Probabilistic and Deterministic Re-entry Risk Mitigation Using ASTOS

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Weikert, S., Cremaschi, F., Ortega, G.

Contact: sven.weikert@astos.de

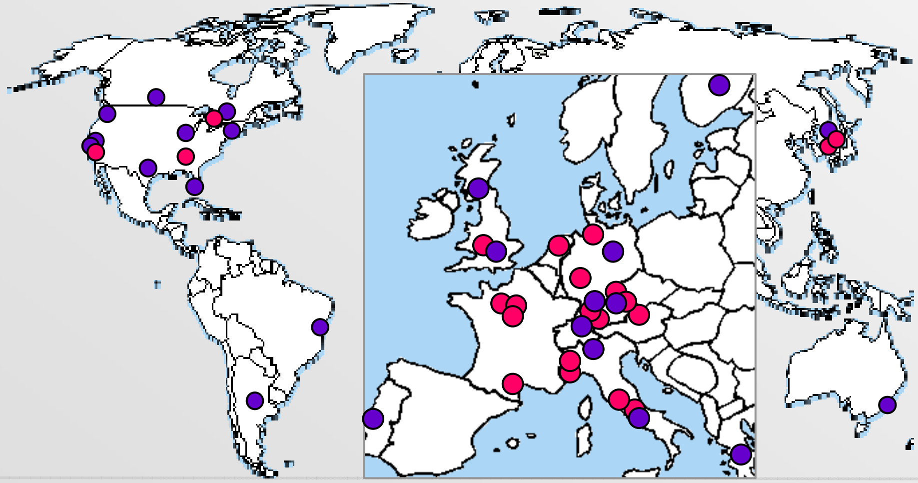
Outline

- Introduction to ASTOS
- Applications in the past
- ASTOS impact analyses
- Risk assessment
- Current development
- Conclusion

ASTOS, a Multi-purpose Analysis and Optimization Tool

ASTOS ↔ **A**ero**s**pace **T**rajectory **O**ptimization **S**oftware

- Simulation and optimization tool for aerospace applications
- Co-funded by ESA/ESTEC
- Nearly 20 years of continuous development
- Used by universities, industry and agencies all around the world



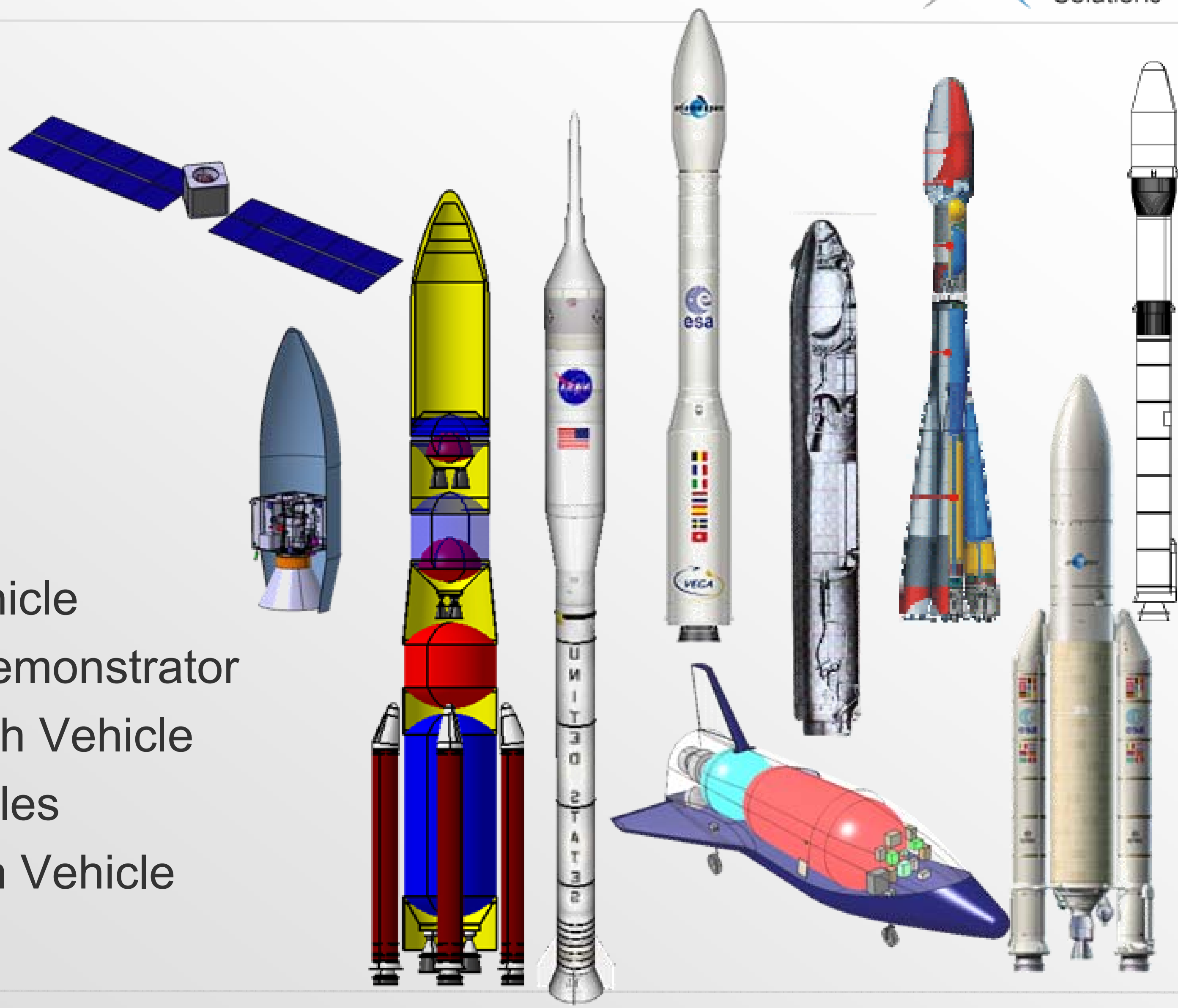
ASTOS Applications

- Phase 0/A studies
- Reference Trajectories for Controller Design
- Concept Validation
- Mission Analysis
- Operational Support
- Safety/Risk Analysis

- Performance evaluations of specific launch (ELV & RLV) and re-entry vehicles
- Trajectory and vehicle design w.r.t. mission constraints
  - Engine & stage design
- Mission design and analysis (e.g. scientific mission design)
- Orbit transfer missions
- Mission support in ground segment

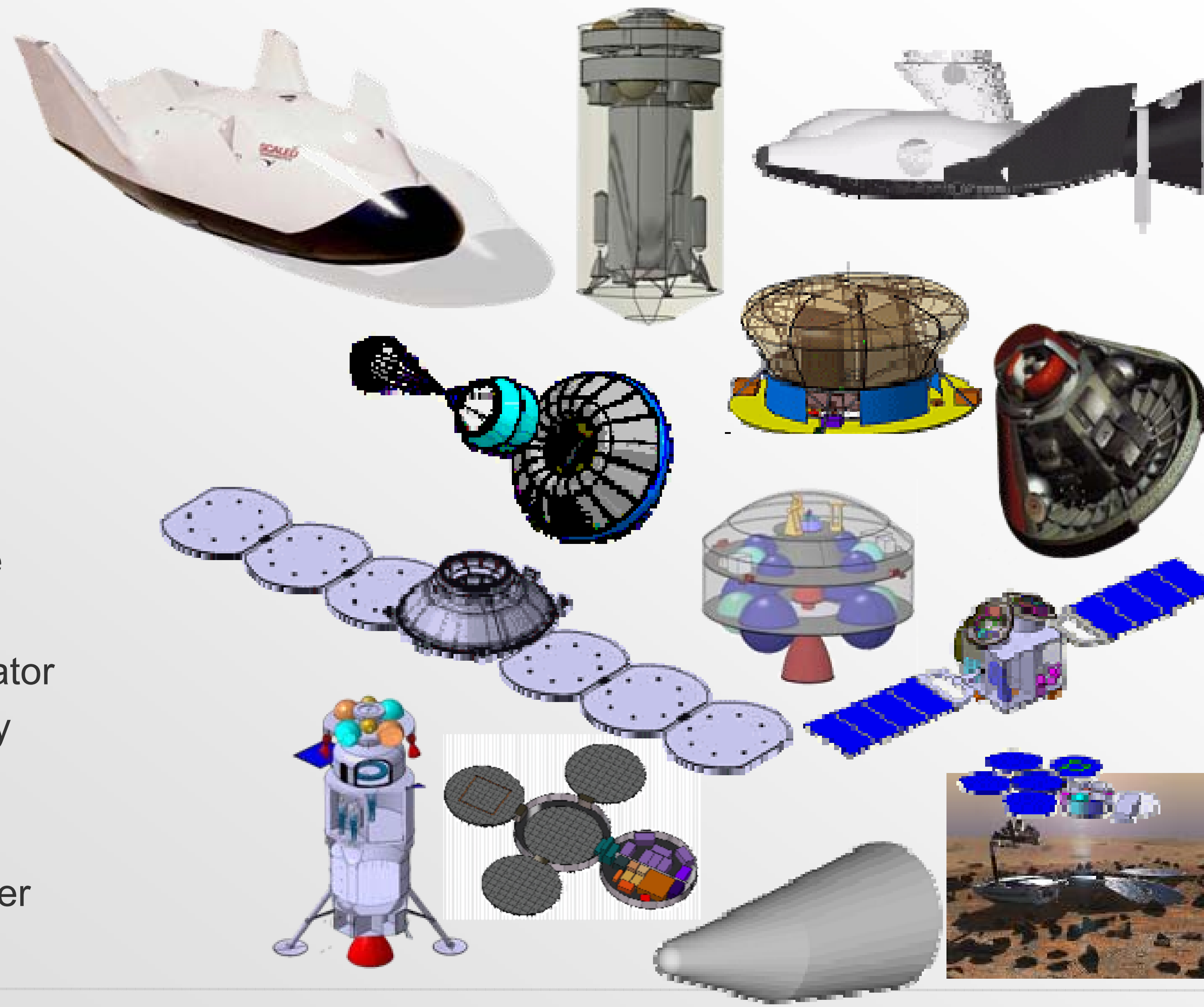
ESA projects with ASTOS Launch Vehicles

- Ariane 5
- MLV
- VEGA
- VEGA 1st flight
- Electrical VEGA
- CTV
- CTV 2
- Mars Ascent Vehicle
- Socrates RLV Demonstrator
- Heavy Lift Launch Vehicle
- IXV launch vehicles
- Crew Exploration Vehicle



ESA projects with ASTOS
Re-entry, Exploration, Science

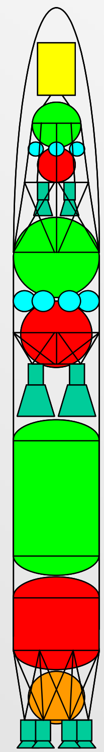
- X38/CRV
- Sphynx
- ACRV
- ARD
- JEP
- Beagle-2 & BeagleNet
- ExoMars09
- Mars Demo Lander
- Mars Sample Return
- Mars Excursion Vehicle
- coneXpress-OLEV
- Aerocapture Demonstrator
- Lunar Exploration Study
- Expert
- VRAE
- Lunar Exploration Orbiter



Industrial ASTOS Projects

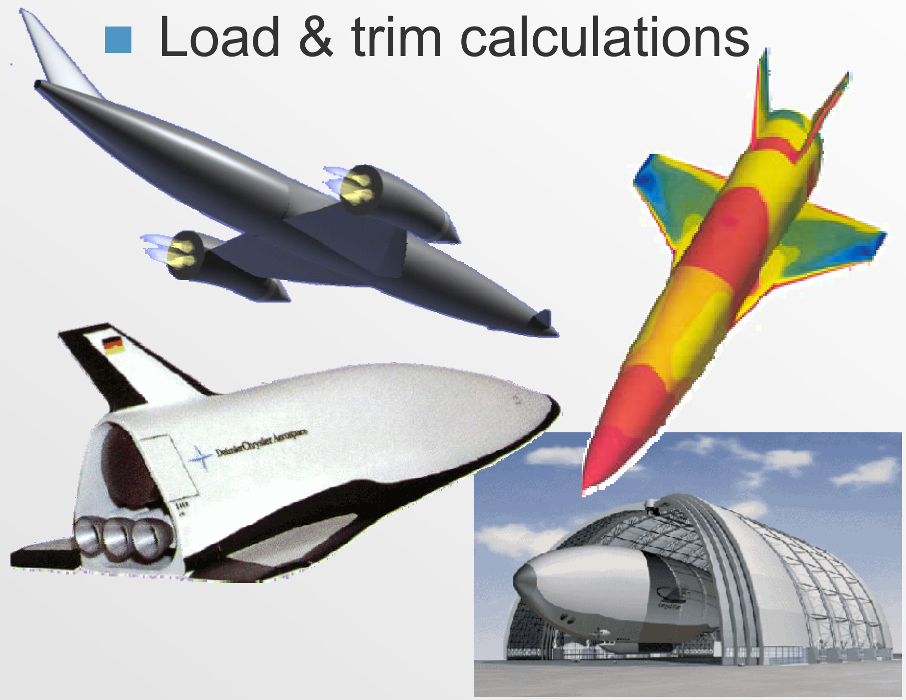
Industrial Studies

- Launch Vehicles
  - Hopper
  - Skylon
  - Fly-back Booster
  - MicroLauncher
  - Small US launcher
- Reentry
  - Capree
  - ATPE
  - USV
- Others
  - Aurora preparatory
  - L2 missions
  - CargoLifter

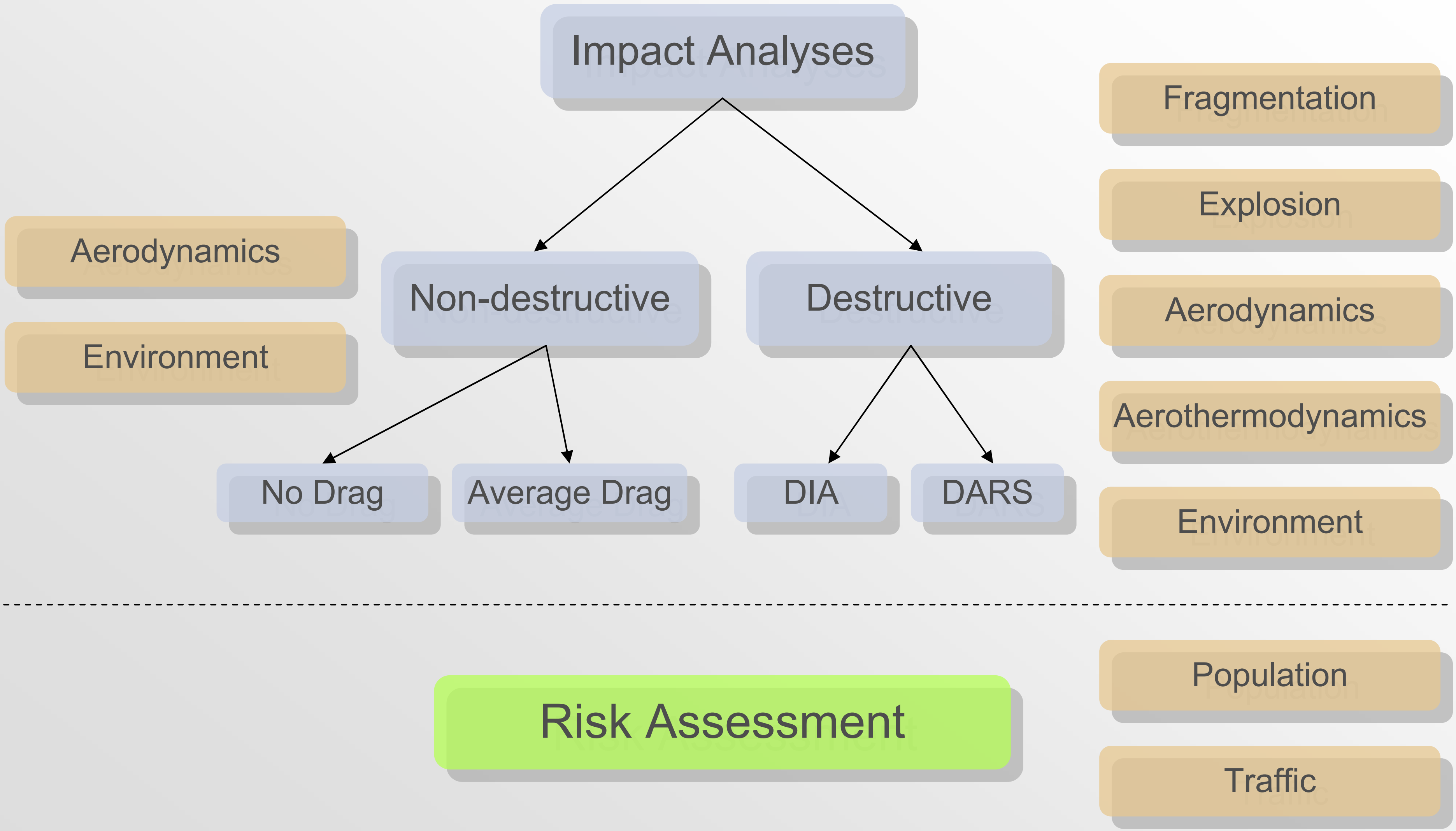


Activities

- Reference trajectory
- Guidance
- Approach corridor
- Load & trim calculations



ASTOS Risk Analysis

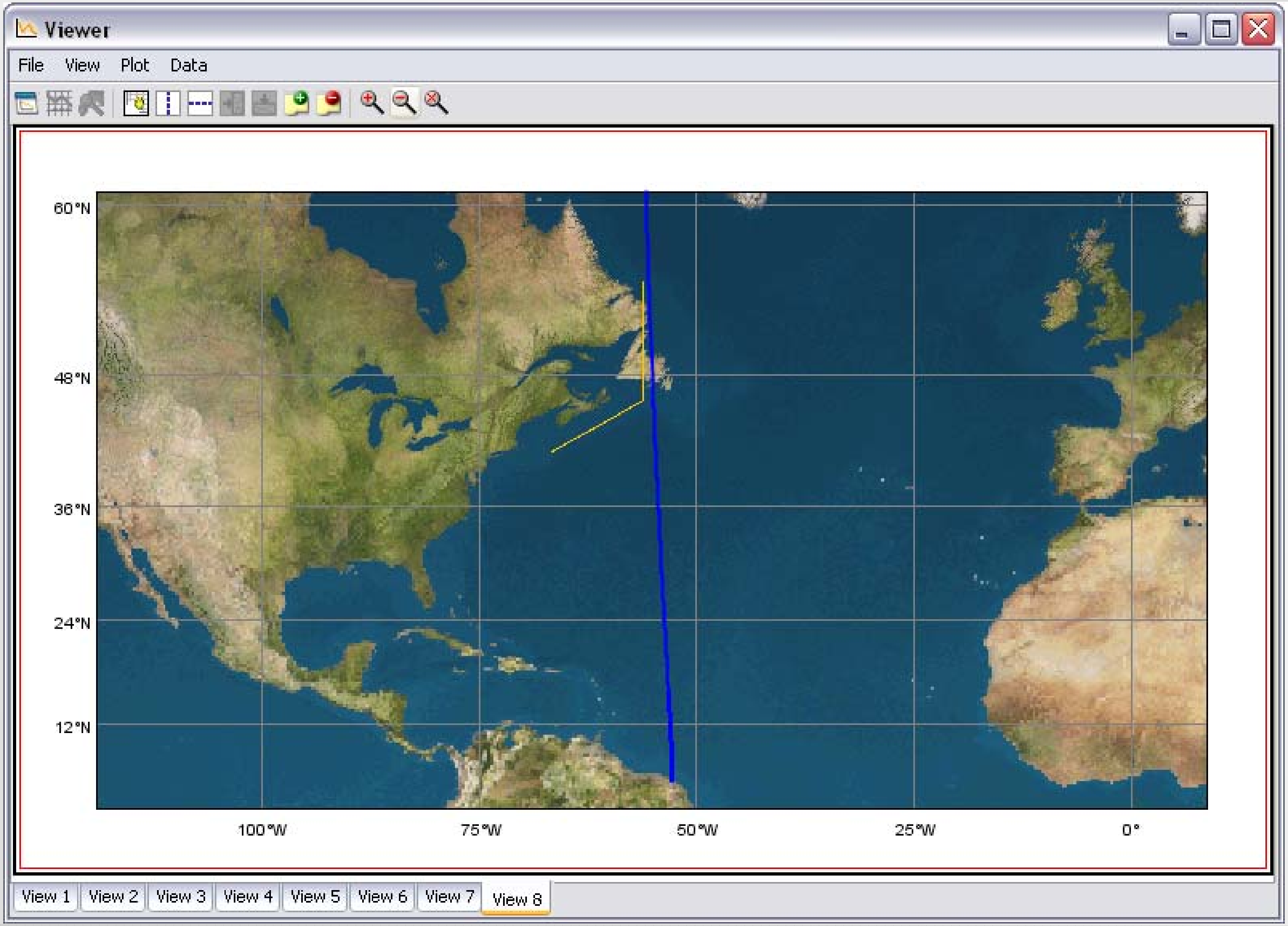


Non-Destructive Re-entry

- Propagation of the initial state Keplerian until ground
  - Useful for trajectory optimization, since it is very fast
  - Large errors!
- Combined Average Drag Profile
  - Utilizes user-specified CD profile to describe the aerodynamics of the debris
  - No fragmentation, only one impact object
  - Also useful for trajectory optimization

Both methods are not meant to be used for safety analyses.

Risk-Sensitive Trajectory Optimization



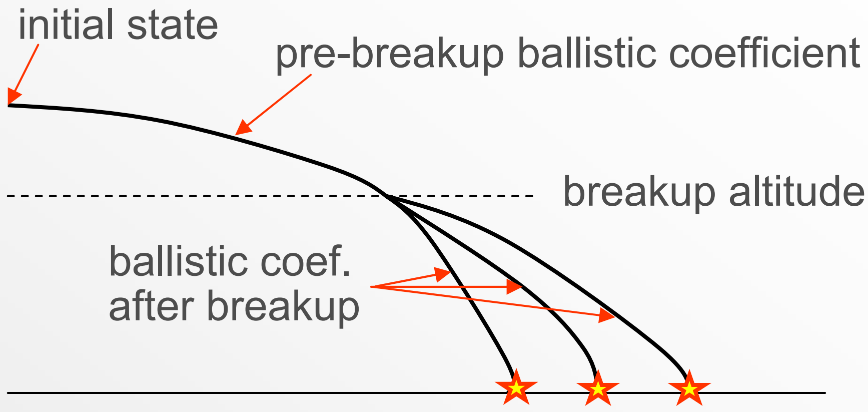
Characteristics of a Destructive Re-entry

The analysis of a destructive re-entry consists of the following tasks:

- Estimation of fragmentation events
- Estimation of explosion events and the resulting velocity increment
- Estimation of the aerodynamics based on the current shape
- Propagation of the trajectory based on aerodynamics, mass, external forces and the initial conditions
- Calculation of thermal loads and heating of the vehicle
- Calculation of mechanical loads
- Determination of melted material

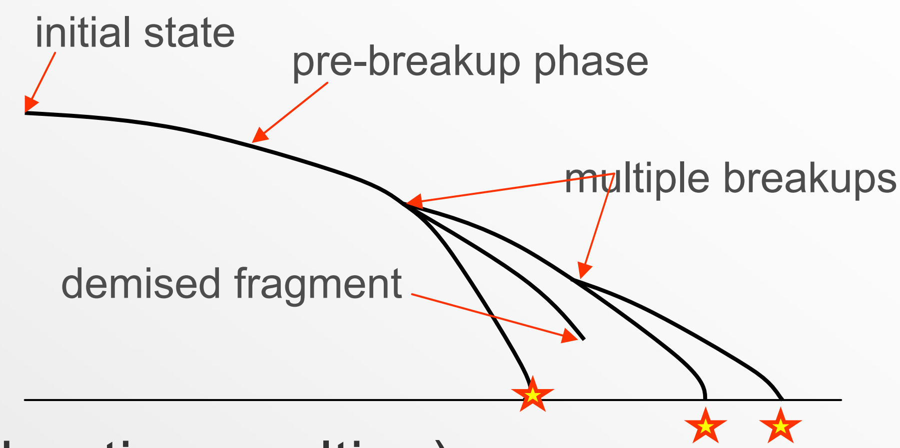
Destructive Analysis Based on Ballistic Coefficients (DIA)

- User input
  - Either range (lower bound, step size, upper bound) or
  - Table of ballistic coefficients
  - Breakup altitude
  - Final cross sections
- Single breakup event
- Pre-breakup phase defined by ballistic coefficient or ASTOS simulation (3-dof, 6-dof)
- A range of induced velocities may be applied at the breakup to simulate the effect of an explosion



DARS

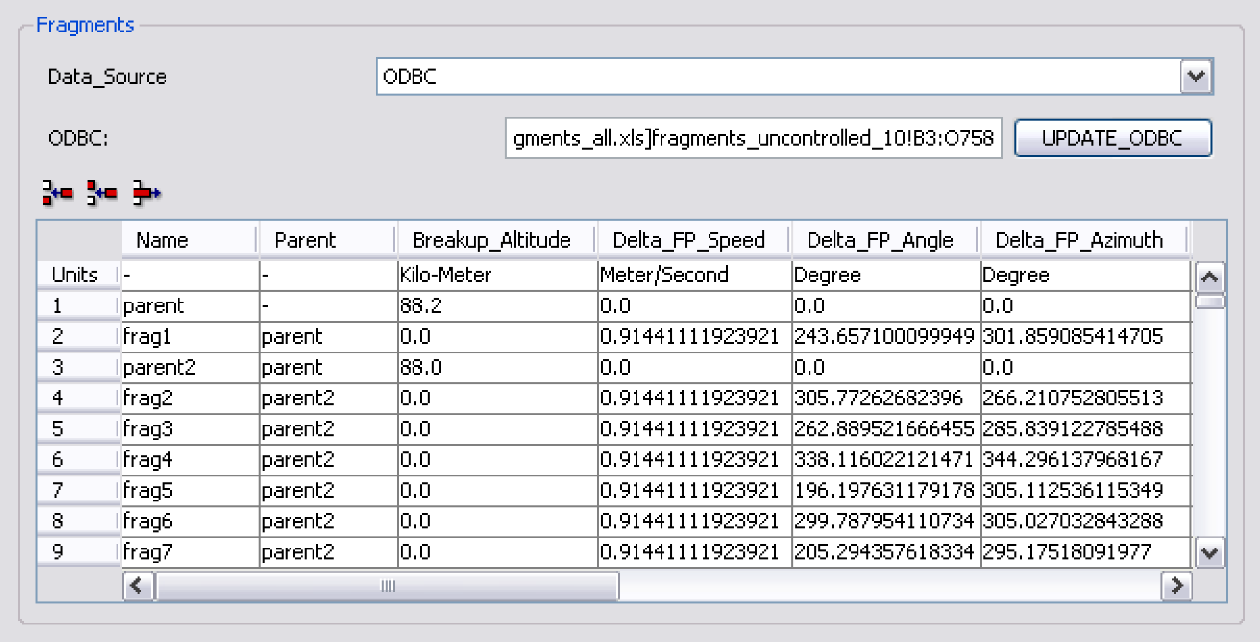
DARS ↔ **D**ebris **A**nalysis for **R**e-entry **S**pacecraft



- Developed by ESA/ESTEC
- Destructive re-entry analysis based on the assumption that fragments have primitive shape (spheres, boxes, ...)
- Lumped thermal mass model (heating, melting)
- Fragments are assumed to be tumbling
- Supports multiple breakup events
- An induced velocity may be applied at each breakup
- User-defined breakup altitude

DARS Fragment Definition

- DARS fragments are defined by:
  - Parent object
  - Breakup altitude
  - Induced velocity
  - Shape
  - Size
  - Material
  - Mass
  - Initial wall temperature

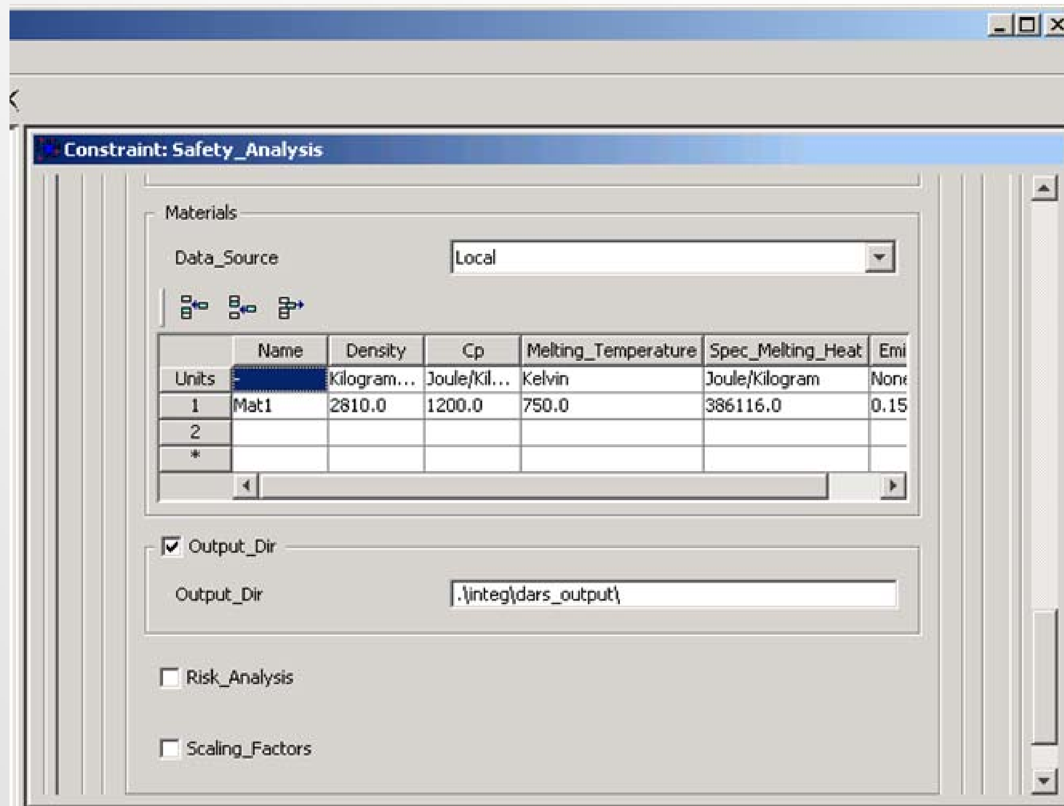


	Name	Parent	Breakup_Altitude	Delta_FP_Speed	Delta_FP_Angle	Delta_FP_Azimuth
Units	-	-	Kilo-Meter	Meter/Second	Degree	Degree
1	parent	-	88.2	0.0	0.0	0.0
2	frag1	parent	0.0	0.91441111923921	243.657100099949	301.859085414705
3	parent2	parent	88.0	0.0	0.0	0.0
4	frag2	parent2	0.0	0.91441111923921	305.77262682396	266.210752805513
5	frag3	parent2	0.0	0.91441111923921	262.889521666455	285.839122785488
6	frag4	parent2	0.0	0.91441111923921	338.116022121471	344.296137968167
7	frag5	parent2	0.0	0.91441111923921	196.197631179178	305.112536115349
8	frag6	parent2	0.0	0.91441111923921	299.787954110734	305.027032843288
9	frag7	parent2	0.0	0.91441111923921	205.294357618334	295.17518091977

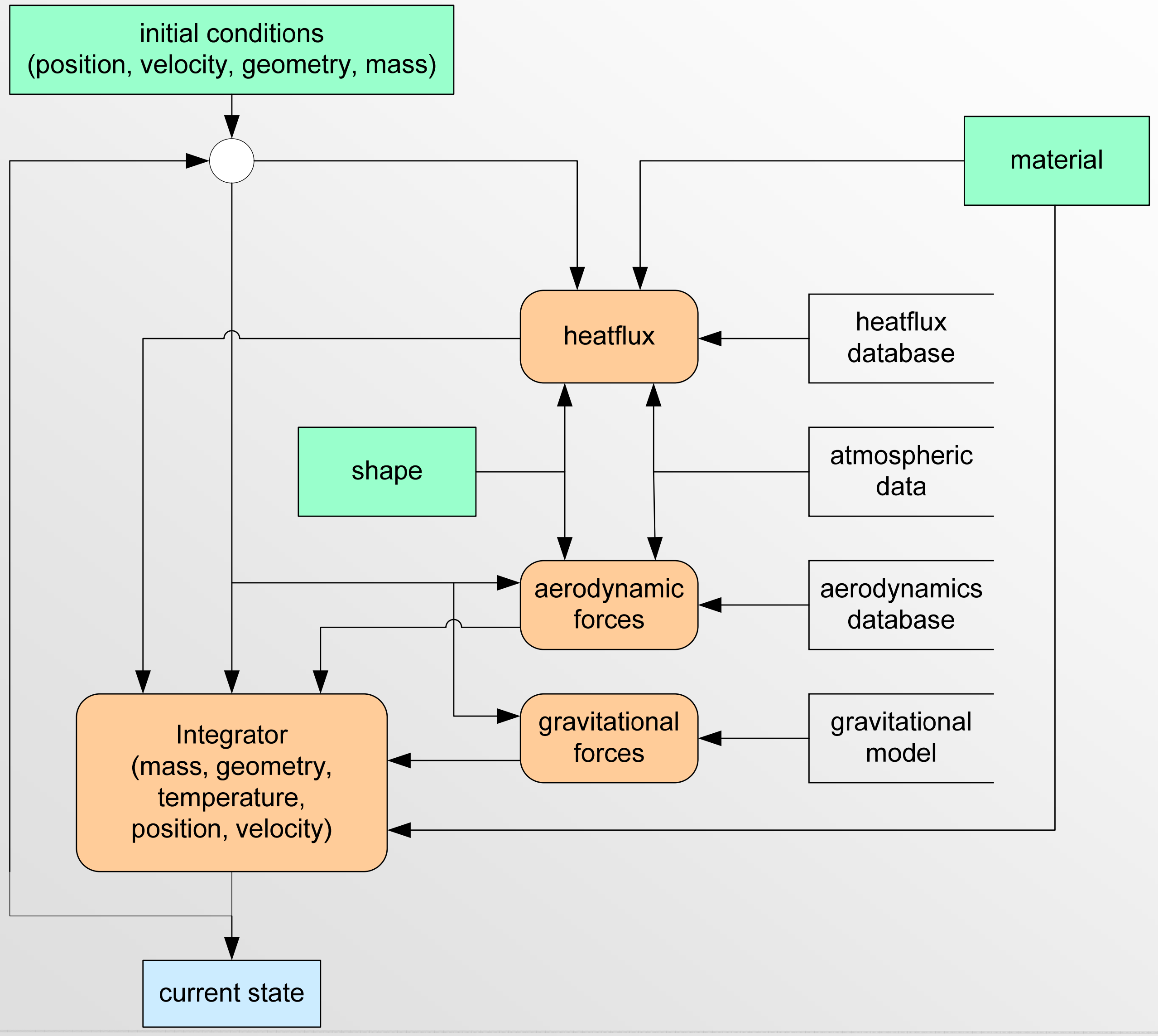
- Fragments may be read from external sources like text files, Excel tables or any other ODBC source

DARS Material Definition

- Materials are characterized by
  - Density
  - Spec. heat capacity
  - Melting temperature
  - Spec. melting heat
  - Emissivity
- Materials may be stored in a central database (Excel or text file) and are referenced by name



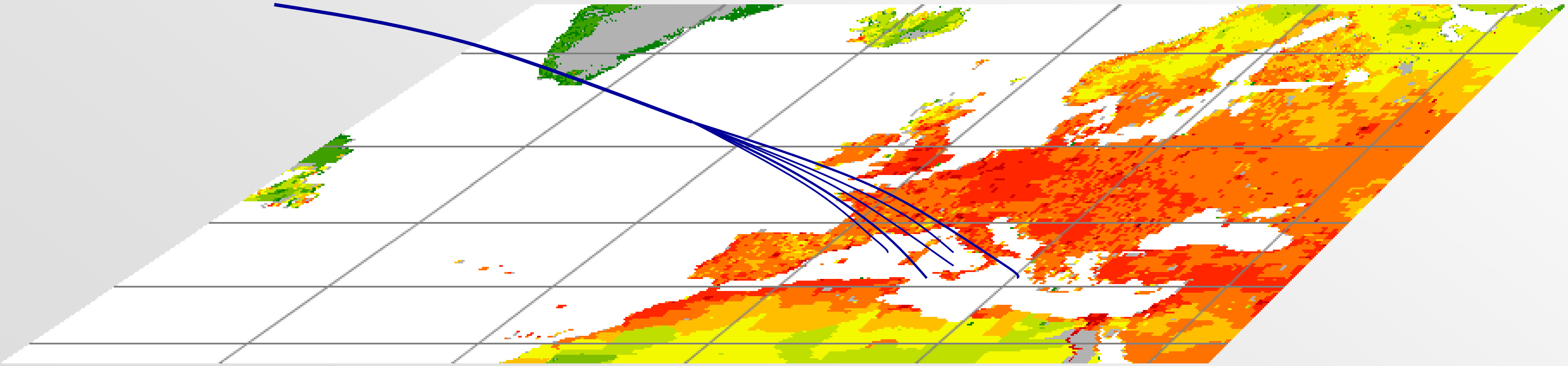
DARS Data Flow and Structure



ASTOS/RAM

ASTOS Risk Assessment Module

Analysis of risk for humans due to re-entering fragments

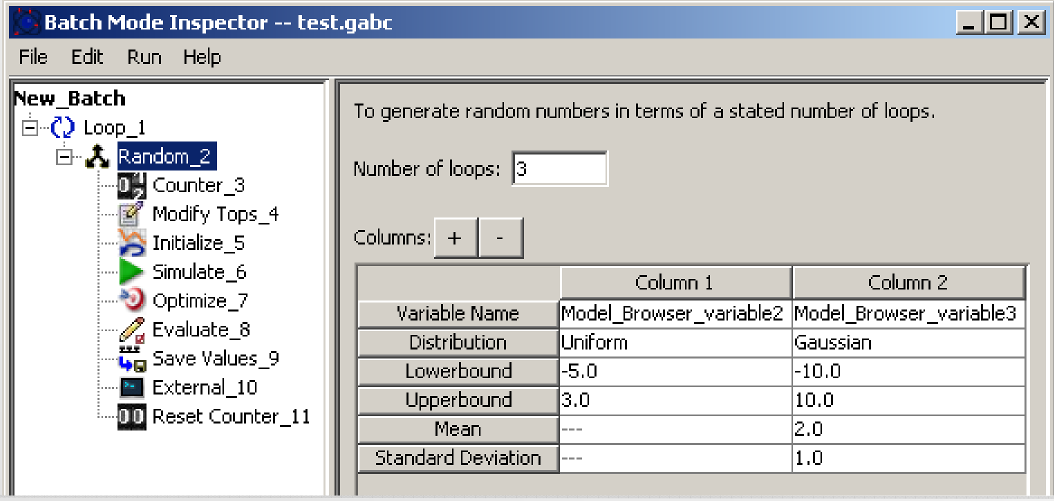


Risk Assessment

- Calculation of casualty area according to NSS 1740.14
- Population data taken from Gridded Population of the World Version 3 (GPWv3), Socioeconomic Data and Applications Center (SEDAC), Columbia University
- 2.5 arc minutes population data resolution
- Adjustment of the population density to the scenario date assuming an exponential growth of the population
- Considering the kinetic energy of the impacting fragments, casualty and fatality probabilities are estimated
- User-specified uncertainties
  - atmospheric properties (density, wind, ...)
  - initial state
  - material properties (density, melting temperature, ...)
  - breakup altitude
  - induced velocities

Monte Carlo Analysis

- All settings in the ASTOS model may be used as a variable in the Monte Carlo analysis
- Uniform or Gaussian distributions
- Alternatively, also monotonous loop variables defined by start, stop and increment value may be defined
- Fully integrated into the ASTOS environment
  - Simulations or optimizations may be started by the Monte Carlo analysis
  - Results may be plotted
    - As footprints
    - As distribution vs. value
  - Numerical summary
    - Casualty probability
    - Fatality probability
    - Both for each object and total value



Current Developments

- Explosion Model
  - Probabilistic model
  - Based on debris observations (e.g. by SSN, JV-MAC)
  - Similar to NASA EVOLVE model
- Fragmentation Model
  - Semi-probabilistic model
  - Based on observed fragmentation events
  - Shall consider “weak” joints and sheltering of inner objects
- Extension of the database for
  - Ship lines
  - Air traffic
  - Population Density Data (sheltering, ...)

Summary

- ASTOS contains several methods to compute the risk associated to the re-entry of vehicles
- The user can select stochastic or deterministic approaches depending on the required accuracy, his knowledge of the vehicle structure and the targeted application
- This flexibility allows the user to perform impact analyses for several different purposes: from risk-sensitive trajectory optimization as performed for Vega to the safety analysis for the destructive re-entry of ATV Jules Verne
- With the future implementation of explosion and fragmentation models the ASTOS user becomes independent from third-party tools


Thank you!