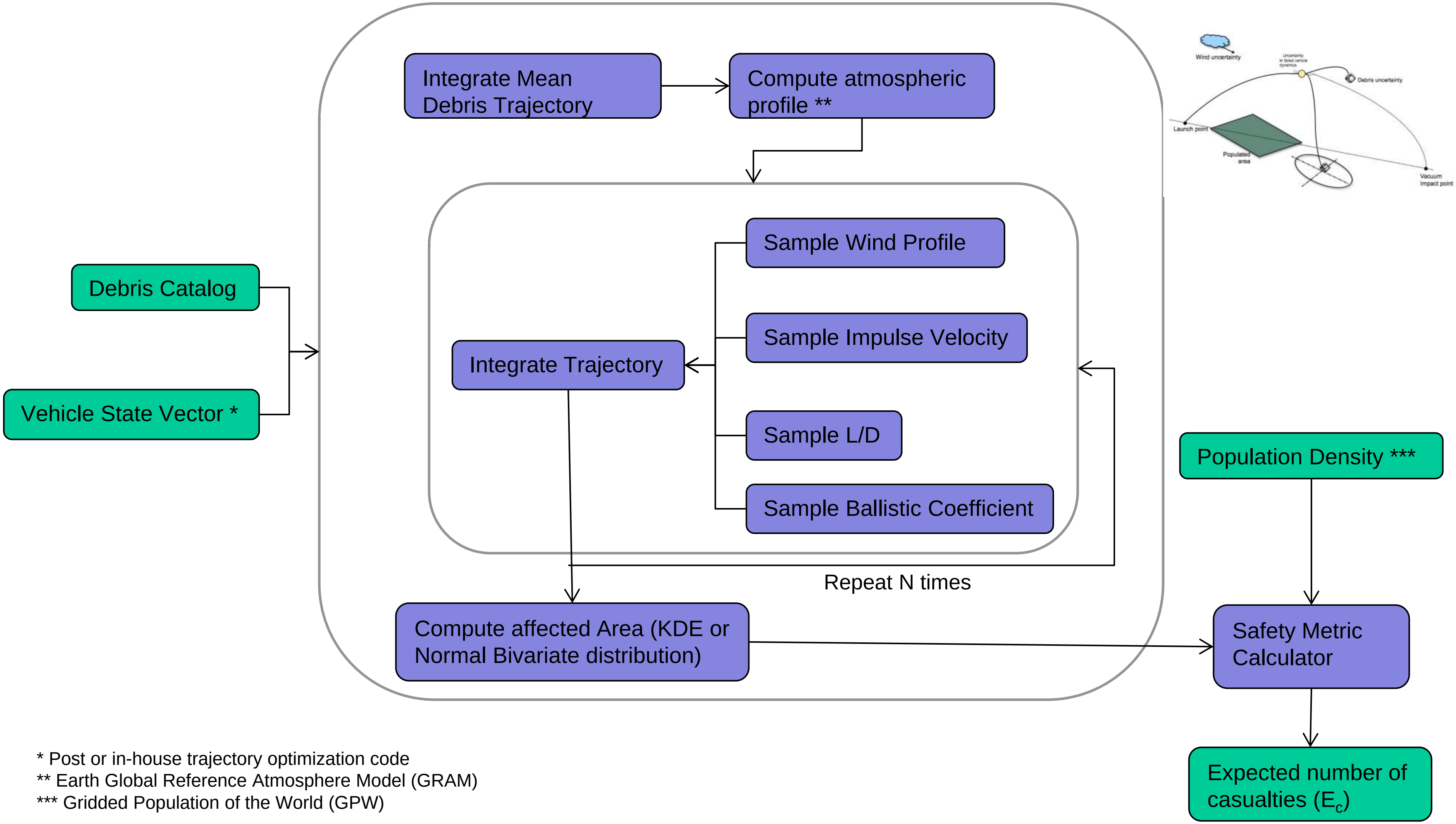


First Stage



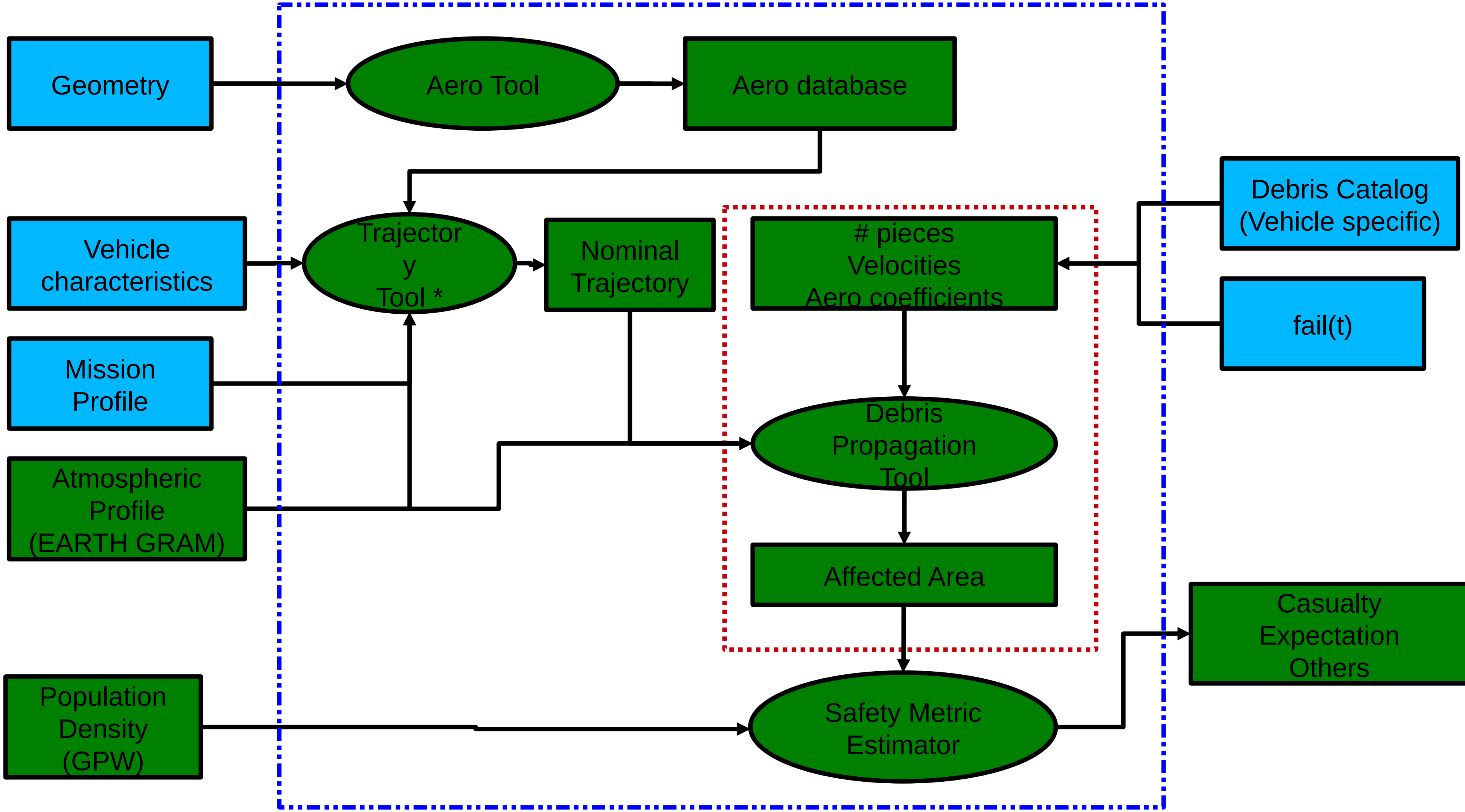
Second Stage

# Analysis Environment: Debris Propagation



* Post or in-house trajectory optimization code
** Earth Global Reference Atmosphere Model (GRAM)
*** Gridded Population of the World (GPW)

# Debris Modeling



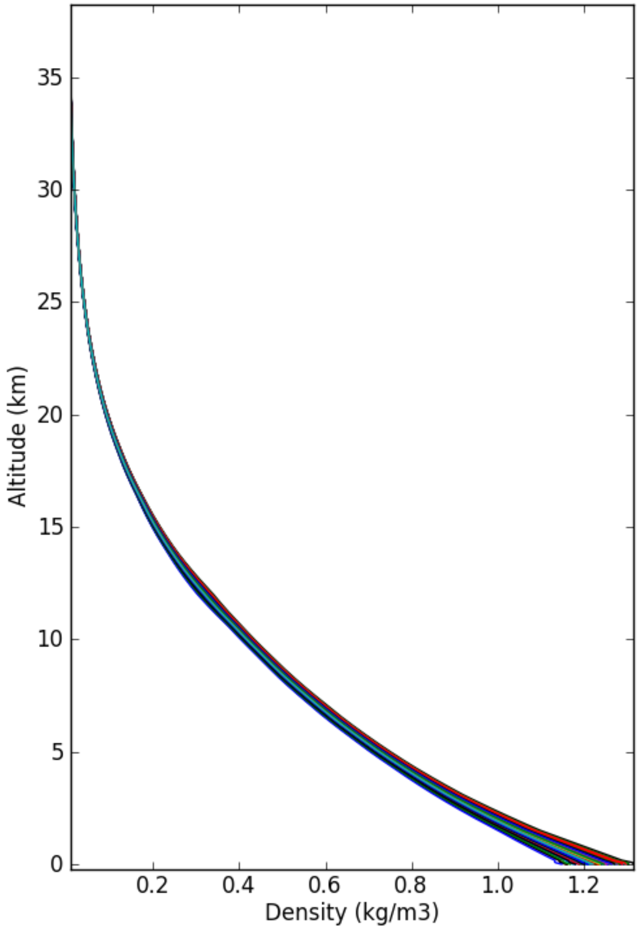
* Access to POST or Stanford Trajectory Optimization Program (STOP)

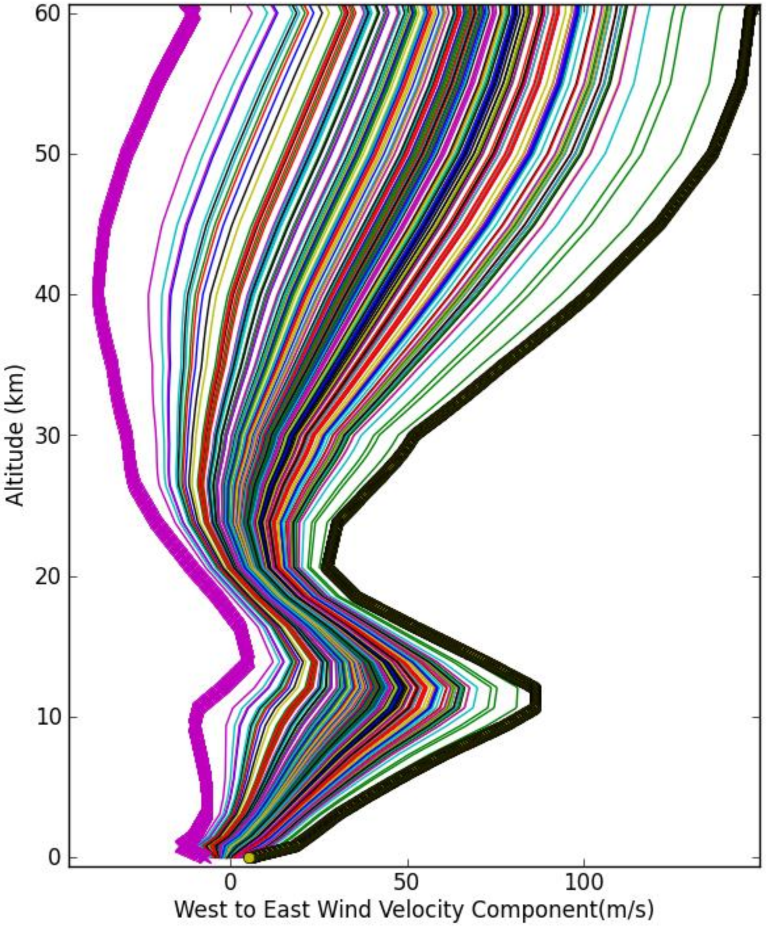
# Debris Modeling

- The following assumptions/considerations were made to the debris dispersion tool :
    - Spherical/Oblate rotating Earth.
    - Debris pieces have constant mass.
    - Debris pieces treated as point masses.
    - Lift and drag coefficients functions of Mach number.
    - Explosion effects simulated by giving impulse velocities to the debris.
    - Earth Gram used to obtain atmospheric profiles.
    - Wind effects in all 3 orthogonal directions are considered.
    - Affected ground area obtained by using Kernel Density Estimation or assuming a Normal Bivariate distribution

# Debris Propagation

Uncertainty in atmospheric parameters

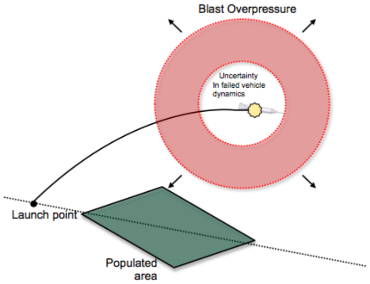


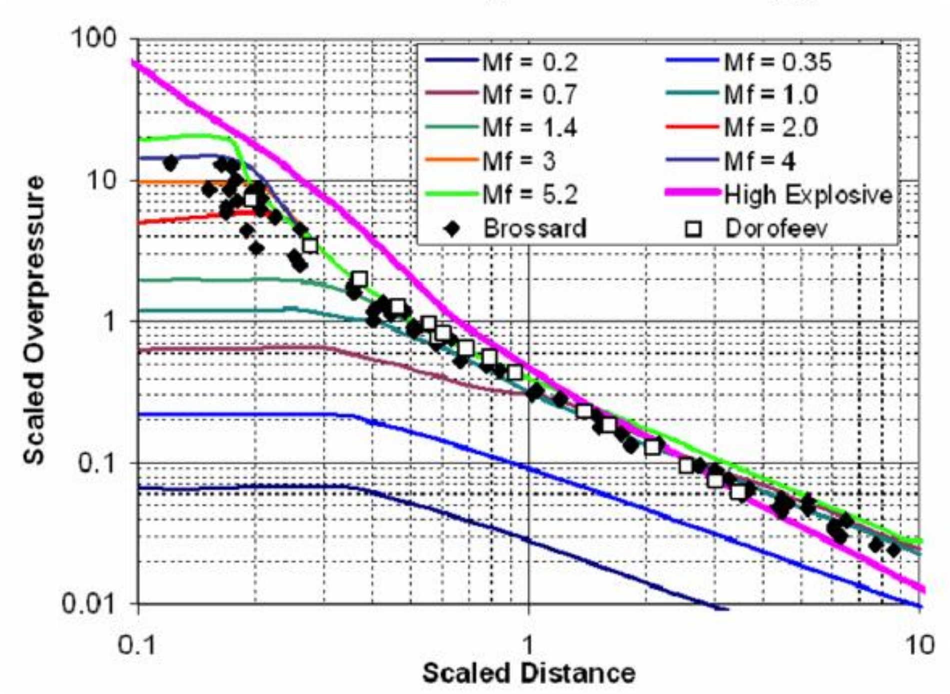


# Analysis Environment: Blast Overpressure

- Blast Overpressure is one of the main threats associated with catastrophic booster failure leading to explosion.
- The Baker-Strehlow-Tang curves are used because of their ease of use and good agreement with experiments in the supersonic and subsonic regimes.

$$E_t=\eta_p m_p E_{TNT} \qquad \bar{P}=\frac{p-p_0}{p_0} \qquad \bar{R}=\frac{R}{E_t/p_0^{1/3}}$$

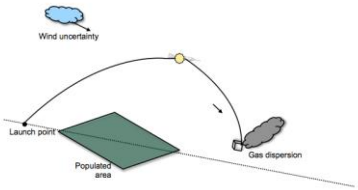




| | |
|---|---|
| $p_0$ | atmospheric pressure |
| $p$ | absolute peak pressure |
| $R$ | stand-off distance |
| $E_{TNT}$ | blast energy per unit mass of TNT |
| $E_T$ | blast energy |
| $\eta_p$ | yield factor |
| $m_p$ | propellant mass |

Blast Overpressure Modeling Enhancements for Application to Risk Informed Design of Human Space Flight Launch Abort Systems. Scott Lawrence, and Donovan Mathias

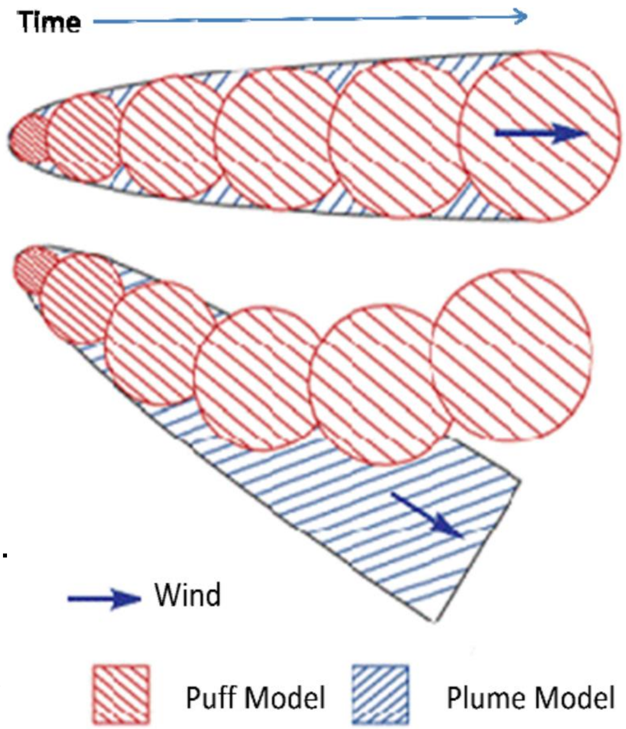
# Analysis Environment: Gas Dispersion



- The most common air dispersion models are Plume and Puff types.
- Modeling systems considered :
    - CALPUFF => Puff
    - AERMOD => Plume

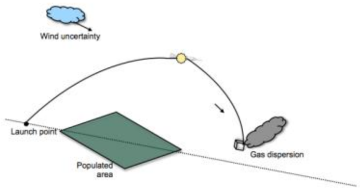
- AERMOD :
    - Steady state model which assumes that a plume disperses in the horizontal and vertical directions.
    - Plume follows the wind direction in a straight line.
    - Valid Range up to 50 km from the source.
- CALPUFF :
    - Uses discrete puffs emitted from sources.
    - Puffs can follow a curved trajectory (due to changing winds).
    - Valid Range up to 200~300 km from the source.

- Due to complexities in CALPUFF's input parameters, AERMOD is used in our modeling environment.
    - Studies suggests that CALPUFF and AERMOD return comparable results for dispersion near the sources.

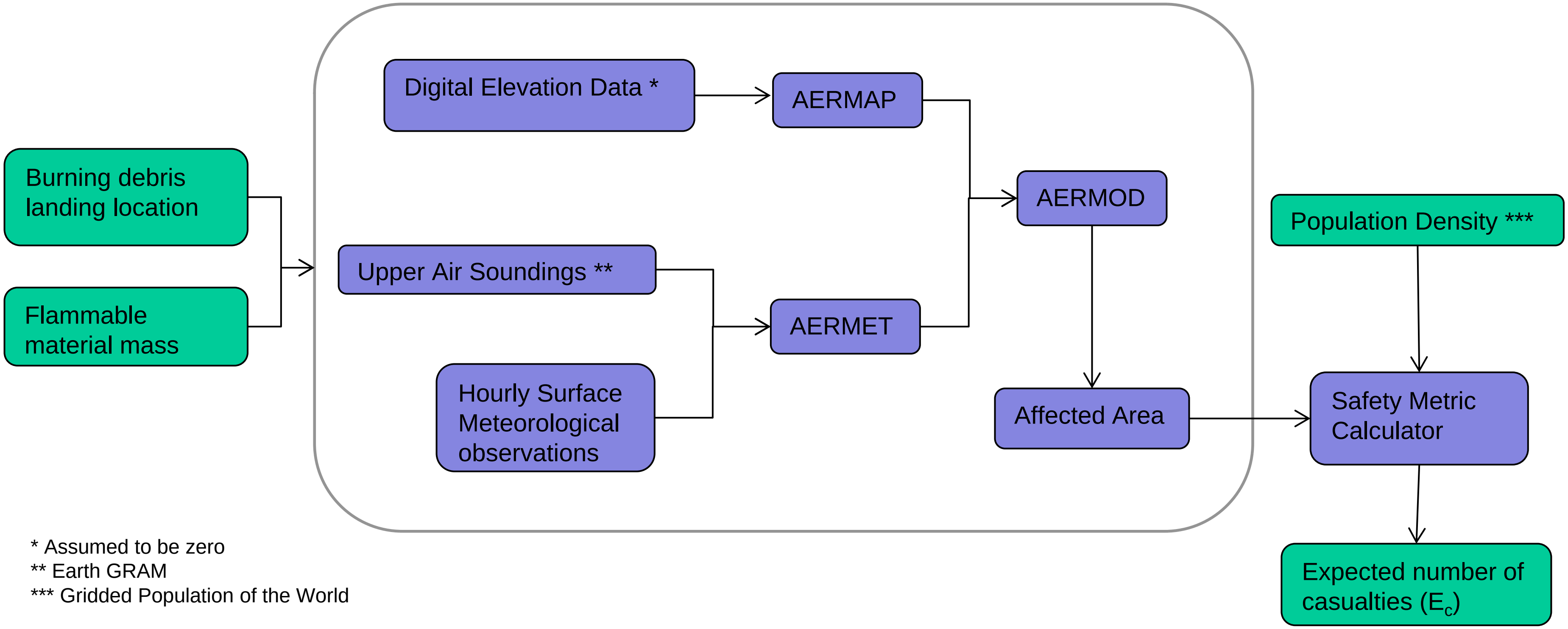


*Integrated Environmental Solutions White Paper – Puff and Plume Models

# Analysis Environment: Gas Dispersion



- Currently using AERMOD (Atmospheric Dispersion Modeling):
  - Tool used by the U.S Environmental Protection Agency (EPA) for regulation purposes.
  - It incorporates air dispersion based on planetary boundary layer turbulence structure and scaling concepts, including treatment of both surface and elevated sources, and both simple and complex terrain.



Burning debris landing location

Flammable material mass

Digital Elevation Data *

AERMAP

Upper Air Soundings **

Hourly Surface Meteorological observations

AERMET

AERMOD

Affected Area

Population Density ***

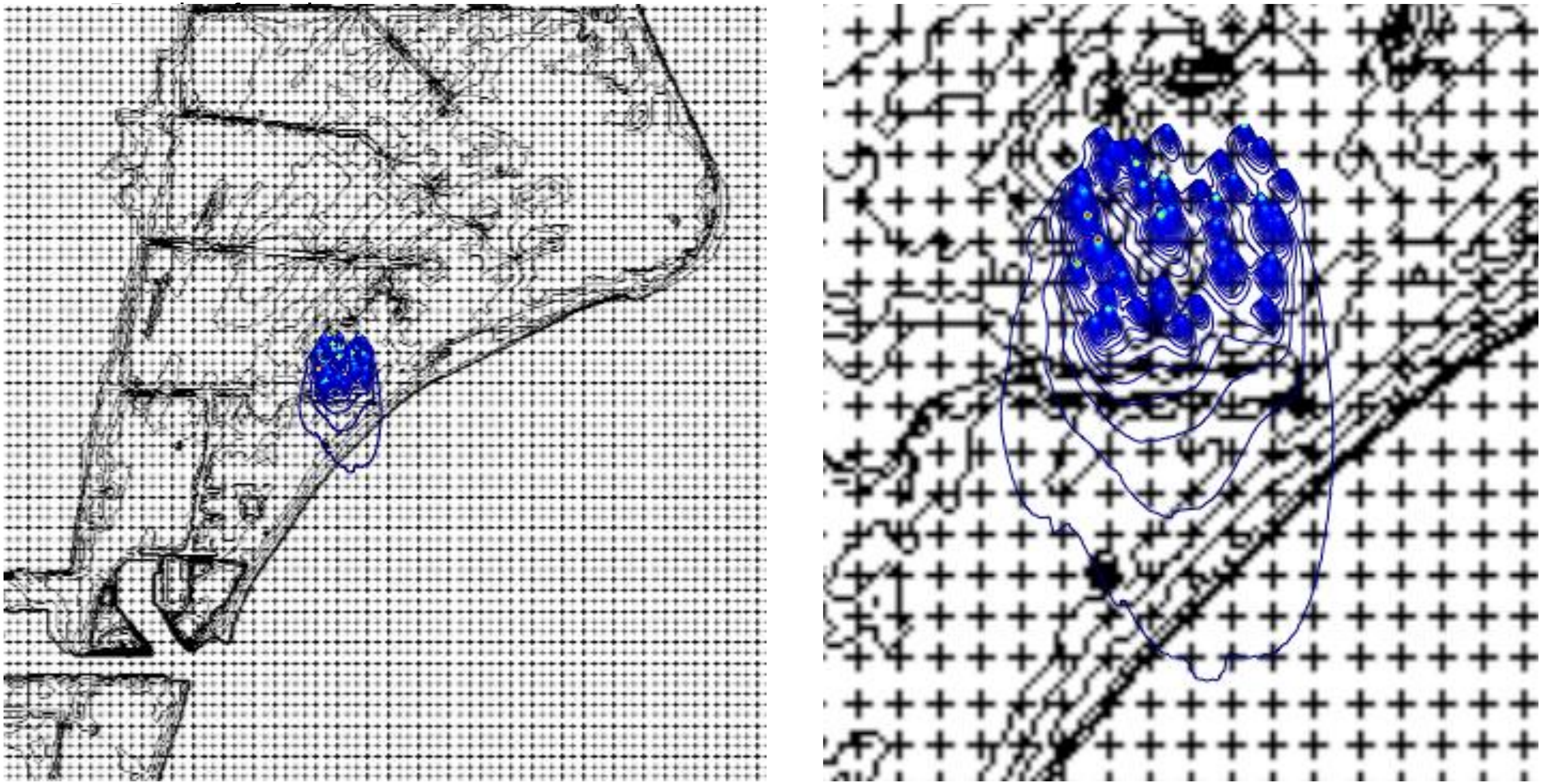
Safety Metric Calculator

Expected number of casualties ($E_c$)

* Assumed to be zero
** Earth GRAM
*** Gridded Population of the World

# Gas Dispersion Simulation

- Sample gas dispersion case (add more details: location, test case made up, wind profiles, etc, etc)
    - 50 pieces of burning debris



# Technical Approach

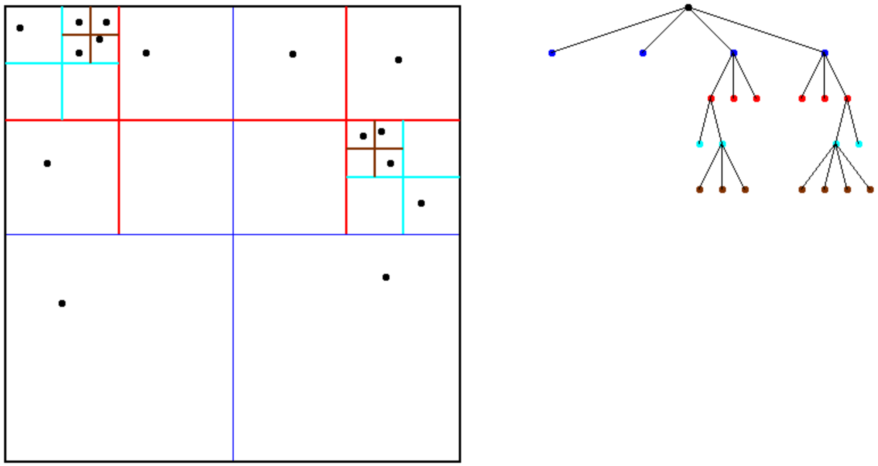
Risk area debris formulation

$$X_i = [Latitude_i, Longitude_i]^T$$

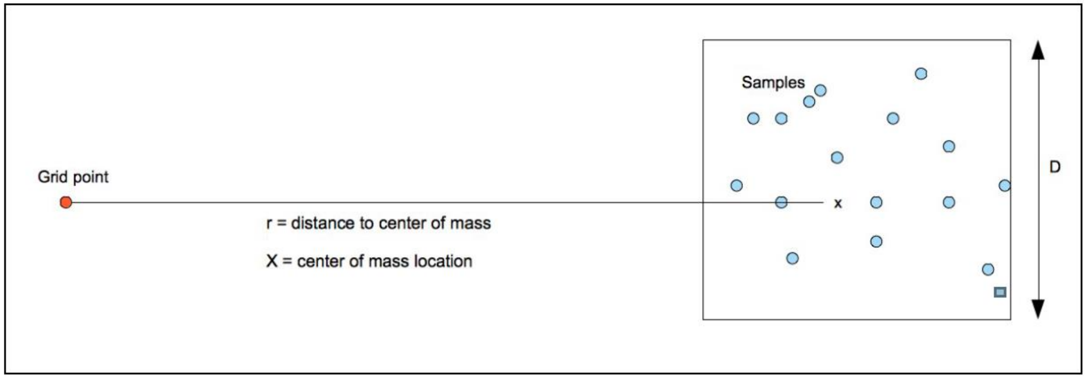
| Normal Bivariate | Kernel Density |
|---|---|
| $\bar{X} = \frac{1}{n} \sum_{i=1}^{n} X_i$<br>$S = \frac{1}{n-1} \sum_{i=1}^{n} (X_i - \bar{X})(X_i - \bar{X})^T$<br>$\hat{f}(x) = \frac{1}{2\pi \sqrt{det(S)}} e^{\frac{1}{2}(x-\bar{X})^T S^{-1} (x-\bar{X})}$ | $\bar{X} = \frac{1}{n} \sum_{i=1}^{n} X_i$<br>$S = \frac{1}{n-1} \sum_{i=1}^{n} (X_i - \bar{X})(X_i - \bar{X})^T$<br>$\begin{bmatrix} S_1 & 0 \\ 0 & S_2 \end{bmatrix} = U^{-1} S U$<br>Compute eigenvalues and eigenvectors<br>$U = \begin{bmatrix} s_x & -s_y \\ s_y & s_x \end{bmatrix}$<br>$[P_i \quad Q_i] = X_i^T U$<br>Compute *h* from *P* and *Q*<br>$h = 1.06 \left( min \left\{ \sigma, \frac{IQR}{1.34} \right\} \right) n^{-1/5}$<br>$H_2 = U \begin{bmatrix} h_1^2 & 0 \\ 0 & h_2^2 \end{bmatrix} U^{-1}$<br>$\hat{f}(x) = \frac{1}{2\pi n \sqrt{det(H_2)}} \sum_{i=1}^{n} e^{\frac{1}{2}(x-X_i)^T H_2^{-1} (x-X_i)}$ |

Procedure suggested in "Range Safety Application of Kernel Density Estimation". Gary Clonek, et al.

# Kernel Density Estimation via Adaptive Quadtrees


Adaptive quadtree where no square contains more than 1 particle

$$\hat{f}(x) = \frac{1}{2\pi n \sqrt{\det(H_2)}} \sum_{i=1}^{n} e^{\frac{-1}{2}(x - X_i)^T H_2^{-1} (x - X_i)}$$



Quadtree formulation

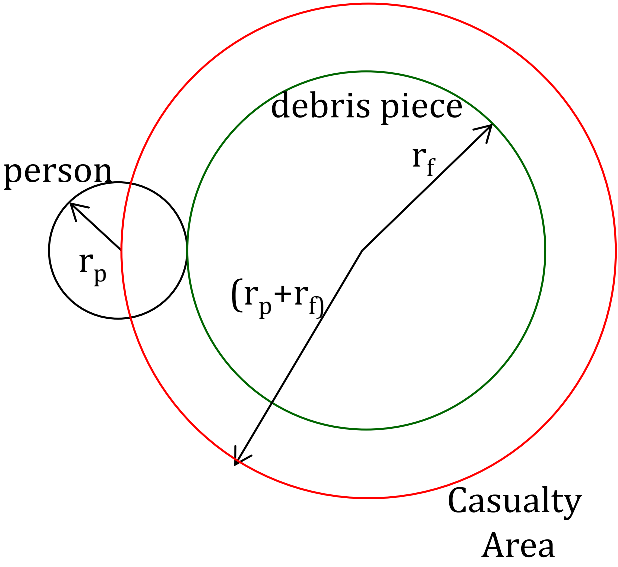
$$\frac{D}{r} < q$$

$$\hat{f}(x) = \frac{1}{2\pi n \sqrt{\det(H_2)}} \sum_{k=1}^{Nr} n_k e^{\frac{-1}{2}(x_{cm} - X_i)^T H_2^{-1} (x_{cm} - X_i)}$$

# Expected Casualty Calculation

$A_C$ : Casualty area
$A_f$ : fragment projected area
$r_p$ : person radius

$$A_C = \pi\left(\sqrt{\frac{A_f}{\pi}} + r_p\right)^2$$



Casualty Area Calculation

$E_C$ : Casualty Expectation
$P_{Iij}$ : probability that the jth piece of debris will land in $A_i$
$N_i$ : number of people
$A_i$ : Area of interest

$$E_C = \sum_{i=1}^{n} \sum_{j=1}^{m} P_{Iij} A_{Cij} \frac{N_i}{A_i}$$

* "A Hazard Model for Exploding Solid-Propellant Rockets"
J.C. McMunn, et al.

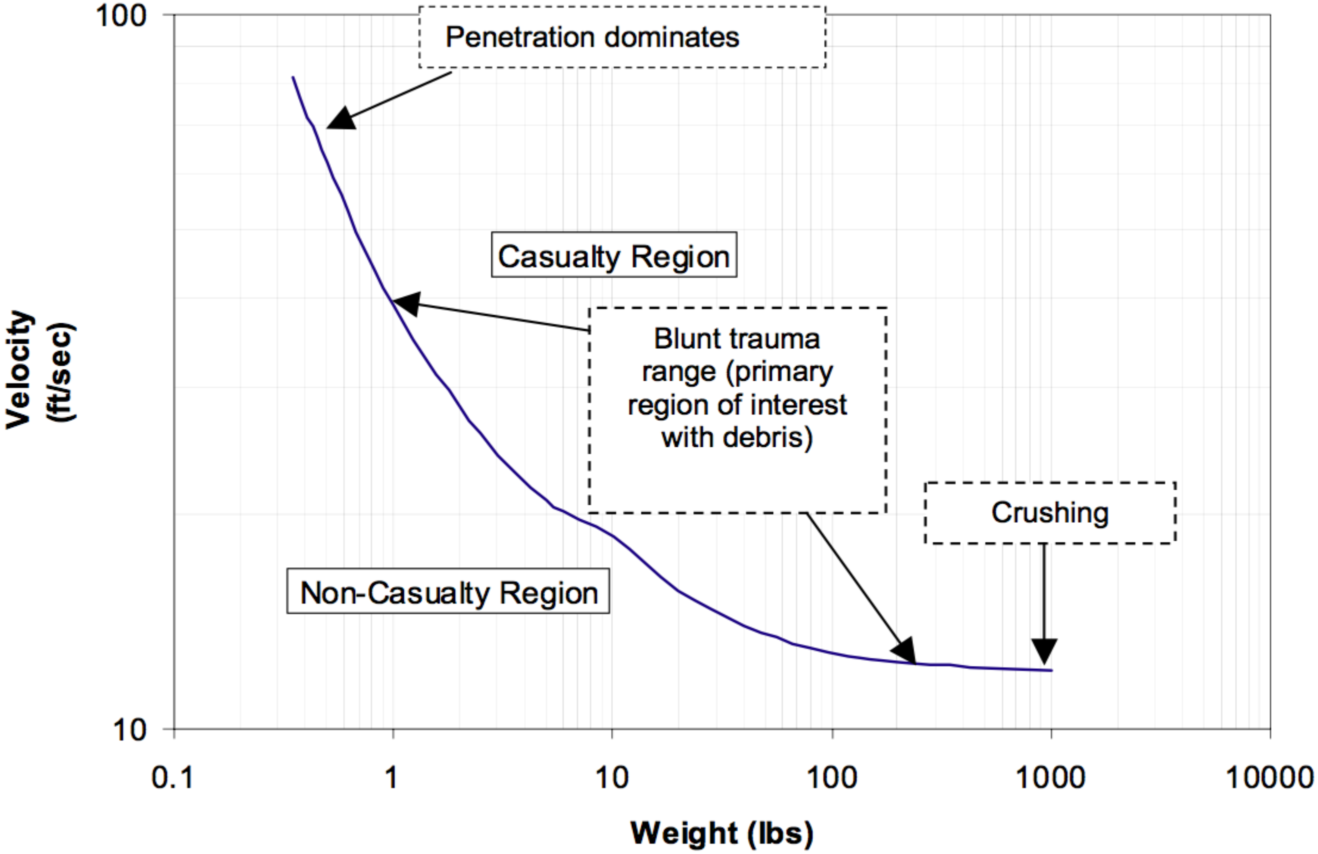
# Ec Calculation

- The following assumptions/considerations were made in the Expected Casualty (safety metric) calculation:

  - Population divided in square grid cells, and uniformly distributed within each cell.
  - No bouncing debris considered.
  - An empirical formula is used to calculate debris piece lethality.
  - Gridded Population of the World used for population density

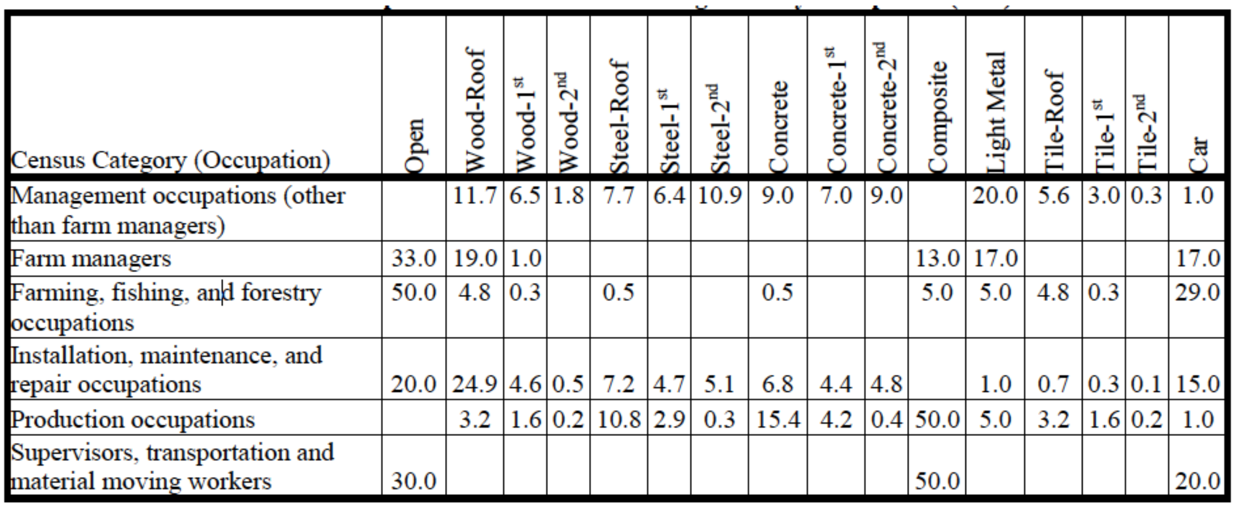
# Ec Calculation

- Debris piece lethality assessment

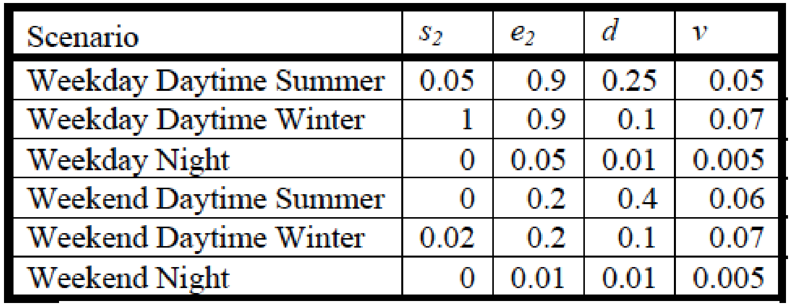


* "Estimation of Space Shuttle Orbiter Reentry Debris Casualty Area" Jon D. Collins, Randolph Nyman, and Isaac Lottati

# Example Distribution of Sheltering



| Census Category (Occupation) | Open | Wood-Roof | Wood-1st | Wood-2nd | Steel-Roof | Steel-1st | Steel-2nd | Concrete | Concrete-1st | Concrete-2nd | Composite | Light Metal | Tile-Roof | Tile-1st | Tile-2nd | Car |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Management occupations (other than farm managers) | | 11.7 | 6.5 | 1.8 | 7.7 | 6.4 | 10.9 | 9.0 | 7.0 | 9.0 | | 20.0 | 5.6 | 3.0 | 0.3 | 1.0 |
| Farm managers | 33.0 | 19.0 | 1.0 | | | | | | | | 13.0 | 17.0 | | | | 17.0 |
| Farming, fishing, and forestry occupations | 50.0 | 4.8 | 0.3 | | 0.5 | | | 0.5 | | | 5.0 | 5.0 | 4.8 | 0.3 | | 29.0 |
| Installation, maintenance, and repair occupations | 20.0 | 24.9 | 4.6 | 0.5 | 7.2 | 4.7 | 5.1 | 6.8 | 4.4 | 4.8 | | 1.0 | 0.7 | 0.3 | 0.1 | 15.0 |
| Production occupations | | 3.2 | 1.6 | 0.2 | 10.8 | 2.9 | 0.3 | 15.4 | 4.2 | 0.4 | 50.0 | 5.0 | 3.2 | 1.6 | 0.2 | 1.0 |
| Supervisors, transportation and material moving workers | 30.0 | | | | | | | | | | 50.0 | | | | | 20.0 |



| Scenario | $s_2$ | $e_2$ | $d$ | $v$ |
|---|---|---|---|---|
| Weekday Daytime Summer | 0.05 | 0.9 | 0.25 | 0.05 |
| Weekday Daytime Winter | 1 | 0.9 | 0.1 | 0.07 |
| Weekday Night | 0 | 0.05 | 0.01 | 0.005 |
| Weekend Daytime Summer | 0 | 0.2 | 0.4 | 0.06 |
| Weekend Daytime Winter | 0.02 | 0.2 | 0.1 | 0.07 |
| Weekend Night | 0 | 0.01 | 0.01 | 0.005 |

*Tables from "Large Region Population Sheltering Models for Space Debris Risk Analysis.
Eric W.F Larson"

# Safety Metric Estimator

## .Expected Casualty Formulation

$$
\begin{aligned}
P_{I_{ij}} &= f(\vec{r}, \vec{v}, ae\vec{r}o) \\
A_{C_{k_r}} &= g(m) \quad , r \geq 1
\end{aligned}
$$

$$
E_{1k}(\vec{A_{C_k}}, \vec{r}, \vec{v}, ae\vec{r}o) = \sum_{i=1}^{n} \sum_{j=1}^{m} (P_{k_{Iij}} [A_{C_{k_0}} \rho_{ij} c_0 + \sum_{r=1}^{\#roofs} (A_{C_{k_r}} \rho_{ij} c_r)])
$$

$$
E_k(\vec{r}, \vec{v}, ae\vec{r}o) = \sum_{i=1}^{n} \sum_{j=1}^{m} (P_{k_{Iij}} [E(A_{C_{k_0}}) \rho_{ij} c_0 + \sum_{r=1}^{\#roofs} E(A_{C_{k_r}}) \rho_{ij} c_r])
$$

$$
E(A_{C_{k_r}}) = \int_0^{\infty} g(m) p(m) \, dm \quad , r \geq 1
$$

$P_{I_{k_{ij}}}$ => $PDF$ *on the ground for debris group* $k$ (*from* $KDE$ *or Normal distribution assumption*)
$A_{C_{k_0}}$ => *Casualty area* (*debris piece projected area for people in the open*)
$A_{C_{k_{1\ldots R}}}$ => *Casualty Area for different roof types*
$c_r$ => *fraction of people in different shelter categories*
$\rho_{ij}$ => *Population Density*
$k =$ *debris group*

# Safety Metric Estimator

## .Sheltering Formulation

$$E_{1k}(\vec{A}_{C_k}, \vec{r}, \vec{v}, ae\vec{r}o) = \sum_{i=1}^{n}\sum_{j=1}^{m}(P_{k_{Iij}}[A_{C_{k_0}}\rho_{ij}\underline{c_0} + \sum_{r=1}^{\#roofs}(A_{C_{k_r}}\rho_{ij}\underline{c_r})])$$

$$\vec{c} = e_1e_2O\vec{o} + s_1s_2\vec{q} + (1 - e_1e_2 - s_1s_2)[(1 - d - v)H\vec{h} + (0\ \ 0 \ldots v\ \ d)^T]$$

| **Variable** | **Description** |
|---|---|
| $e_1$ | Fraction of people who are employed |
| $e_2$ | Fraction of those employed who are at work |
| **o** (vector) | Fraction of people who are at work in each occupation category |
| **O** (matrix) | Fraction of people in each sheltering class by occupation |
| | |
| $s_1$ | Fraction of people who are students |
| $s_2$ | Fraction of students who are at school |
| **q** (vector) | Fraction of people at school in each sheltering class |
| | |
| d | Fraction of people not at work or school who are outside |
| v | Fraction of people not at work or school who are in vehicles |
| **h** (vector) | Fraction of people in each housing type |
| **H** (matrix) | Fraction of people in each sheltering class by housing type |

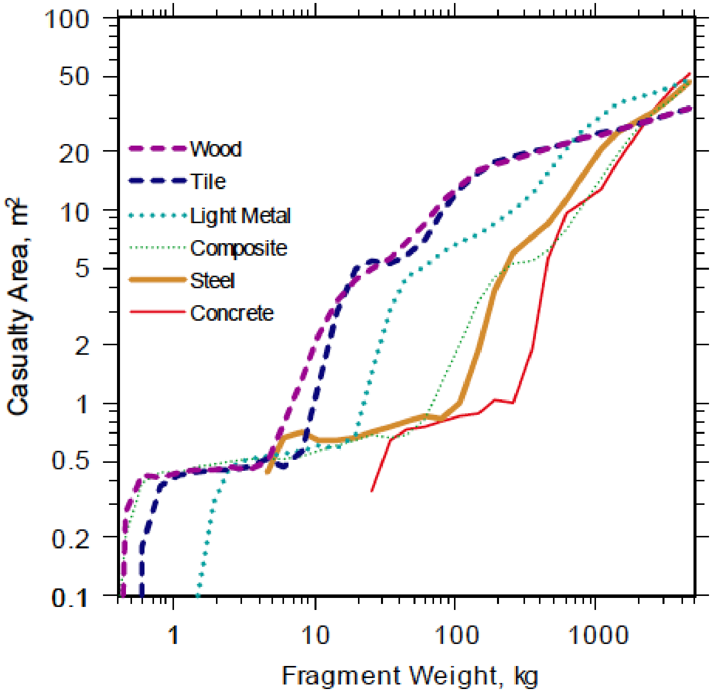
*Formulation from “Large Region Population Sheltering Models for Space Debris Risk Analysis. Eric W.F Larson”

# Safety Metric Estimator

## .Roof Models

- Casualty Area of Roof Penetration Models

$$E_{1k}(\vec{A_{C_k}}, \vec{r}, \vec{v}, ae\vec{r}o) = \sum_{i=1}^{n}\sum_{j=1}^{m}(P_{k_{Iij}}[A_{C_{k_0}}\rho_{ij}c_0 + \sum_{r=1}^{\#roofs}(A_{C_{k_r}}\rho_{ij}c_r)])$$



*from “Large Region Population Sheltering Models for Space Debris Risk Analysis. Eric W.F Larson”

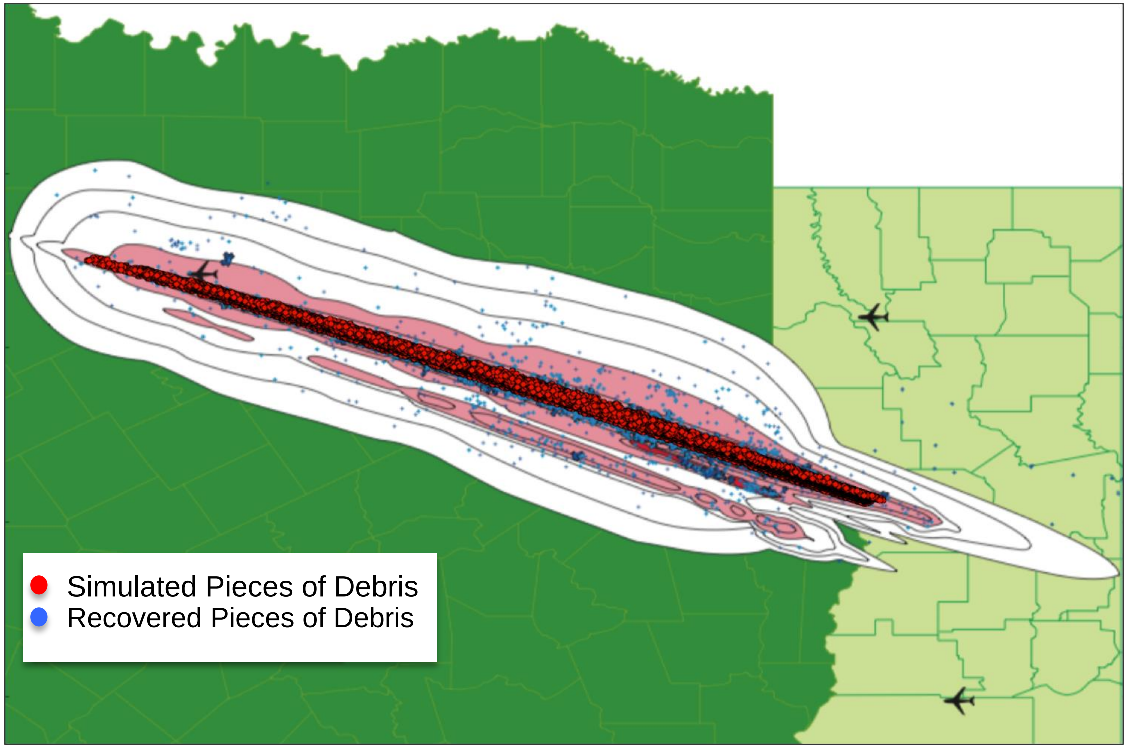
# Validation Test Cases

- Two test cases have been simulated:
  - STS-107 (Columbia) accident simulations
  - STS-111 over-flight of Eurasia simulations
- Experimental data available for STS-107
- Other computations available for STS-111
- Results of current framework compare favorably with existing data:
  - Debris impact locations
  - Expected casualty numbers
  - Sensitivities

# Validation Test Case

## STS-107 Columbia Accident

- Breakup during re-entry
- Debris catalog from Columbia Accident Investigation Board (CAIB) report.
- 11 debris groups considered (grouped by ballistic coefficient and projected area).
- More than 80,000 debris pieces recovered over more than 10 counties.

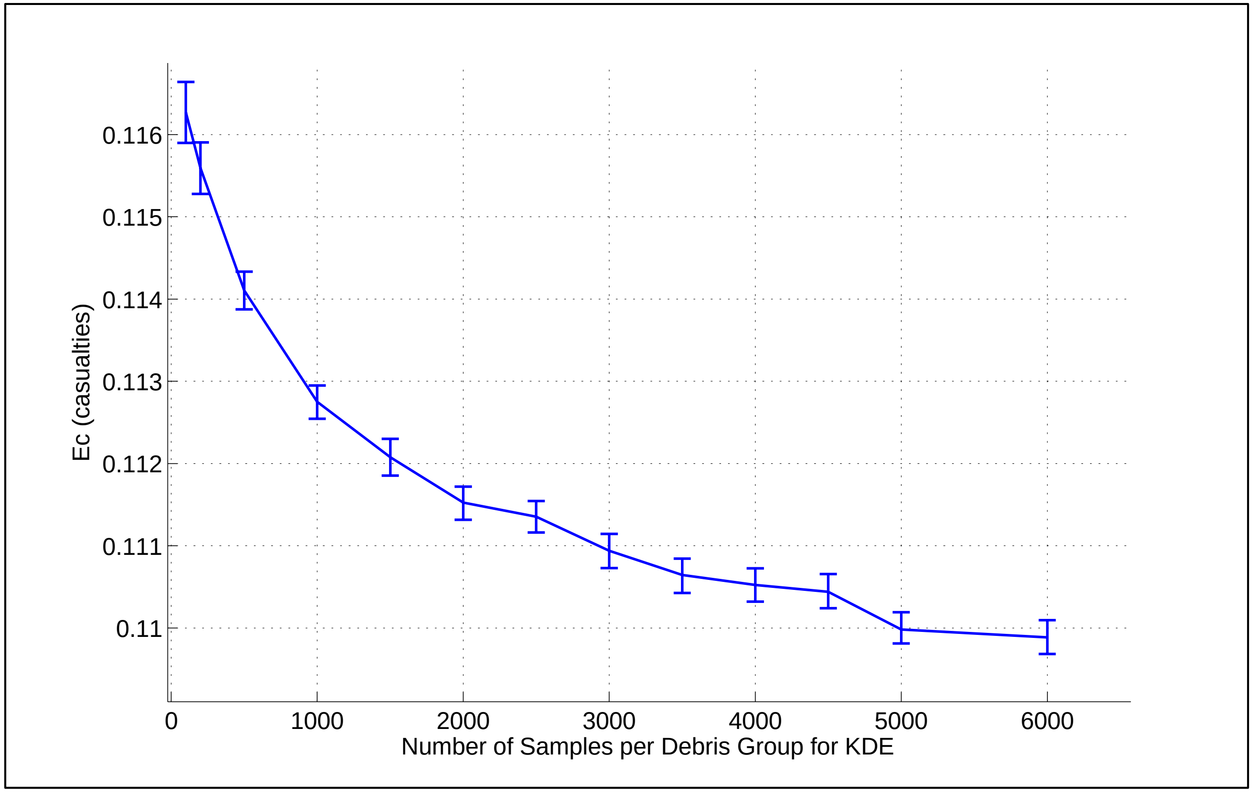


Columbia Accident Debris Locations Comparison (original figure from CAIB Report)

# Validation Test Case

## STS-107 Columbia Accident

- Expected casualties, $E_c$, convergence for kernel density estimation.
- Population density from Gridded Population of the World (GPW)



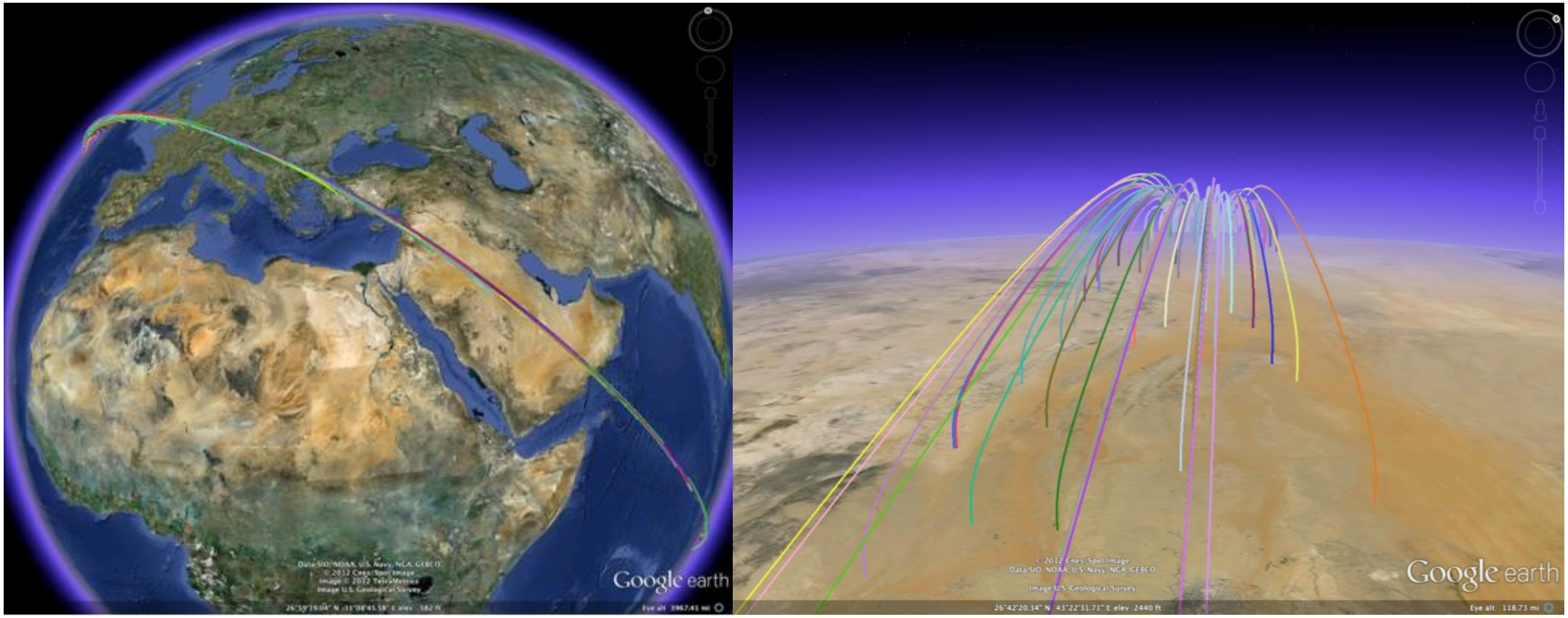
Casualty Expectation Convergence

| | % People in the open | $E_c$ |
|---|---|---|
| CAIB Report* | 18.7 | 0.14 |
| Simulation | 18.7 | 0.11 |

*Results from Columbia Accident Investigation Board

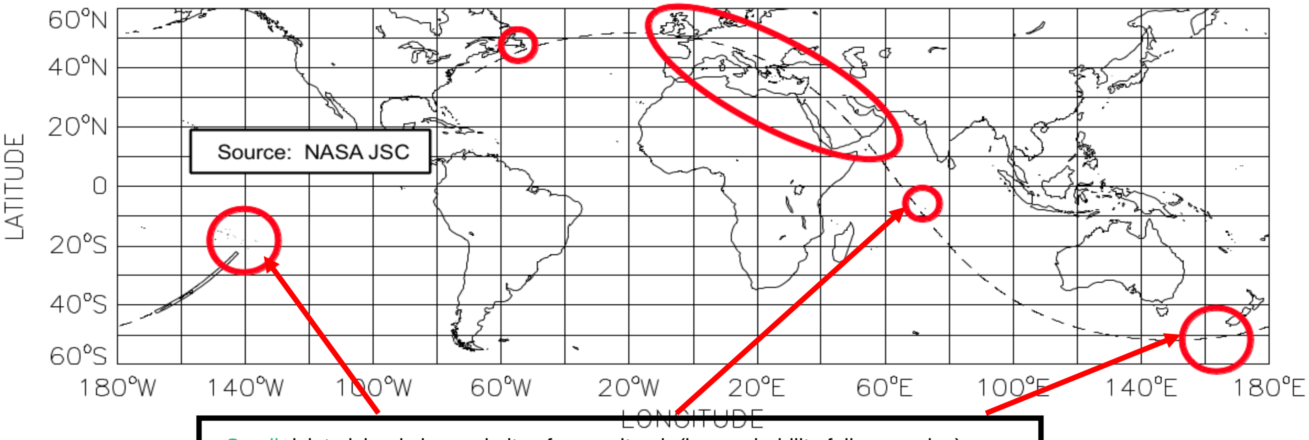
# STS-111Over-Flight of Eurasia Simulations

- Stage II, on trajectory, orbiter failures.
- Reentry breakup altitude ~ 250,000 ft.
- Failure times 490-500 seconds.
- Orbiter debris catalog from Columbia accident.
- 3-sigma trajectories provided by Paul Wilde.



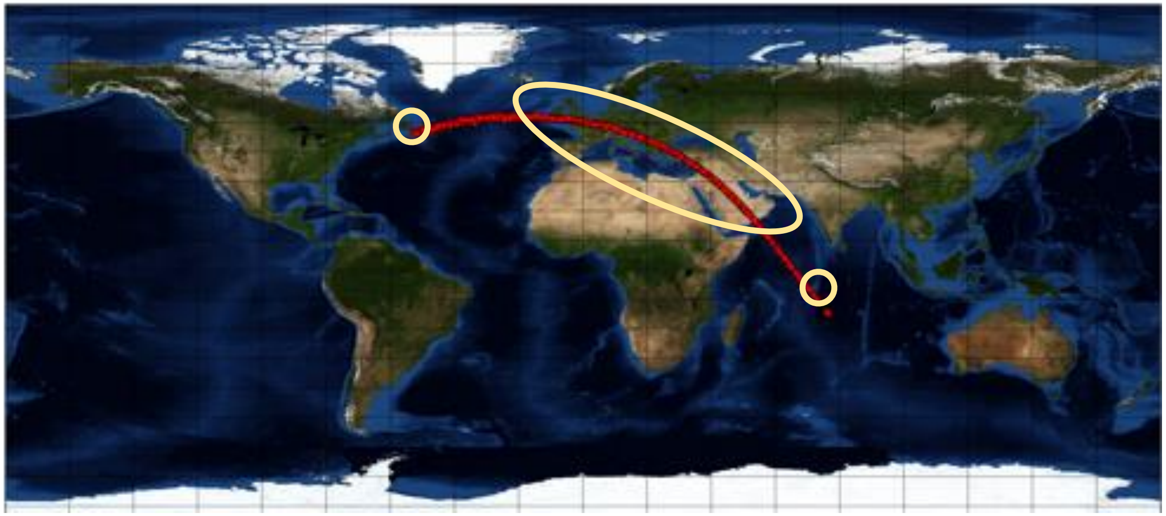
Simulated Debris Trajectories

# STS-111Over-Flight of Eurasia Simulations



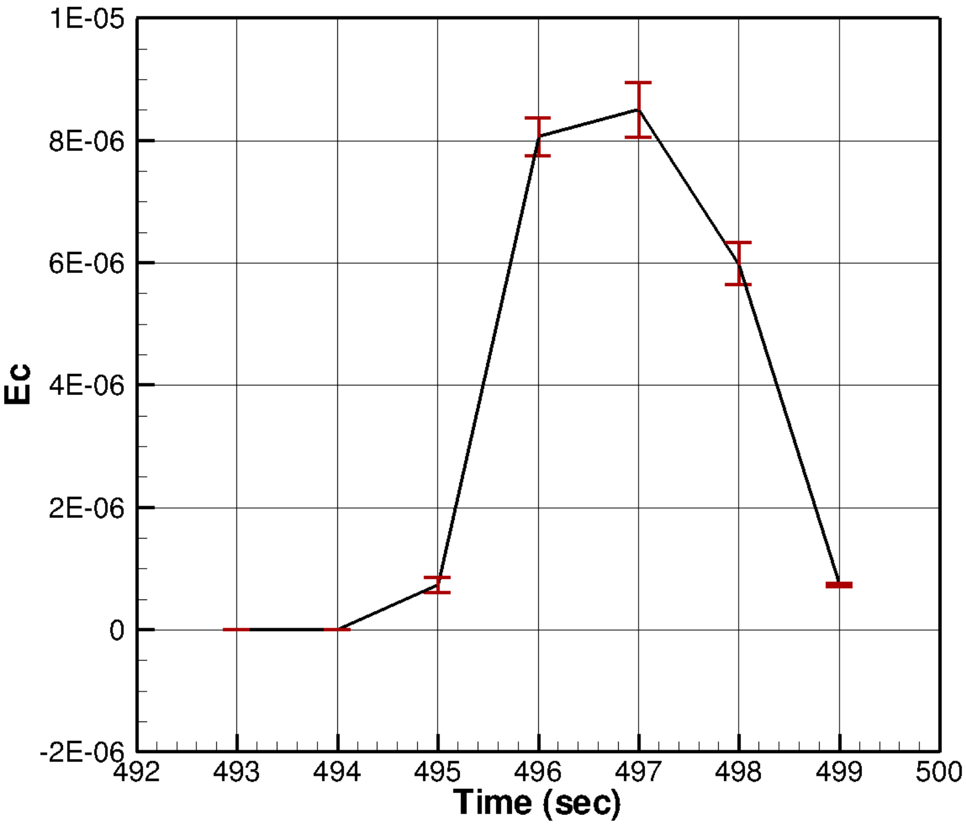
Source: NASA JSC

Small risk to islands in proximity of groundtrack (low probability failure modes)



Simulated Debris Impact Location

# STS-111 Over-Flight of Eurasia Simulations and UQ



Casualty Expectation vs. Flight Time with 99% Confidence Intervals

Ec values reported by ACTA range from 2.8e-6 to 4.6e-6.

- Differences in results probably due to sheltering, guidance and performance, and wind uncertainty.

# STS-111Over-Flight of Eurasia Simulations and UQ

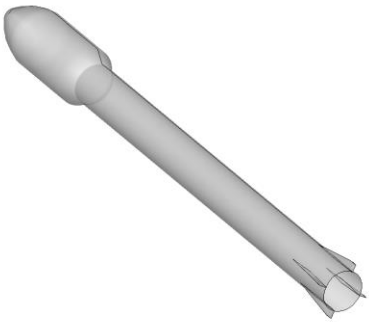
- Uncertainty effects on risk area determination:
  - On trajectory failure at t = 497 sec.
  - Ballistic coefficient = 100 lb/ft$^2$.

| | |
|---|---|
| Debris Location spread due to uncertainties in initial debris velocity |  |
| Debris location spread due to uncertainties in :<br>• Ballistic coefficient.<br>• L/D.<br>• Wind.<br>• Atmospheric density. |  |

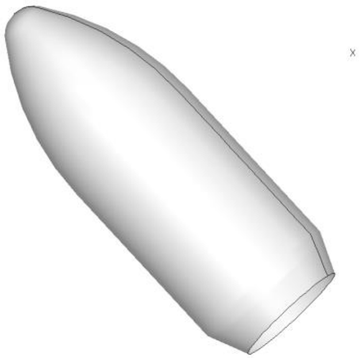
# Sample Test Case

## ELV to ISS orbit

- Generic ELV vehicle launching towards ISS orbit.
- Aerodynamic data obtained from Missile Datcom.
- SPOT was used to generate optimal trajectories.
- Wind variations obtained from Earth GRAM.
- Performed expected casualties calculation due to inert debris impacts, gas dispersion, and blast overpressure.



First Stage

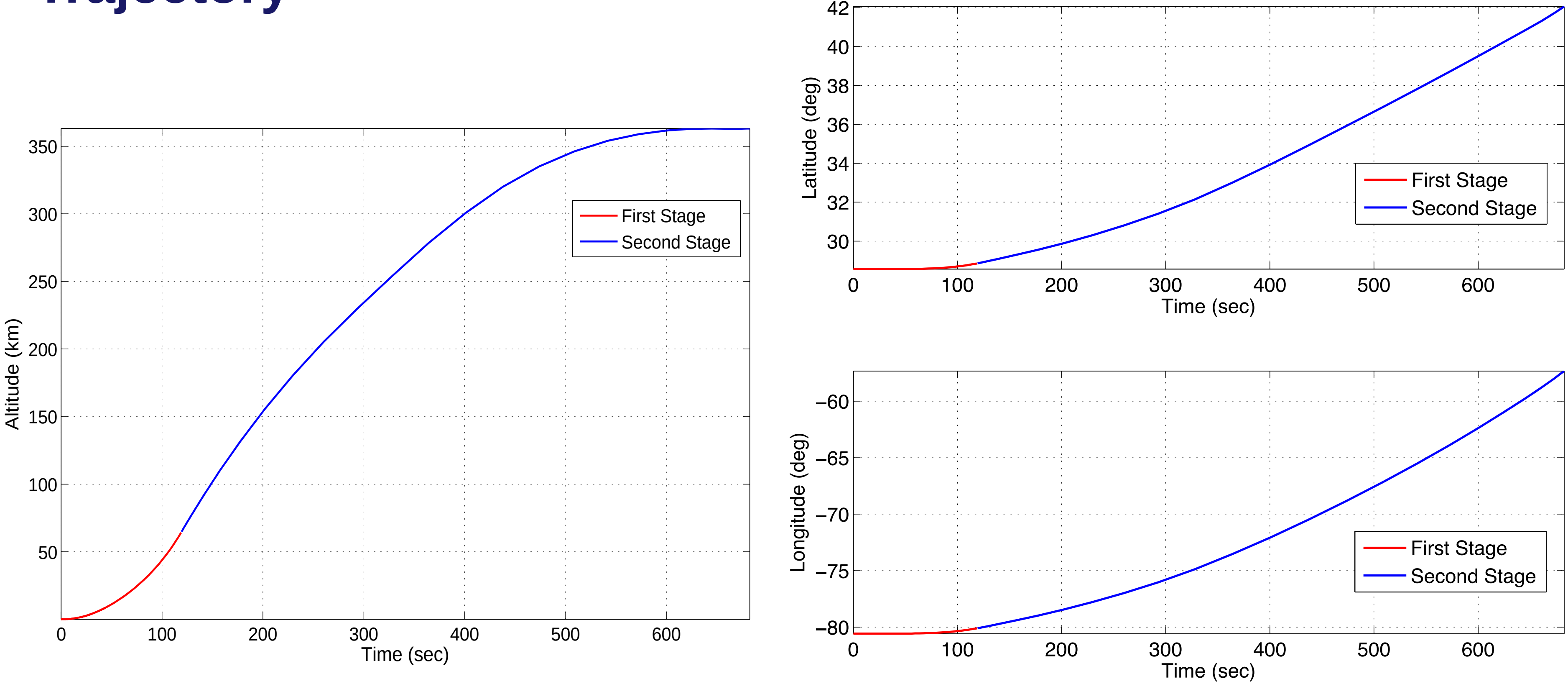


Second Stage

# Sample Test Case

## ELV to ISS orbit

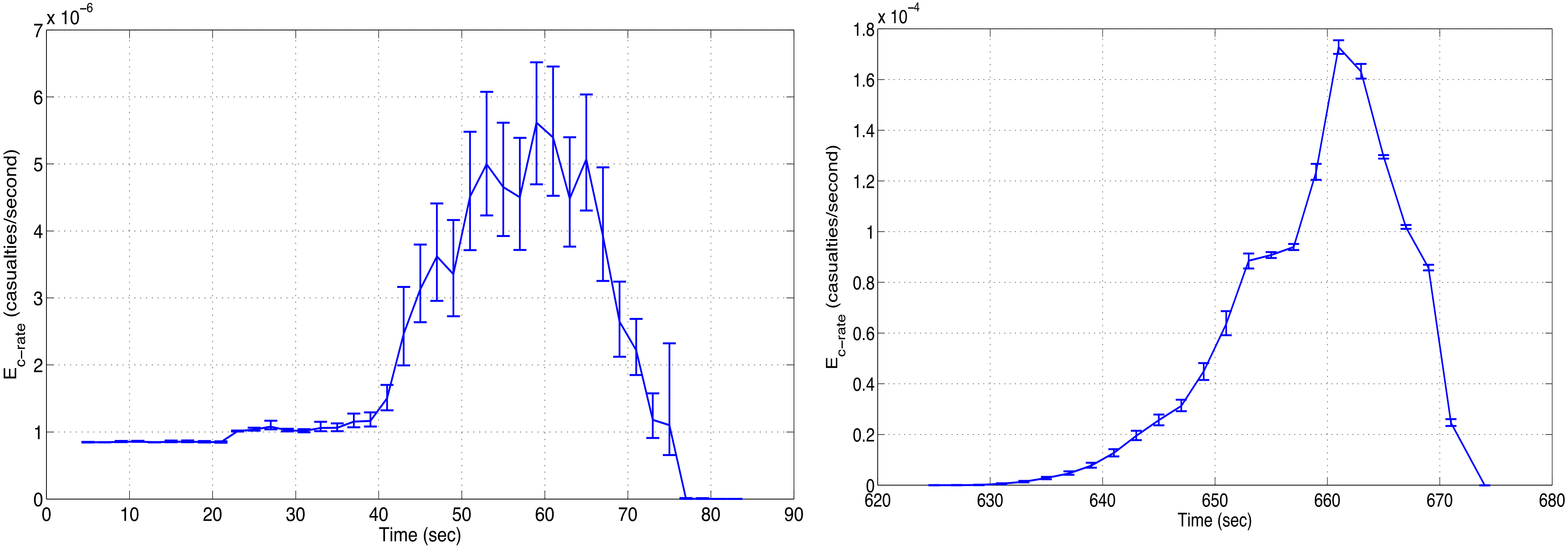
## Trajectory



Nominal Trajectory

# Sample Test Case

## ELV to ISS orbit
## Debris Propagation

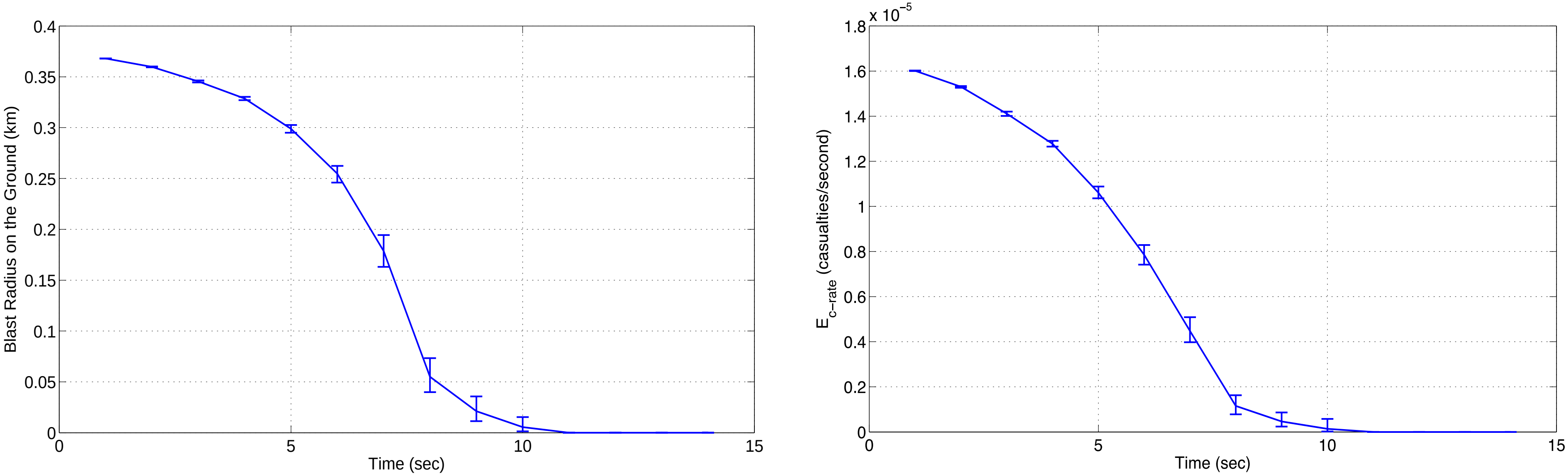


Expected Casualty Results

# Sample Test Case

## ELV to ISS orbit

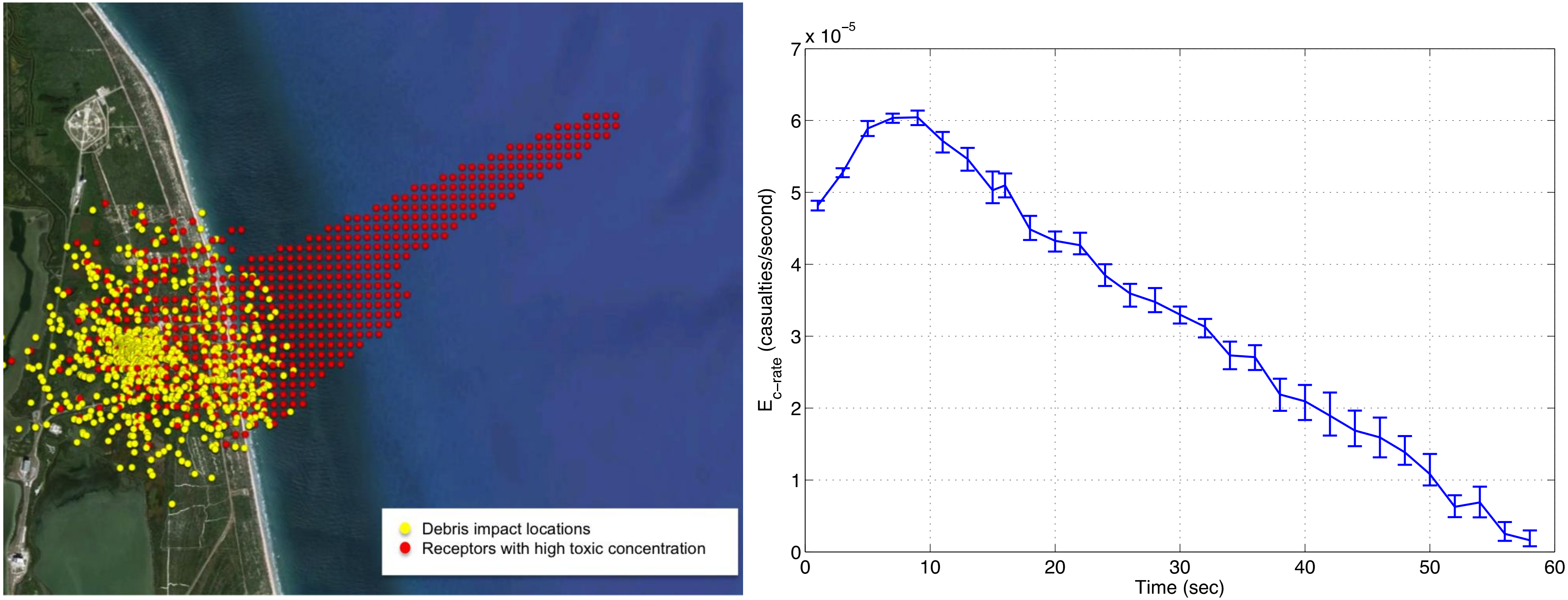
## Blast Overpressure



Blast Radius and Expected Casualty Results

# Sample Test Case

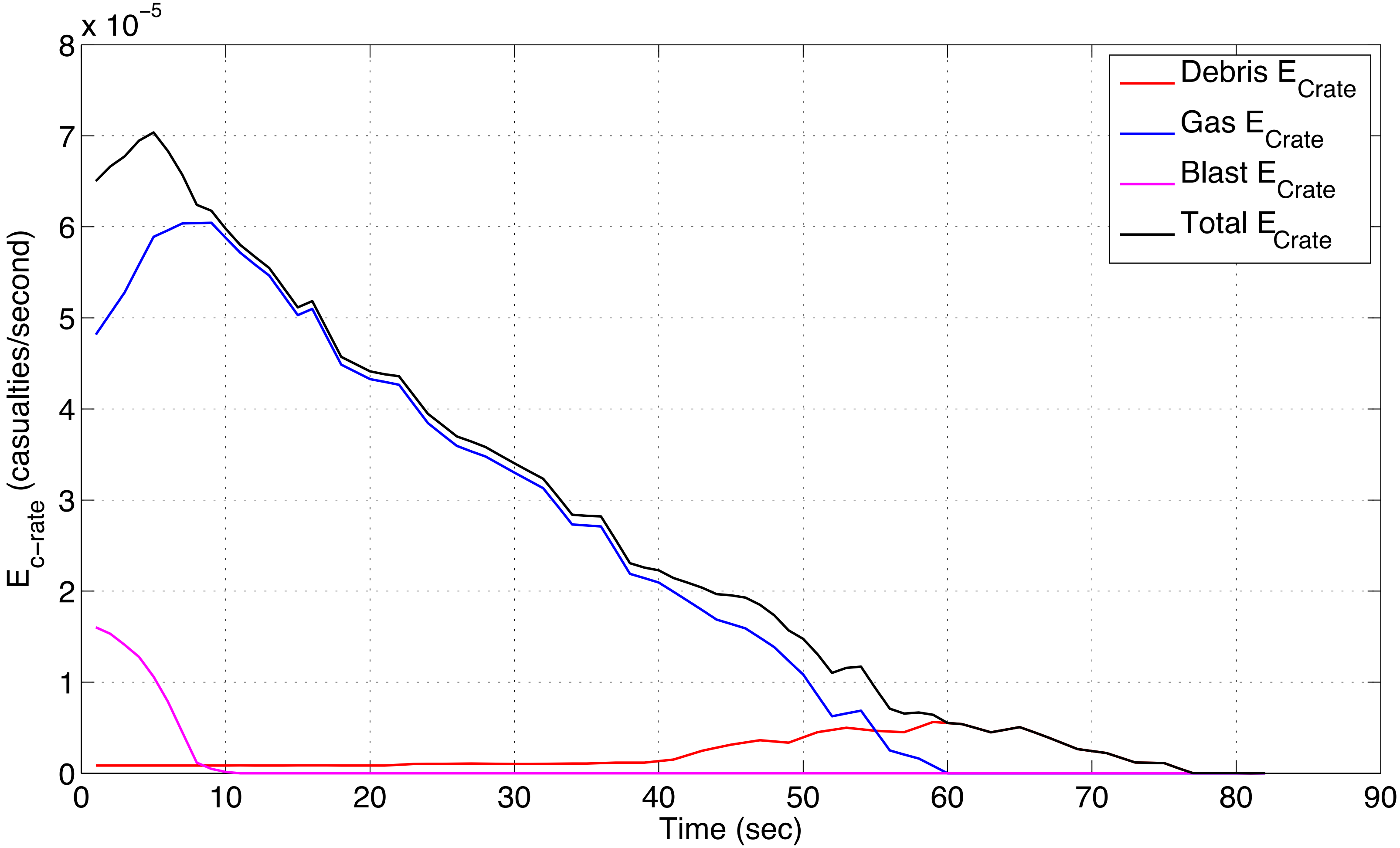
## ELV to ISS orbit
## Gas Dispersion



Receptor locations and expected casualties results

# Sample Test Case

## ELV to ISS orbit



$E_{crate}$ comparison for different hazards