Federal Aviation
Administration

Task 258: Analysis Environment for Safety of Launch and Re-Entry Vehicles

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Overview

- Team Members
- Purpose of Task
- Research Methodology
- 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

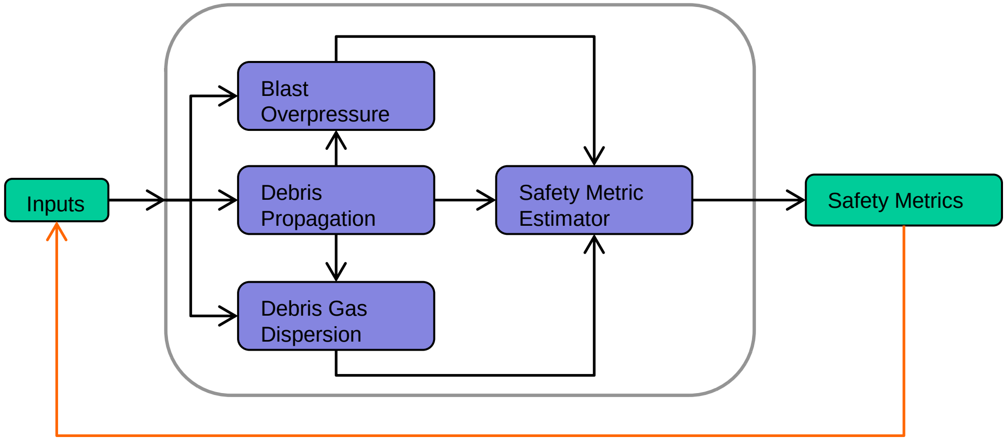
- To provide the FAA and the community with an independent safety analysis capability for launch and re-entry vehicles that is based on tools of the necessary fidelity.
- To develop and establish quantitative safety metrics appropriate for commercial space transportation.
- To validate the resulting 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.

Research Methodology

- Currently the FAA uses procedures and tools to assess the safety of future commercial launch and re-entry vehicles that are mostly based on ELV systems. There are concerns with potential diversity of future systems.
- Some uncertainty effects in safety assessment methodologies are not well understood. Thus, there might be important safety metric data currently being ignored.
- Safety considerations may include:
  - Human rating.
  - Acceptable probability of failure.
  - How to account for safety risks not associated with component, sub-system, and system failure (unknown unknowns).
  - Safety assessment modeling is nondeterministic.

Current Approach

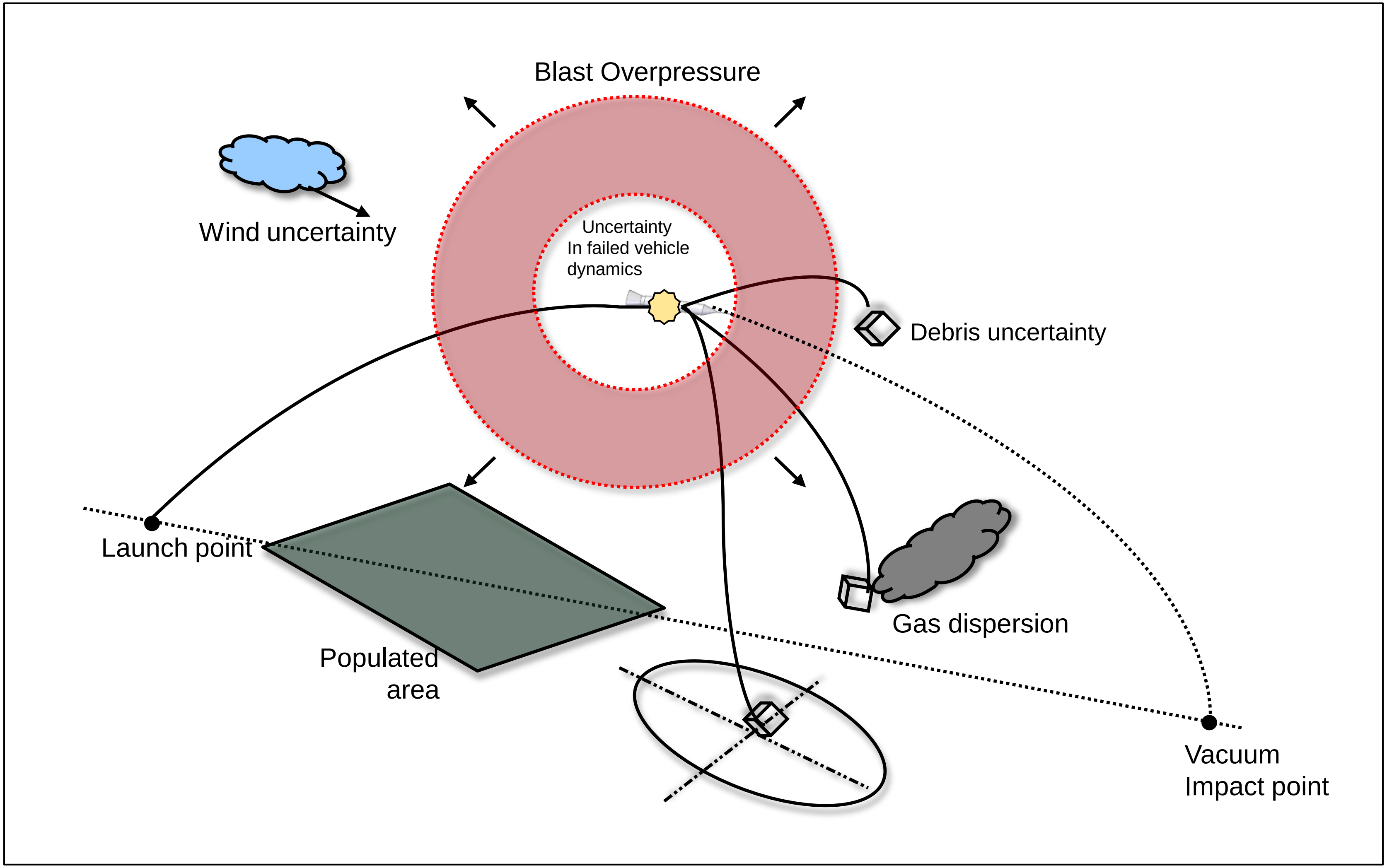
- Main focus is on safety on the ground (expected casualty measures).
- Long term goal is to look at the different licensed activities
  - ELV
  - Suborbital
  - RLV
- Develop safety metrics.



Inverse Problem

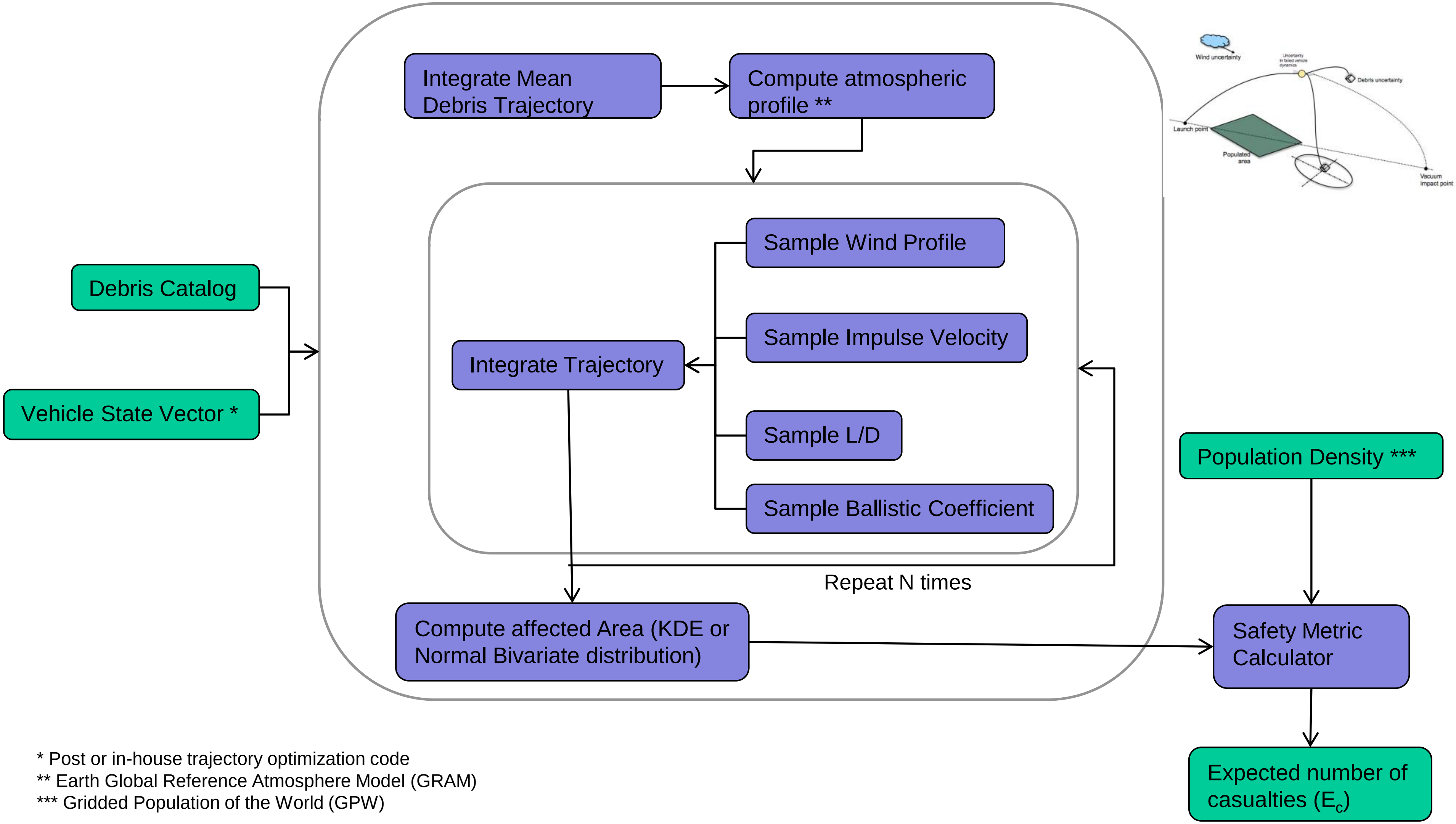
- We are in the process of understanding the input parameter combinations that lead to worst case scenarios (tails of distribution).
- Results obtained by solving the reverse problem could be used to inform licensing restrictions, or influence design

Current Approach



Safety Analysis Environment Schematic

Analysis Environment: Debris Propagation



Integrate Mean Debris Trajectory

Compute atmospheric profile **

Debris Catalog

Vehicle State Vector *

Sample Wind Profile

Sample Impulse Velocity

Integrate Trajectory

Sample L/D

Sample Ballistic Coefficient

Repeat N times

Compute affected Area (KDE or Normal Bivariate distribution)

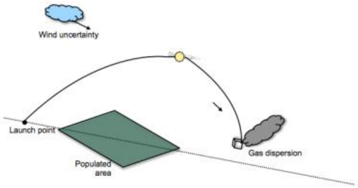
Population Density ***

Safety Metric Calculator

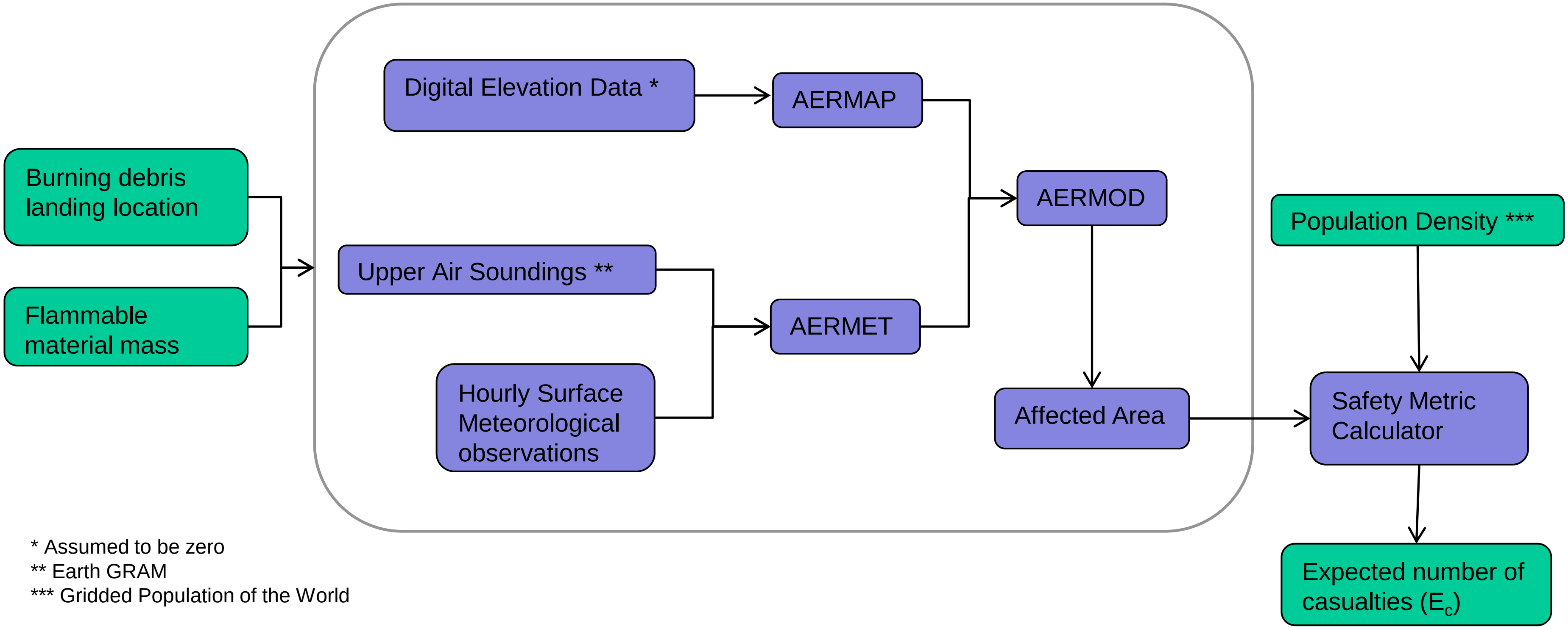
Expected number of casualties (E_c)

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

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 ***

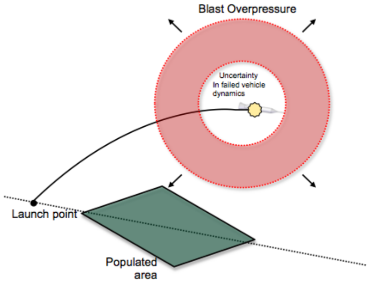
Safety Metric Calculator

Expected number of casualties (E_c)

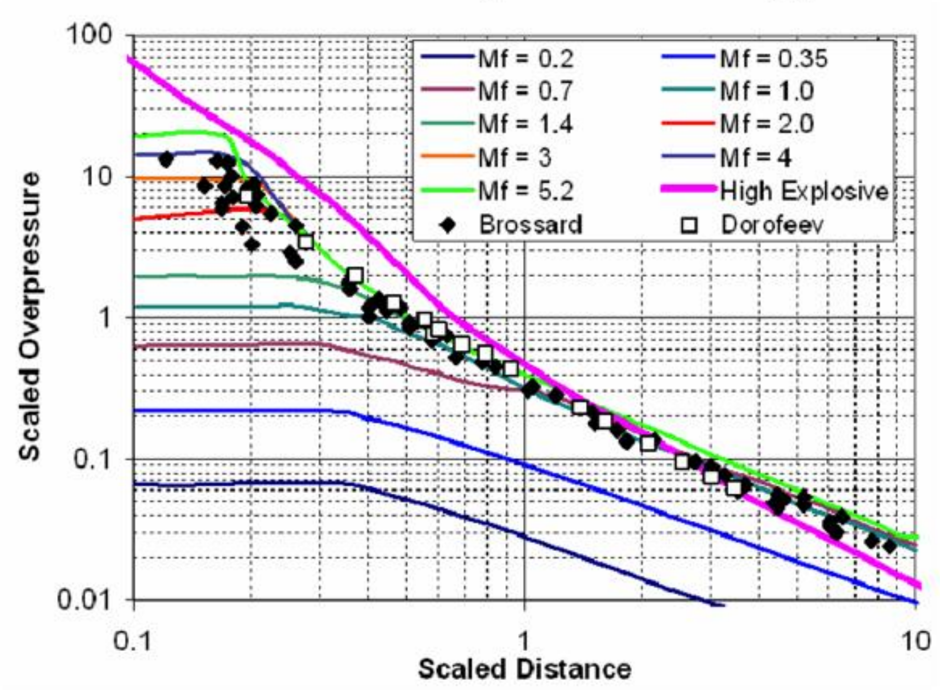
* Assumed to be zero
** Earth GRAM
*** Gridded Population of the World

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
η_p	yield factor
m_p	propellant mass

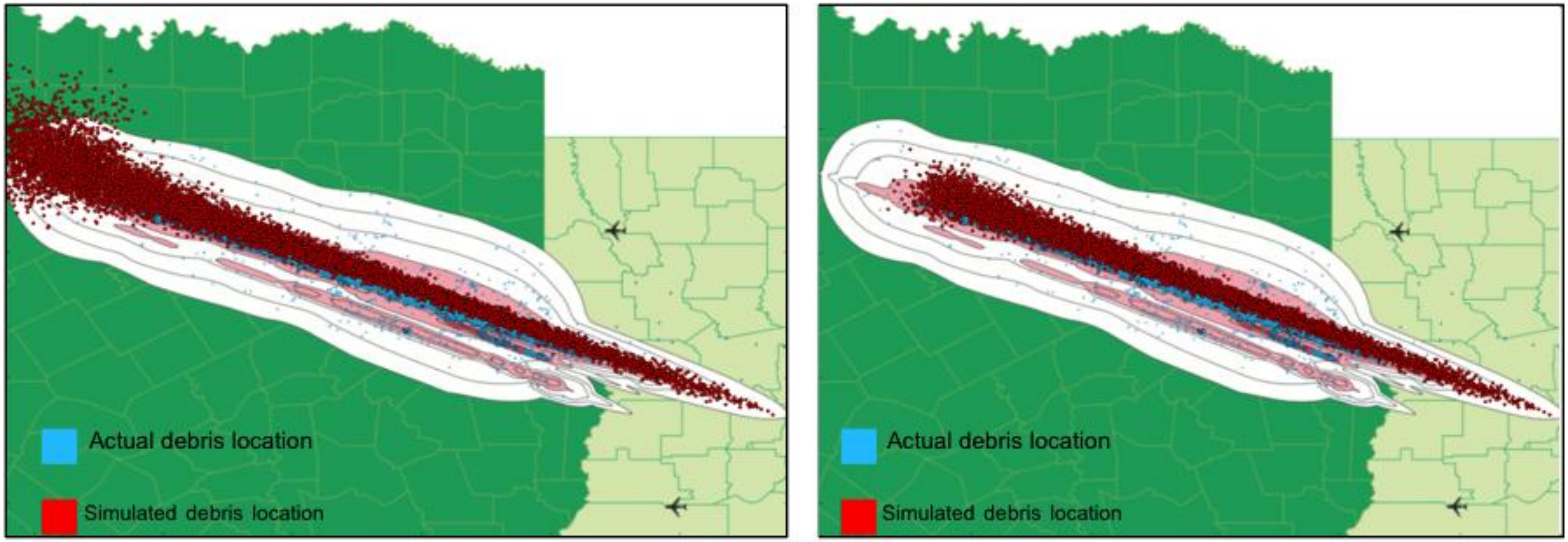
Blast Overpressure Modeling Enhancements for Application to Risk Informed Design of Human Space Flight Launch Abort Systems. Scott Lawrence, and Donovan Mathias

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

Columbia Accident Simulations

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



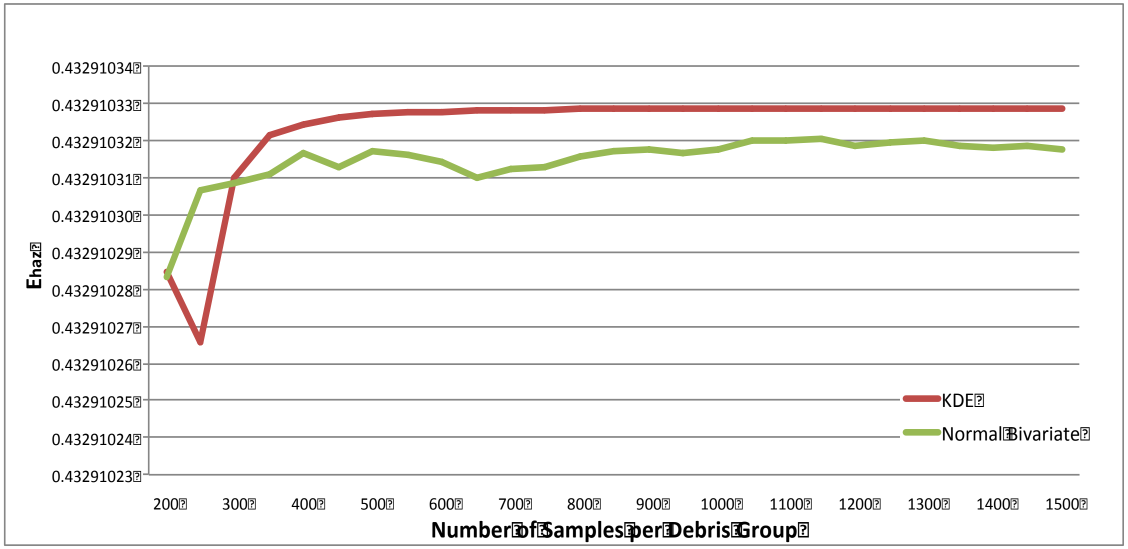
All simulated pieces

Lethal simulated debris pieces

Debris Location. From CAIB report Volume II Appendix D.16

Columbia Accident Simulations

- E_{haz} covers cases of impacts without injury, non-fatal injury, and fatal injury.
- Atmospheric profile from Earth GRAM (NASA Global Reference Atmospheric Model).
- No sheltering.



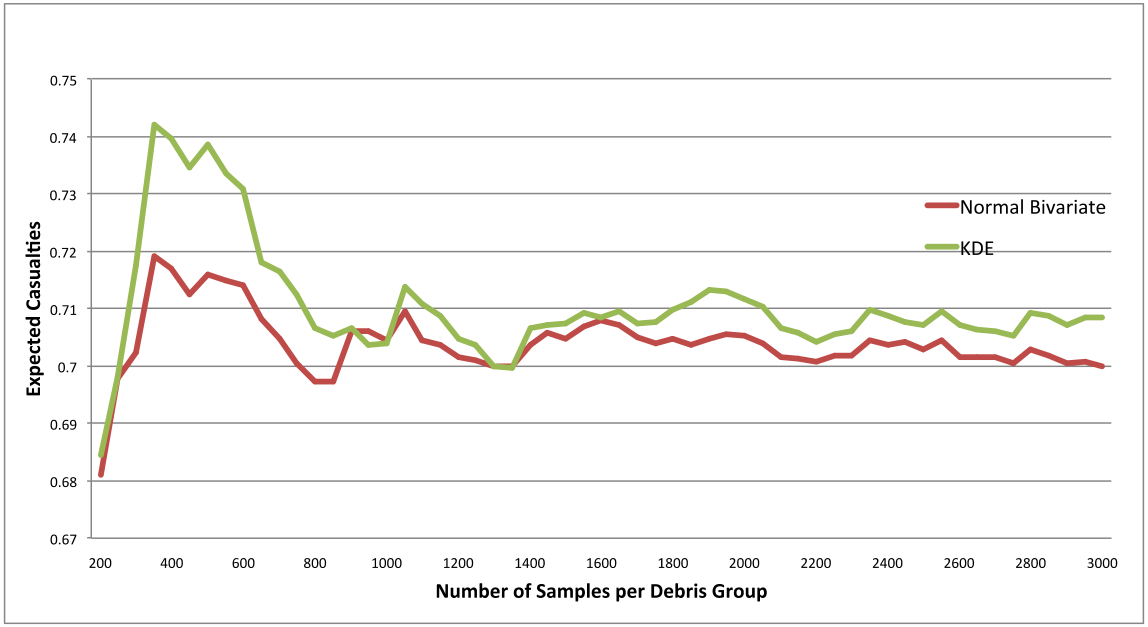
E_{haz} convergence for a constant population of 85 people/nm^2

	Percentage of Total Orbiter and Payload Weight survived	E_{haz}
CAIB Report*	38%	.41
Simulation	38%	.43

*Results from Columbia Accident Investigation Board. Ground wind 10 ft/s and a population density of 85 people/per square nautical mile

Columbia Accident Simulations

- Expected casualties convergence for normal bivariate, and kernel density estimation.
- Population density from Gridded Population of the World (GPW)



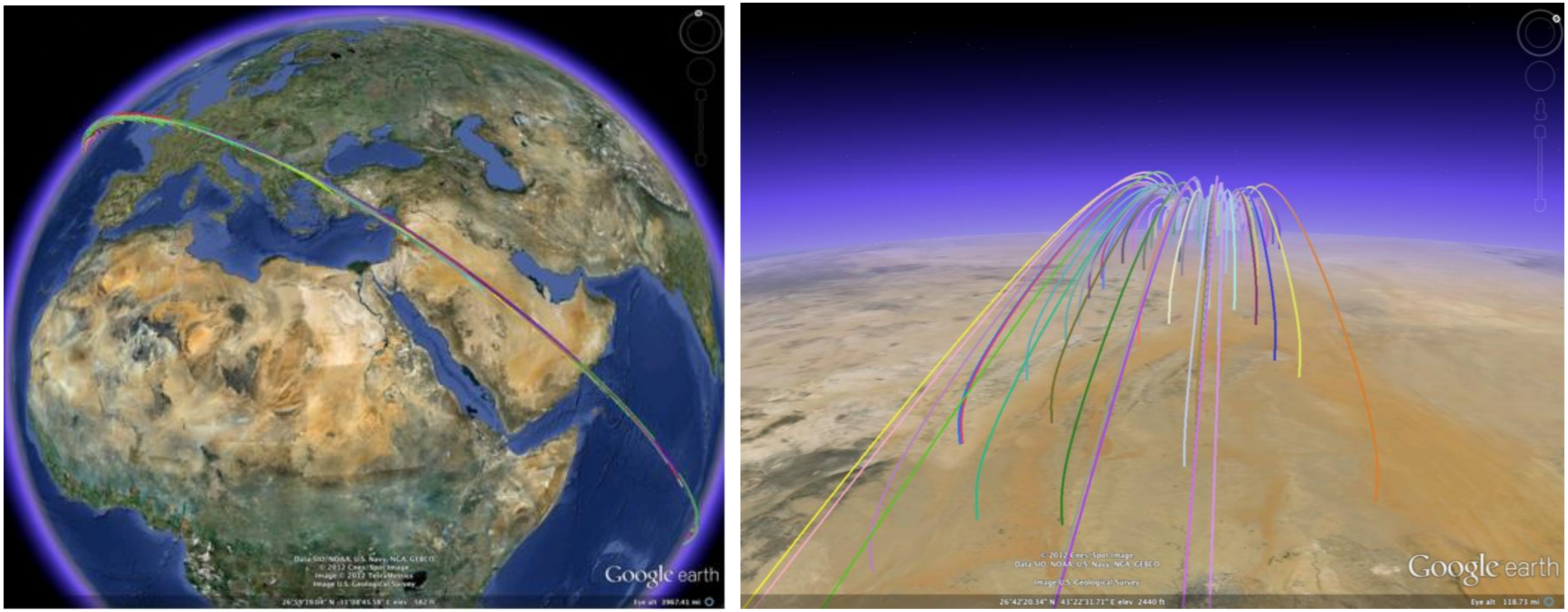
Casualty Expectation Convergence

	% People in the open	E_c
CAIB Report*	30	0.21
Simulation	100	0.71

*Results from Columbia Accident Investigation Board

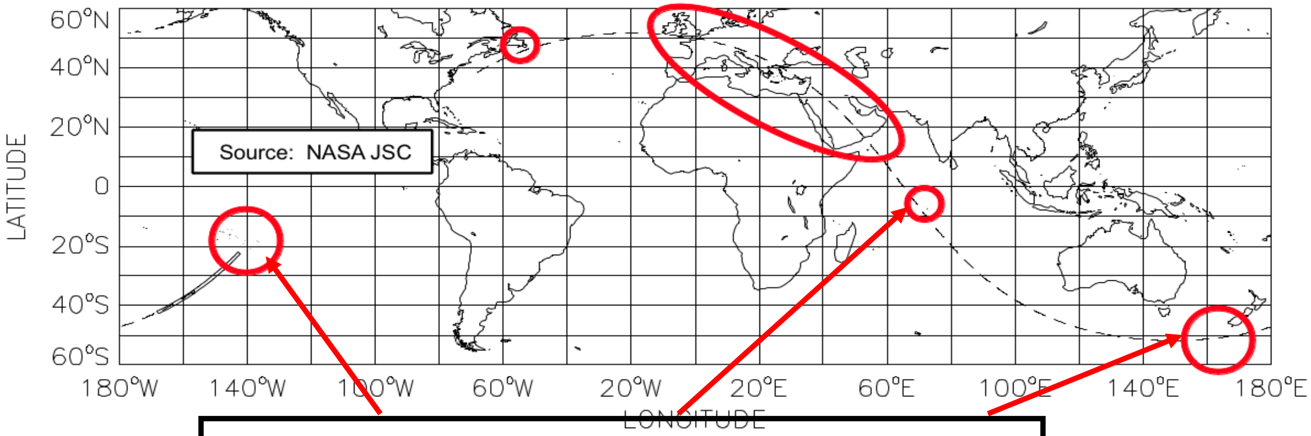
STS-111Over-Flight of Eurasia Simulations

- 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.



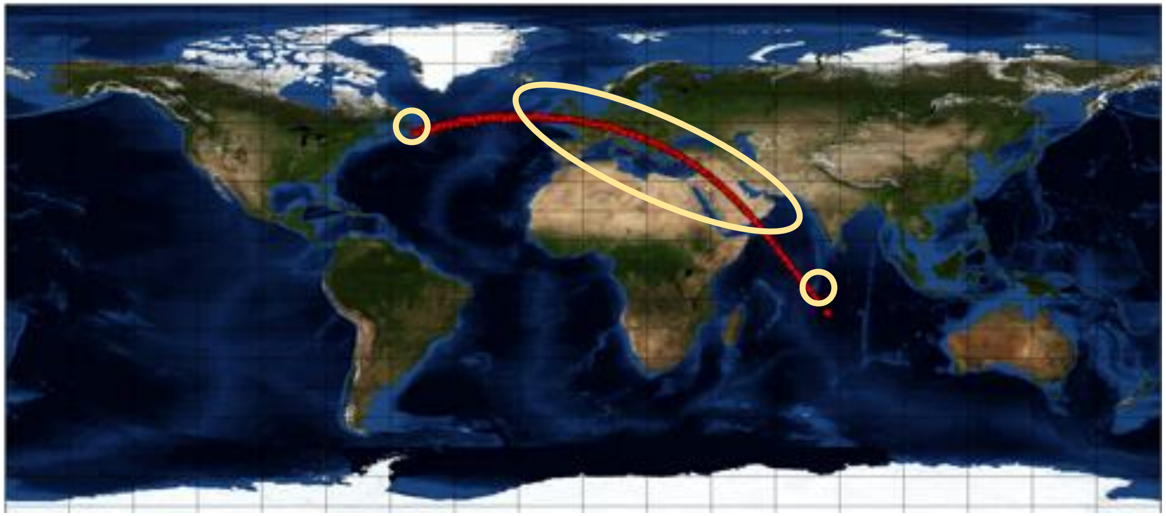
Simulated Debris Trajectories

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-111Over-Flight of Eurasia Simulations

- 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 :

- Ballistic coefficient.
- L/D.
- Wind.
- Atmospheric density.

STS-111Over-Flight of Eurasia Simulations

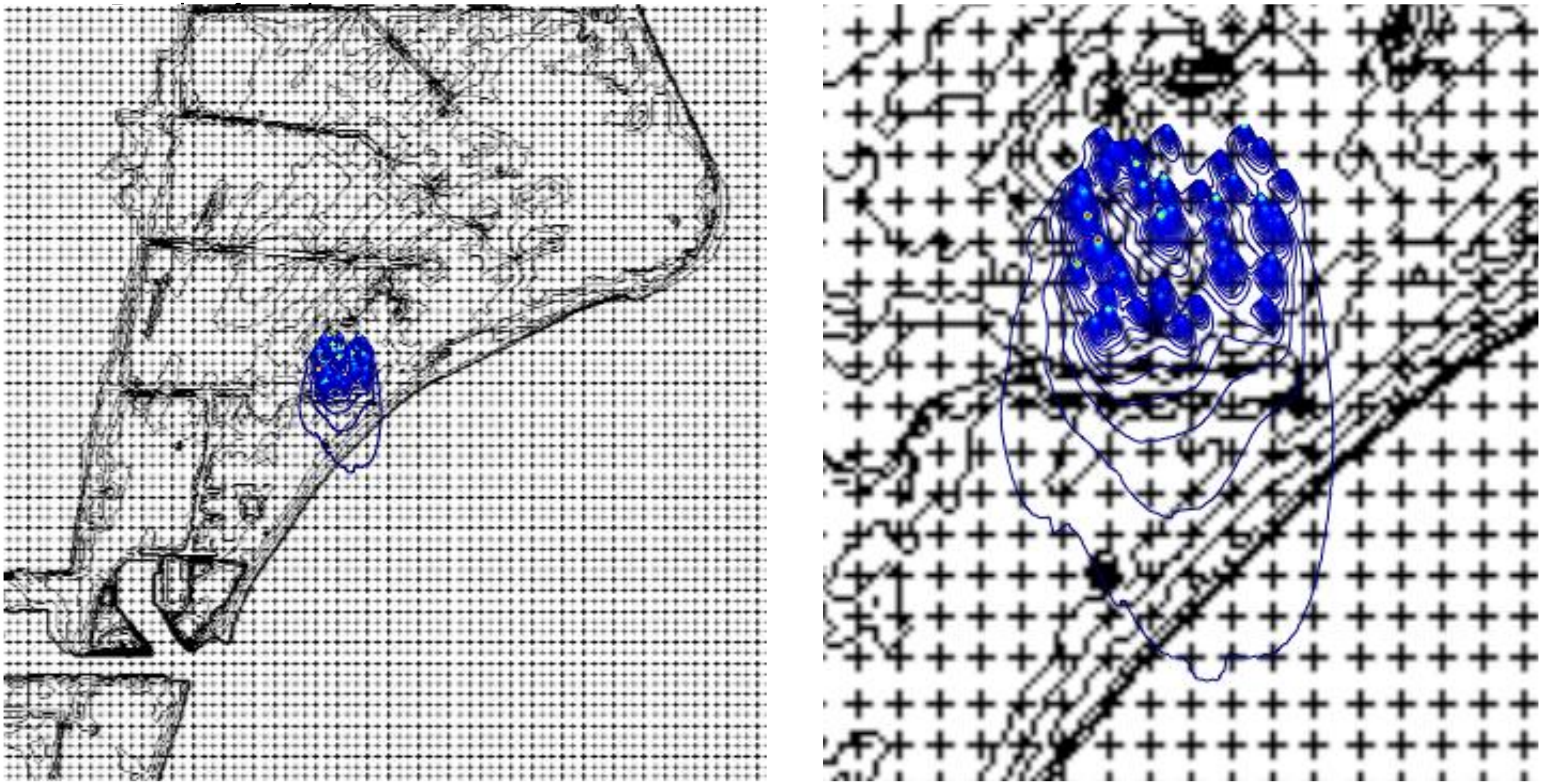
Time (sec)	Ec Mean	Lower Bound (99% confidence)	Upper Bound (99% confidence)
493	8.7826e-13	2.3759e-13	1.9933e-12
494	3.7907e-9	3.0509e-9	4.6156e-9
495	7.3525e-7	6.1156e-7	8.6083e-7
496	8.0740e-6	7.7570e-6	8.3725e-6
497	8.5043e-6	8.0616e-6	8.9514e-6
498	5.9722e-6	5.6483e-6	6.3338e-6
499	7.3254e-7	7.0098e-7	7.6073e-7

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.

Gas Dispersion Simulation

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



Trajectory Optimization

- 3 DOF trajectory optimization tool based on pseudospectral collocation methods (SU STOP)
- Initial development done in MATLAB, but currently transitioning to PYTHON + FORTRAN

Falcon 9 type launch vehicle trajectory to ISS orbit

Conclusions and Future Work

Conclusions

- A debris propagation tool has been implemented, and successfully automated to generate thousands of Monte Carlo evaluations.
- Kernel density estimation successfully implemented for calculating non-parametric probability density functions.
- Debris propagation tool is capable of using different debris catalog depending on time and/or distance travelled.
- Safety metric estimator coupled with debris propagation tool.
- Gas dispersion and blast overpressure model have been included.
- In-house trajectory optimization code (STOP) can provide initial trajectories for safety assessment.

Future work

- Add malfunction turns to the simulation.
- Add sheltering models to the Ec calculation.
- Further investigate how input uncertainties affect Ec calculations.
- Further validate the modeling tools.
- Fully integrate all the pieces for the analysis environment.
- Identify parameters of interest to solve the inverse problem.

Contact Information

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TASK 258. Analysis Environment for Safety of Launch and Re-Entry Vehicles

MAJOR MILESTONES – PAST

- Development of basic analysis framework including debris propagation, blast overpressure, and gas dispersion
- Validation of analysis environment with STS-107 (Columbia re-entry) and STS-111
- Kernel density estimation approaches for expected casualty measurements

MAJOR MILESTONES - FUTURE

- Addition of malfunction turns and sheltering models to simulation environment
- Investigate sources of uncertainty and variance in Ec calculations (principally debris catalogs)
- Assessing the impact of safety metric choice on licensing requirements
- Establish and maintain an open environment for safety analysis

SCHEDULE

- Basic environment development – Jun 2012
- Basic environment validation – Dec 2012
- Complete environment development – Jun 2013
- Complete environment validation – Dec 2013
- Development of probabilistic debris catalogs for commercial space – Jun 2014
- Safety metric identification, inverse licensing problem – Dec 2014
- Full environment demonstration, Jun 2015
- Seeking partnerships with prospective users as we speak

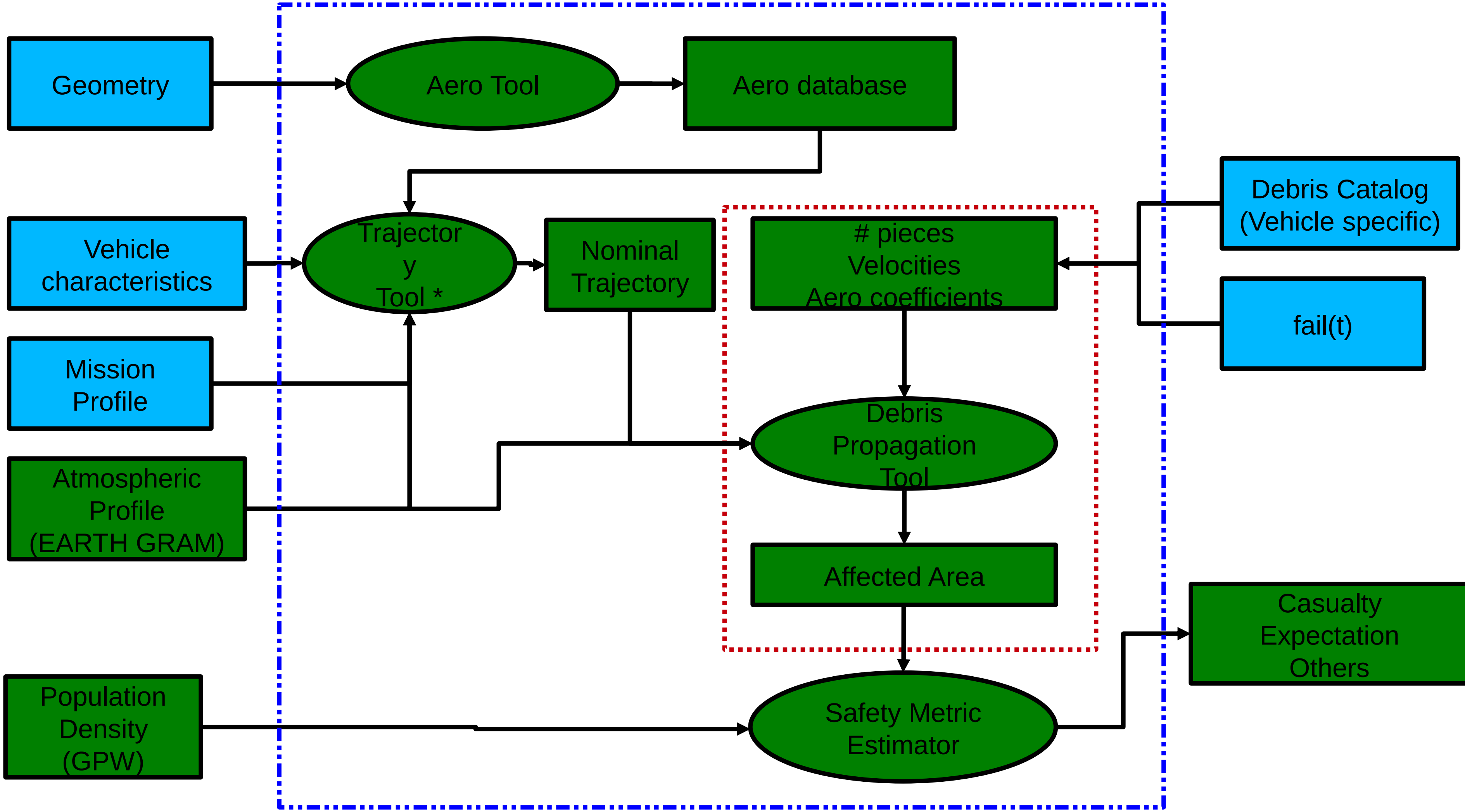
BUDGET

FY13	FY14	FY15	FY16	FY17
$80K	$80K	$80K	$0	$0K

- Total amounts shown. 50/50 cost share included

Backup Slides

Debris Modeling



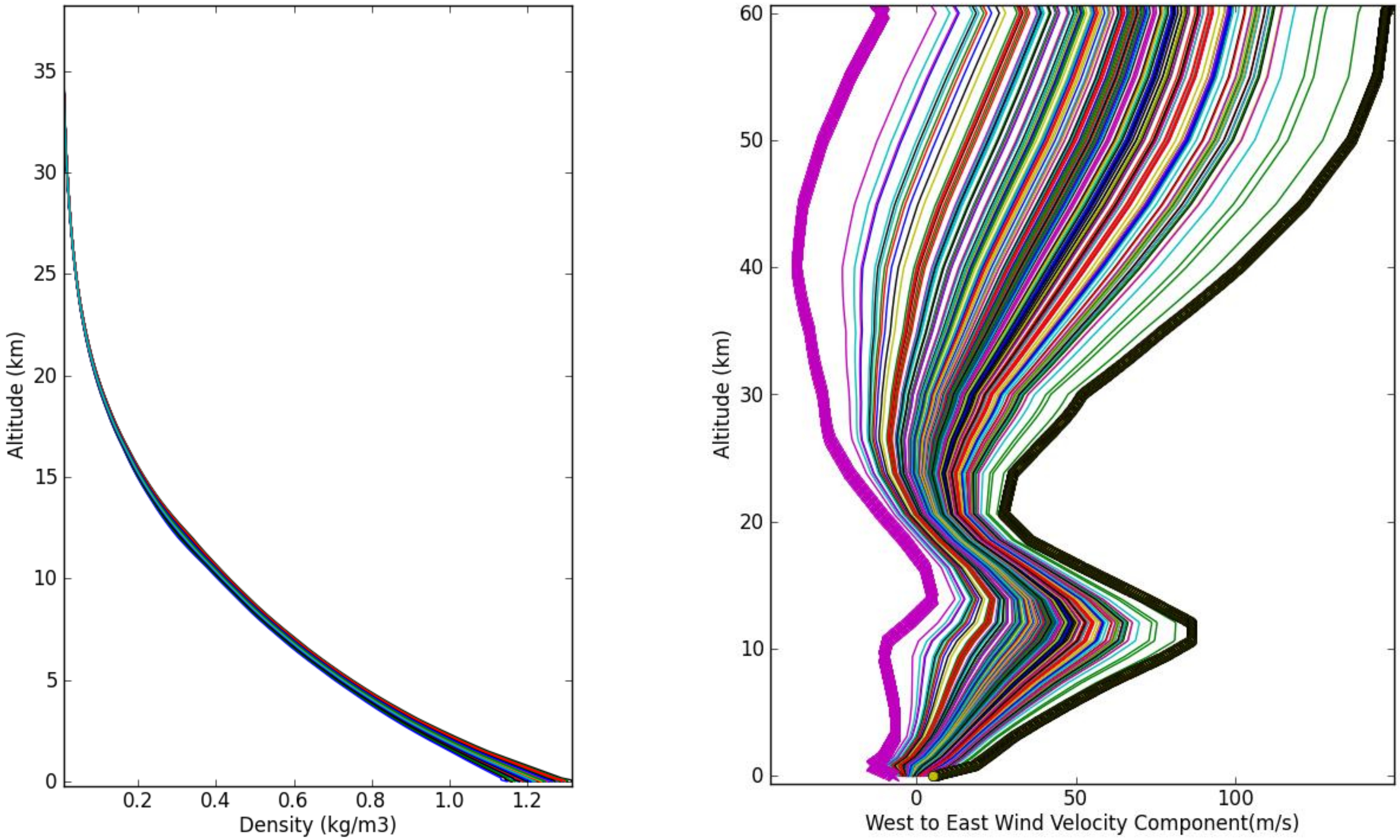
* Access to POST or Stanford Trajectory Optimization Program (STOP)

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.
    - Malfunction turns not implemented.
    - Affected ground area obtained by using Kernel Density Estimation or assuming a Normal Bivariate distribution

Debris Propagation

Uncertainty in atmospheric parameters



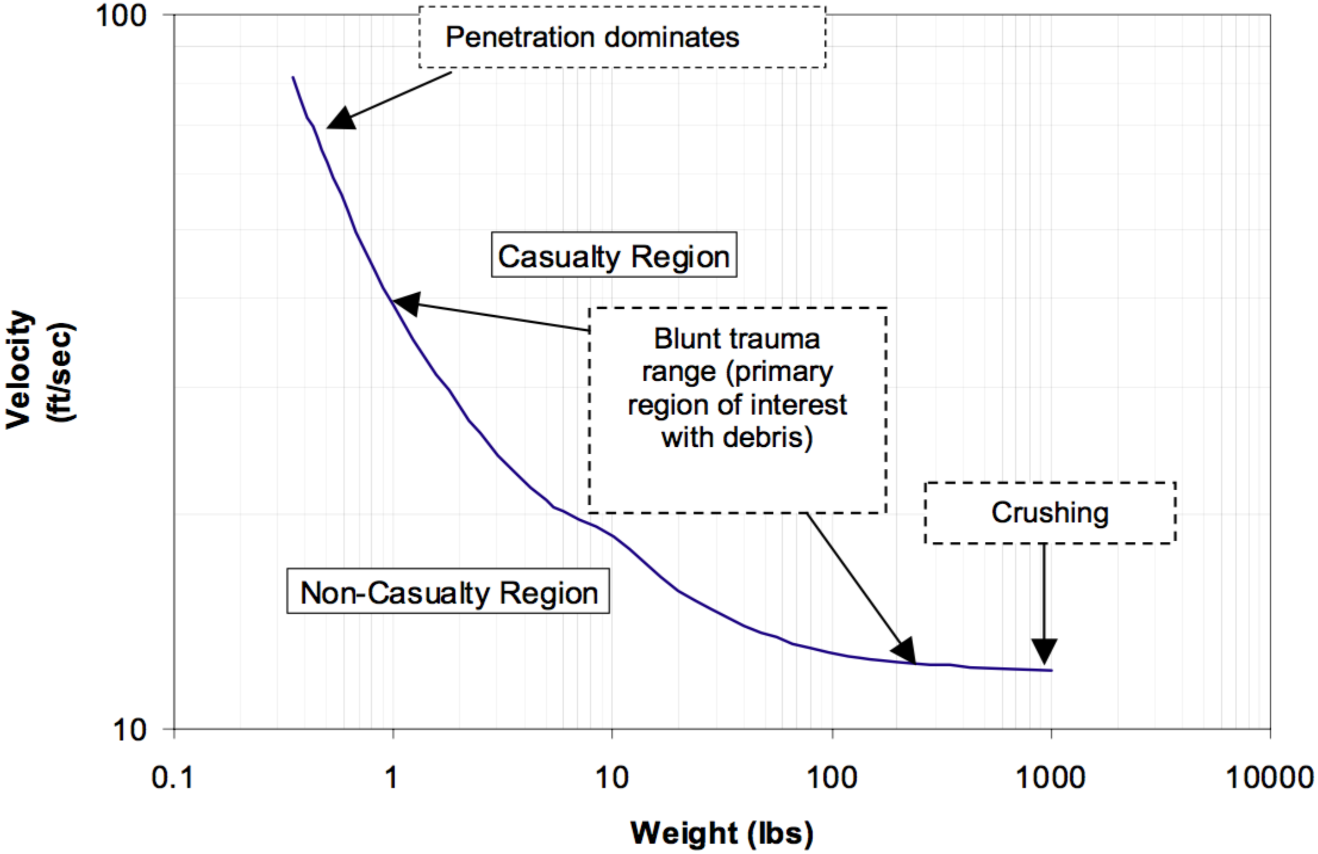
Ec Calculation

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

  - No sheltering.
  - 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

Technical Approach

Risk area debris formulation

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

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

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

Expected Casualty Calculation

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

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

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.