NUMERICAL SIMULATIONS FOR SPACECRAFT CATASTROPHIC DISRUPTION ANALYSIS

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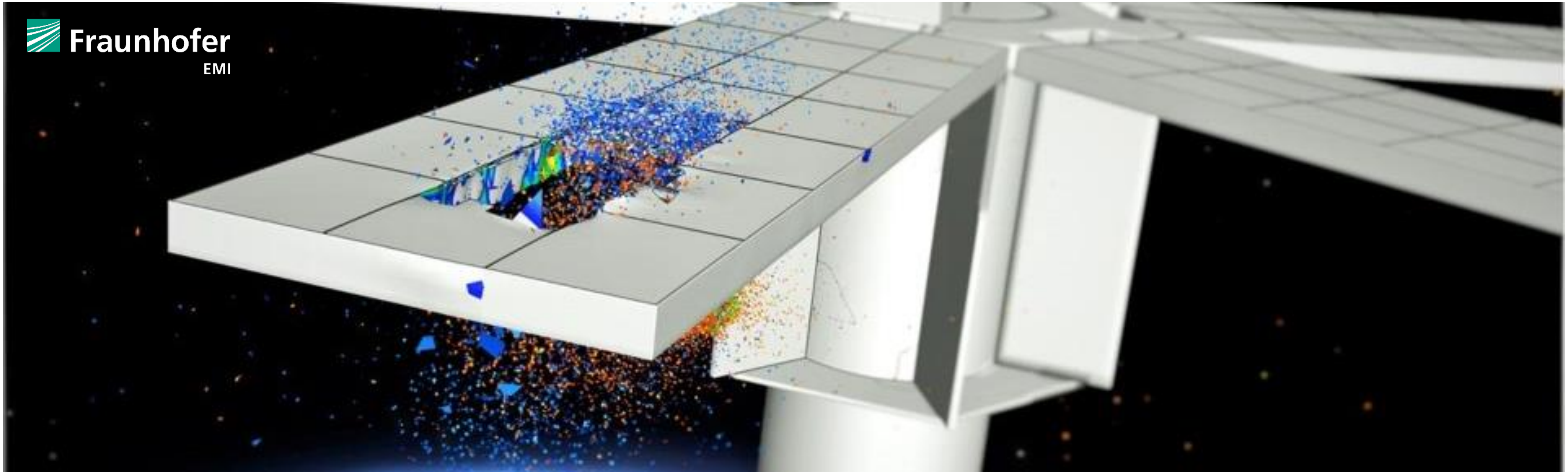

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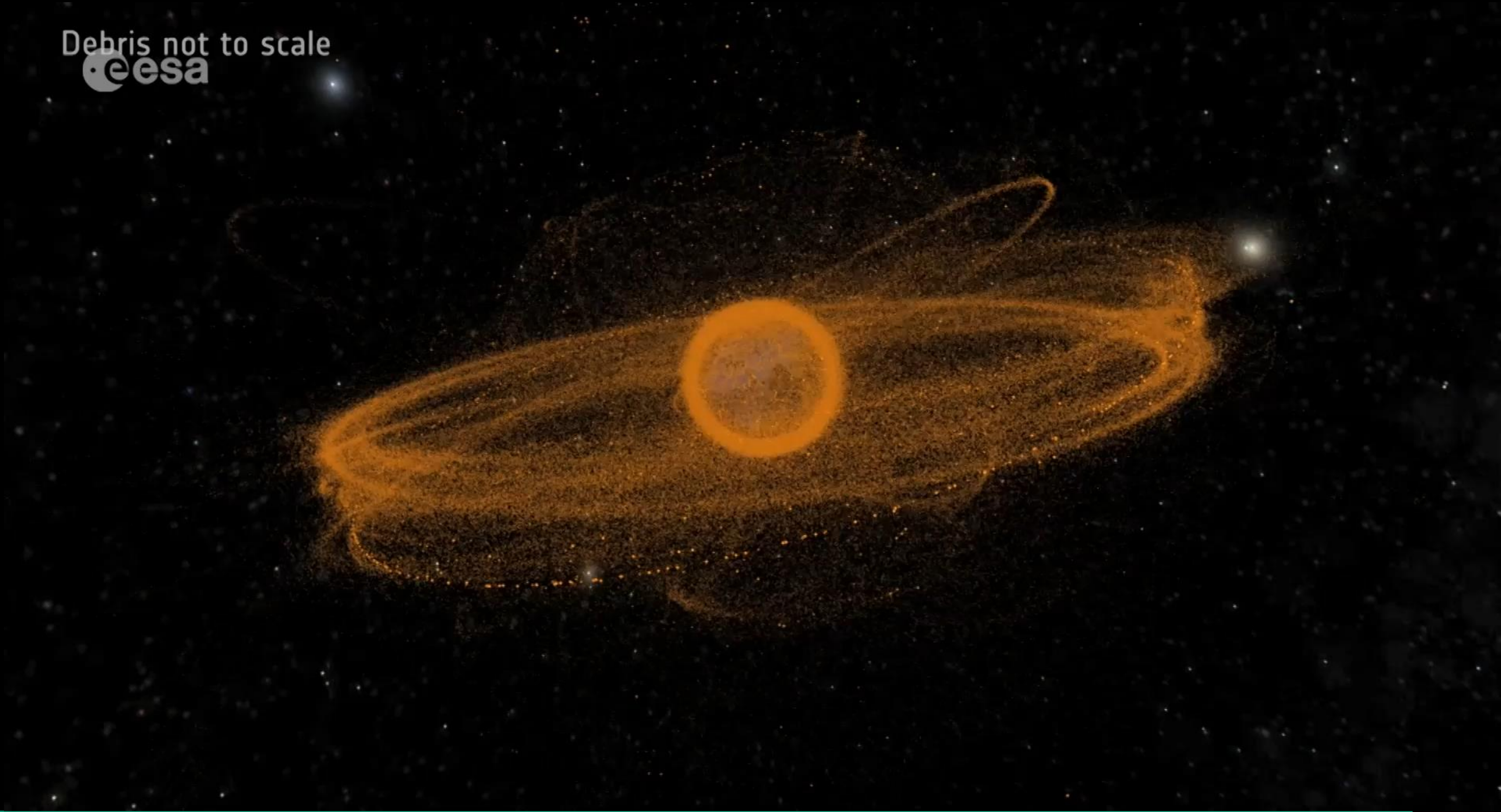
Background
Space Debris Environment Modeling

Space debris models for analysis and predictions are based on

- Databases
- Space surveillance catalogs
- Supporting models
    - Orbit propagation
    - Spacecraft breakup



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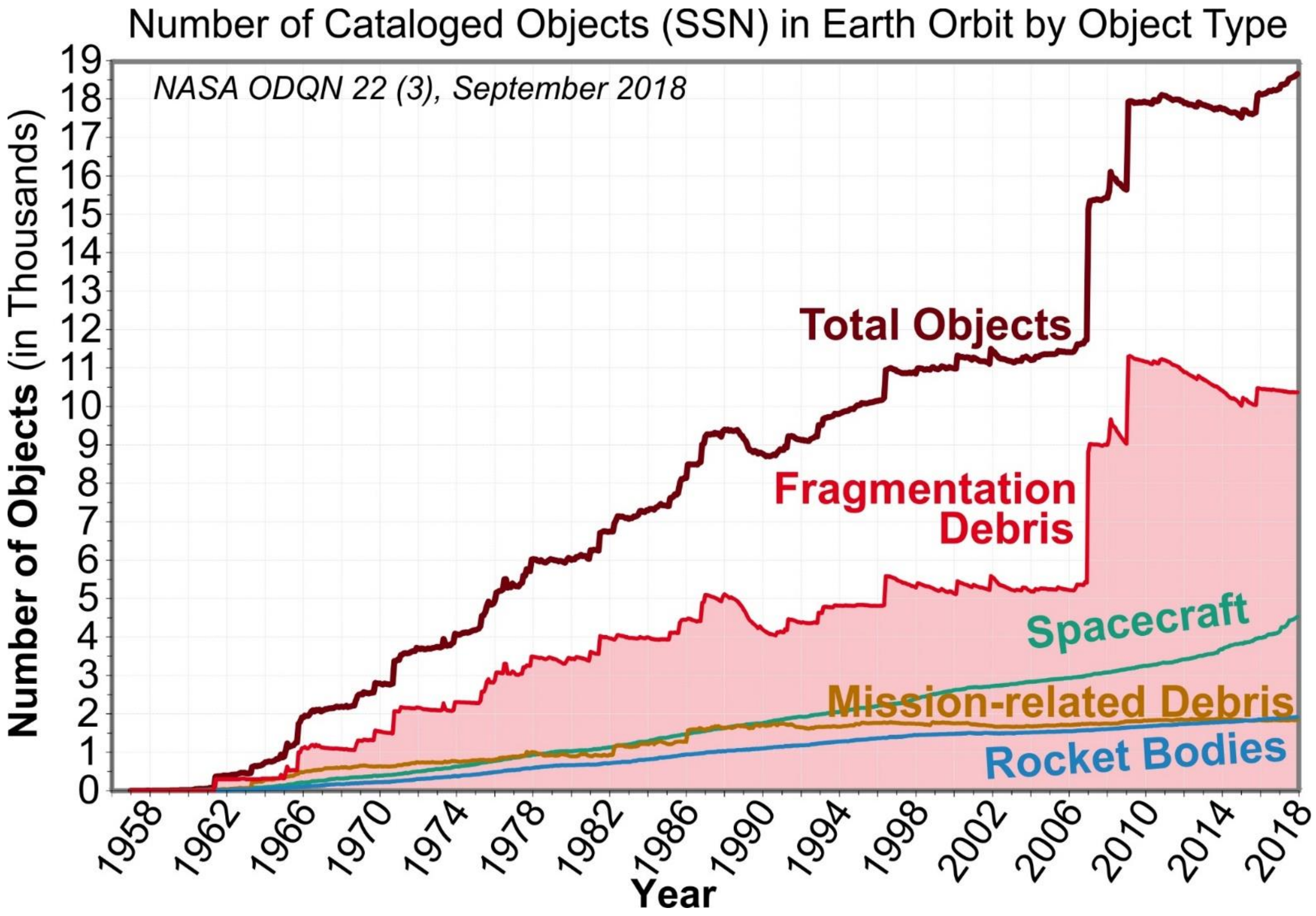
Background
Fragmentations on orbit

- Fragmentation debris (explosions and collisions) dominant population
- Collisions predicted to be the dominant source in mid-term future

➡ Quality of breakup modeling is critical for environment models and spacecraft risk analysis

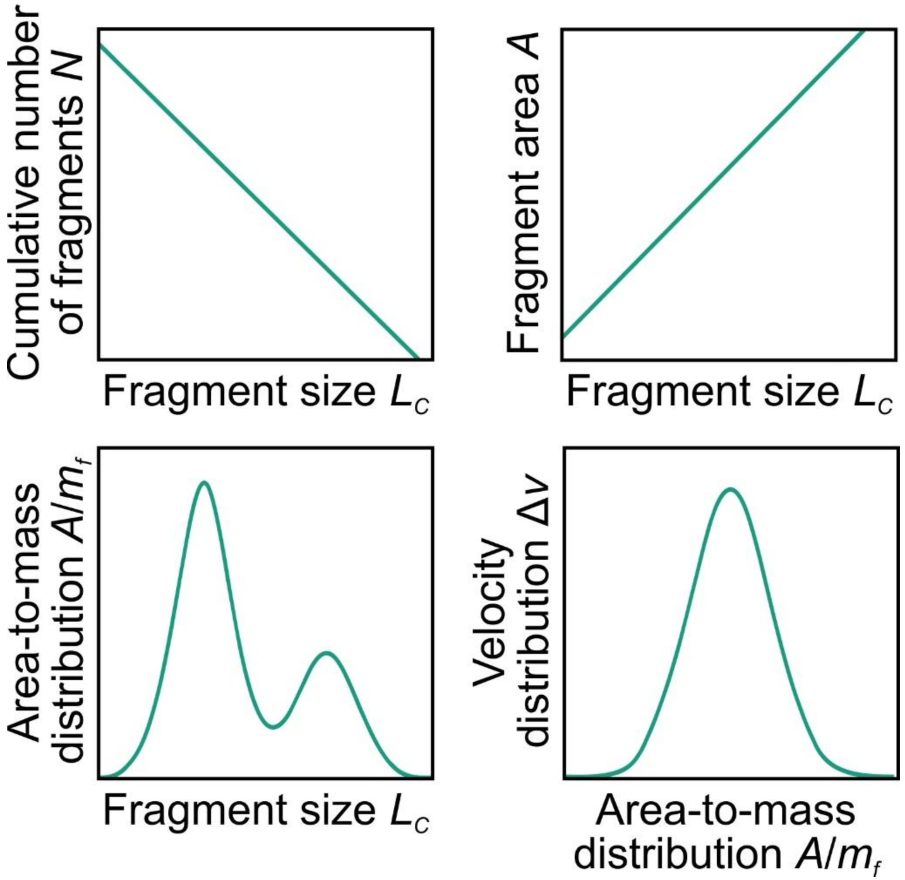


Background
NASA Standard Satellite Breakup Model

→ No individual fragment characteristics

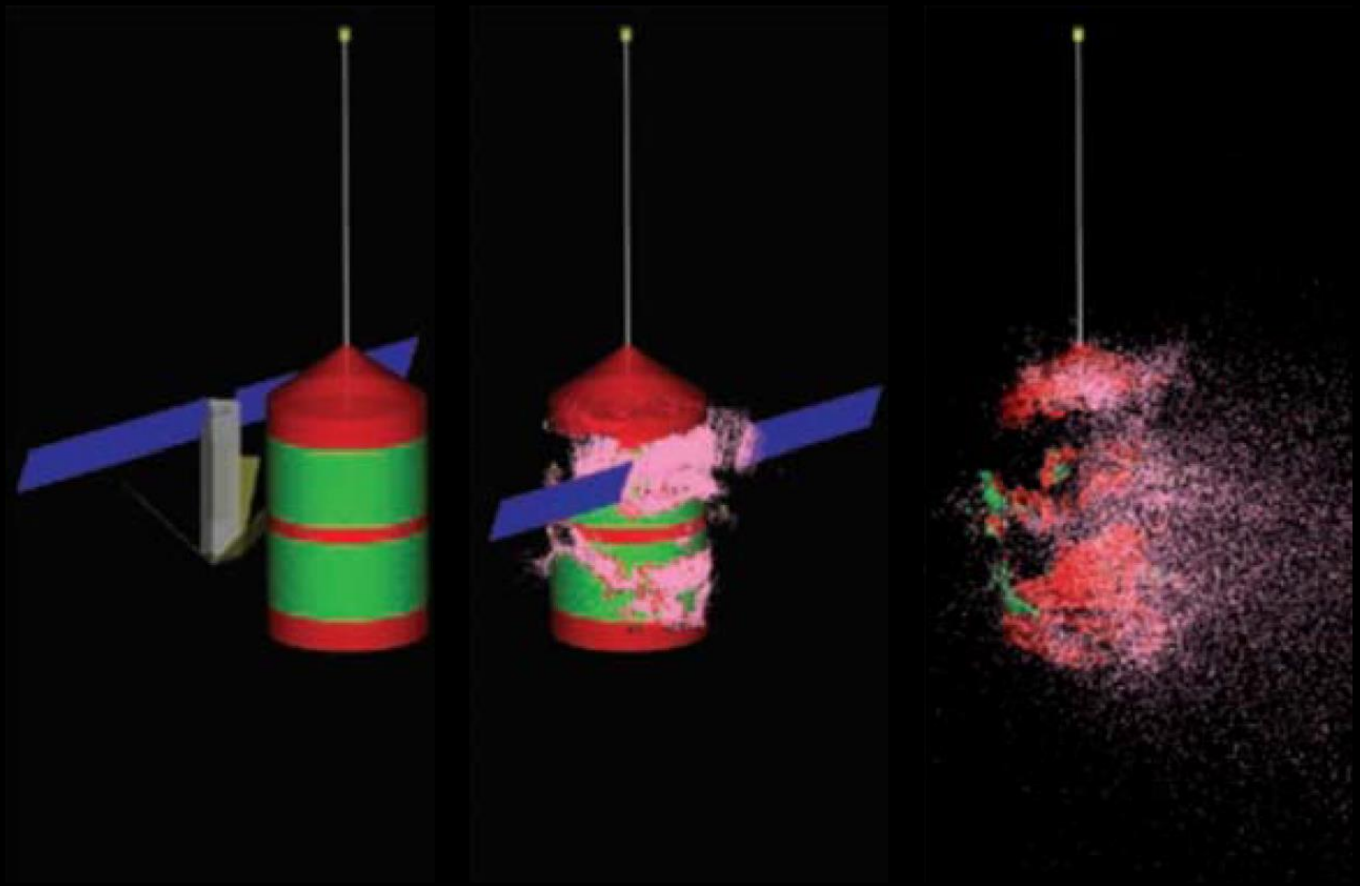
→ Not physics based

- Three input parameters:
  - Overall mass of colliding objects M
  - Mass m_p and velocity v of smaller object
- One variable: Characteristic fragment size L_C
- Simple breakup criteria: $EMR = ½\, m_p\, v^2 / m_t > 40$ J/gr
- Empirical model based on
  - Observational data of on-orbit tests (Solwind P78-1, Delta-180, unspecified)
  - Ground testing (SOCIT impact test, Ariane upper stage explosions, DebriSat)



Numerical Simulations for Spacecraft Catastrophic Disruption Analysis
Objectives

- Establish a numerical methodology for characterizing on-orbit collisions of satellites
- Demonstrate numerical tool by performing simulations with complex target satellite
- Analyze breakup events and the standard 40 J/g *EMR* catastrophic disruption criteria



K. Walter et al. 2009, LLNL

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Software tool PHILOS-SOPHIA
Hydrocodes – Continuum Description & Constitutive Material Modelling

- Conservation laws:

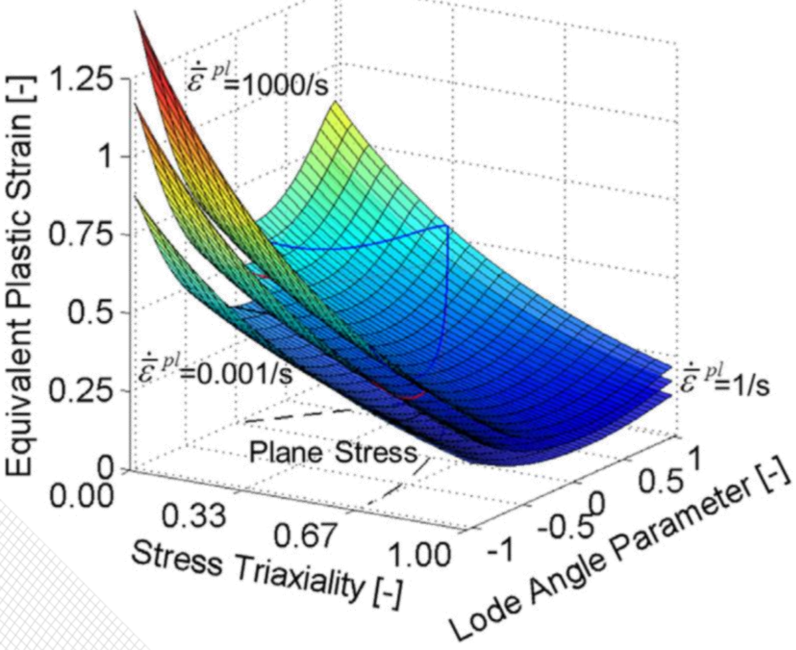
Mass $$\frac{\partial\rho}{\partial t}+v_i\frac{\partial\rho}{\partial x_i}=\frac{D\rho}{Dt}=-\rho\frac{\partial v_i}{\partial x_i}$$

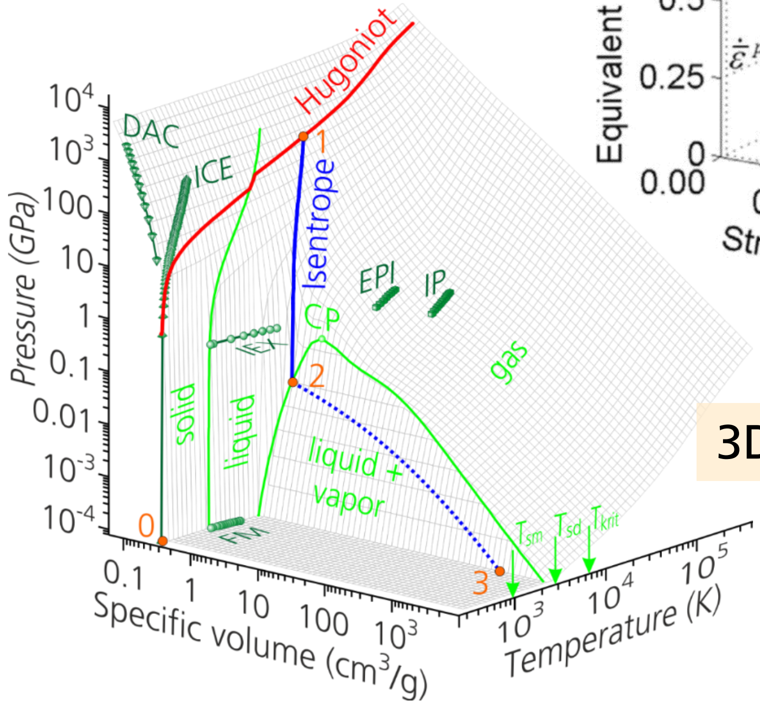
Momentum $$\frac{\partial v_i}{\partial t}+v_j\frac{\partial v_i}{\partial x_j}=\frac{Dv_i}{Dt}=f_i+\frac{1}{\rho}\frac{\partial\sigma_{ij}}{\partial x_j}$$

Energy $$\frac{\partial e}{\partial t}+v_i\frac{\partial e}{\partial x_i}=\frac{De}{Dt}=f_i v_i+\frac{1}{\rho}\frac{\partial(\sigma_{ij}v_i)}{\partial x_j}$$

- Equation of state $p=p(\rho,e)$
- Structural dynamics $\mathbf{S}_{ij}=\sigma_{ij}+p\,\mathbf{I}_{ij}\quad p=-\frac{1}{3}\sigma_{ii}$
- Strength model $\mathbf{S}_{ij}=\mathbf{S}_{ij}(\varepsilon_{ij},\dot{\varepsilon}_{ij},e_{in},D)$
- Failure model $\boldsymbol{D}=\boldsymbol{D}(\boldsymbol{S}_{ij},\varepsilon_{ij},p,\ldots)$

Strength and failure





3D phase diagram

V.E. Fortov & I.V. Lomonosov 2010

T. Fras et al. 2018

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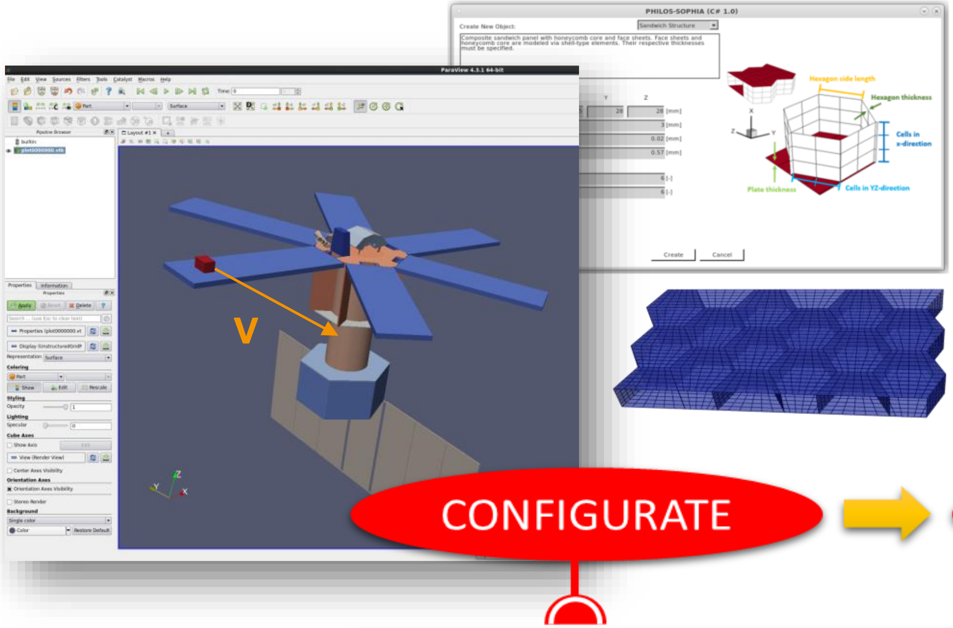
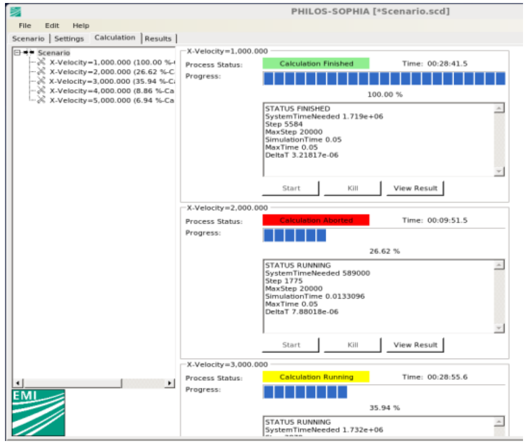
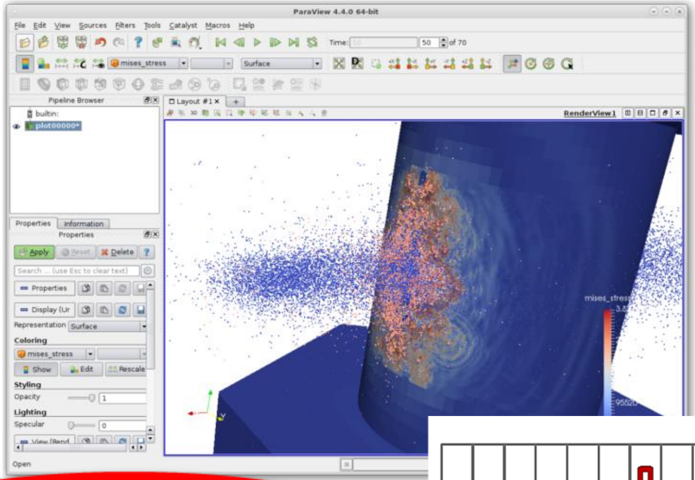
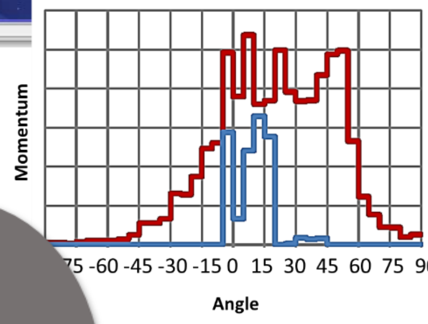
Software tool PHILOS-SOPHIA
Process chain







CONFIGURATE → SIMULATE → EVALUATE



Scenario Configurator
- S/C Model Database
- Space Debris Object Modeler
- Parameter setting
- Batch mode operation

Hydrocode Simulation

Fragment Analyzer
- Number
- Mass Distribution
- Momentum Transfer
- etc.

Damage Viewer

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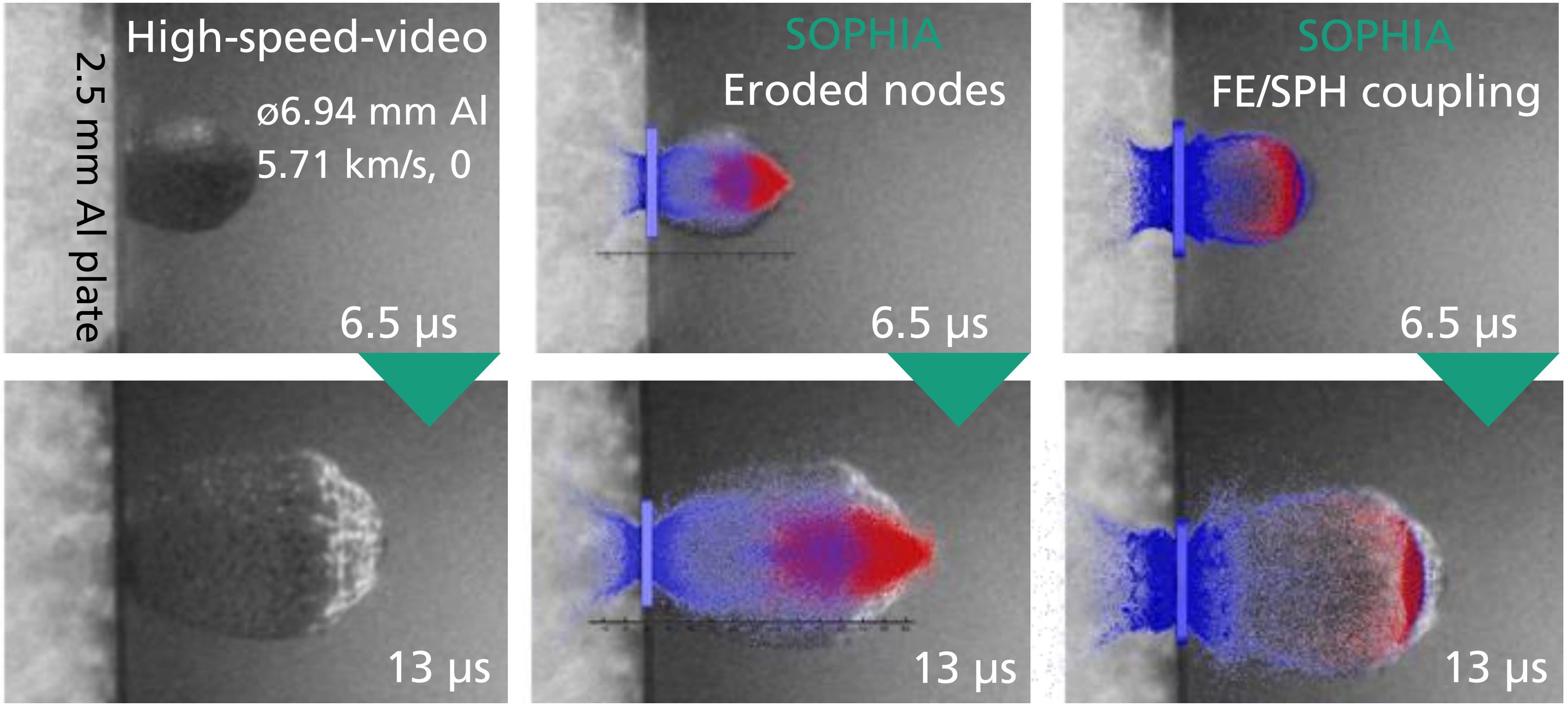
Software tool PHILOS-SOPHIA

Validation - Experiment reproduction

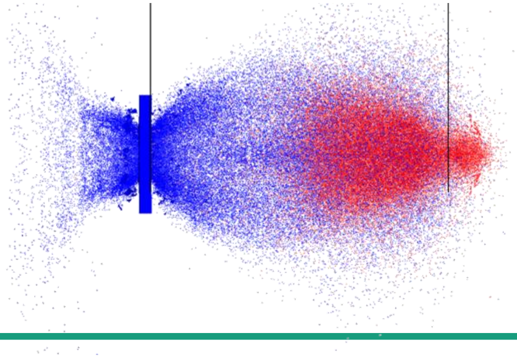
402,216 finite elements
8.7 hours computation

68,208 finite elements
210 hours computation



402,216 finite elements
27 hours computation

ANSYS-AUTODYN
Eroded nodes



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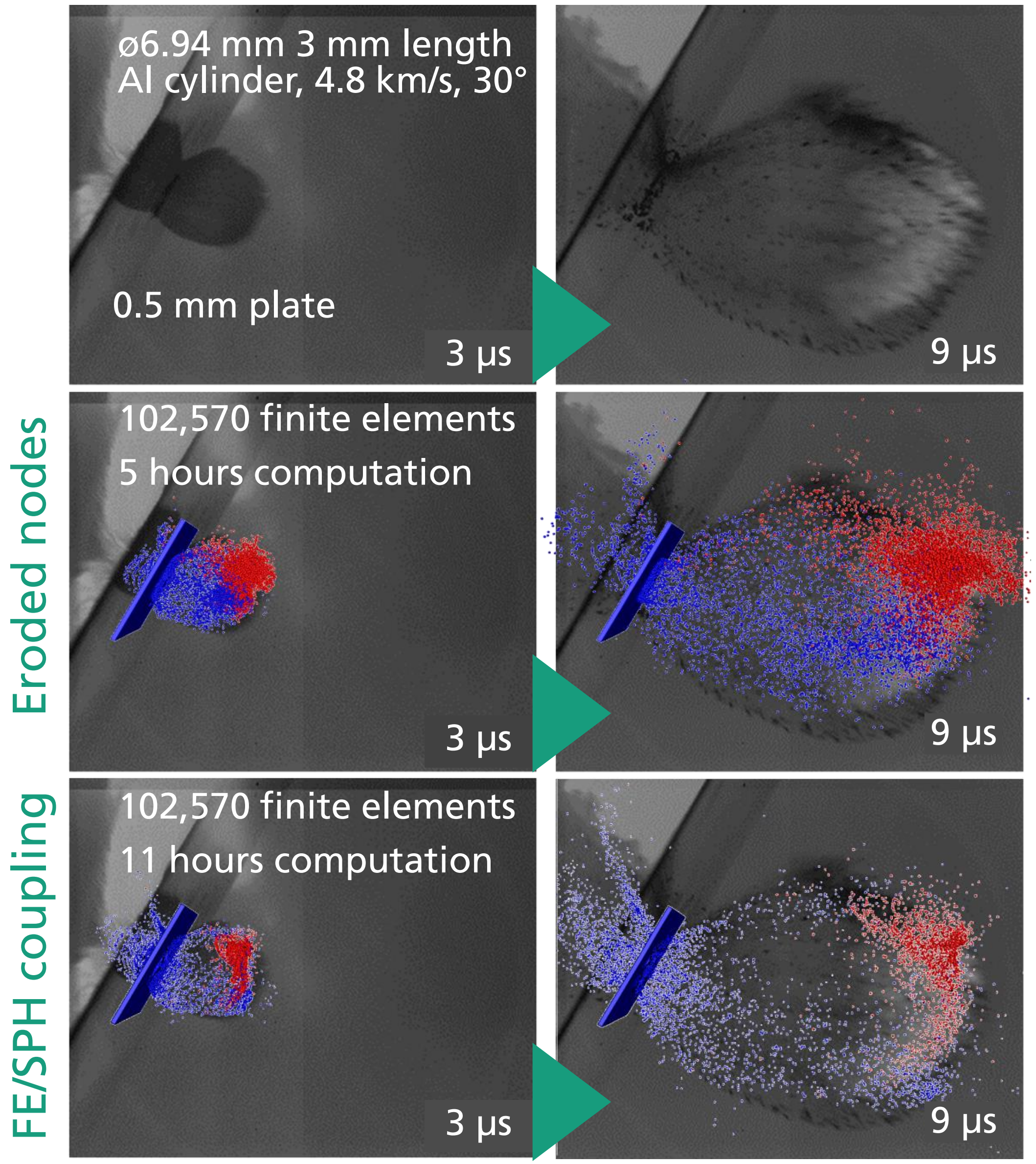
Software tool PHILOS-SOPHIA
Validation - Experiment reproduction

- Hypervelocity impact experiment reproduction
  - SOPHIA reproduces all fragmentation features
  - Analysis needs dictate computation effort

- Experimental data needed for quantitative validation



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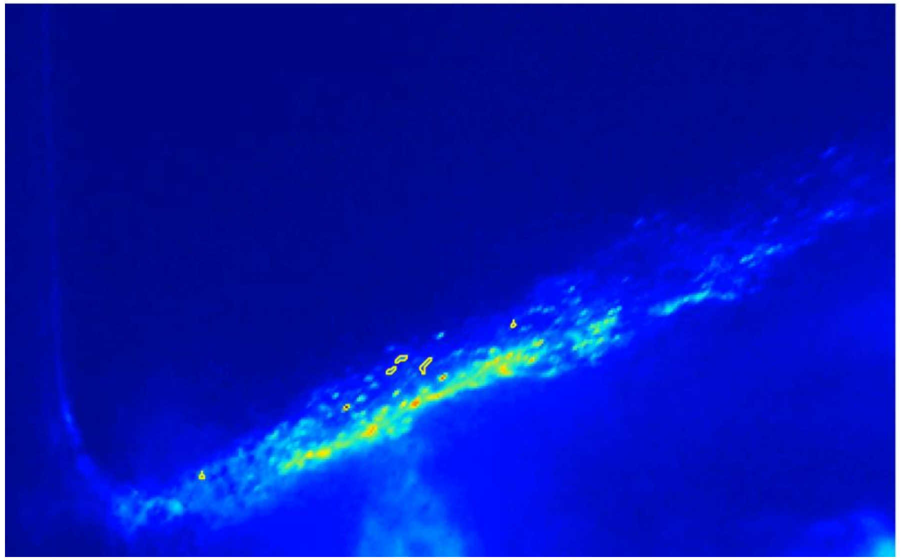
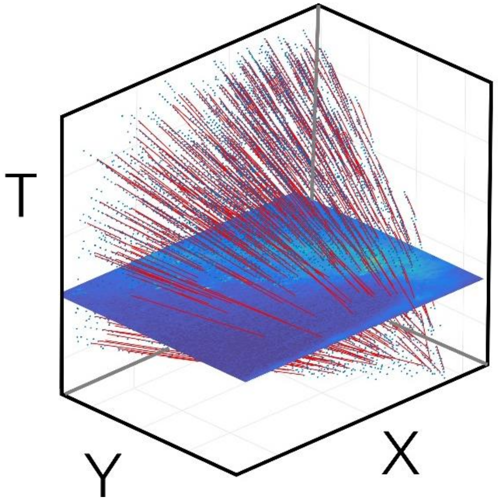
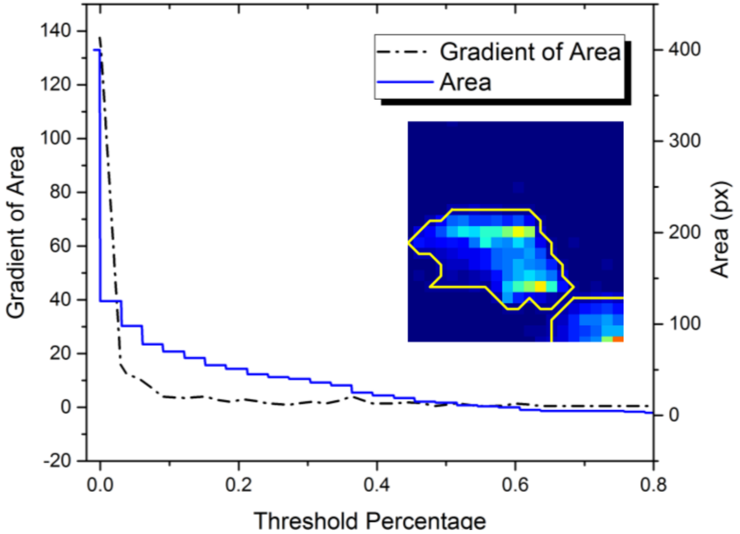
Software tool PHILOS-SOPHIA
Validation - Experiment reproduction



- Hypervelocity impact experiment reproduction
  - SOPHIA reproduces all fragmentation features
  - Analysis needs dictate computation effort
- Experimental data needed for quantitative validation

➡ Advanced particle tracking methods for measuring contour, trajectory and velocity of individual fragments





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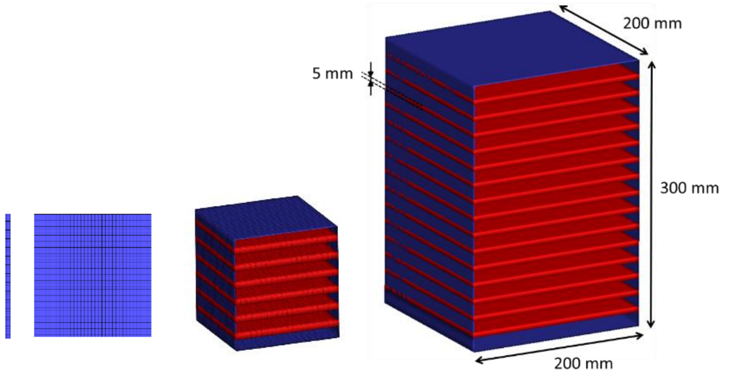
Numerical Simulations for Spacecraft Catastrophic Disruption Analysis

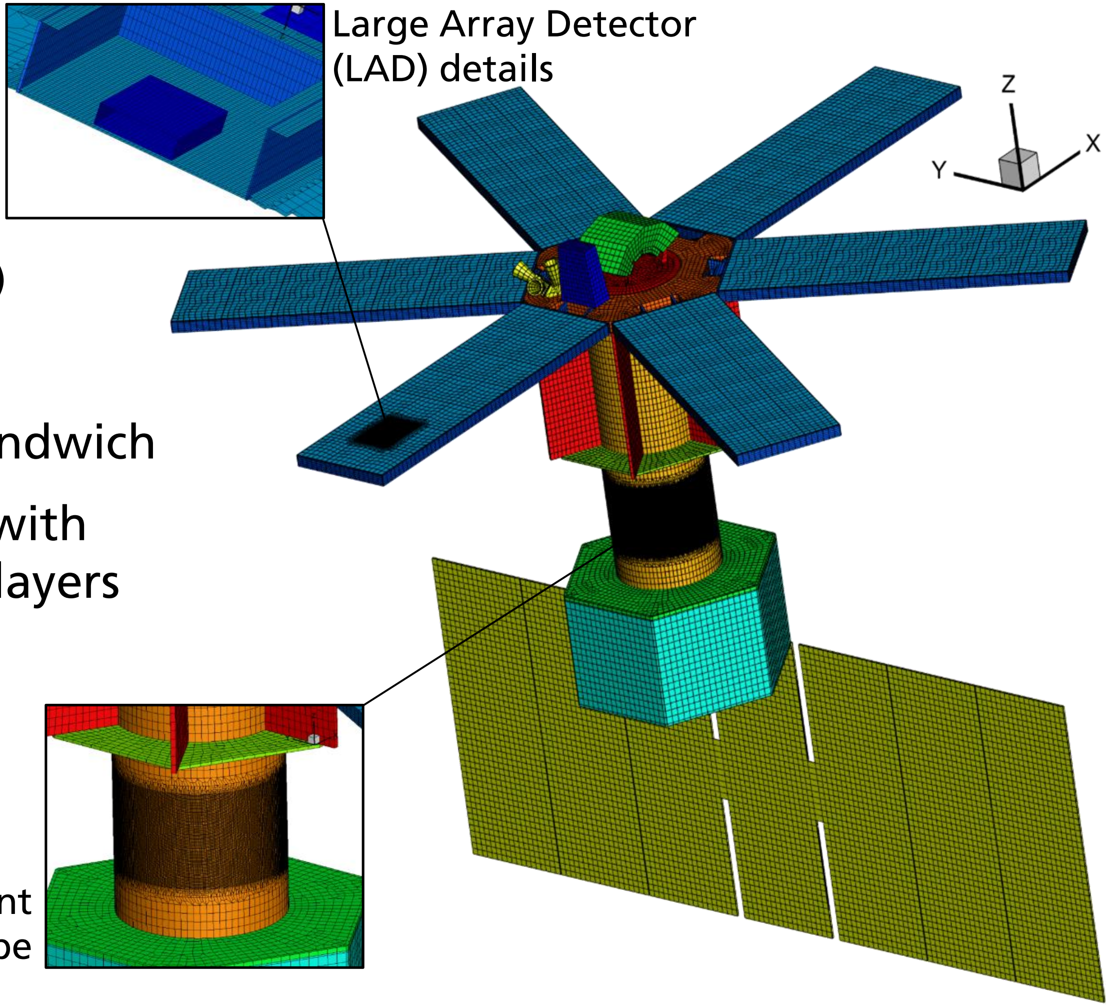
Spacecraft finite element models

- Impactors
  - Thin plate, 0.1 kg
  - 1U CubeSat, 1 kg
  - 12U CubeSat, 10 kg



- Target: ESA LOFT
  - Internal components
  - Silicon detectors (LAD)
  - Titanium tank
  - Al- and CFRP-based sandwich

→ Analogous model with two shell element layers



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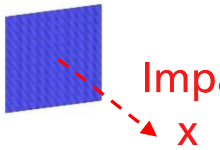
Numerical Simulations for Spacecraft Catastrophic Disruption Analysis
ESA LOFT non-catastrophic collision – scenario 1) & 2)

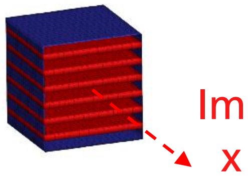
Impacts on center of geometry/mass with EMR < 40 J/g

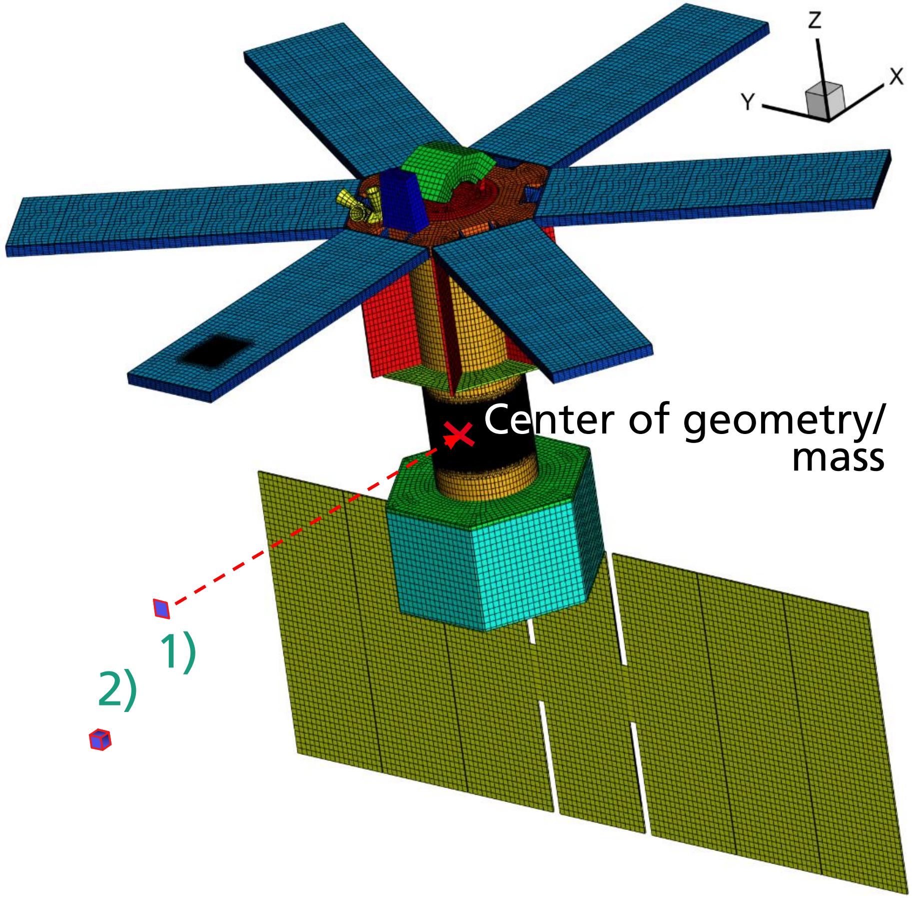
Impact velocity: 11 km/s

1) Plate impactor central impact
   Dimension: 4×100×100 mm^3
   Mass: 0.1 kg
   EMR: 3.025 J/G (12.1 J/g)



2) 1U CubeSat impactor central impact
   Dimension: 100×100×100 mm^3
   Mass: 1 kg
   EMR: 30.25 J/G (121 J/g)





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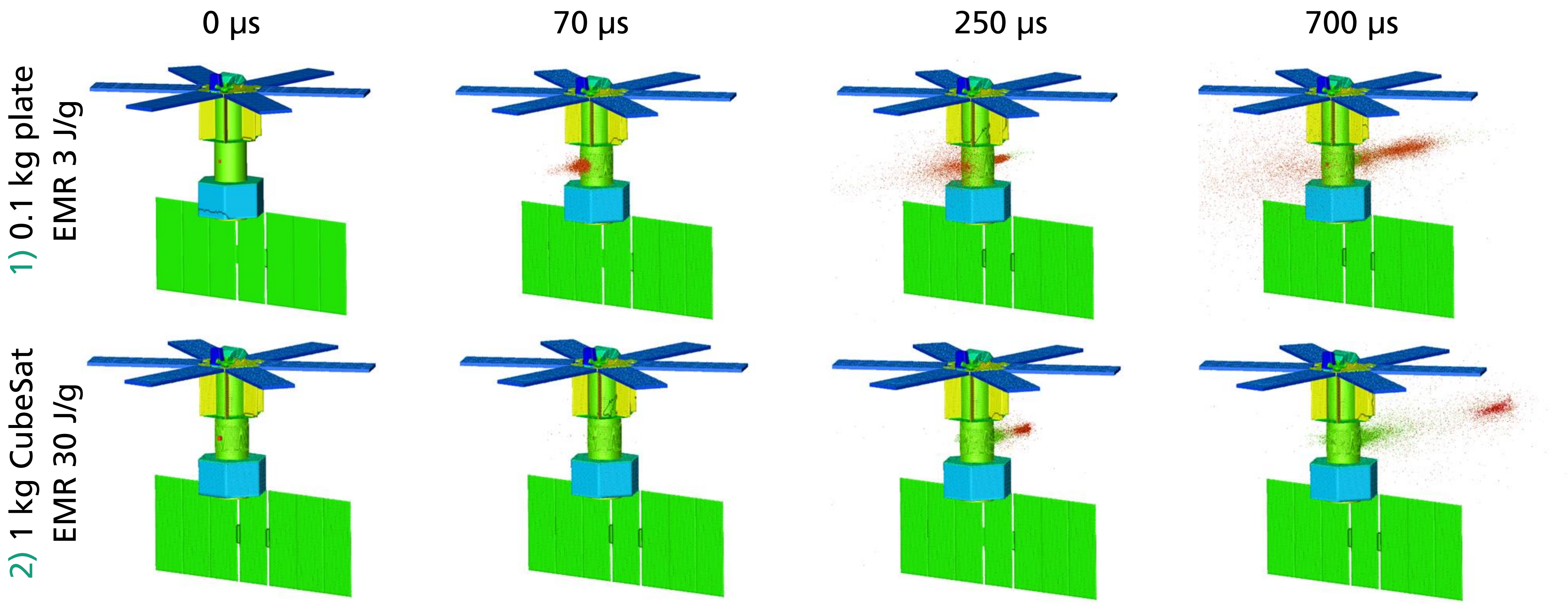
Numerical Simulations for Spacecraft Catastrophic Disruption Analysis

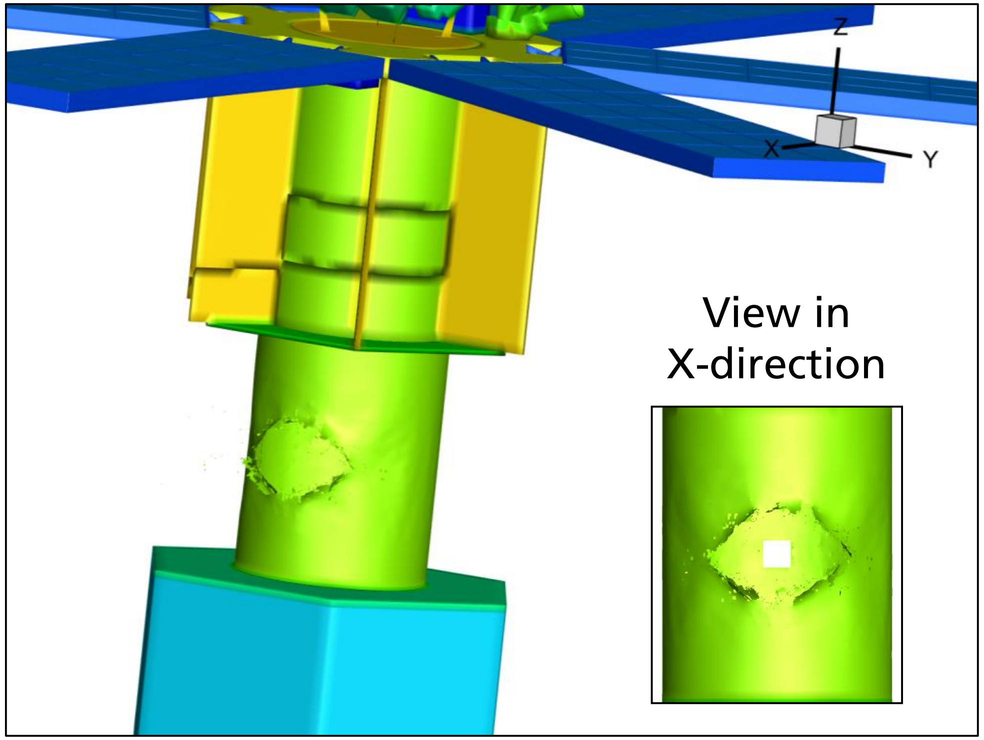
ESA LOFT non-catastrophic collision – Fragmentation process



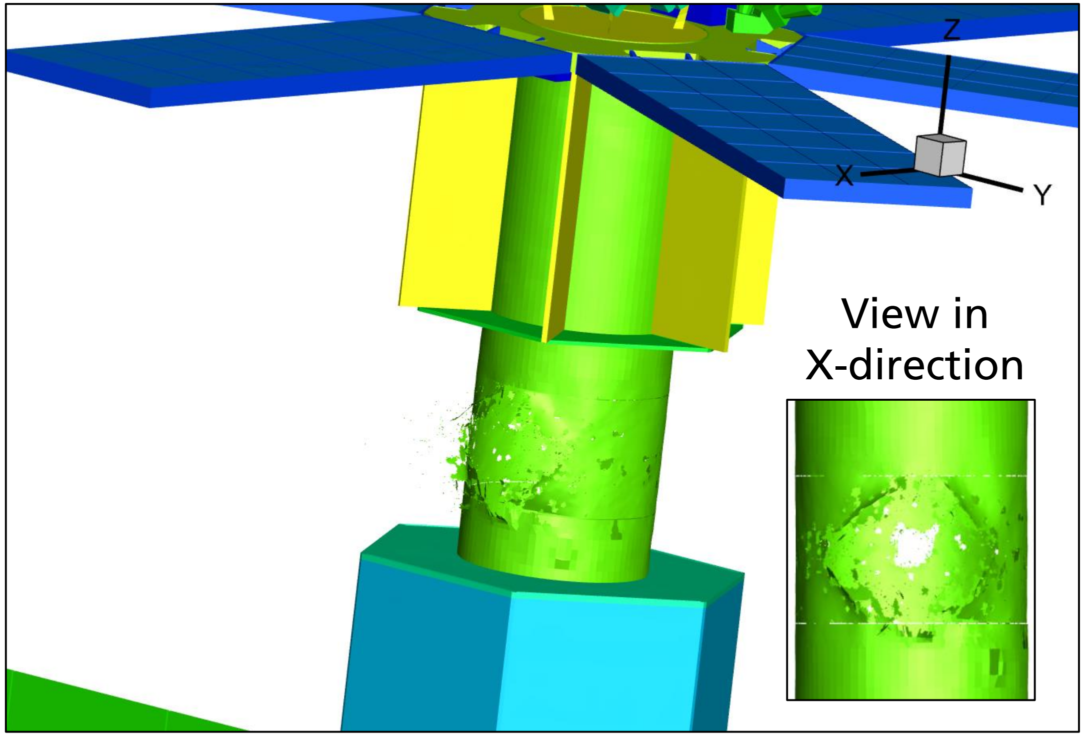
Numerical Simulations for Spacecraft Catastrophic Disruption Analysis
ESA LOFT non-catastrophic collision – Damages

Non eroded fragments

1) 0.1 kg plate, EMR 3 J/g



2) 1 kg CubeSat, EMR 30 J/g



Numerical Simulations for Spacecraft Catastrophic Disruption Analysis

ESA LOFT catastrophic collision – scenario 3) & 4)

12U CubeSat impactor with 11 km/s

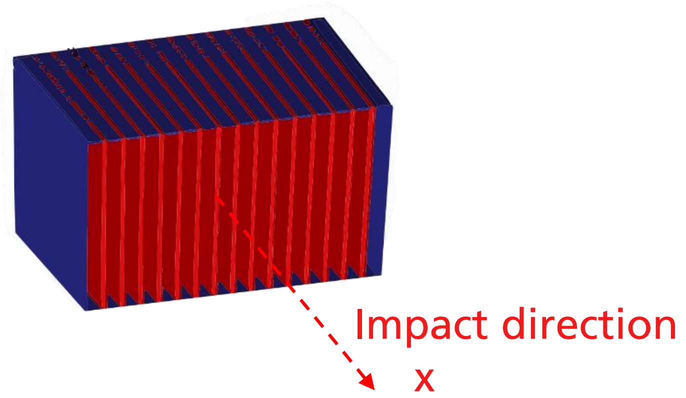
Dimension: 200×200×300 mm^3

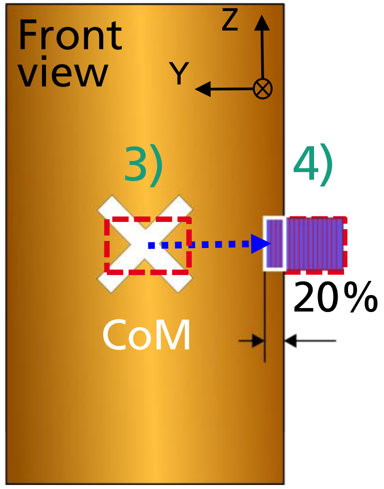
Mass: 10 kg

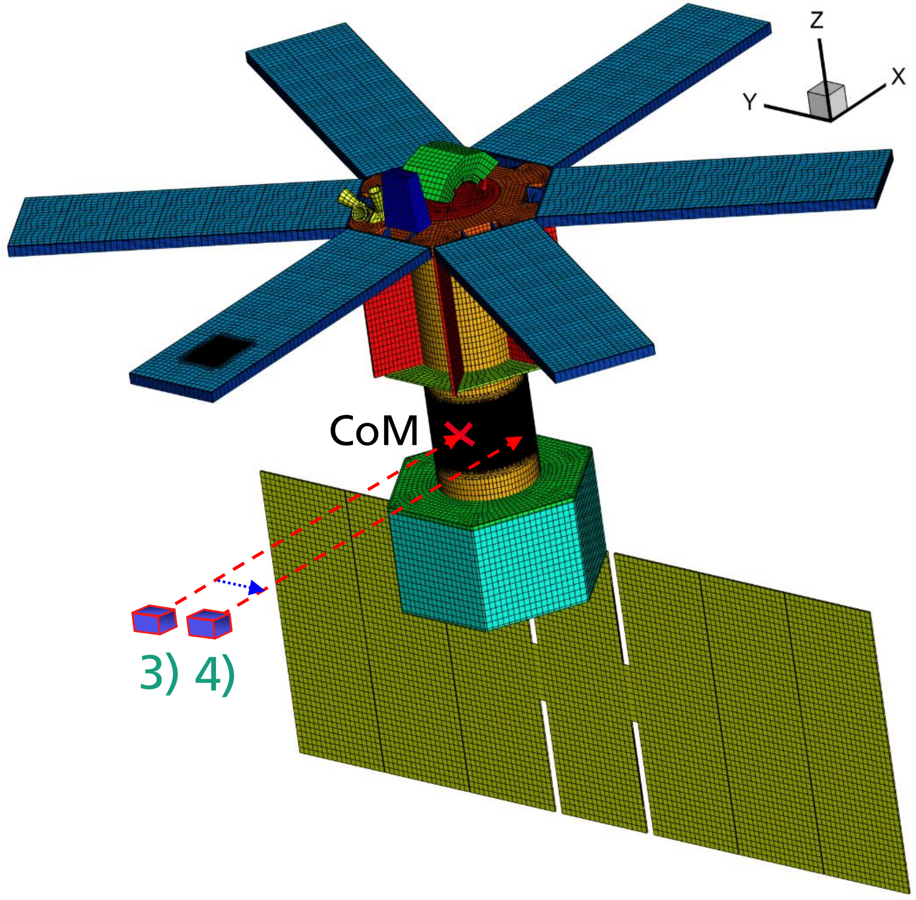
EMR: 302.5 J/G (1210 J/g)

3) Central impact on CoM

4) Grazing collision with 20% overlap







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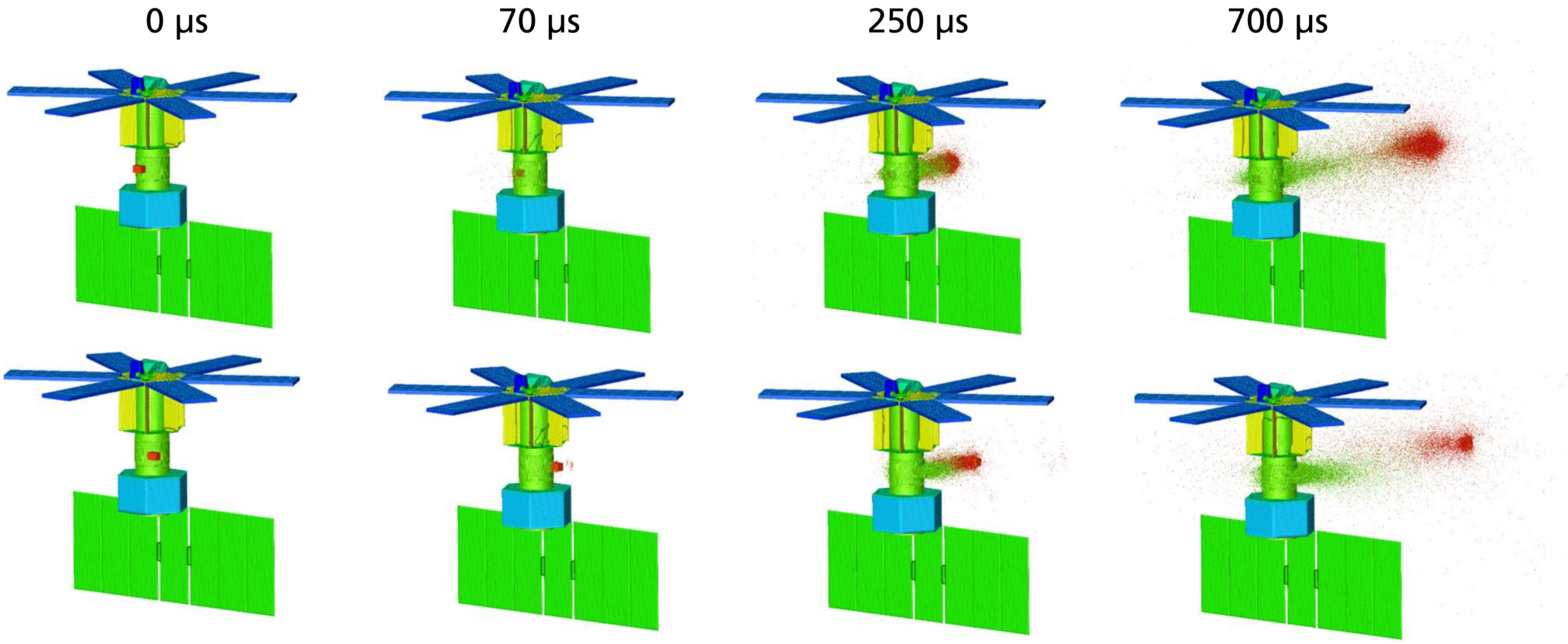
Numerical Simulations for Spacecraft Catastrophic Disruption Analysis

ESA LOFT catastrophic collision – Fragmentation process

3) 10 kg CubeSat
EMR 302.5 J/g
CoM impact

4) 10 kg CubeSat
EMR 302.5 J/g
Grazing impact



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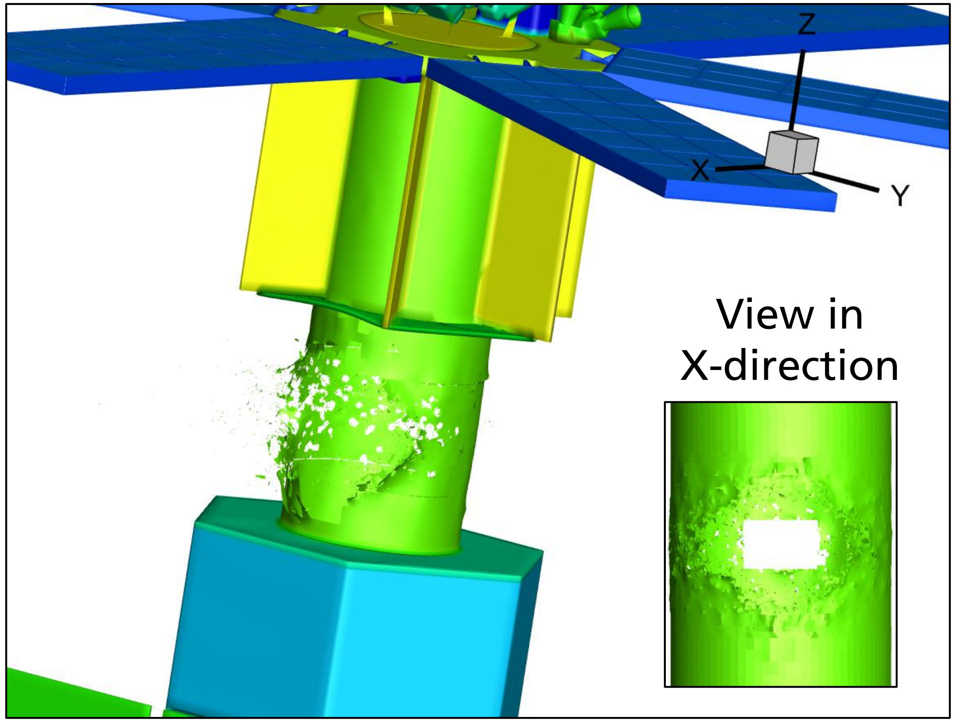
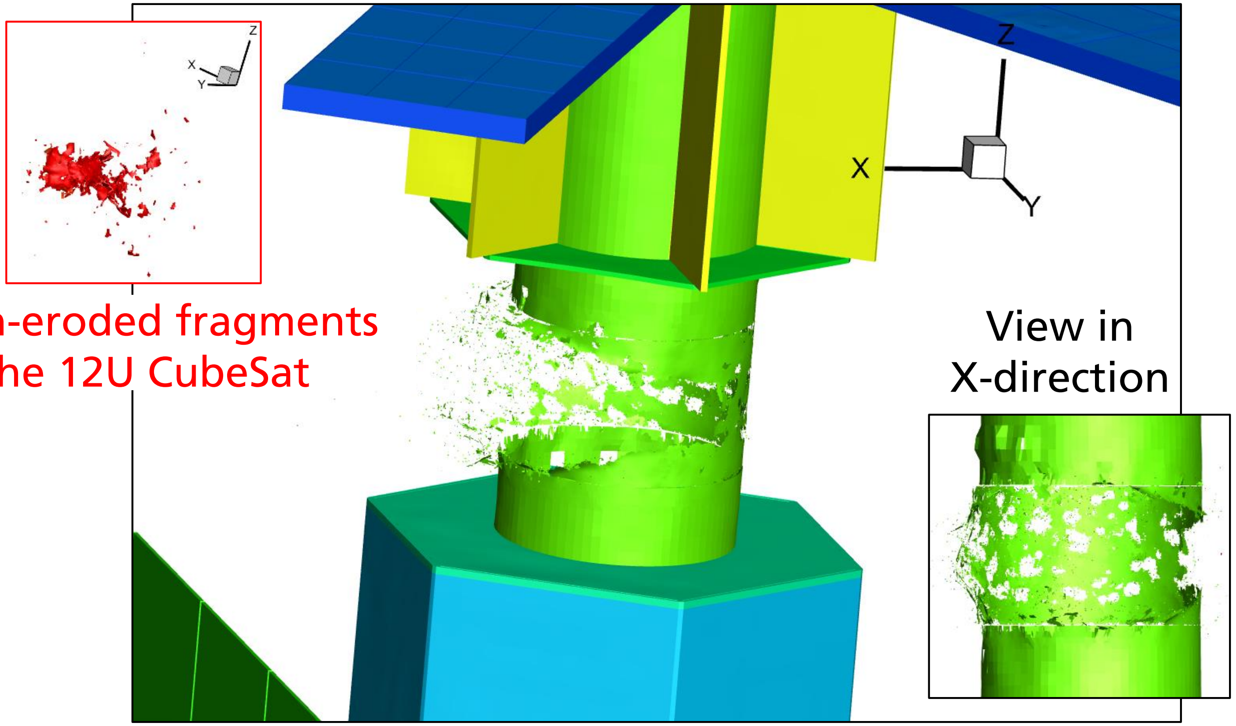
Numerical Simulations for Spacecraft Catastrophic Disruption Analysis
ESA LOFT catastrophic collision – Damages

Non eroded fragments - 10 kg CubeSat, EMR 302.5 J/g

3) Impact on Center of mass/geometry



4) Grazing impact with 20% offset



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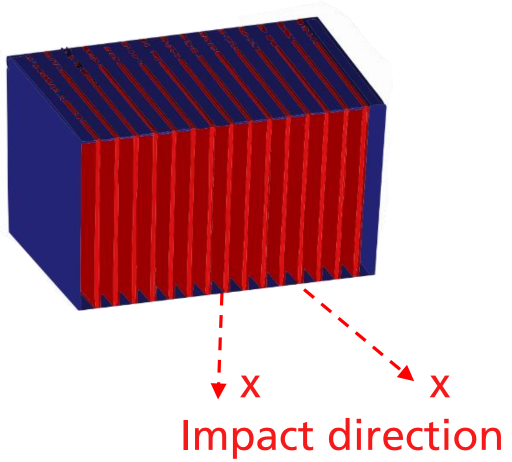
Numerical Simulations for Spacecraft Catastrophic Disruption Analysis

ESA LOFT catastrophic collision – scenario 5) & 6)

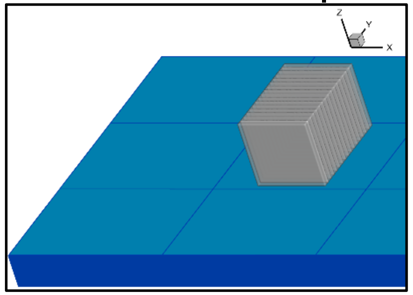
12U CubeSat impactor with 11 km/s
Dimension: 200×200×300 mm^3
Mass: 10 kg
EMR: 302.5 J/G (1210 J/g)

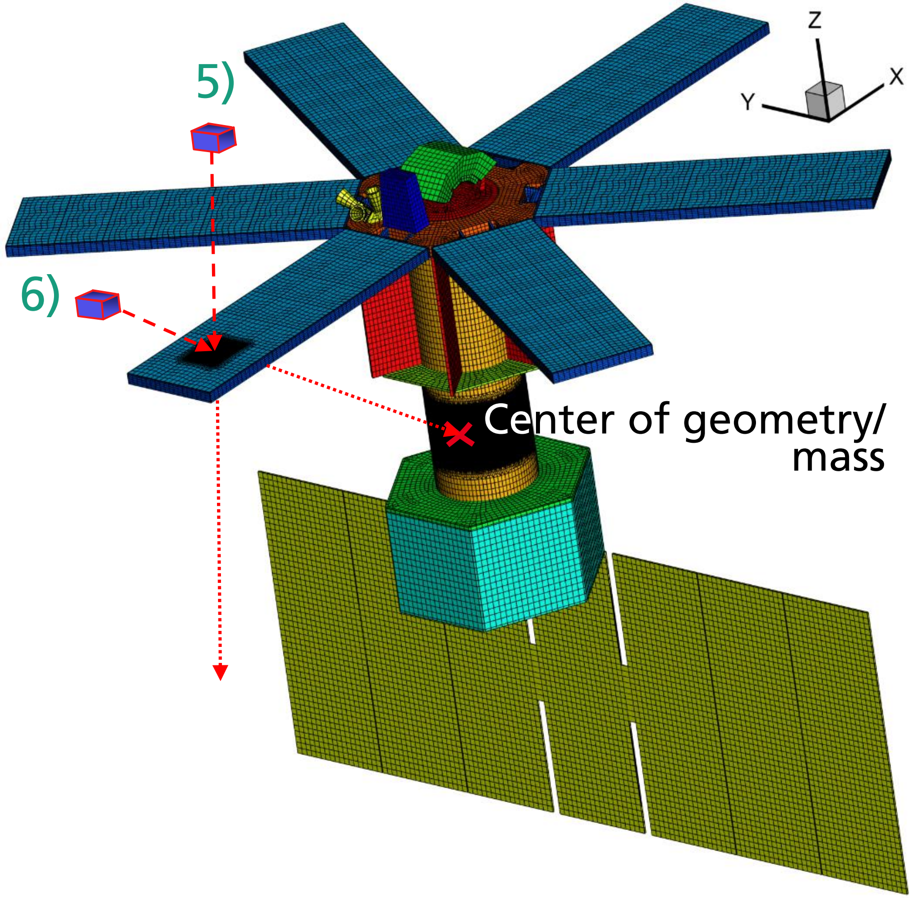
5) Impact on LAD vertical

6) Impact on LAD with impact vector pointing to CoM



Detail of the impact





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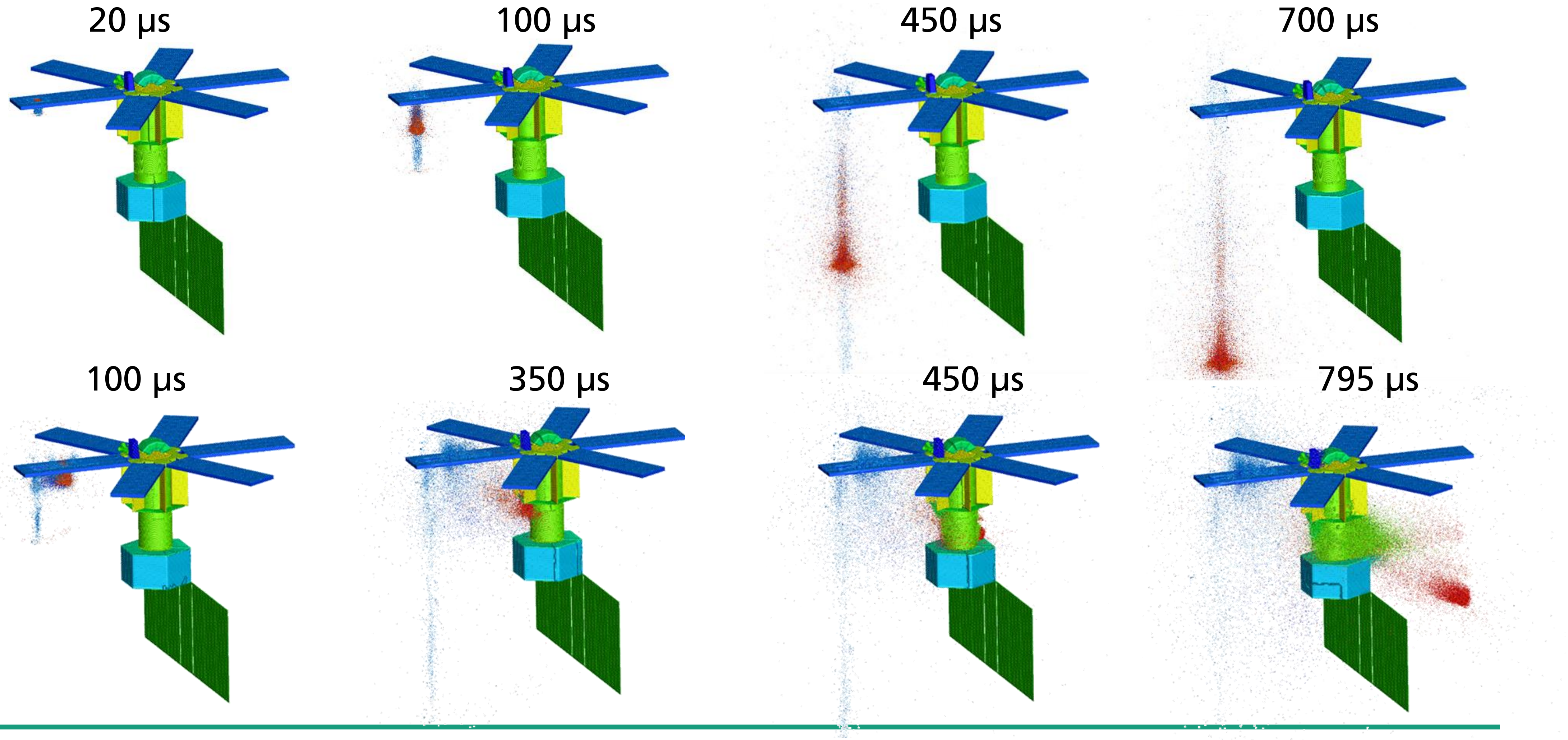
Numerical Simulations for Spacecraft Catastrophic Disruption Analysis

ESA LOFT catastrophic collision – Fragmentation process

5) 10 kg CubeSat
EMR 302.5 J/g
LAD impact vertical

6) 10 kg CubeSat
EMR 302.5 J/g
LAD impact pointing to CoM



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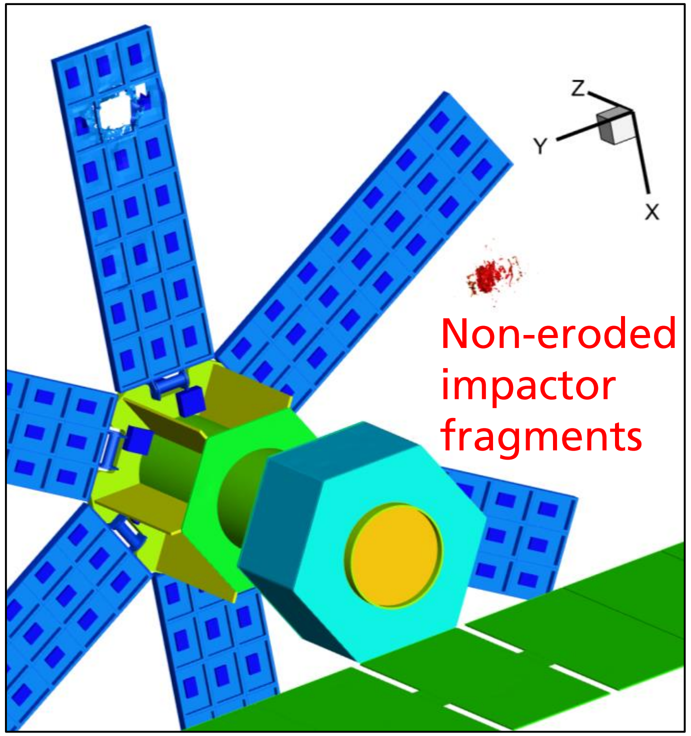
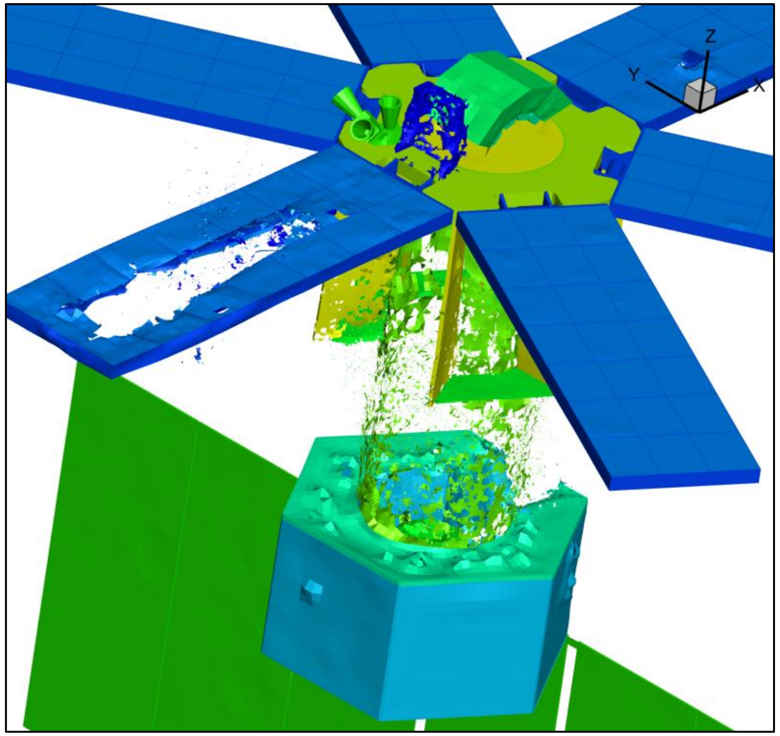
Numerical Simulations for Spacecraft Catastrophic Disruption Analysis
ESA LOFT catastrophic collision – Damages

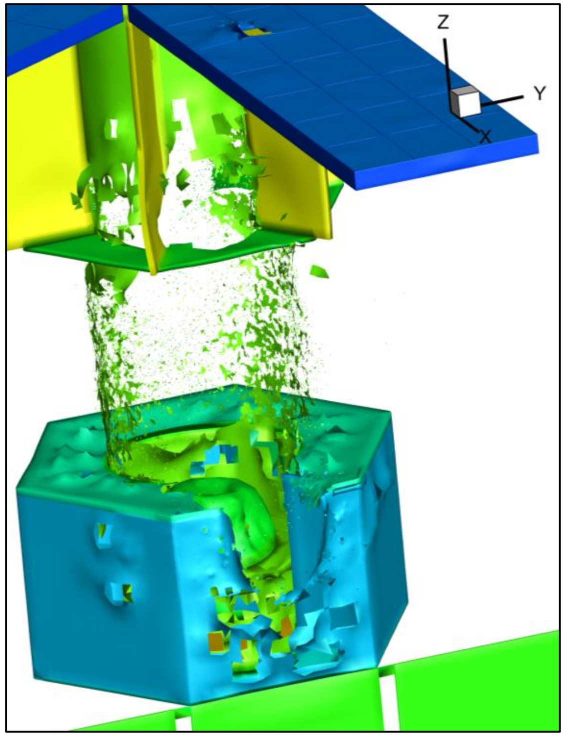
Non eroded fragments - 10 kg CubeSat, EMR 302.5 J/g

5) Vertical LAD impact



6) LAD impact pointing to CoM





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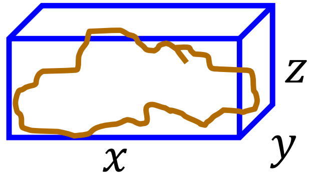
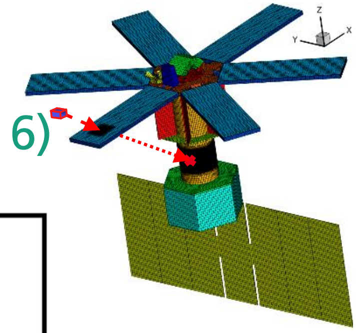
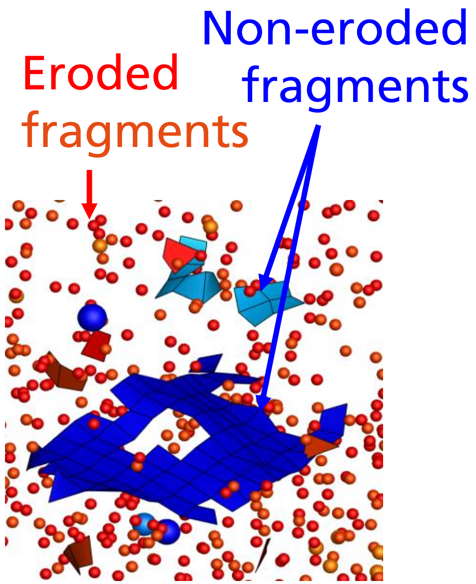
Numerical Simulations for Spacecraft Catastrophic Disruption Analysis

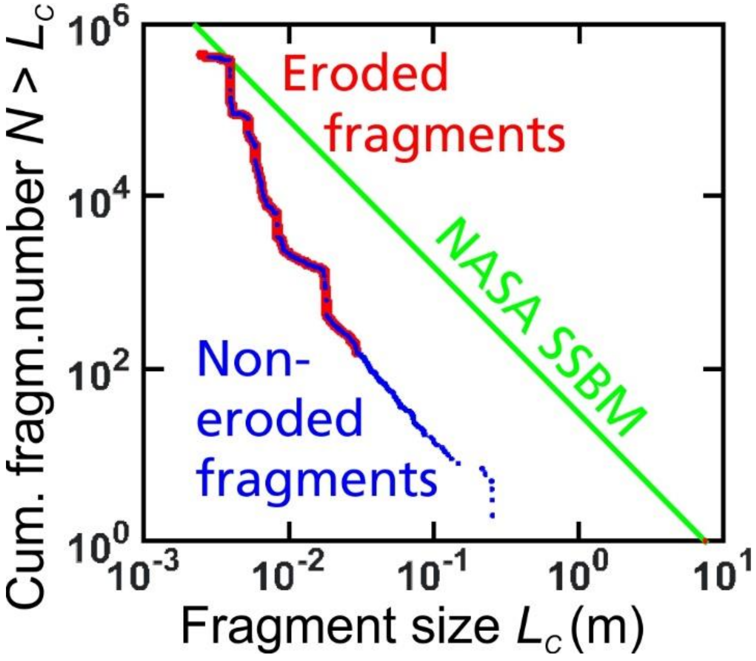
Comparison with NASA Breakup Model – Scenario 6)

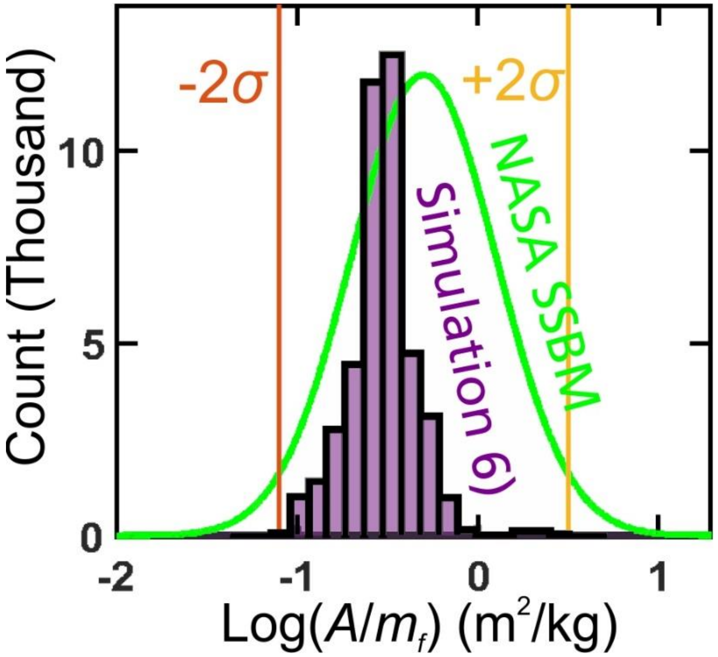


$$L_c = \frac{x + y + z}{3}$$









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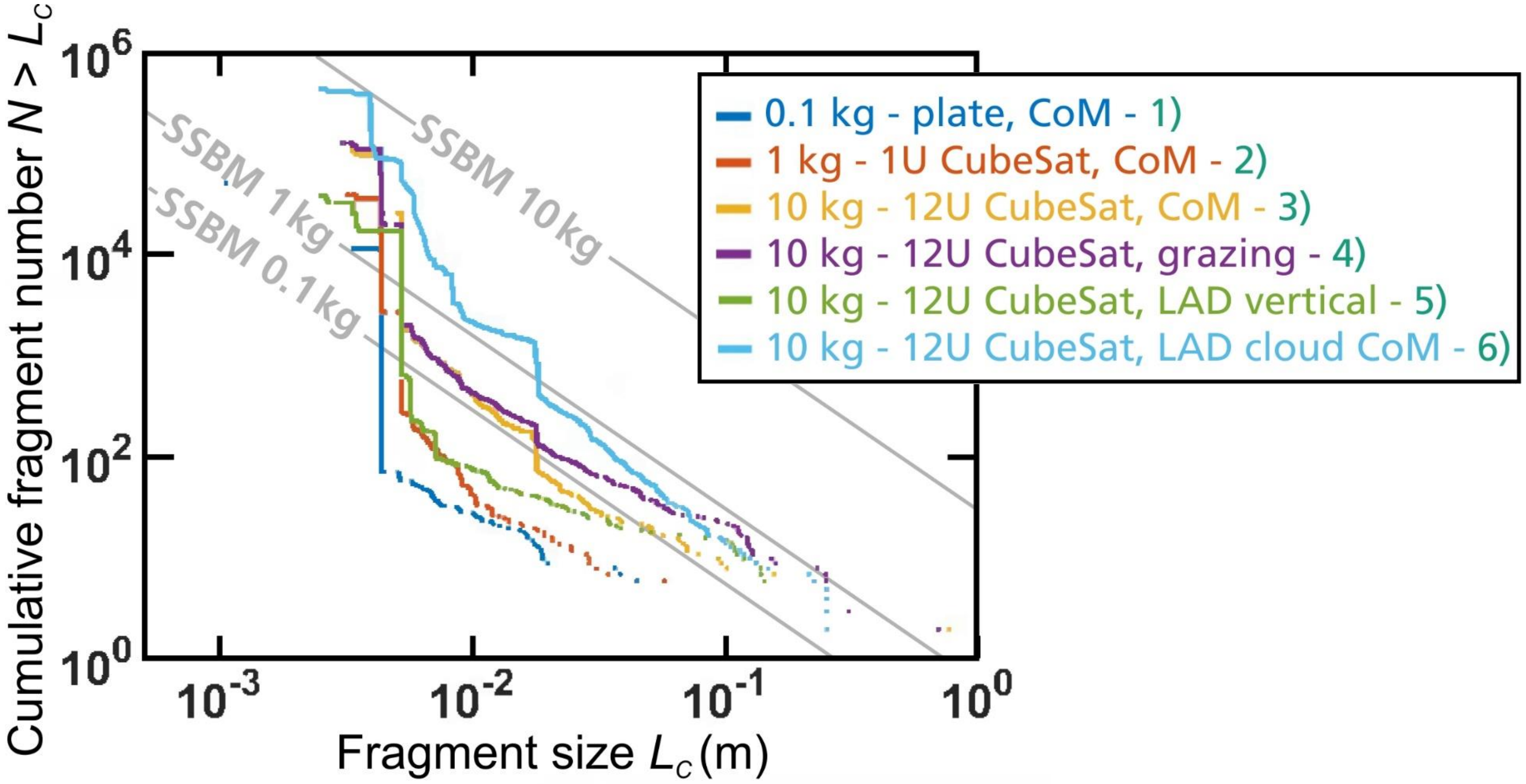
Numerical Simulations for Spacecraft Catastrophic Disruption Analysis

Comparison with NASA Breakup Model - Scenario Comparison

- Fragmentation strongly depends on collision configuration
- EMR-criteria does not reflect fragmentation complexity



Numerical Simulations for Spacecraft Catastrophic Disruption Analysis

Conclusions

- We developed the numerical tool PHILOS-SOPHIA for characterizing spacecraft fragmentations
- We simulated complex collisions
  - fragmentation and incurred damages strongly depend on collision geometry and configuration
  - EMR-criteria for catastrophic breakups does not reflect collision complexity
- Proposed future work
  - Dedicated experiments with particle tracking for quantitative validation
  - Analogous models for complex structures
  - ➡ Systematic studies of breakup behavior