DRAMA's Spacecraft Entry Survival Analysis Codes

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Introduction

- Spacecraft re-entering the Earth atmosphere can pose a potential risk to life on ground

- United nation Liability convention:

  Article II. A launching State shall be absolutely liable to pay compensation for damage caused by its space object on the surface of the earth or to aircraft in flight.

  - Re-entry from space (controlled, uncontrolled, and all in between)
  - Launch range safety
  - Airspace

- ISO-24113 (ECSS-U-AS-10C):

  6.3.4 Re-entry

  6.3.4.1 For the re-entry of a spacecraft or launch vehicle orbital stage (or any part thereof), the maximum acceptable casualty risk shall be set in accordance with norms issued by approving agents.

- ESA ADMIN-IPOL-2014-002e:

  b) For ESA Space Systems for which the System Requirements Review has not yet been kicked off at the time of entry into force of this Instruction, the casualty risk shall not exceed 1 in 10,000 for any re-entry event (controlled or uncontrolled). If the predicted casualty risk for an uncontrolled re-entry exceeds this value, an uncontrolled re-entry is not allowed and a targeted controlled re-entry shall be performed in order not to exceed a risk level of 1 in 10,000.

- ESA Re-entry Safety Requirements & ESA Space Debris Mitigation Compliance Verification Guidelines
  - Provide a process during the design of a mission for the risk evaluation
  - The process is captured in a tool which makes the choices on the physical details

- DRAMA‘s Survival And Risk Analysis module (SARA) supports the process

Re-entry risk hazards:

- Need physics-based models to be identified:
  - **Impacting fragments**
  - **Floating fragments**

- Need to be identified by design review**:**
  - **Pressurized or explosive fragments**
  - **Hazardous chemical substances**
  - **Radioactive substances**

- ESA perspective on casualty/fatality risks (physics-based model part):

Casualty expectancy per fragment

$$E_{f,i} = \sum_i \sum_n \sum_m (P_i)_{n,m} \cdot (\rho_p)_{n,m} \cdot (A_C)_{n,m} \cdot (\eta_f)_{n,m}$$

Bins on Earth surface

Impact probability

Population density

Casualty cross-section

Casualty index

- Similar definitions are in use around the globe:
  - NASA, JAXA, France (casualty expectancy vis-à-vis casualty probability),
  - The value 1 in 10 000 original came from aviation safety,
  - Keeping the terms 'simple' enables comparison and understandable verification.

- SARA v1 was released in 2004 in support of the European Code of Conduct
- SARA v2 development was started in 2016 to adapt to new engineering practices and scientific data

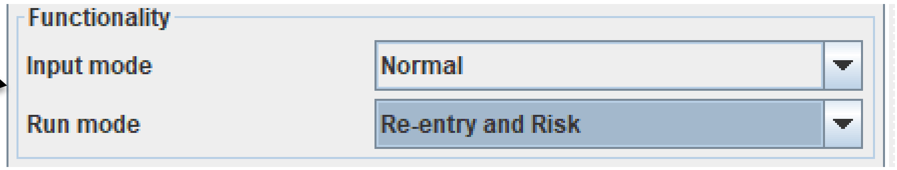
- Objectives:
  - Build further on the heritage methods which are in every day use;
  - Allow object to be “nested” and “connected” in view or re-entry break-up;
  - Extend toward temperature and surface dependent properties;
  - Provide an ablation model for carbon fibre reinforced polymers materials;
  - Introduce break-up triggers;
  - Enable direct statistical analysis of a re-entry event.

Overview

- Upgraded DRAMA GUI
  - Integration of the new SARA modules into the DRAMA GUI
  - Extended functionality and usability
- SESAM - Spacecraft Entry Survival Analysis Module
  - Aerodynamic and aero-thermodynamic simulation
  - Entirely re-engineered from scratch with up-to-date methods
- SERAM - Spacecraft Entry Risk Analysis Module
  - Ground risk analysis based on up-to-date population models
  - Completely revised and newly coded
- Monte-Carlo Wrapper
  - Newly developed for statistical analysis
  - Calculates Declared Re-entry Area (DRA, 99% of ground fragments) and Safety Re-entry Area (SRA, 99.999% of ground fragments)

DRAMA GUI
Simulation input and settings

- Sidebar sections
  - Basic Settings
  - Model
  - *Fragmentation Model*
  - *Monte Carlo*
  - Plot Options



DRAMA GUI
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Simulation parameters
- SESAM
- SERAM

Satellite model
- 3D position, shape, attitude, material, etc.
- Relations between components
- Events trigger

Fragment model
- Standalone risk analysis
- Position, velocity and shape of ground fragment, etc.

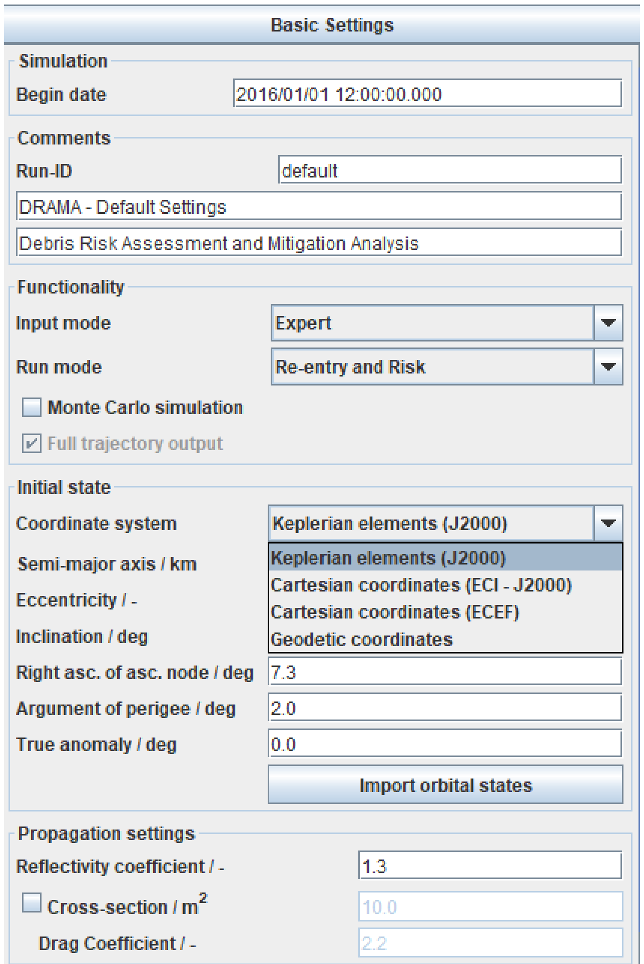
Statistical analysis
- Variation of simulation and model parameters

Standard input

Standard and expert input

Expert input

DRAMA GUI
Simulation input and settings



- Sidebar sections
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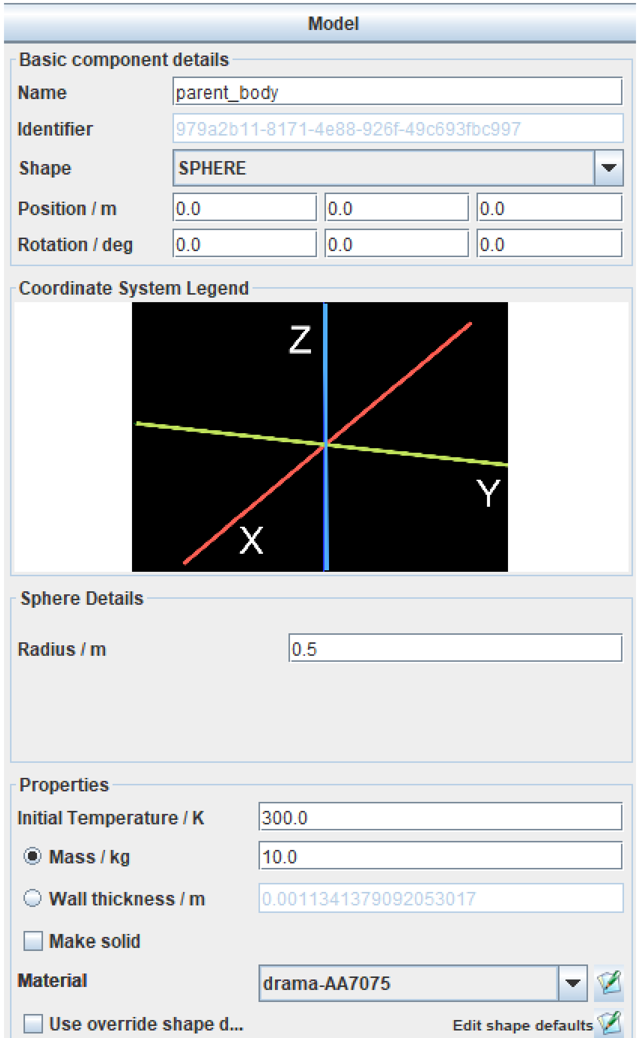
  - Plot Options

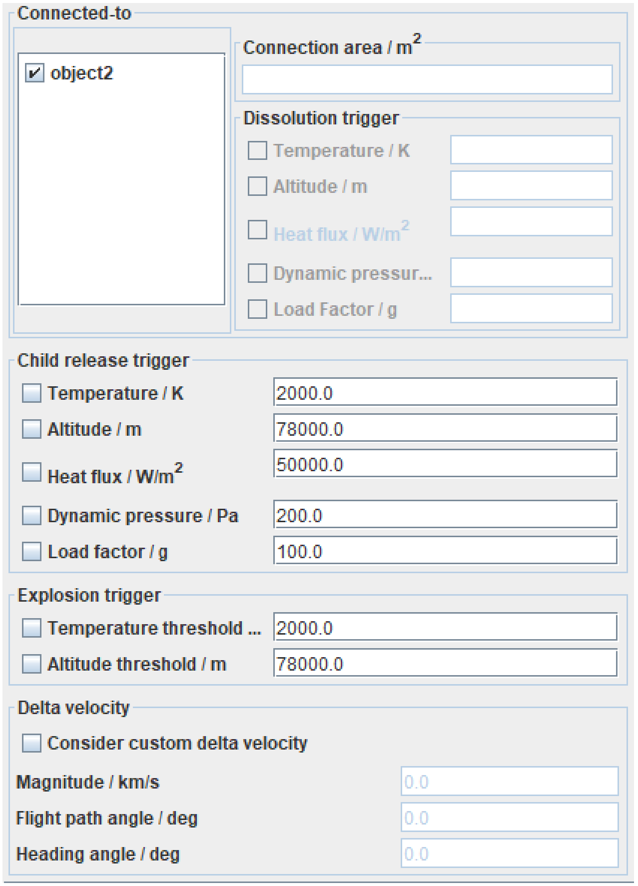
- Input states in various formats:
  - Re-entry starts below 140 km
  - Propagation with OSCAR
  - Given object properties or derived from SARA model



- Sidebar sections
  - ➢ Basic Settings
  - ➢ Model
  - ➢ *Fragmentation Model*
  - ➢ *Monte Carlo*
  - ➢ Plot Options

- Hierarchical object model:
  - ➢ “Make solid”
  - ➢ “Flat”
  - ➢ Top-bottom inclusion
  - ➢ Same level object can connect

DRAMA GUI
Simulation input and settings



- Sidebar sections
  - Basic Settings
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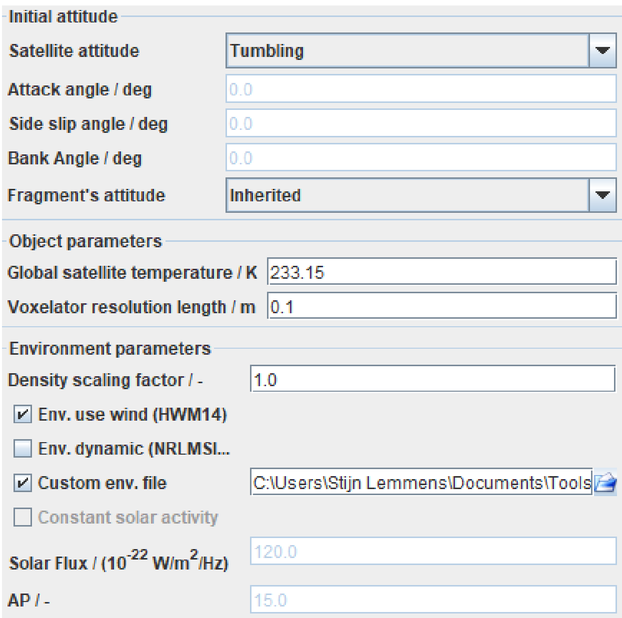
  - *Monte Carlo*
  - Plot Options

- Connections can break
  - Area defines conduction
- Inclusions can release objects
  - The object vanishes
- Objects can explode
  - NASA break-up model
- Genesis can introduce a delta V

DRAMA GUI
Simulation input and settings



- Sidebar sections
  - Basic Settings
  - Model
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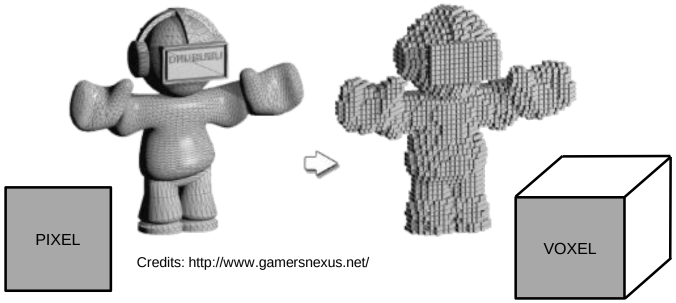
  - Plot Options

- Satellite attitude defines the aerothermodynamics
- Default atmosphere based on US76 extended with O content.
- Space weather based on the OSCAR data

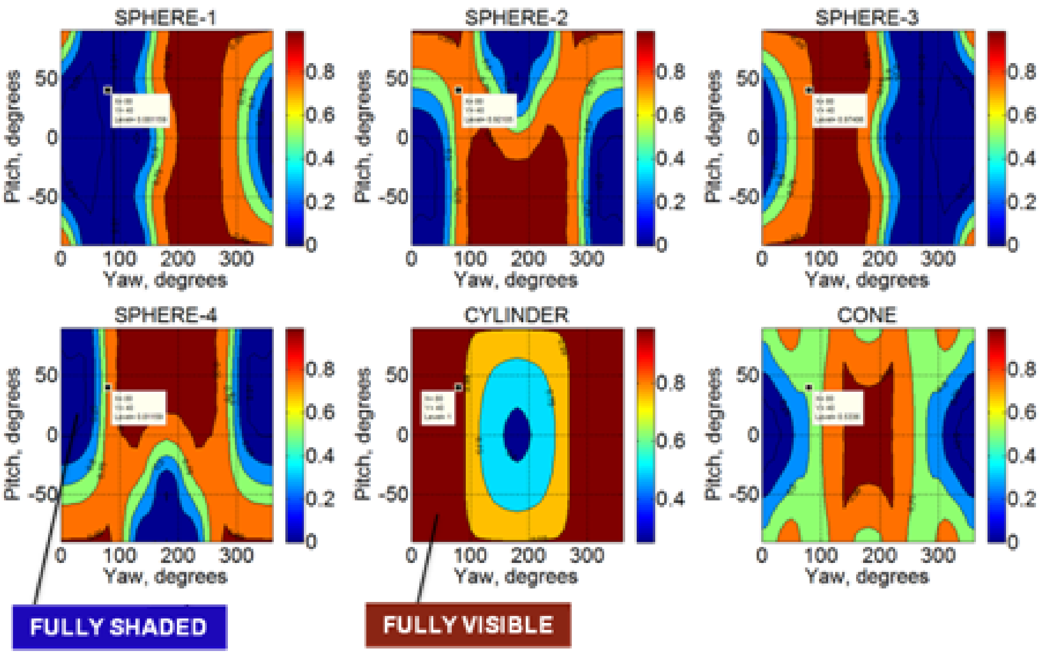
- Voxelator settings have an influence

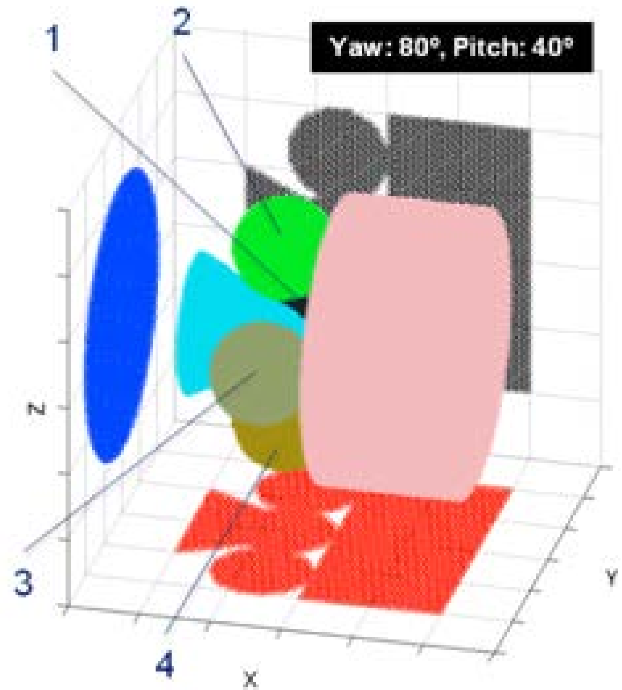
SESAM
Voxelator module

- Shadowing of „connected“ objects
  - ➢ Partial exposure → reduced heat income
- Visibility factor calculated for pitch and yaw angle
  - ➢ Object’s contribution to the fragment’s aerothermodynamics



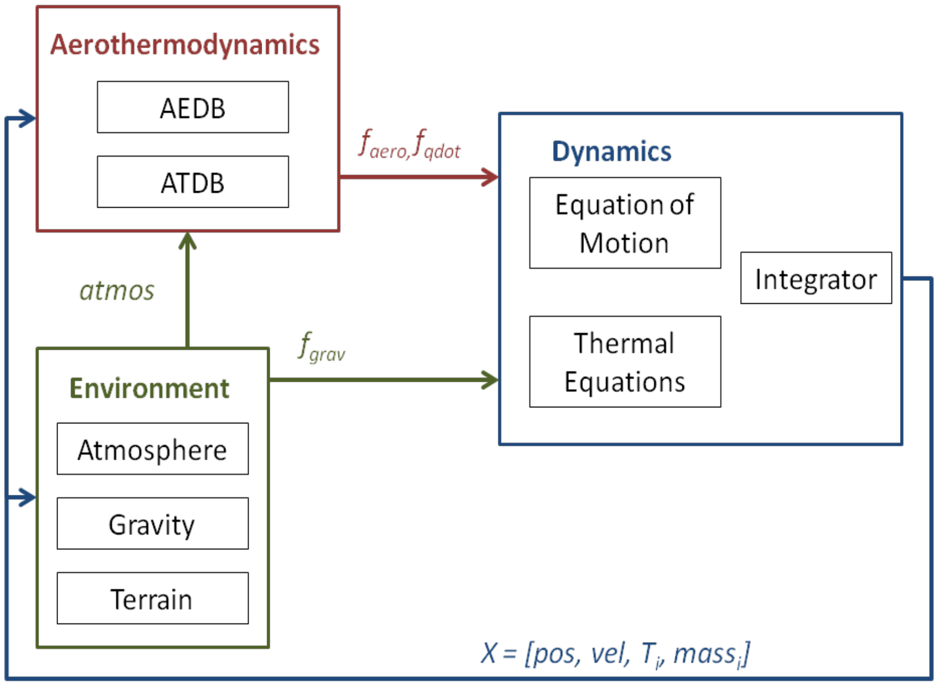
Example: Simplified upper stage model





- Spacecraft model consists of multiple geometric shapes
  - Box, cone, cylinder, sphere
- Pre-computed aerodynamic and aerothermodynamic coefficients
  - Shape dependent
  - Drag, lift and side force
- 4/5th Runga-Kutta with adaptive step size.
  - J2 Earth model
  - US76, NRLMSIS00, HWM14

SESAM High-level System Context:

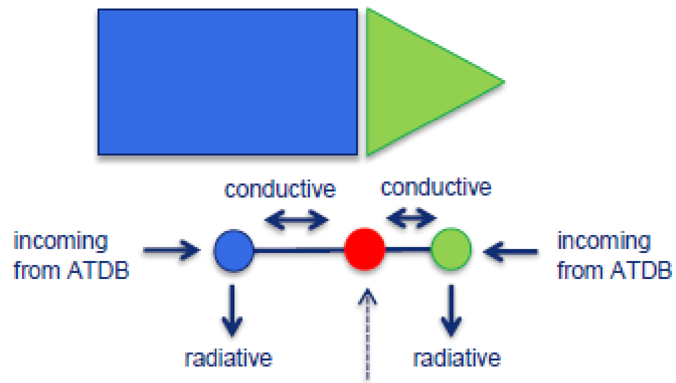


THERMAL MODEL

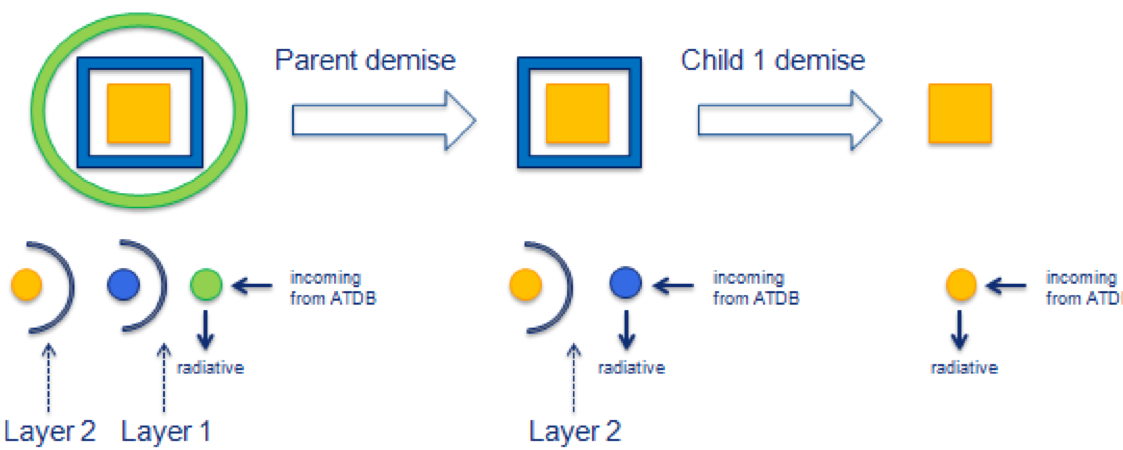
$$Q = (Q_c + Q_r + Q_d - \sigma \varepsilon T_w^4 A_r)$$

$$\begin{cases} \dot{T}_w = \dfrac{Q}{c_p m}; \quad \dot{m} = 0 \quad \text{for } T_w < T_m \\ \dot{m} = -\dfrac{Q}{h_f}; \quad \dot{T}_w = 0 \quad \text{for } T_w \geq T_m \end{cases}$$

where:
- T_w = wall temperature (K)
- m = mass (kg)
- Q = total heat flux (W)
- Q_c = incoming convective heat flux (W)
- Q_r = incoming radiative heat flux (W)
- Q_d = conductive heat flux (W)
- A_r = effective radiation surface (m^2)
- h_f = material heat of fusion (J/kg)
- c_p = thermal capacity (J/kgK)
- σ = Stefan-Boltzmann constant, 5.670508
- ε = material emissivity
- T_m = melting temperature (K)

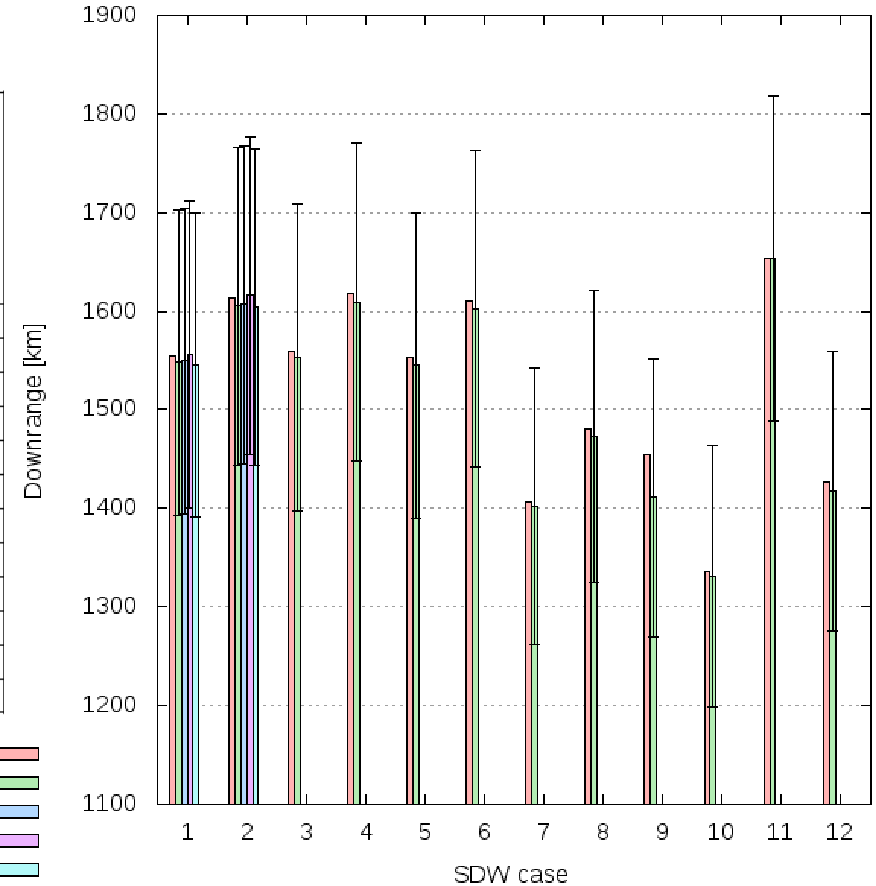


Virtual node defined by: thermal conduction, connection area



- „Analytical tumbling“ method:
  - ➢ Box, cylinder, sphere re-implemented from DRAMA2: Heating and Drag
  - ➢ SDW as reference case

Case N°	Shape	Width/ Diam. (m)	Length (m)	Height (m)	Mass (kg)	Thickness (mm)	Material
1	Sphere	1.0			247.2	30.0	AA7075
2	Sphere	1.0			393.6	30.0	Ti-6Al-4V
3	Cylinder	1.0	1.0		370.8	30.0	AA7075
4	Cylinder	1.0	1.0		590.4	30.0	Ti-6Al-4V
5	Box	1.0	1.0	1.0	472.2	30.0	AA7075
6	Box	1.0	1.0	1.0	751.7	30.0	Ti-6Al-4V
7	Plate	1.0	1.0		86.6	30.0	AA7075
8	Plate	1.0	1.0		133.1	30.0	Ti-6Al-4V
9	Sphere	1.0			34.7	4.0	AA7075
10	Cylinder	1.0	1.0		52.1	4.0	AA7075
11	Box	0.3	0.3	0.3	17.9	13.0	AA7075
12	Plate	0.5	0.5		10.5	15.0	AA7075



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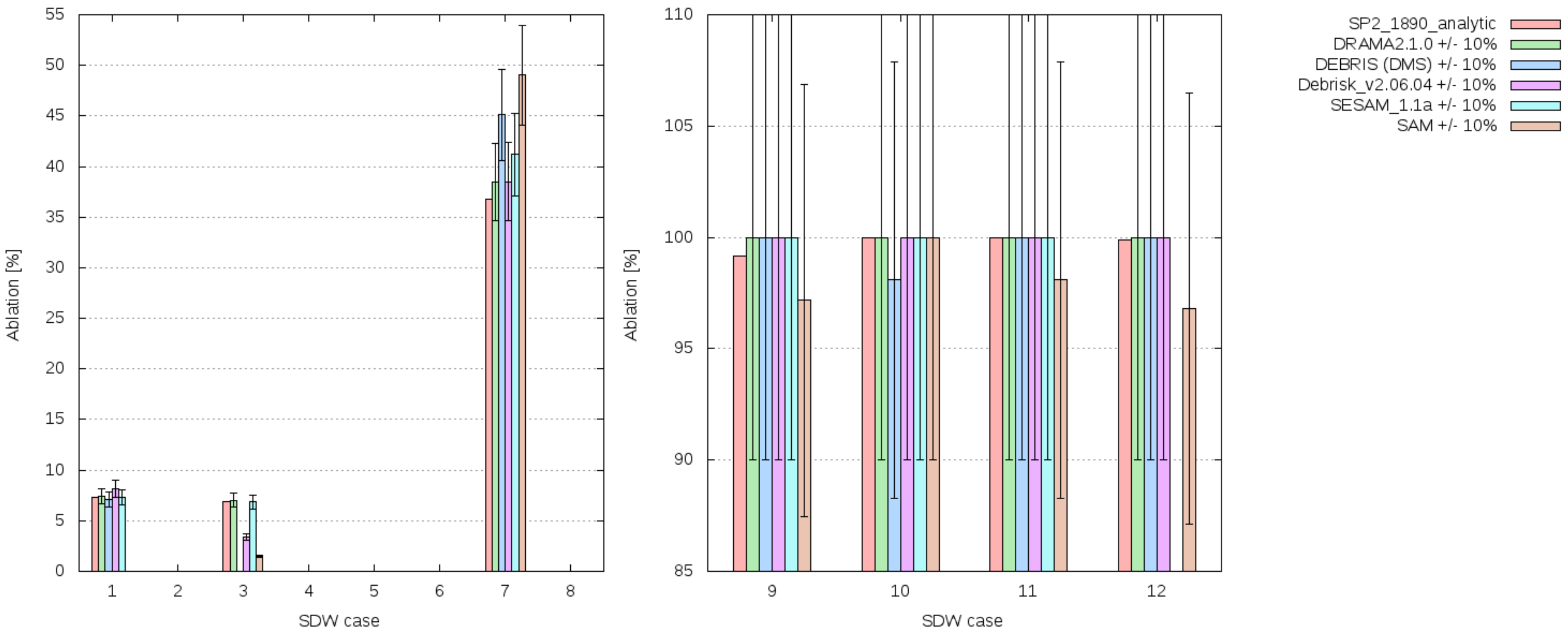
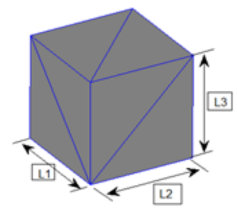
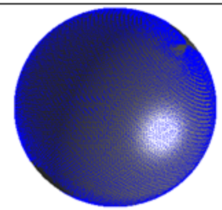
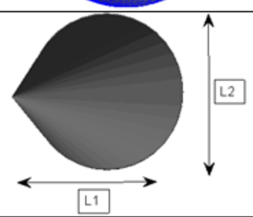
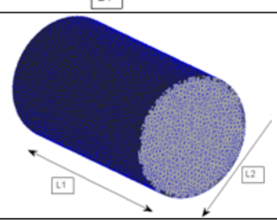
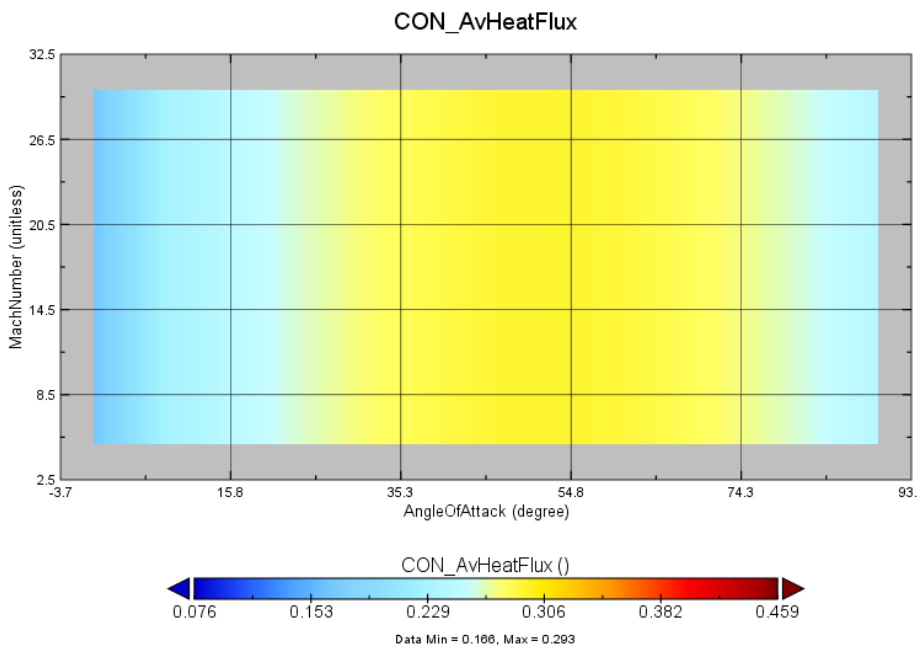


- „Tumbling & Fixed“ method:
  - Box, cylinder, cone, sphere implemented based on a panel method

Primitive	Shape	Flight Conditions		Dimensions	
		Parameter	Range	Parameter	Range
Cube		Angle of Attack Angle of Sideslip Mach Continuous / FMF	[0 – 90] [0 – 90] [5 – 30]	L1/L2 L1/L3	[1/100 – 100] [1/100 – 100]
Sphere		Mach Continuous / FMF	[5 – 30]	Radius	[1/20 – 20]
Cone		Angle of attack Mach Continuous / FMF	[0 – 180] [5 – 30]	L1/L2	[1/20 – 20]
Cylinder		Angle of attack Mach Continuous / FMF	[0 – 90] [5 – 30]	L1/L2	[1/20 – 20]

- „Tumbling & Fixed“ method:
  - Box, cylinder, cone, sphere implemented based on a panel method
  - Free-Molecular Flow model based on full momentum transfer and energy accommodation
  - Continuum Flow force coefficients based on Newtonian theory
  - Continuum Flow heating based on theory and experiments by Klett and Cropp.
  - Bridging :

$$f(Kn) = \sin\left(\pi \cdot (0.5 + 0.25 \cdot \log_{10} Kn)\right)^3$$



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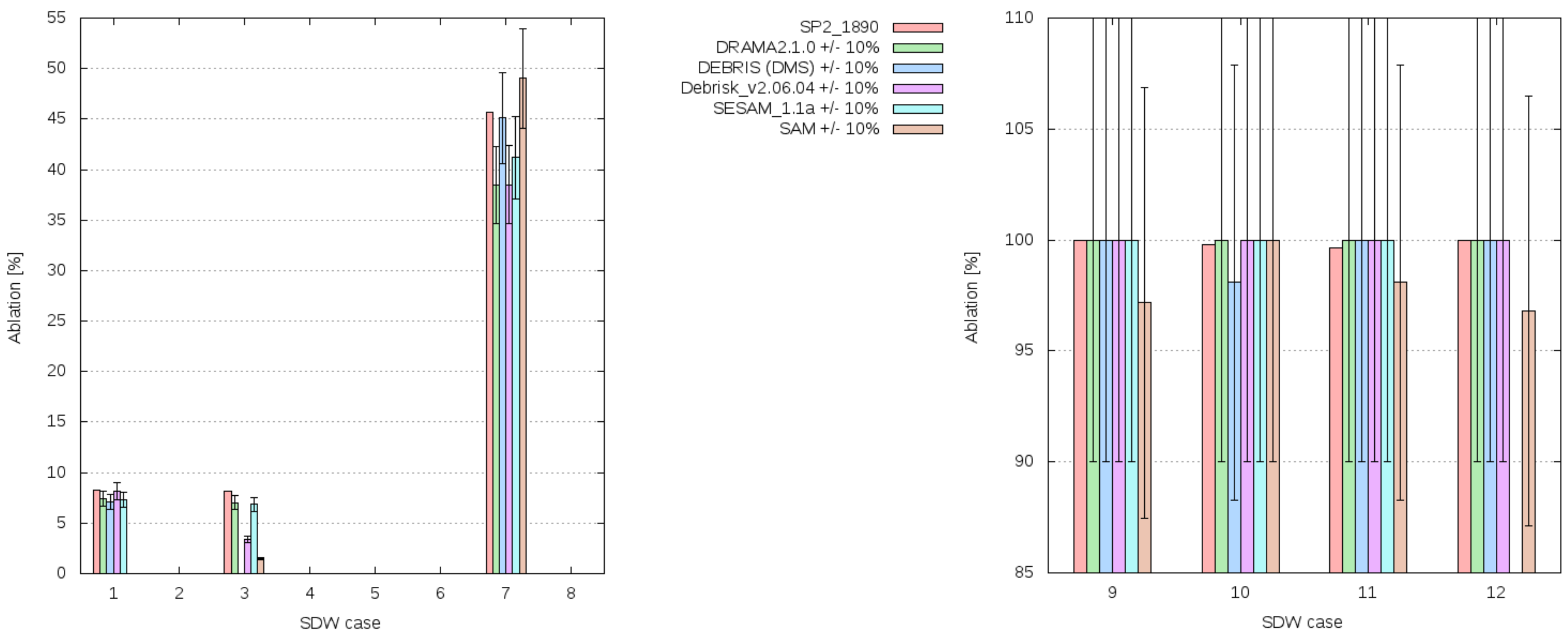
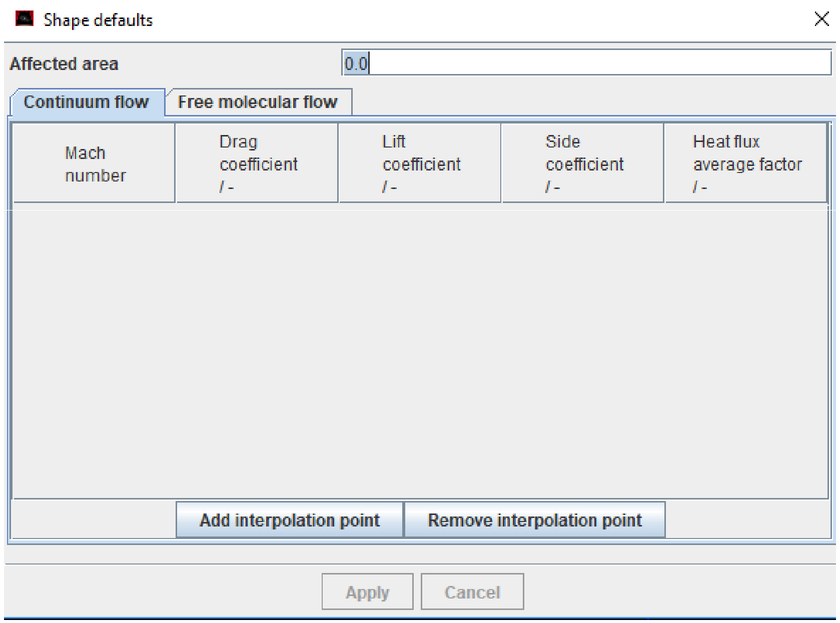
  - ➢ Box, cylinder, cone, sphere implemented based on a panel method



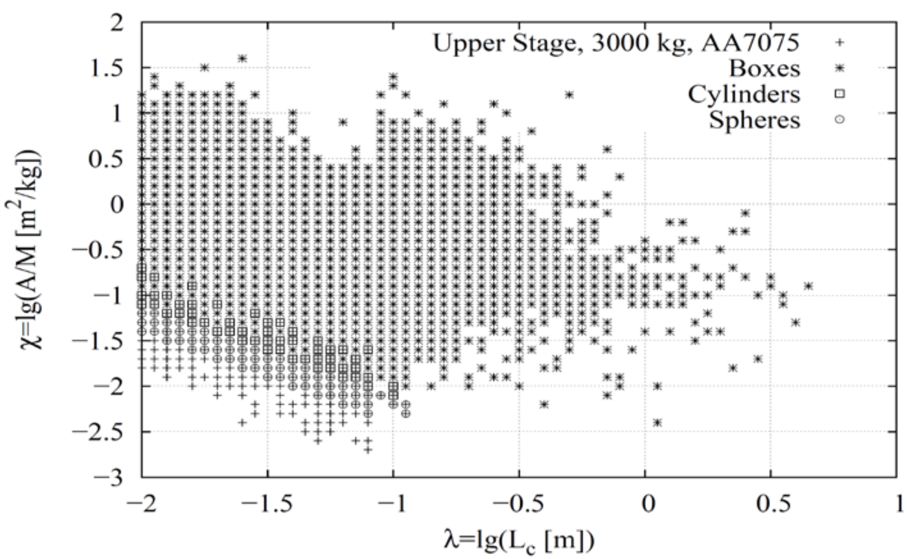
SESAM Aerothermodynamics

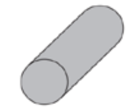
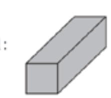
- Database values can be overwritten:
  - Expert user input (e.g. CFD)
- Connected-to objects will be treated optimistically vis-a-vis heating:
  - Convective heating is applied per object with visibility factor
- Radiative heating based on CFD
  - $\dot{q}_r = CR^{a>0}\rho^b f(V)$
  - Applied based on the global radius of the object



SESAM
Explosion Model

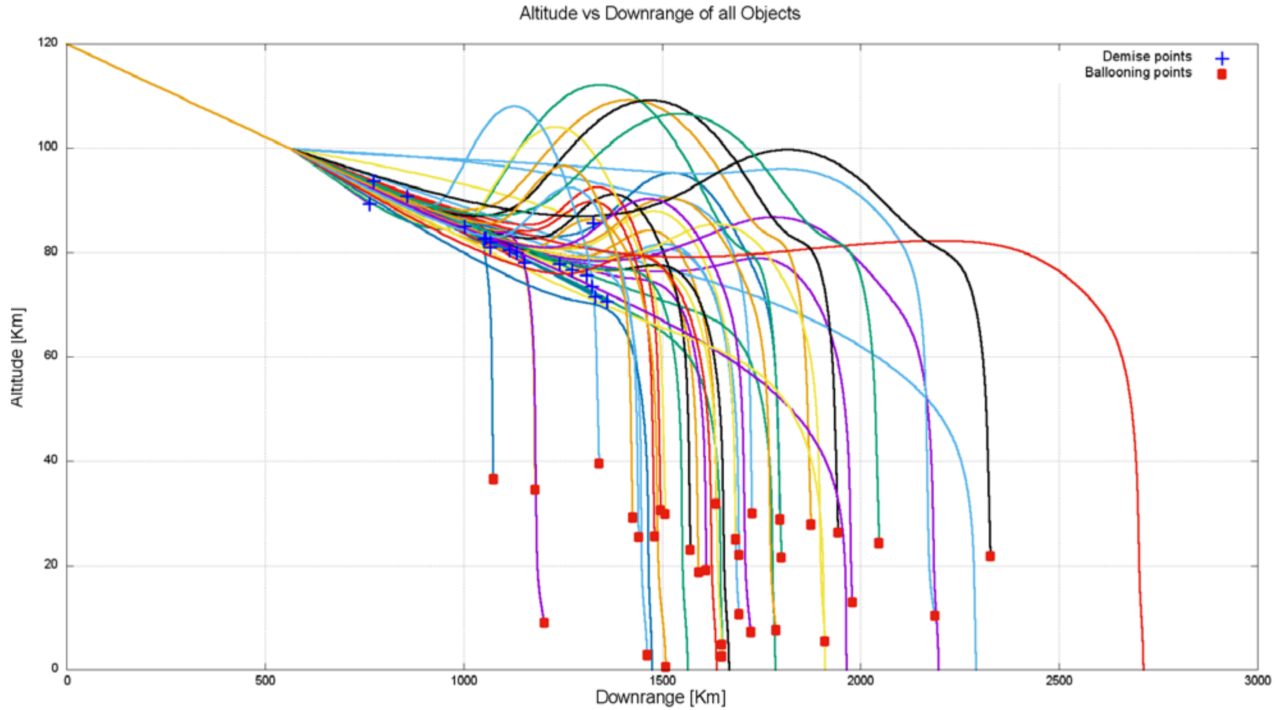
- Explosion model
  - NASA's Evolve 4.0 break-up model
  - Automated shape association
  - ATV-1 heritage, trigger based



Shape	Characteristic Length	Geometric Parameters
Spheres	$L_c = D$	*shape not possible*
Cylinders *Option 1*	$L_c = L_{cyl}$	$D/L = 0.596$ $D_{cyl} = 0.596\,L_c$ 
Option 2	$L_c = D_{cyl}$	$D/L = 11.180$ $L_{cyl} = L_c/11.180$ 
Option 2	$L_c = 0.430\,L_{cyl}$	$D/L = 0.145$ $L_{cyl} = 2.324\,L_c$ $D_{cyl} = 0.338\,L_c$ 
Boxes *Option 1*	$L_c = L_{box}$	$W/L \in [0.461, 1]$, uniform RNG $H/W = f(W/L)$ $W/L = 1$:  $W/L = 0.7$:  $W/L = 0.461$: 
Option 2	$L_c = (L_{box} + W_{box} + H_{box})/3$ $L_{box}/L_c = f(W/L)$	$W/L \in [0.082, 0.173]$, uniform RNG $H/W = f(W/L)$ $W/L = 0.173$:  $W/L = 0.12$:  $W/L = 0.082$: 

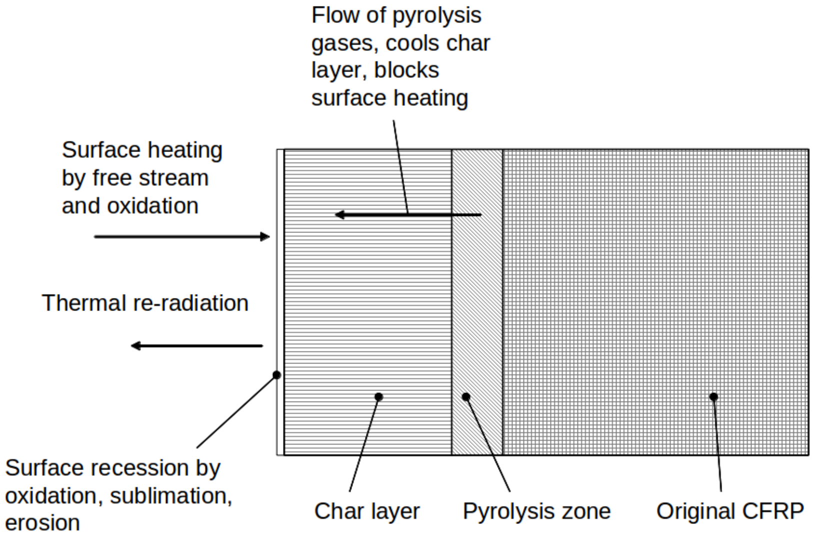
SESAM
Explosion Model

- Event triggered at 100 km altitude
  - 60 new fragments are generated (random)
  - 18 demise, 10 survive to the ground (impact), 32 were dropped when their kinetic energy got below the 15 J limit (uncritical)
  - Not in this example: Escaped and ballooned

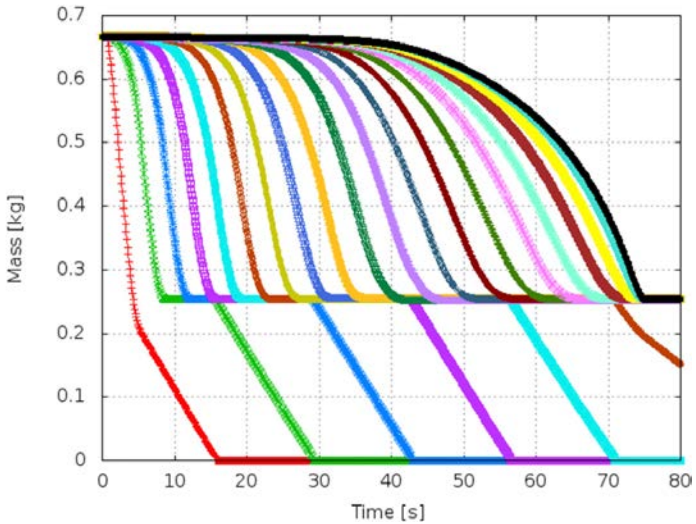


SESAM
Material Models

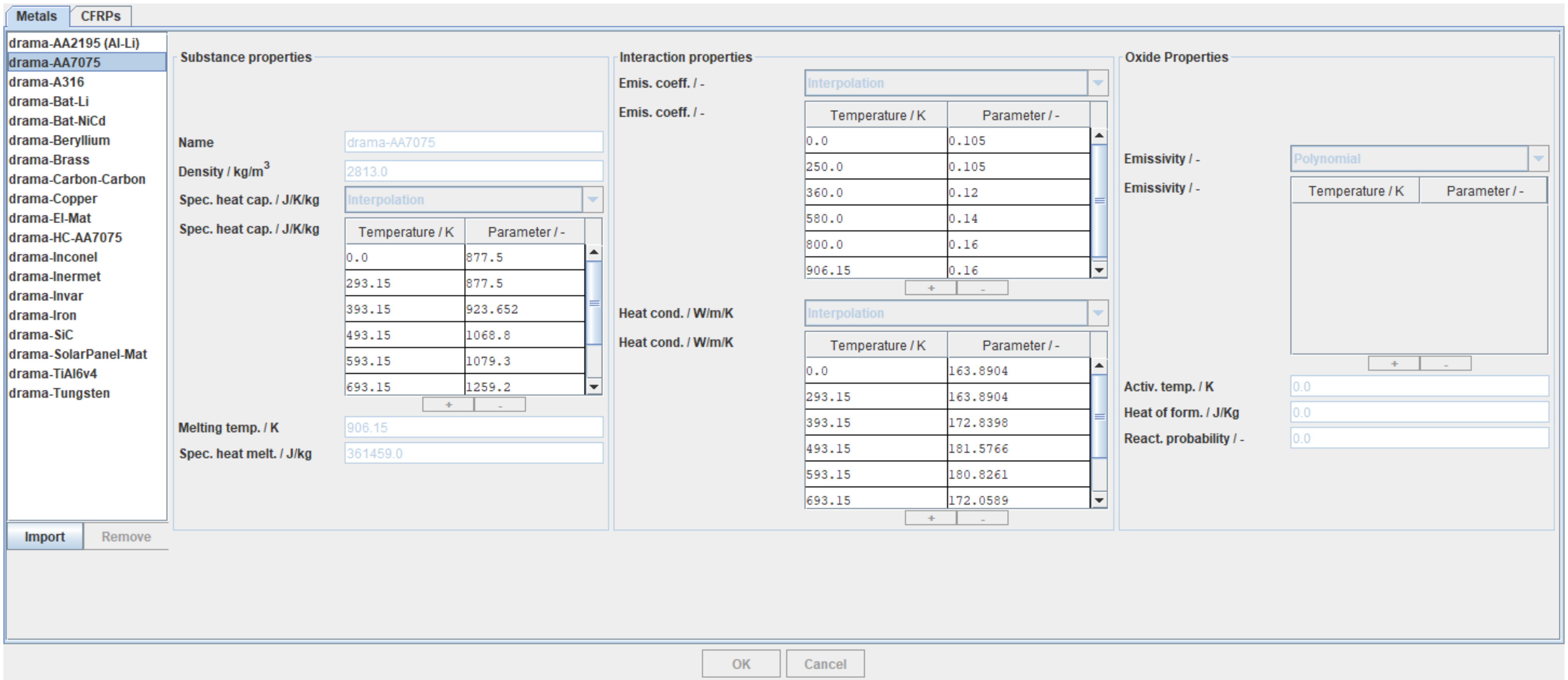
- Metal ablation model
  - 1D lumped mass model, changing thickness
  - Ablation changes propagator parameters
  - Temperature dependent properties used
  - Oxidation can be added



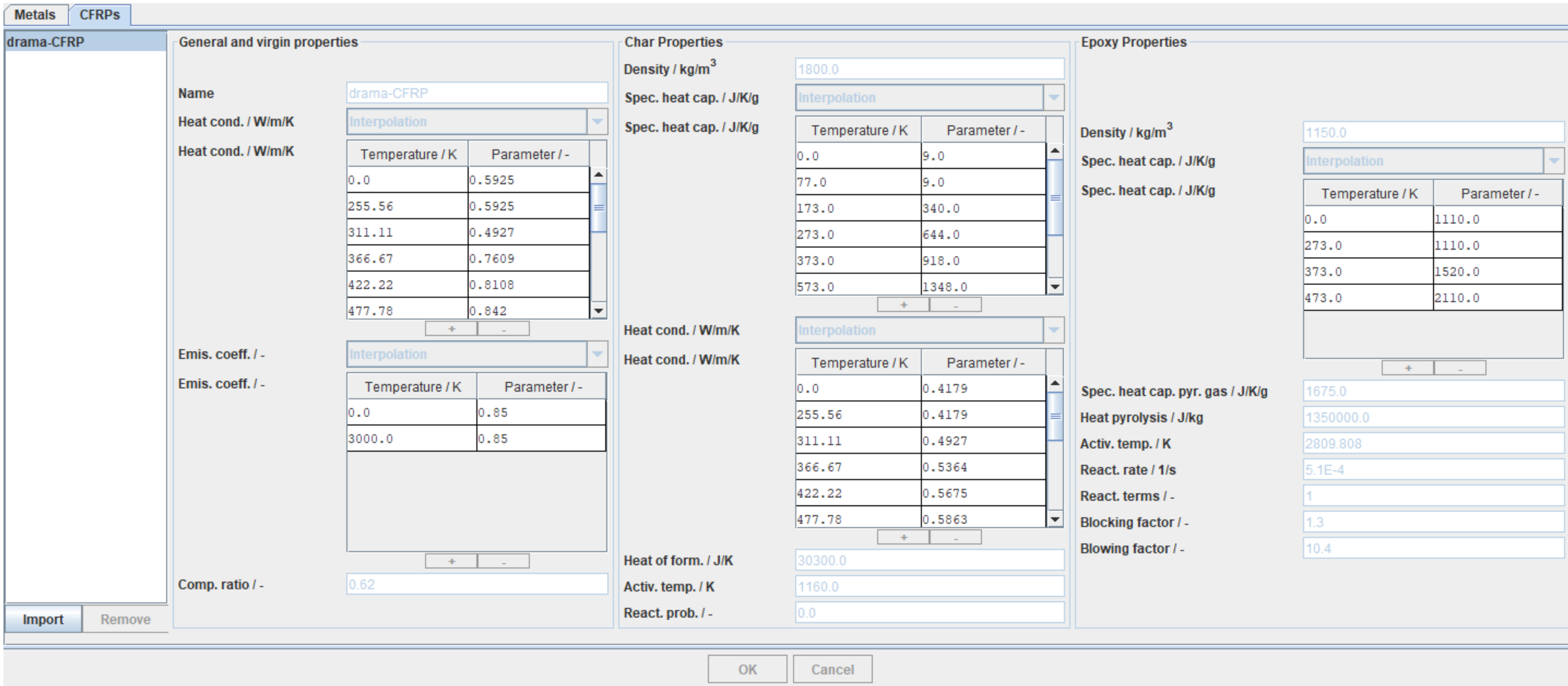
- CFRP ablation model
  - Ablation based on pyrolysis and oxidation
  - Discrete layer numerical approach
  - SCARAB heritage



SESAM
Material Models

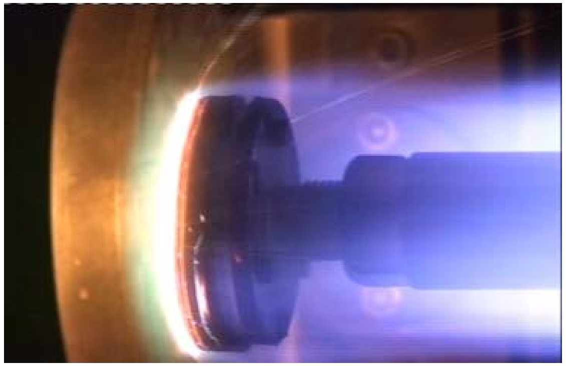


SESAM
Material Models

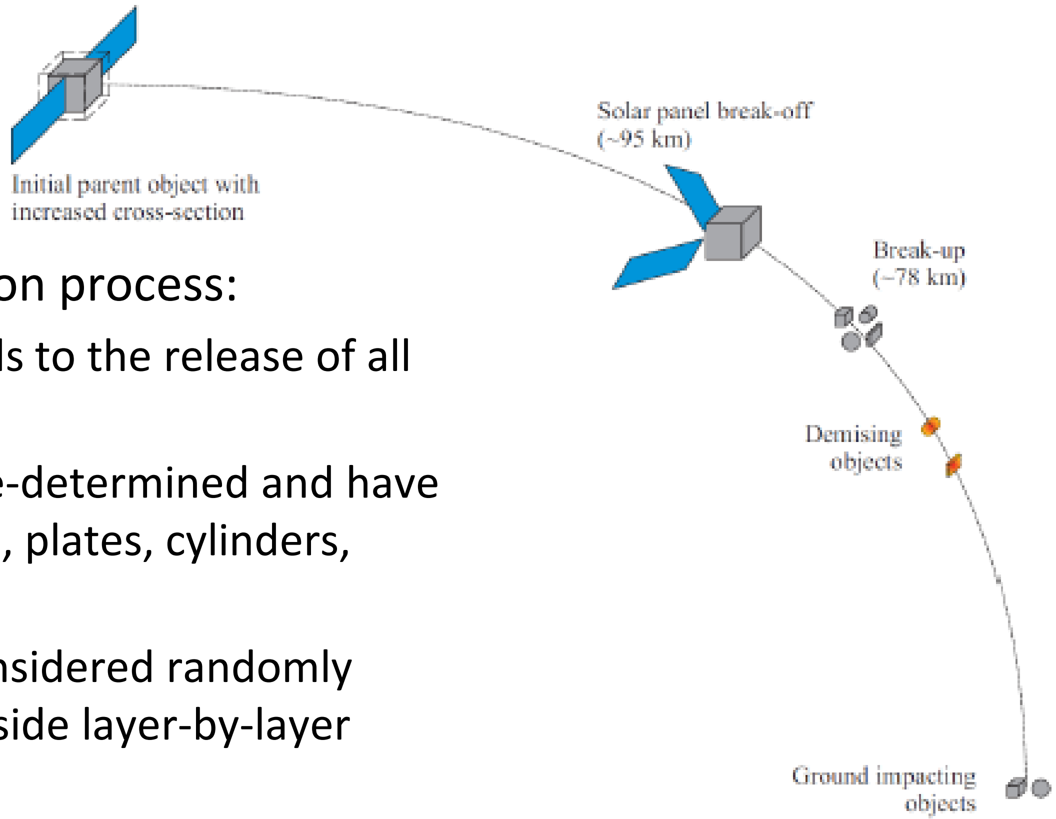


SESAM
Material Models

- European Space maTerIal deMisability dATabasE (ESTIMATE):
  - ➢ Measurement data from Plasma Wind Tunnels
  - ➢ Characterised material parameters.
  - ➢ Reference source for demisability analyses and data
  - ➢ https://estimate.sdo.esoc.esa.int



SESAM
Break-up as a process

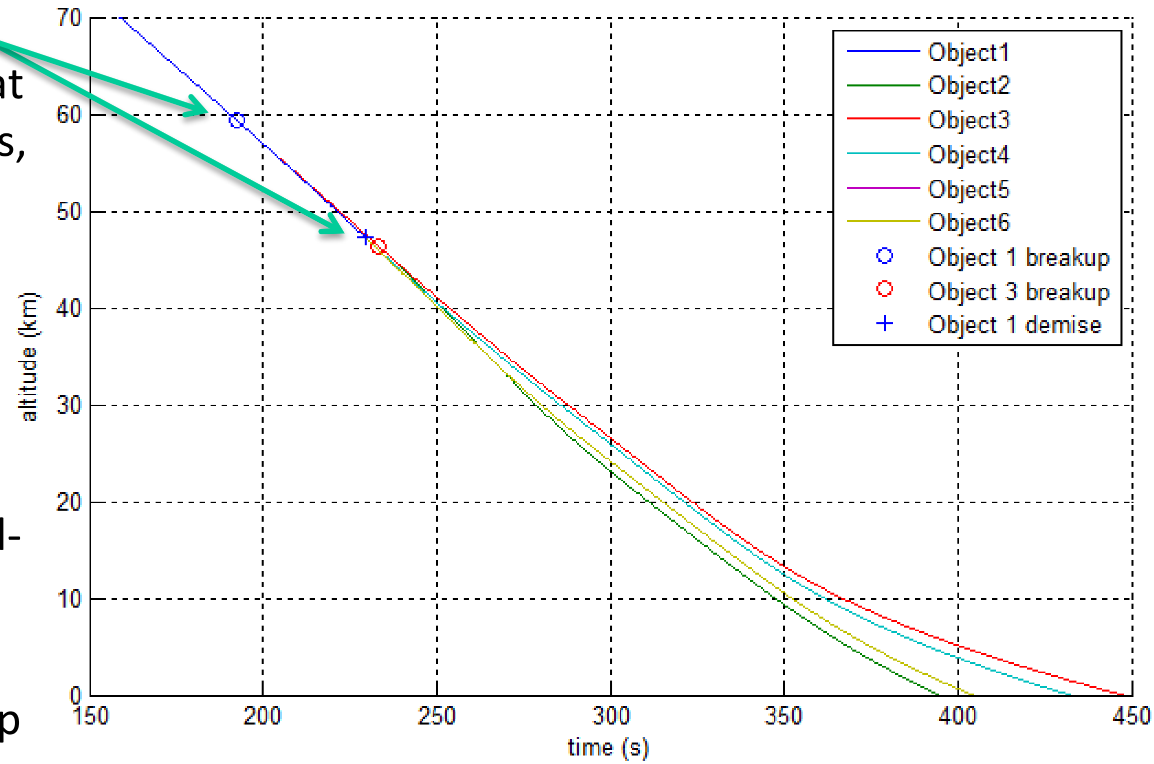


- "Classical" DRAMA2 fragmentation process:
  - The **fixed break-up altitude** leads to the release of all components
  - All released components are pre-determined and have elementary shapes (e.g. spheres, plates, cylinders, boxes).
  - All released components are considered randomly tumbling and melt from the outside layer-by-layer maintaining their shape type.

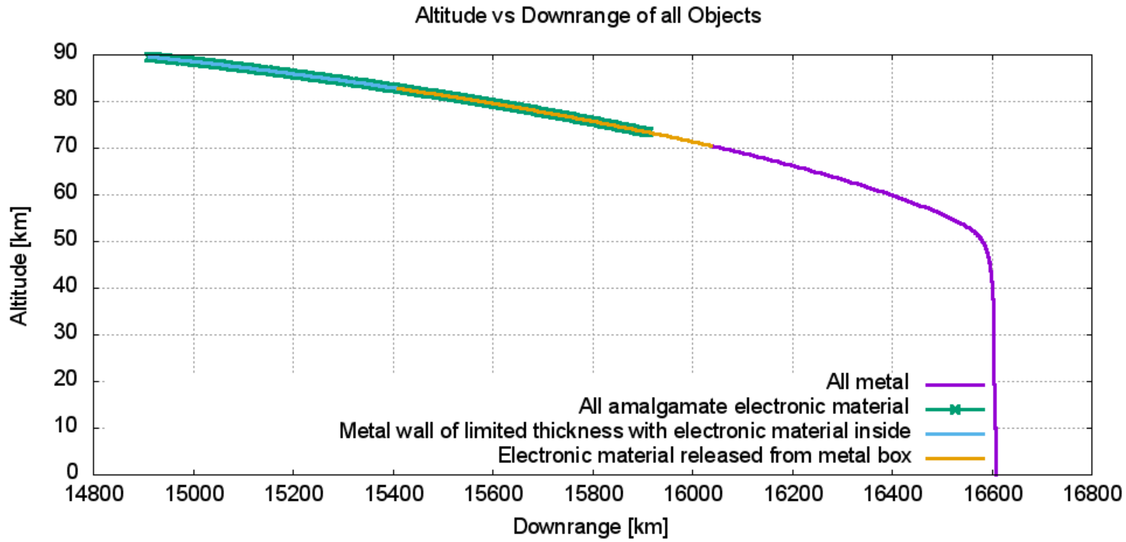
  - The methods suits standardisation, but reached its limits at the design for demise paradigm.

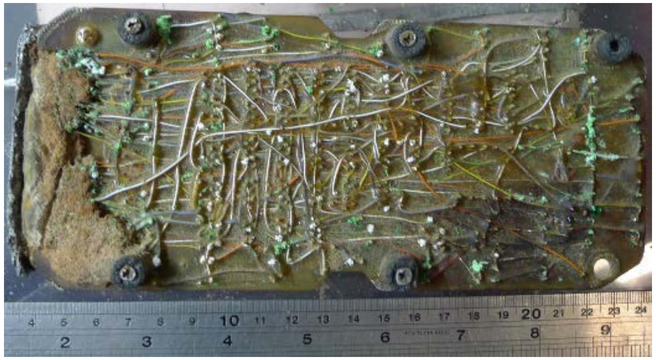
SESAM
Break-up as a process

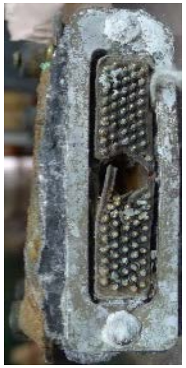
- Improved break-up process
  - ➢ Different objects break-up at different times and altitudes, depending on particular triggers set
- Relationships between spacecraft components
  - ➢ "included-in" or "connected-to" allows for more fine-tuned risk models.
  - ➢ Different (possible) break-up triggers can be empirically identified.



- Improved break-up process
  - ➢ Different objects break-up at different times and altitudes, depending on particular triggers set
- It remains important to define reference behavior
  - ➢ E.g. how to model electronic components?

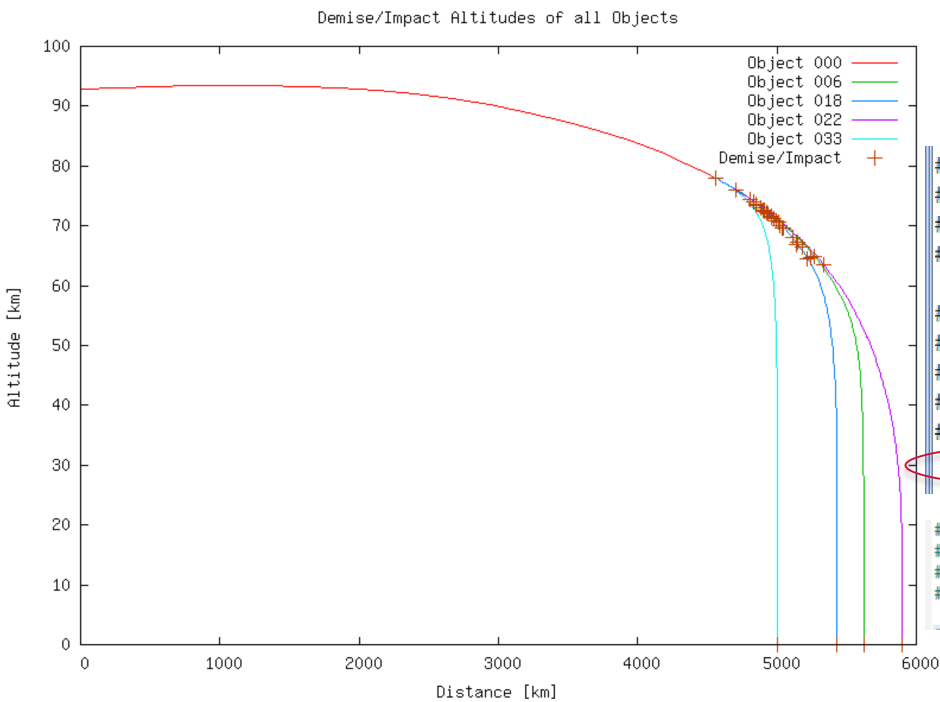






SARA
Complisat example

- DRAMA2 Complisat Recap:
  - Surviving fragments: 2 Bat (heavy housing), 4 RWL (Heavy Steel), 4 Tanks (Light but Titanium), 1 SAR antenna (Large and Copper).




```
# mean effective pop.density within latitude band +/-inc
# (weighted with impact probability as fct(lat)):
# _pop.density[1/km^2]_  _pop.max_
#     avg        max       lat[deg]     comment
    17.737     88.665      35.250      with pop.density=fct(lat)
#
# total casualty probability (for combined casualty cross sections),
# assuming a uniform impact probability distribution over one orbit:
# _______casualty_prob.[-]________
#    min         avg         max          comment
  7.3535E-05 1.2221E-04 1.5098E-04      1D analysis (along track only,

#
# total effective geometric and casualty cross section (all fragments considered):
# ___geom.x-section[m^2]__  __casu.x-section[m^2]__
#   min    avg    max     min    avg    max      comment
  0.3684  1.7375  3.0332  5.4408  9.0425  11.1710  applicable to 1D and 2D analysis
```

- DRAMA3 Complisat:
  - Two hierarchies for the bus
  - Four connected components
  - Analytic tumbling (Inherited) for DRAMA2 comparability
  - Run!

SARA
Complisat example

- DRAMA3 Complisat:
  - Two hierarchies for the bus
  - Four connected components
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  - Same surviving fragments: 2 Batt, 4 RWL, 4 Tanks
  - Additional surviving fragments: TCU and PL3
  - Casualty area increased from 9.04 m^2 to 10.67 m^2
  - Groundtrack shifts by 500km due to the combined aerodynamics.

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  - DRAMA3 mode: Tumbling and bus walls to honey comb material
  - Early fragmentation at ~90km but survival of other heavy components.
  - Casualty area increased from 9.04 m^2 to 10.84 m^2

SARA
Complisat example

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  - Early fragmentation at ~90km but survival of other heavy components.
  - Casualty area increased from 9.04 m^2 to 10.67 m^2

  - DRAMA3 mode: Tumbling and bus walls as initial
  - Model the electric components by means of the amalgam metal and realistic walls
  - Casualty area decreased from 9.04 m^2 to 7.26 m^2

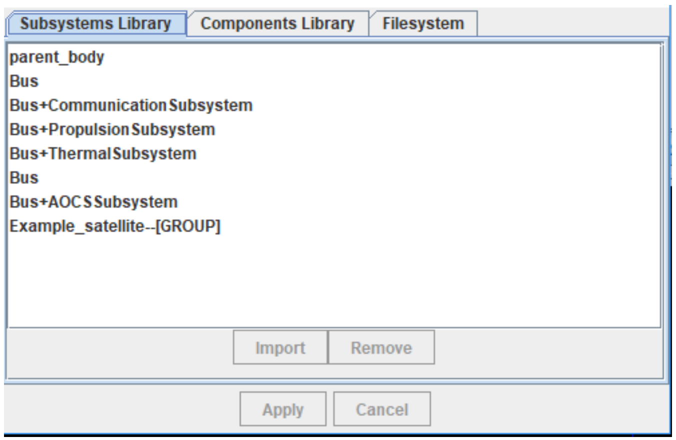
SESAM Text Output

- Re-entry history data for the main object and its fragments
  - Time evolution of the main thermal and trajectory parameters
  - From initial re-entry point down to final condition

- Final state for surviving fragments and ground dispersion
  - Impact location (longitude, latitude)
  - Fragment mass and velocity at impact
  - Cross-section at impact considering mass losses during re-entry
  - Floating capability

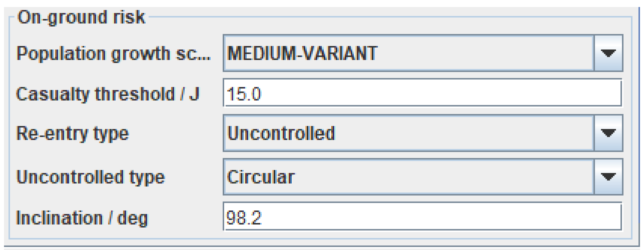
- Graphical output (Figures)
  - Altitude vs. time
  - Altitude vs. downrange flown

DRAMA GUI
Simulation input and settings



- Sidebar sections
  - Basic Settings
  - Model
  - *Fragmentation Model*
  - *Monte Carlo*
  - Plot Options
- Modelled subsystems can be exported and imported across projects
- Materials can be exported and imported across projects

- Sidebar sections
  - Basic Settings
  - Model
  - *Fragmentation Model*
  - *Monte Carlo*
  - Plot Options



- All risk estimate value can be selected:
  - Population growth model
  - Risk threshold
  - Re-entry type and orbit drive the assessment

- Casualty risk for uncontrolled re-entry ($E_{C,unc}$):

$$P_{C,unc} = A_C \rho_p(i, \Delta\varphi, \omega) < 10^{-4}$$

A_C: Total casualty area — Depending on space system design and fragmentation process

$\rho_p(i, \Delta\varphi, \omega)$: Average population density — Depending on orbit inclination, latitude step size (circular orbits), argument of perigee (elliptic orbit)

- Casualty risk for controlled re-entry ($E_{C,con}$):

$$P_{C,con} = 1 - \prod_{k=1}^{N} \left(1 - \sum_{n} \sum_{m} \left(P_{i,k}\right)_{n,m} \left(\rho_p\right)_{n,m} \left(A_{C,k}\right)_{n,m}\right) < 10^{-4}$$

$\left(P_{i,k}\right)_{n,m}$: Local impact probability

$\left(\rho_p\right)_{n,m}$: Local population density

$\left(A_{C,k}\right)_{n,m}$: Local casualty area

- Casualty risk for a failed controlled re-entry ($E_{C,con,fail}$):

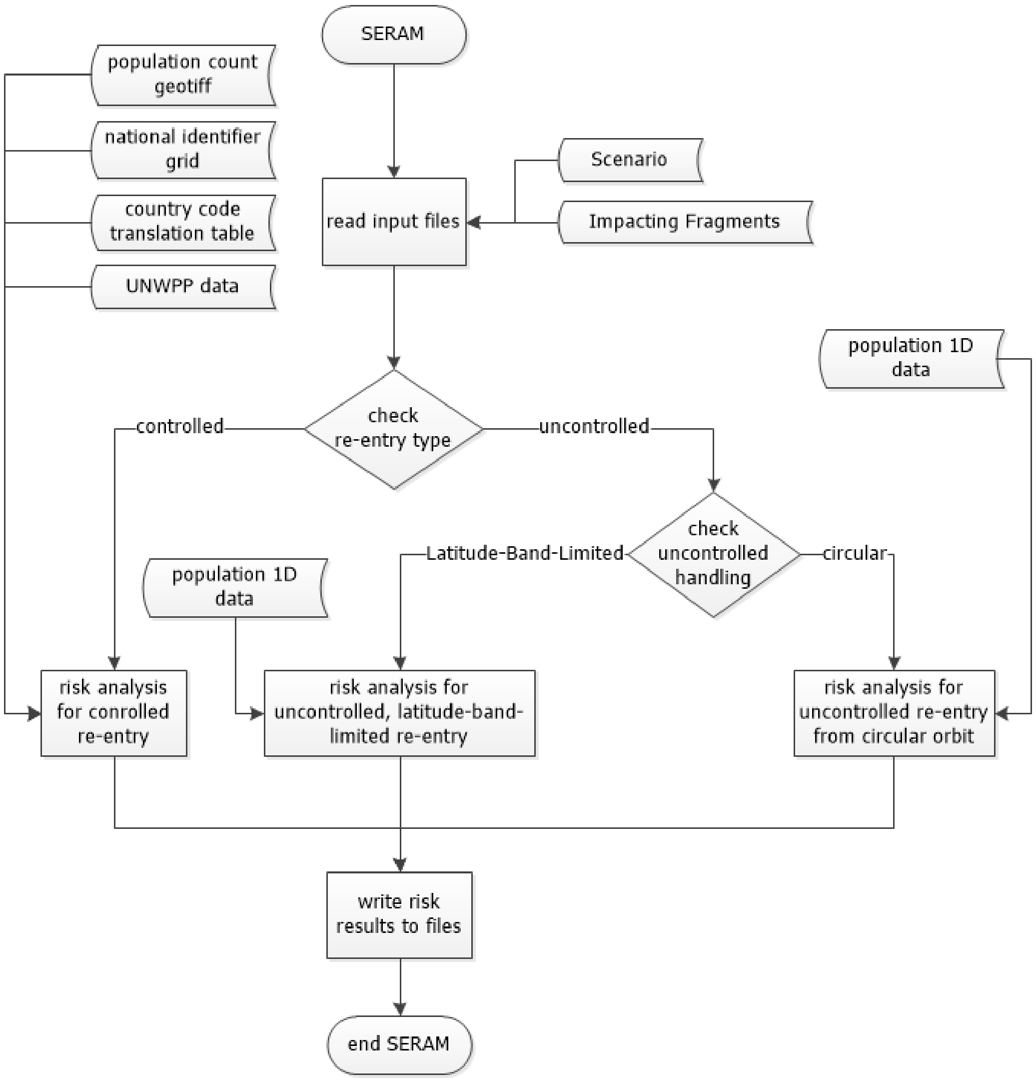
$$P_{C,unc,fail} = E_{C,unc} P_f = A_C \rho_p(i, \varphi, \Delta\varphi) P_f < 10^{-4}$$

P_f: Failure probability

- Definition of scenario and impacting fragments
  - Scenario defined by user
  - List of impacting fragments: SESAM output or user definition

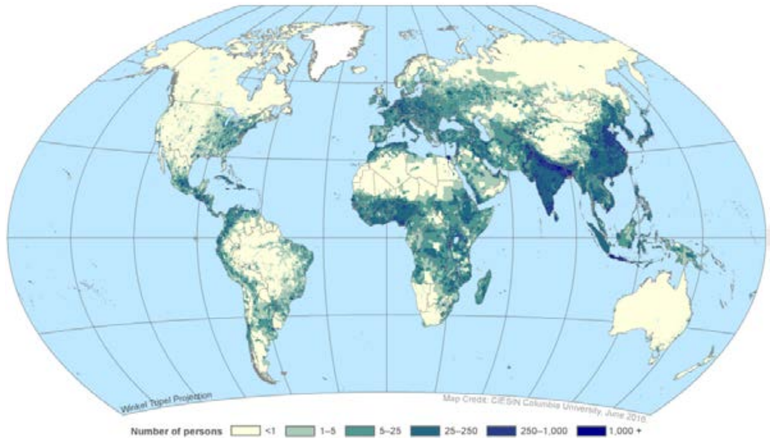
- Risk analyses classes
  - Controlled re-entry
  - Uncontrolled re-entry
  - Latitude-band-limited re-entry (re-entries from HEO)

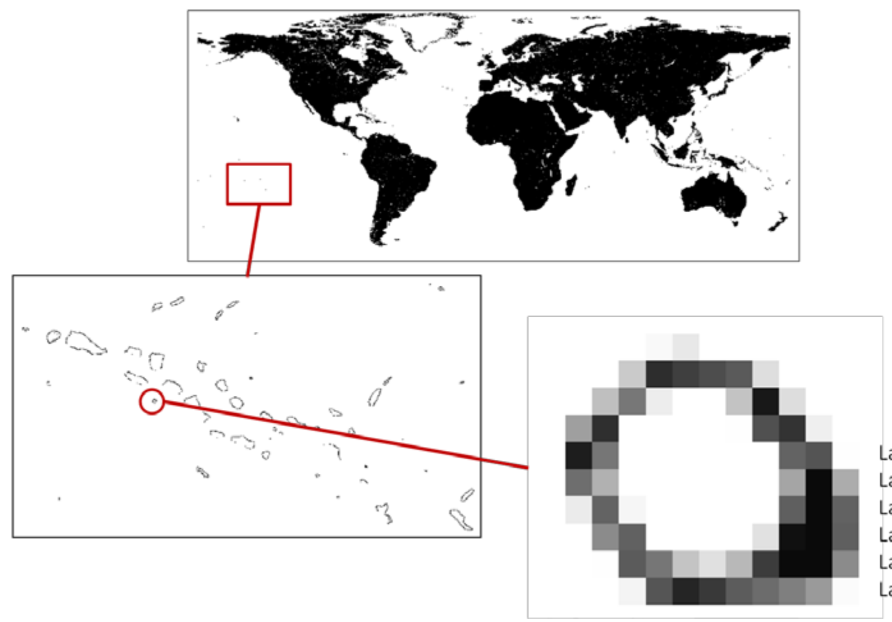
- Casualty & fatality probability calculated for each fragment and the entire event



SERAM
Population Model

- Gridded Population of the World (GPW4)
  - Distribution of human population on world
  - Raster data in 30’’ resolution (1 km x 1 km)
  - 1D population data by averaging over all longitudes





SERAM Population Model

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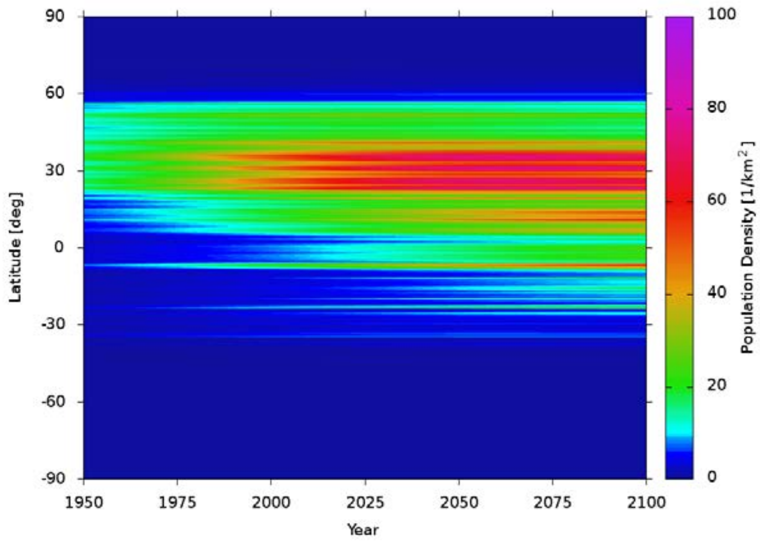
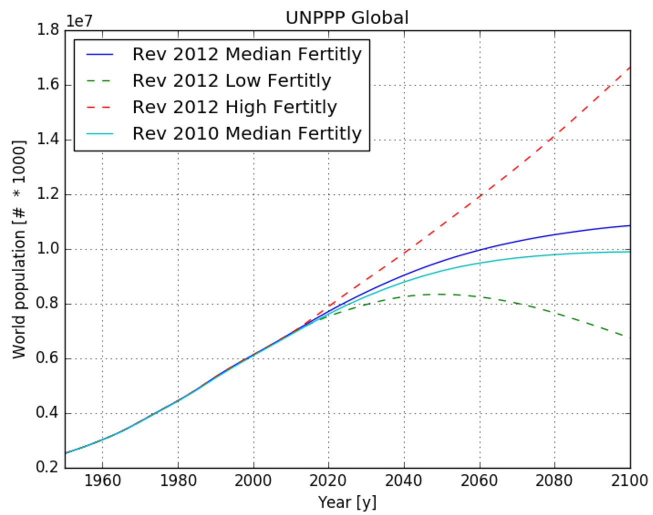
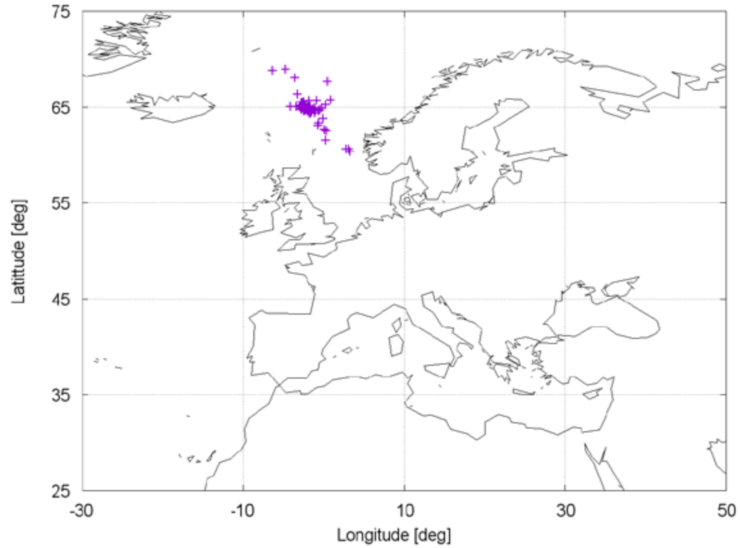


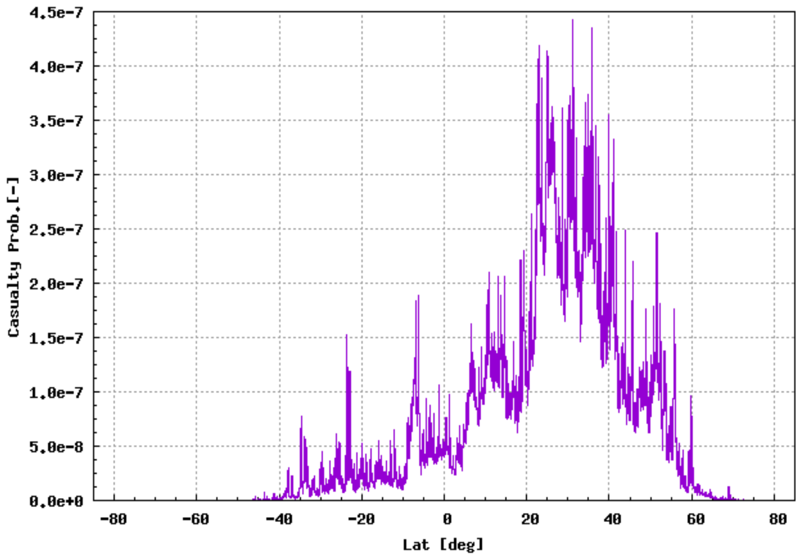
- United Nations World Population Prospects (UNWPP2015)
  - Annual population counts for 1950 – 2100
  - SERAM derives country dependent population growth
  - Eight population growth scenarios, median fertility recommended for use.



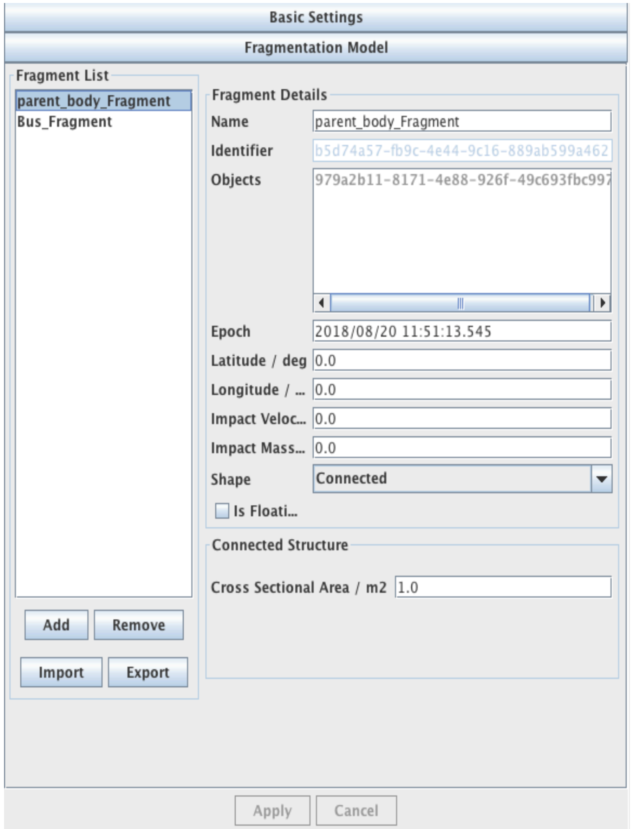
- Risk results
  - Casualty and fatality probability
  - Results given for each fragment and entire re-entry event
  - Summary in RiskResults .xml & .dat file

- Graphical output
  - Impact locations (controlled re-entry)
  - Impact probability vs. latitude
  - Casualty probability vs. latitude
  - Fatality probability vs. latitude





DRAMA GUI
Simulation input and settings



- Sidebar sections
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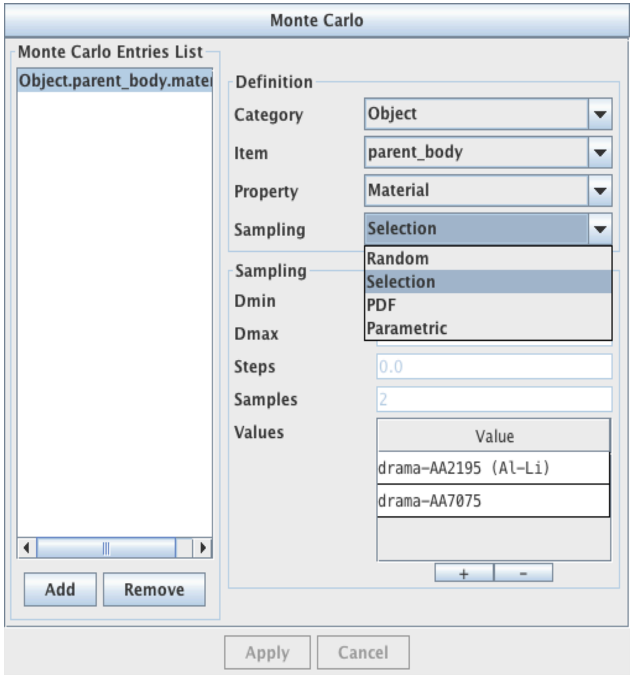
  - Plot Options

- “Risk only” Run mode
- Risk assessment can be run independent
  - After a SESAM run
  - With output from other tools

- Many parameters of re-entry analyses are inherently uncertain:
  - Material properties
  - Break-up phenomenology
  - …
- Or come with estimated error margins:
  - Heating correlations
  - Time of re-entry
  - …
- In some case, a fixed process (a la DRAMA2) is thus not desirable:
  - Determination of the re-entry safety ellipsoids for controlled re-entry
  - Equipment survivability assessment based on release altitude

Monte-Carlo Wrapper
Input and Simulation

- Multiple runs of SESAM and/or SERAM with varied input parameters
- Different variation methods for input parameters
  - Parametric variation (parameter range and fixed step size)
  - Stochastic variation (normal distribution)
  - Probability distribution (arbitrary, user defined probability density function)
  - Selection
- Possible variation of
  - Initial state
  - Object related parameters (e.g. dimensions, mass, explosion trigger conditions)
  - Material properties (e.g. density, melting temperature)
- Results are evaluated after completion of all runs



- Sidebar sections
  - Basic Settings
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  - Plot Options

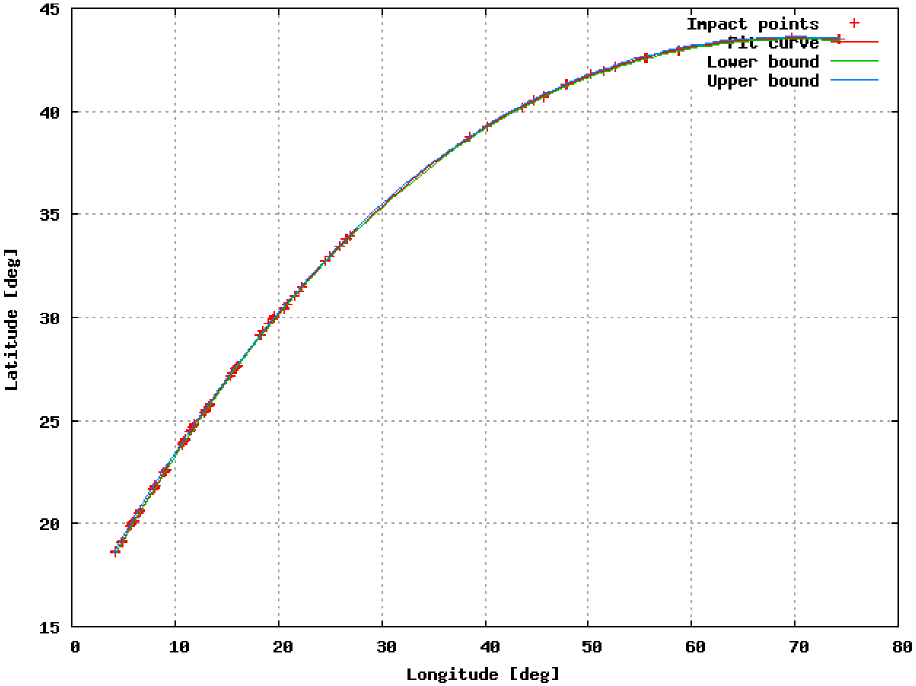
- All GUI parameters are selectable for variation
- Sequential execution of a Cartesian parameter space

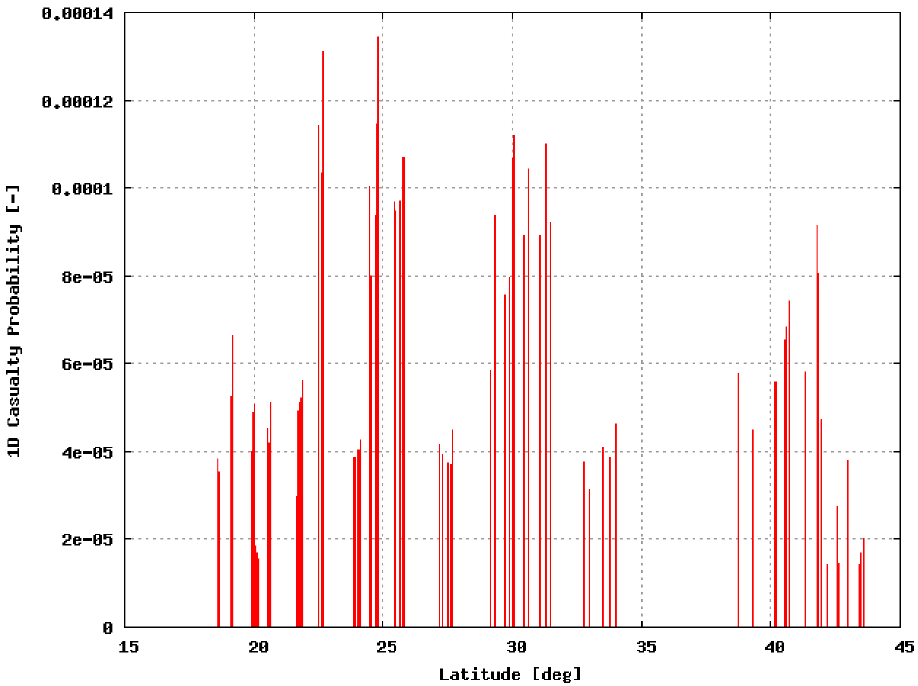
Monte-Carlo Wrapper Evaluation and Output

- Event-related results
  - Total 1D or 2D casualty risk
  - Total 1D or 2D fatality risk
  - Mass of ground fragments and casualty area
- Fragment-related results
  - Impact location (latitude, longitude)
  - 1D/2D casualty risk and 1D/2D fatality risk
  - Fragment mass and casualty area
- Statistics on
  - Ground impact points
    - Ranges (longitude, along-track, cross-track)
    - Areas (Bounding box, DRA, SRA)
  - Total 1D/2D casualty, 1D/2D fatality risk, mass and casualty area

Monte-Carlo Wrapper
Example Results

- Example Monte-Carlo variation of SESAM input
  - ➢ 450 Ground fragments from 150 simulations
  - ➢ Variation of initial altitude, velocity and flight path angle
  - ➢ Impact location fit (3rd degree polynomial), with bounding box (left image)
  - ➢ 1D casualty probability for all impacting fragments (right image)





Summary

- DRAMA‘s SESAM and SERAM modules have been upgraded
  - Improved object oriented method considering object relations and shadowing
  - Large variety of triggers, for break-ups and explosions at different conditions
  - Support for controlled and uncontrolled re-entries from LEO up to HEO
  - Up-to-date population models (GPW/UNWPP)
  - Input and output in XML format, to improve tool comparability
- Newly developed Monte-Carlo module
  - Different methods to vary SESAM and/or SERAM input parameters
  - Statistical analysis, including determination of DRA and SRA
- Implementation of new functionality into the existing DRAMA GUI
  - Import/export functionality for components and materials
  - Databases for components and materials