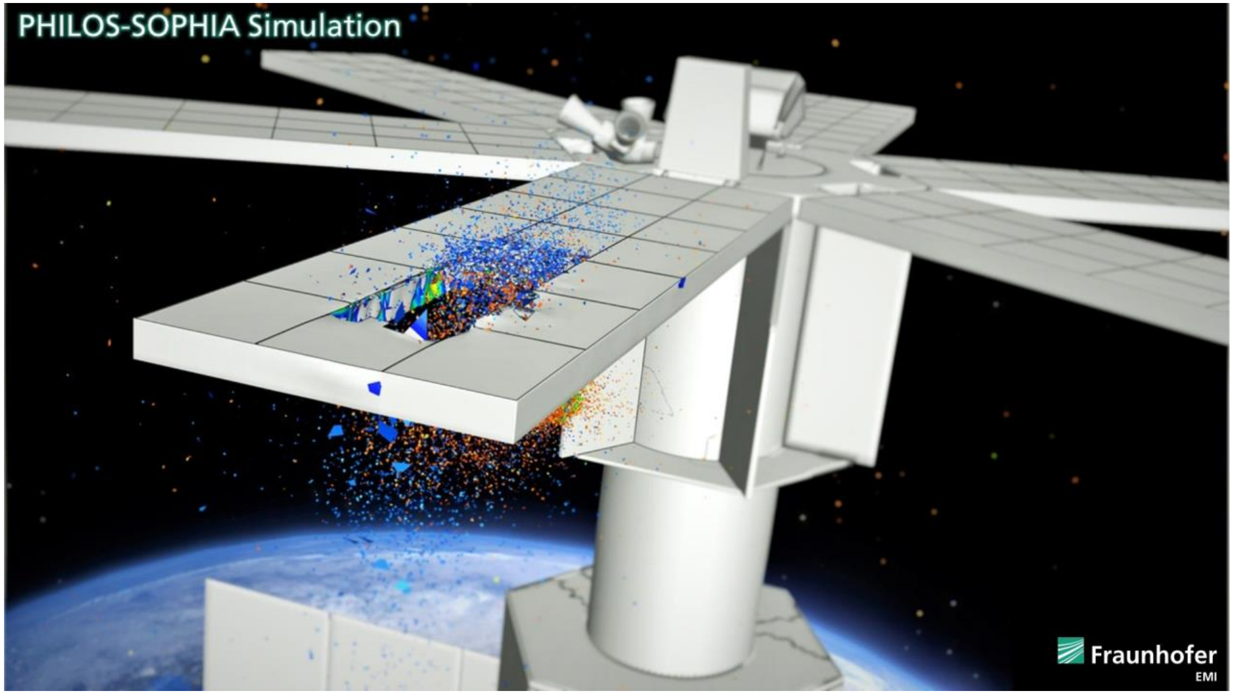
NUMERICAL SIMULATIONS FOR S/C CATASTROPHIC DISRUPTION ANALYSIS

Final Review - ESA Contract N° 4000119400/16/NL/BJ/zk



Martin Schimmerohn
Pascal Matura

ESTEC, Noordwijk
12 September 2018

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AGENDA – FINAL REVIEW

10:00
- Welcome and Introduction
- Management Report (WP1000)
- Final Report
  - Introduction
  - Review, Trade-off, Methodology Selection (WP2000)
  - Software Tool PHILOS-SOPHIA (WP3000)
  - Numerical Simulations (WP4000)
  - Results Evaluation (WP5000)
- Project Finalization

17:00
- End of Meeting

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NUMERICAL SIMULATIONS FOR S/C CATASTROPHIC DISRUPTION ANALYSIS

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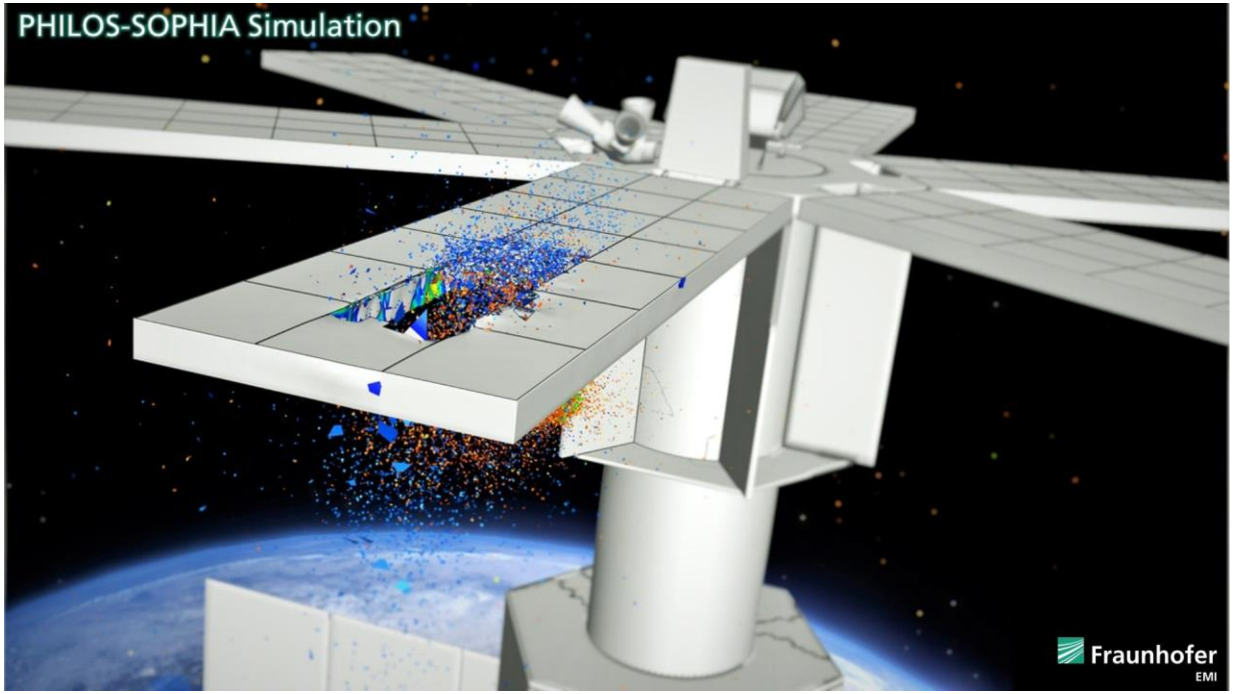
Management Review

WP1000



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12 September 2018

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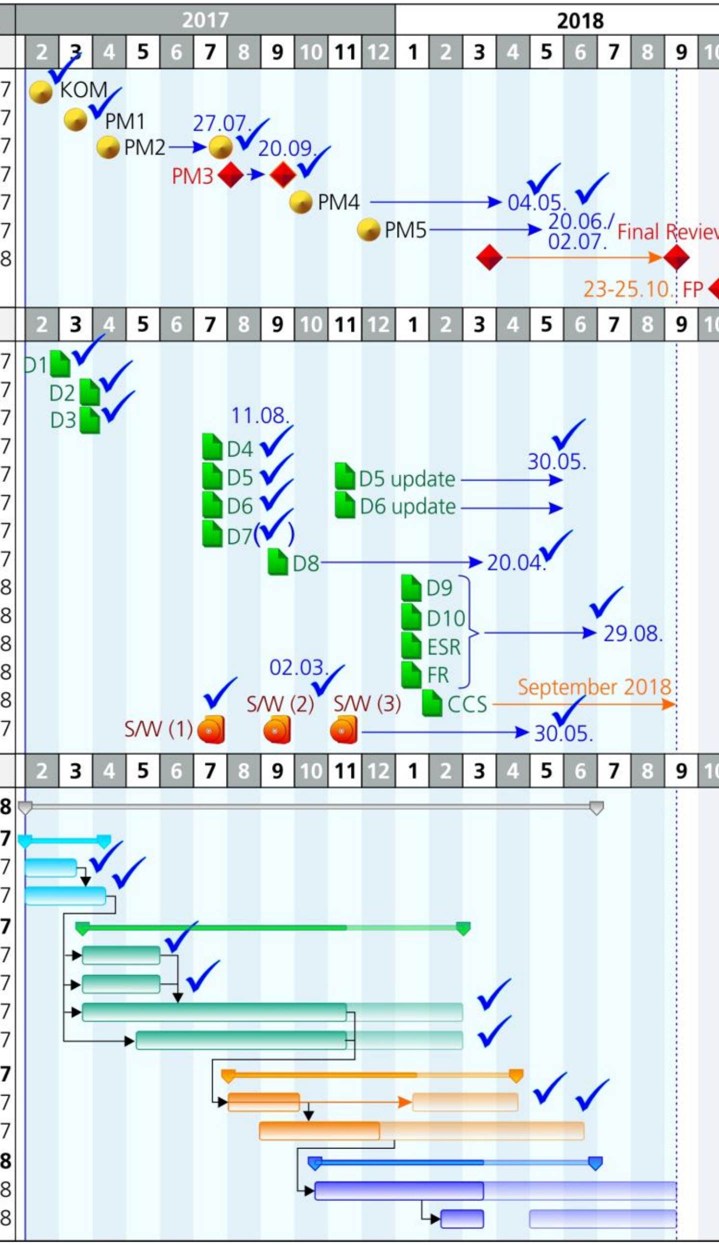
Schedule

ID	Title		Start	Finish
Milestone meetings				
KOM	Kick-off	via Videocon		13.02.17
PM1	Progress Meeting 1	via Videocon		15.03.17
PM2	Progress Meeting 2	via Videocon		12.04.17
PM3	Progress Meeting 3	at ESTEC		02.08.17
PM4	Progress Meeting 4	via Videocon		05.10.17
PM5	Progress Meeting 5	via Videocon		06.12.17
FR	Final Review	at ESTEC		31.01.18
FP	Final Presentation	at ESTEC		TBD
Deliverables				
D1	HV collision model. state-of-the-art			01.03.17
D2	HV collision model. trade-offs			29.03.17
D3	HV collision model. methodology			29.03.17
D4	Software system specifications			19.07.17
D5	Software design document			19.07.17
D6	Software user manual			19.07.17
D7	Tool simple validation case studies			19.07.17
D8	Tool validation document			13.09.17
D9	Tool results evaluation			17.01.18
D10	Experimental test protocol			17.01.18
ESR	Executive Summary Report			17.01.18
FR	Final Report			17.01.18
CCS	Contracts Closure Summary			31.01.18
S/W	S/C Breakup software			19.07.17
Work packages				
1000	**Management**		**01.02.17**	**31.01.18**
2000	**Review & trade-offs**		**01.02.17**	**22.03.17**
2100	State-of-the-art review		01.02.17	01.03.17
2200	Trade-offs & methodol.		01.02.17	22.03.17
3000	**Tool development**		**22.03.17**	**15.11.17**
3100	Adaption of core S/W		22.03.17	31.05.17
3200	Generation of FE models		22.03.17	31.05.17
3300	Devel. of Applic. S/W		22.03.17	15.11.17
3400	GUI development		03.05.17	15.11.17
4000	**Numerical simulations**		**02.08.17**	**13.12.17**
4100	Tool validation		02.08.17	05.10.17
4200	S/C collision simulations		30.08.17	13.12.17
5000	**Results evaluation**		**27.09.17**	**31.01.18**
5100	Tool evaluation		27.09.17	31.01.18
5200	Experimental test plan		03.01.18	31.01.18



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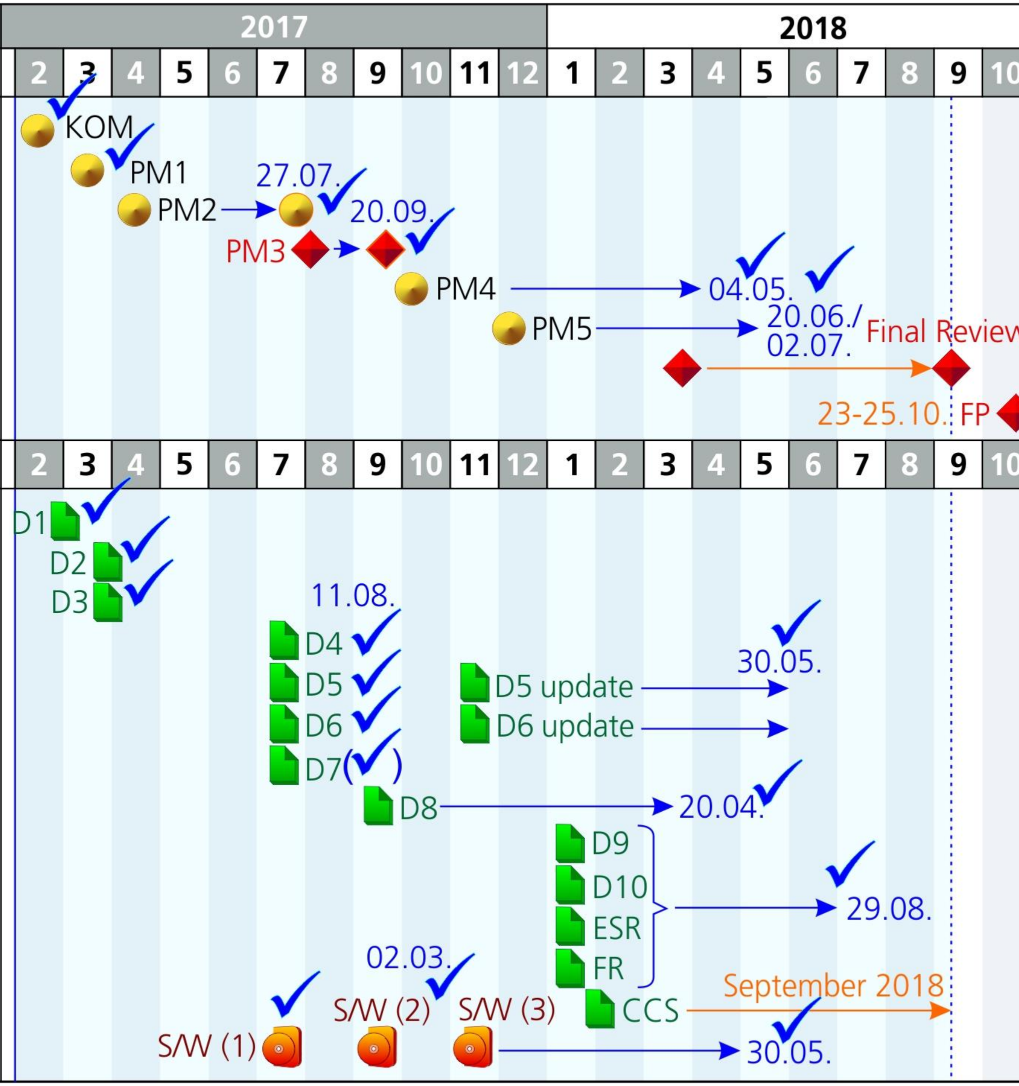

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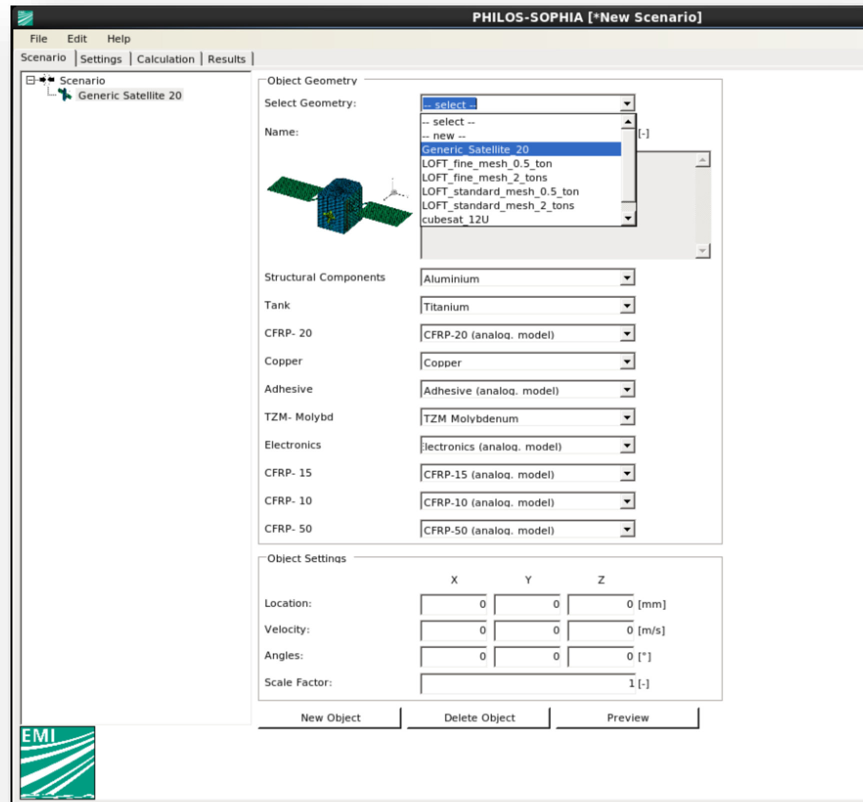
Deliverables
Reports

- 10 Technical Notes
- Since last meeting:
  - D9 Tool results evaluation
  - D10 Experimental test protocol
  - Final Report
  - Executive Summary

Deliverables
Software

PHILOS-SOPHIA (3 releases)

- Executables files + source code (GUI, GeometryMaker)
- 14 predefined scenarios
  - 2 oblique cylinder impacts
  - 12 LOFT collision scenarios
- Predefined finite element models
  - Generic Satellite Model
  - 1U and 12U CubeSats
  - ESA LOFT S/C (standard and fine mesh)



Conclusions – Management Report

- All activities accomplished
  - 6 successful progress/review meetings
  - Final Presentation intended for Clean Space industrial Days (after project finalization)
  - 7 months delay accumulated (within margin as agreed with ESA)
- All deliverables issued
  - 8 Technical Notes accepted, 4 documents to be discussed in this meeting
  - Software tool PHILOS-SOPHIA delivered in three releases
- All management requirements fulfilled

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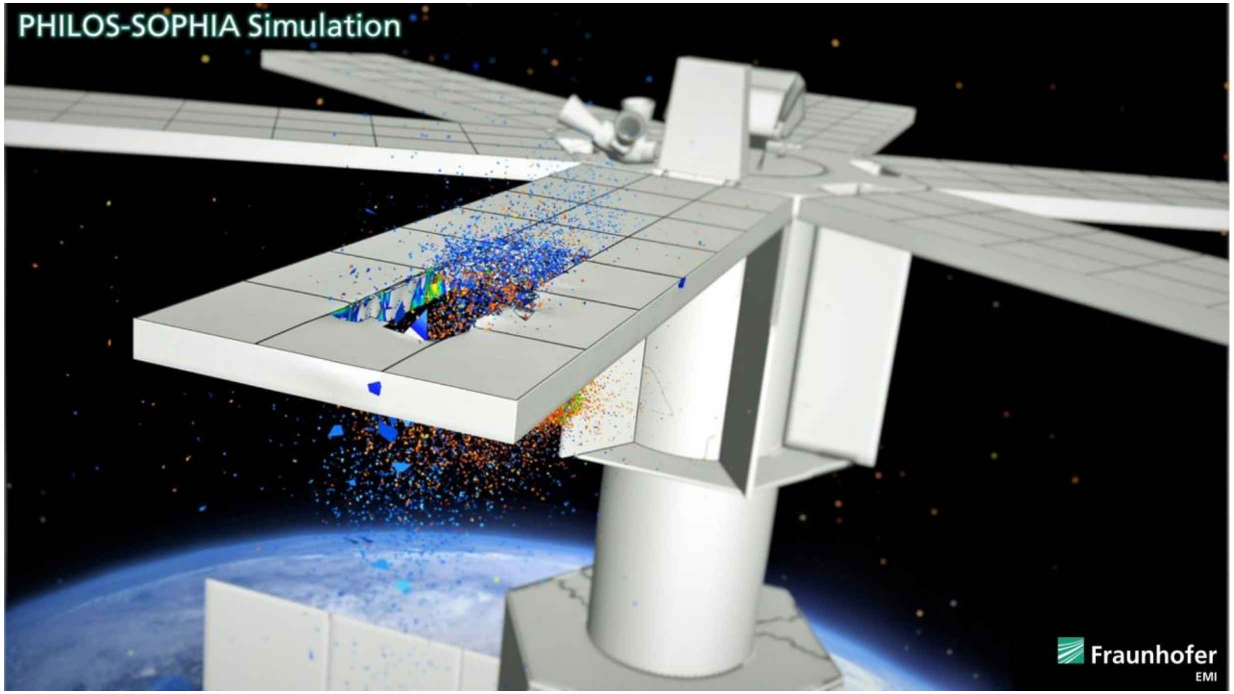
NUMERICAL SIMULATIONS FOR S/C CATASTROPHIC DISRUPTION ANALYSIS

Final Review - ESA Contract N° 4000119400/16/NL/BJ/zk

Introduction



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Introduction
Spacecraft Collision

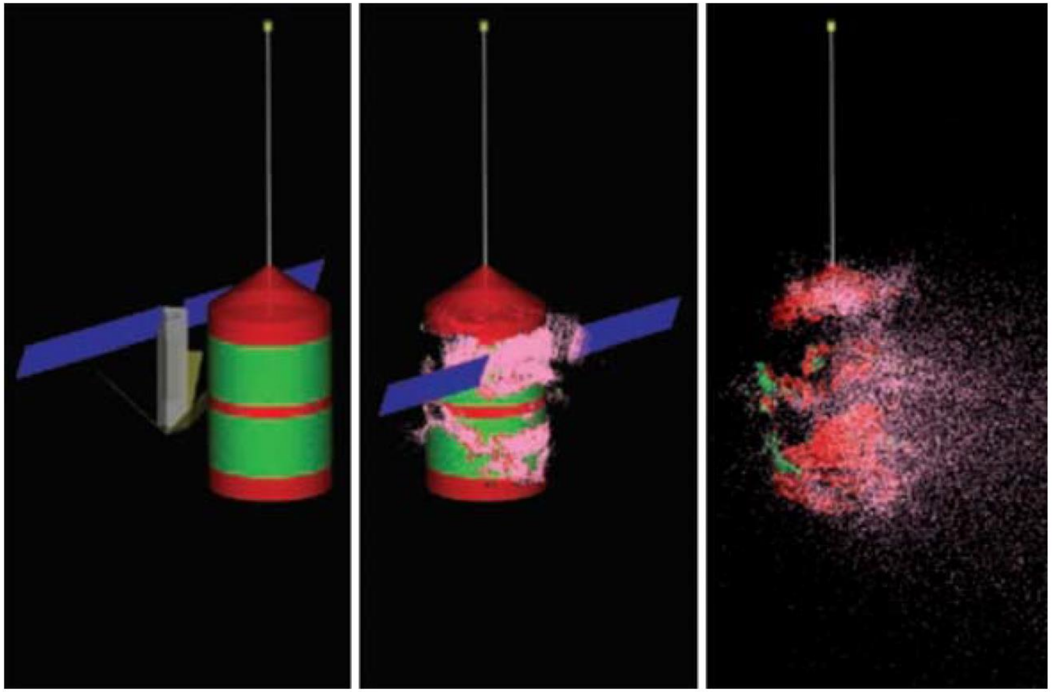


Figure 1: Collision of Cosmos 2251 and Iridium 33 as simulated by Lawrence Livermore National Laboratories [WAL09]. Besides the work presented here, this is to date the only published study on hydrodynamic simulations of an on-orbit collision.

Introduction
Spacecraft Collision

Source: https://cosmosmagazine.com/space/space-junk-catastrophe-horizon

Extreme physical encounter conditions

- Relative impact velocities up to ~15 km/s
- High altitude / harsh environmental conditions
- Complex structures / materials

Main objectives:

- Information on debris characteristics as number, size distribution, area-to-mass ratio, momentum transfer etc.
- and their dependence on collision scenario (orbit parameter, relative orientation, relative velocity), objects (mass, geometry, materials etc.)
- …for further analyses

But: How to get data?

Introduction

Spacecraft Collision – Objectives of the Study

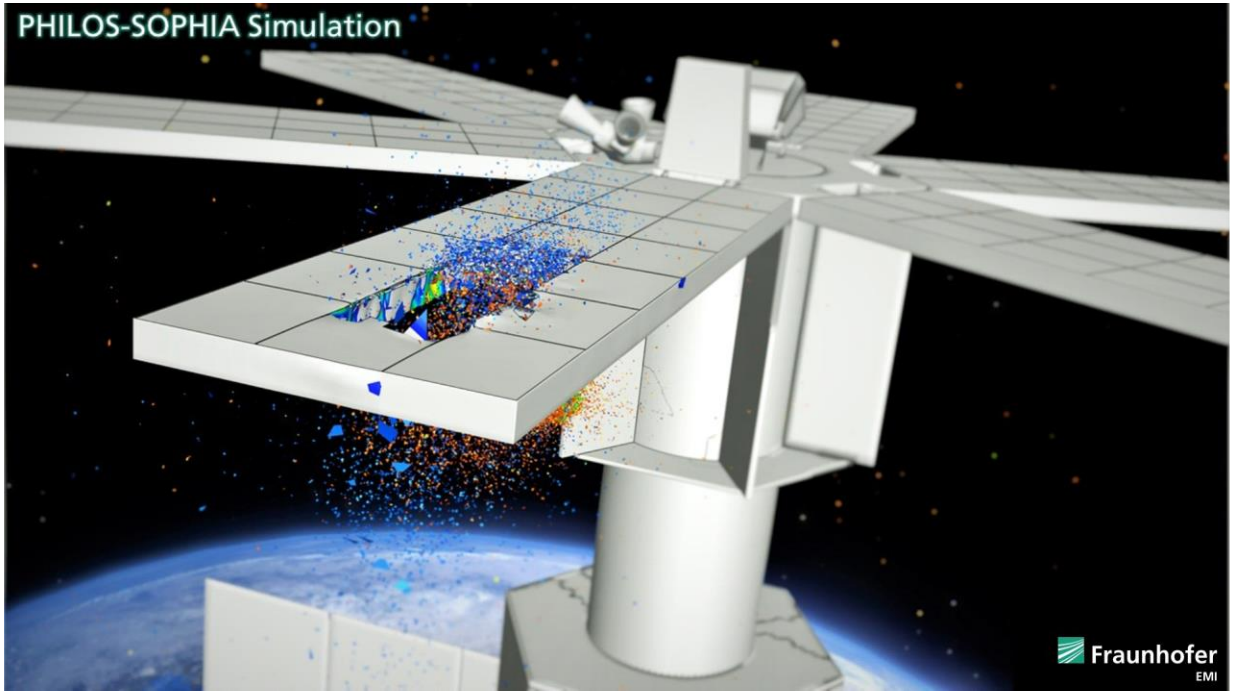
- Establish a numerical methodology that is capable of characterizing hypervelocity collisions of satellites,
- to use this numerical method to perform simulations with a complex target satellite with varied collision scenarios, and
- to analyze the transition between local damage effects and catastrophic disruption in relation to the traditional 40 J/g EMR definition.

NUMERICAL SIMULATIONS FOR S/C CATASTROPHIC DISRUPTION ANALYSIS

Final Review - ESA Contract N° 4000119400/16/NL/BJ/zk

State-of-the-art review and methodology

WP2000



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State-of-the-art review and methodology (WP2000)

General Modelling Approaches – Pros and Cons

Modelling approach	Pros	Cons
Analytical models e.g. models by Schonberg et al.	+ very fast computation → parametric studies in short time + relative simple implementation	- restricted to very simple geometries and idealized physical laws - restricted parameter range - applicability for spacecraft collision questionable
(Semi-) empirical breakup models e.g. NASA breakup model	+ very fast computation → parametric studies in short time + relative simple implementation	- not physics based - developed for a specific purpose, limited application range, extrapolations questionable - poor empirical basis, raw data not publicly available - poor flexibility to include new impact configurations and materials
Sophisticated numerical simulation with hydrocodes (see section 5.3 for more information) Hydrocodes	+ based on fundamental physical laws, high fidelity prognosis (if validated) + full scale models and realistic scenarios + full parameter control, parameter studies feasible to a greater extend + insight in physical processes during and after collision + complete and fast automated fragment analysis → data available for further investigations, e.g. fragment propagation	- complex modelling (geometry, material) - high computational effort, simulation run may last up to several days (depending on available computing power)

Increase in

- flexibility and range of applicability
- ability to model scenarios and objects close to reality
- complexity of the models and effort for model setup
- computational effort and time needed to perform analyses, resp.

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State-of-the-art review and methodology (WP2000)

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Selected methodology

Increase in

- flexibility and range of applicability
- ability to model scenarios and objects close to reality
- complexity of the models and effort for model setup
- computational effort and time needed to perform analyses, resp.

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State-of-the-art review and methodology (WP2000)

Hydrocodes – Continuum Description & Constitutive Material Modelling

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

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

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

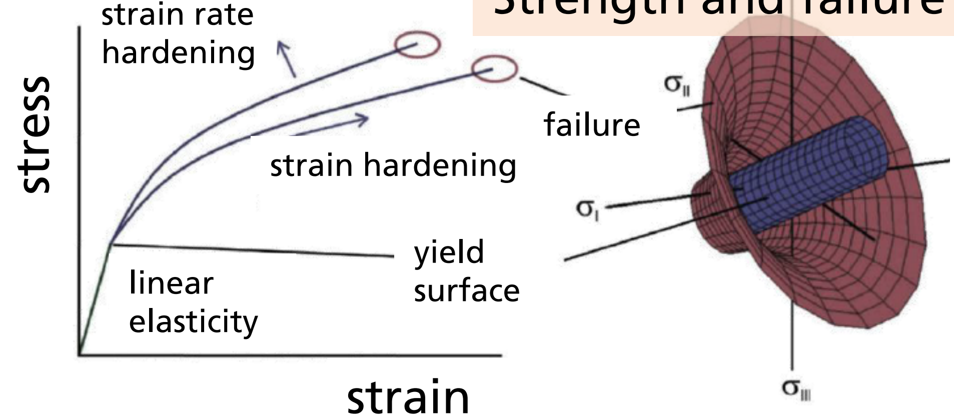
$$\mathbf{S}_{ij} = \sigma_{ij} + p\,\mathbf{I}_{ij} \qquad p = -\frac{1}{3}\sigma_{ii}$$

$p = p(\rho, e)$ Equation of State (EOS)

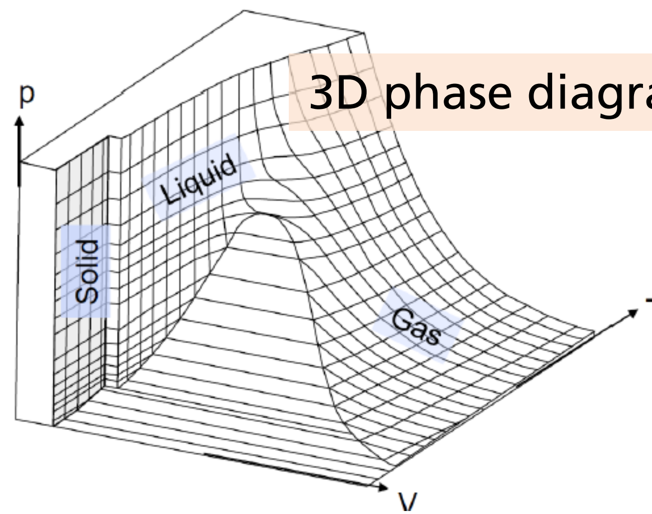
$\mathbf{S}_{ij} = \mathbf{S}_{ij}(\varepsilon_{ij}, \dot{\varepsilon}_{ij}, e_{in}, D)$ Strength model

$\boldsymbol{D} = \boldsymbol{D}(\boldsymbol{S}_{ij}, \varepsilon_{ij}, p, \ldots)$ Failure model

Strength and failure



3D phase diagram



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State-of-the-art review and methodology (WP2000)

Conclusions

- **Analytical** and **(semi-)empirical models** can be very elaborate and scientifically advanced,
  but
  they are generally not suitable for modelling more complex situations for which they have not been tailored
- **Hydrocodes** are advanced physics based time-explicit dynamic analysis tools for the numerical simulation of highly dynamic processes covering crash, impact, penetration, explosion etc.
  allowing
  to perform "virtual experiments" with models and loading conditions close to reality
- **Trade-off considerations for hydrocode modelling**:
  Geometrical details & complex material models ⟺ computational effort

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NUMERICAL SIMULATIONS FOR S/C CATASTROPHIC DISRUPTION ANALYSIS

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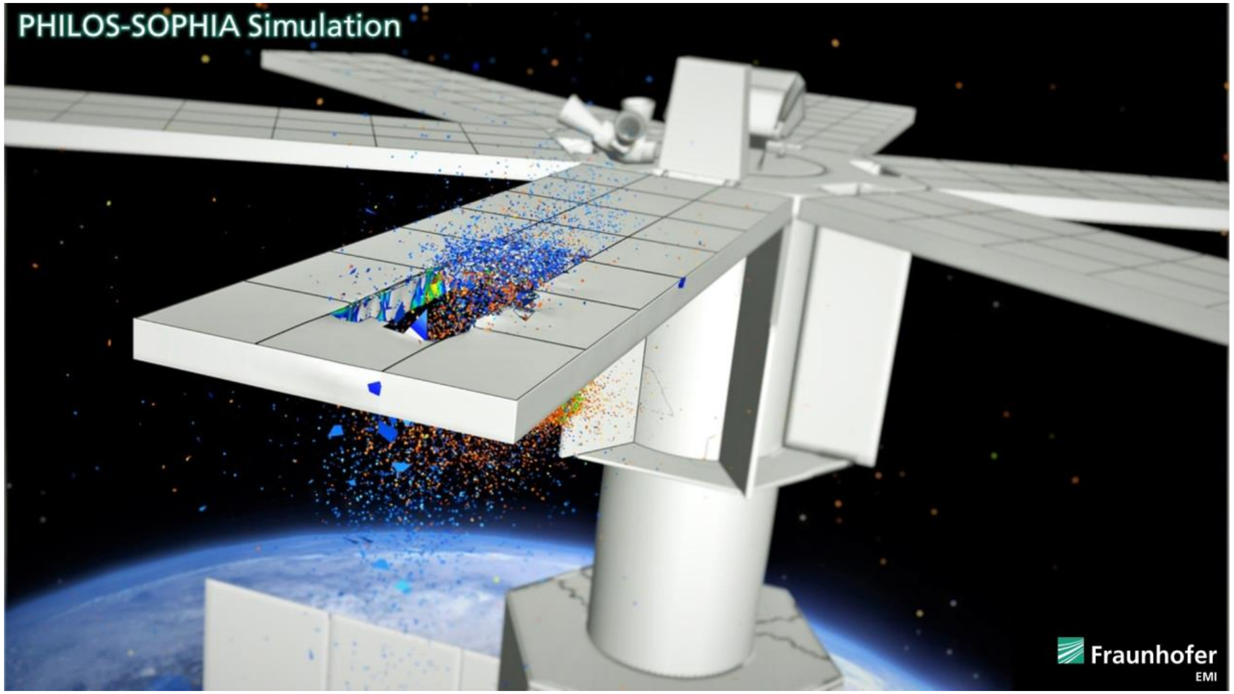
Software tool PHILOS-SOPHIA

WP3000



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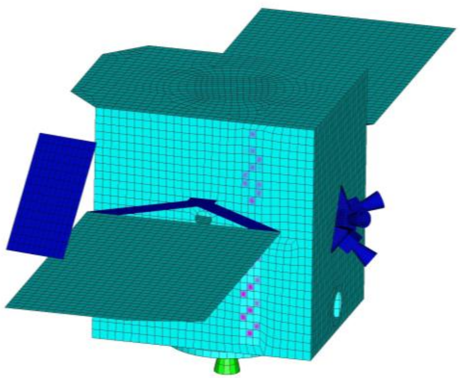
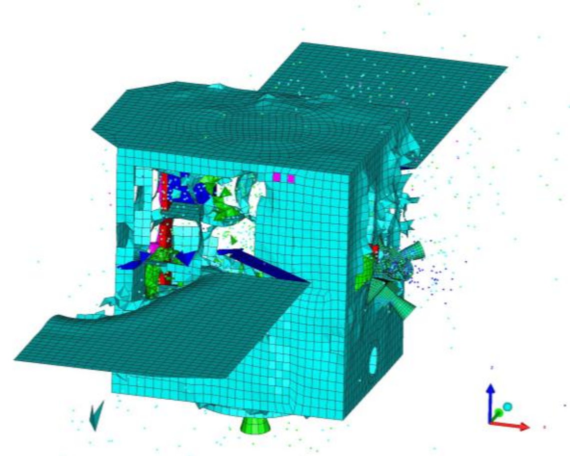
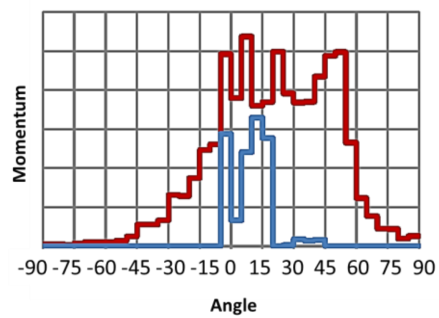
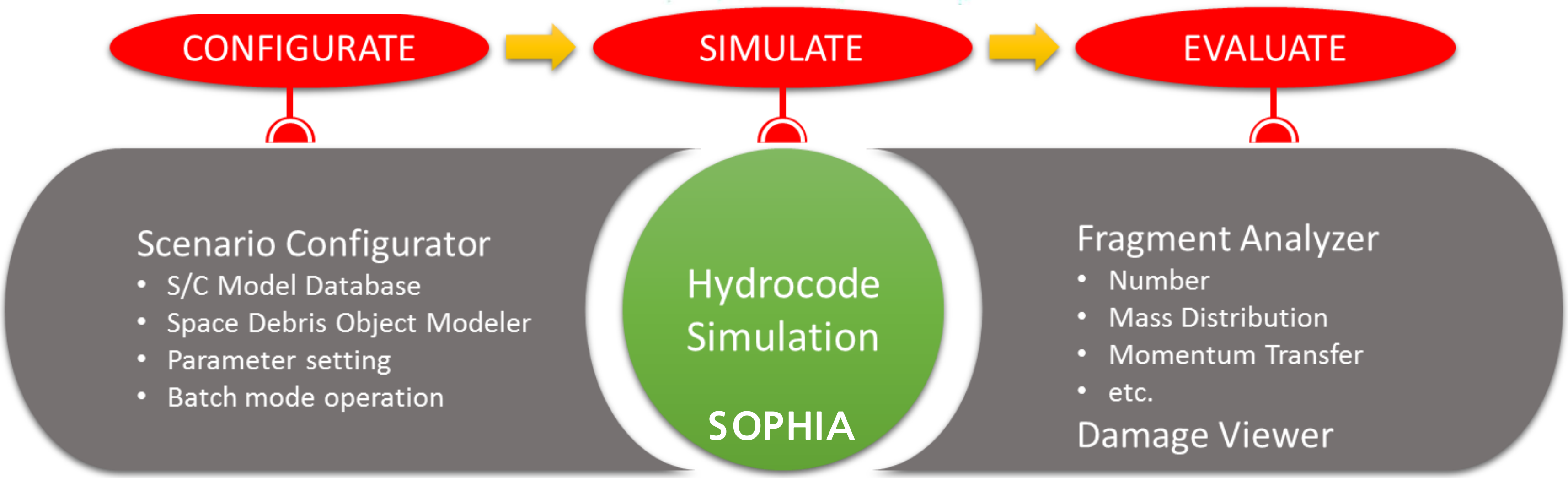
Software tool PHILOS-SOPHIA (WP3000)

Schematic Process Chain by using PHILOS-SOPHIA



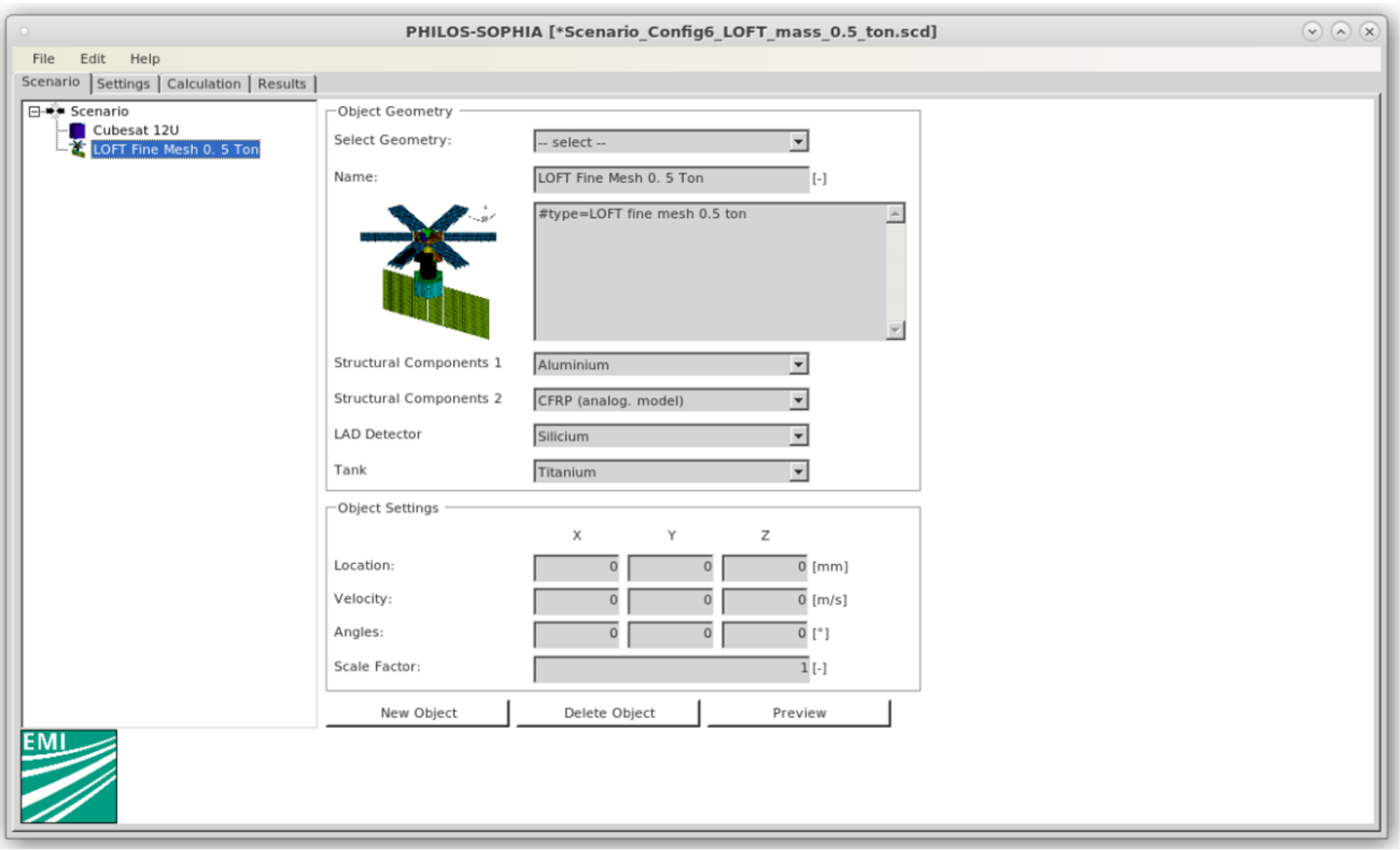






Software tool PHILOS-SOPHIA (WP3000)

Graphical User Interface – Scenario Definition



PHILOS: Program for **H**ypervelocity **I**mpact mode**LL**ing **O**f S/C collision **S**cenarios

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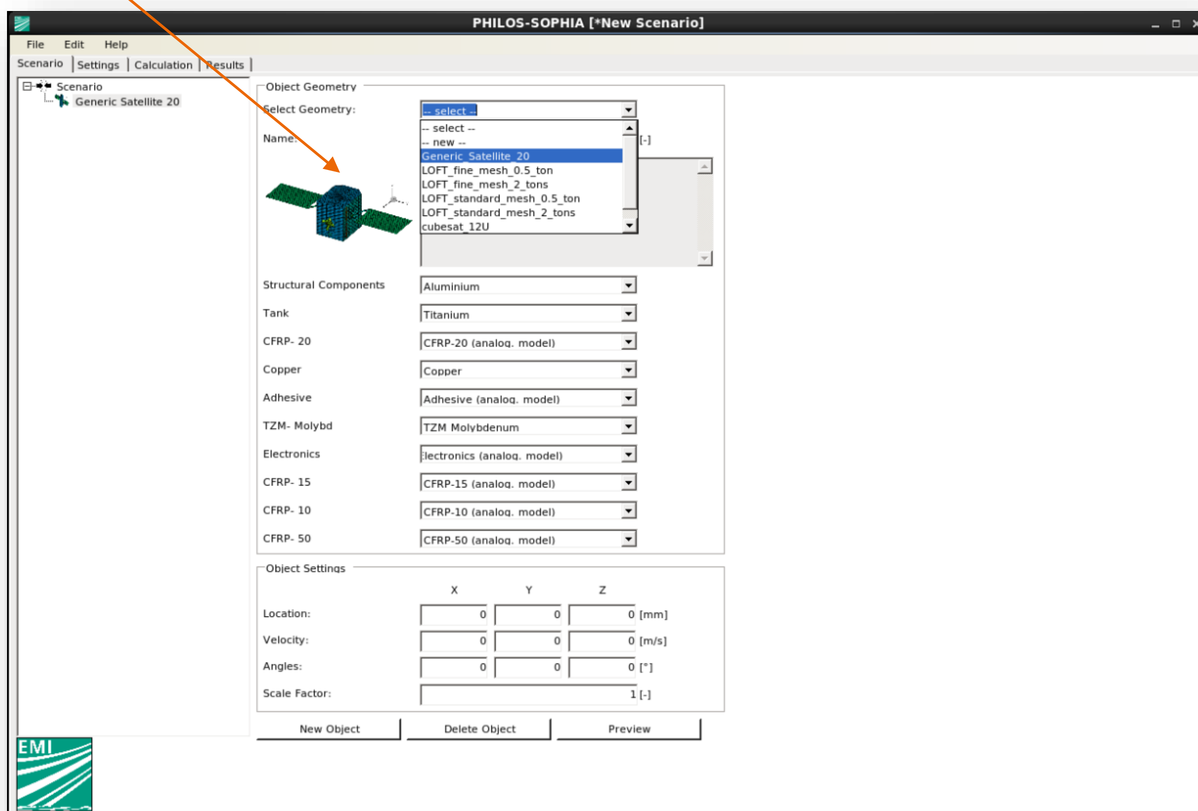
Software tool PHILOS-SOPHIA (WP3000)

Graphical User Interface – Predefined Models

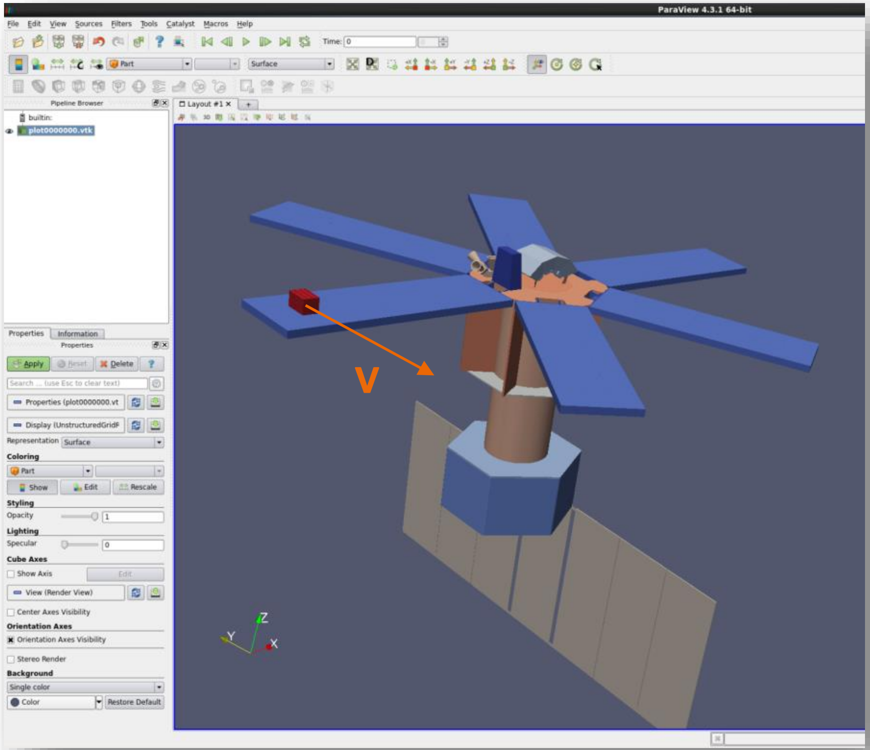
- Generic Satellite Model
- 4 LOFT S/C Models
- 1U-CubeSat Model
- 12U-CubeSat Model



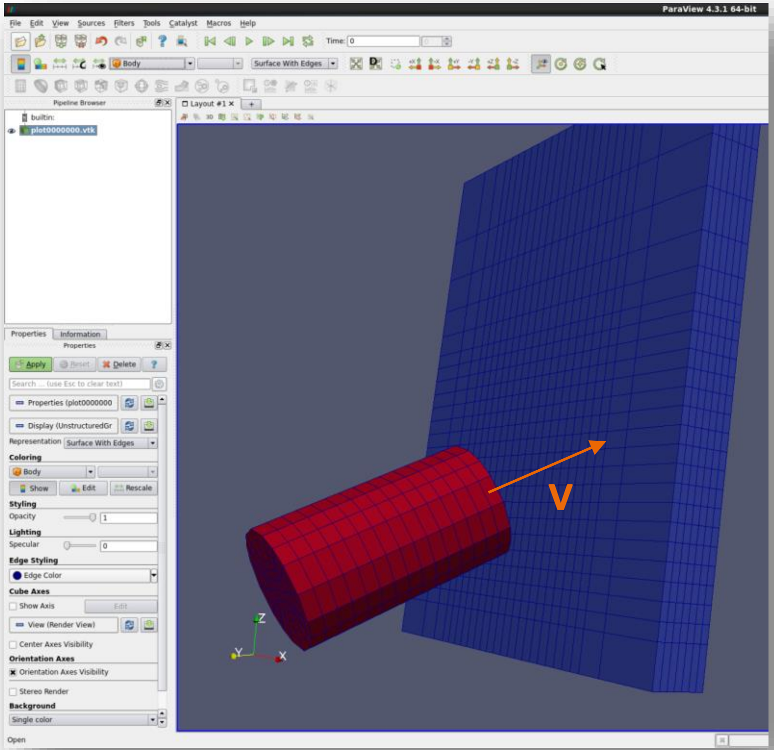
Software tool PHILOS-SOPHIA (WP3000)

Graphical User Interface – Predefined Scenarios, Examples

12U-CubeSat collision with LOFT S/C



Oblique cylinder impact, graded mesh



14 delivered scenarios: 2 oblique cylinder impact sc., 2 x 6 LOFT S/C scenarios

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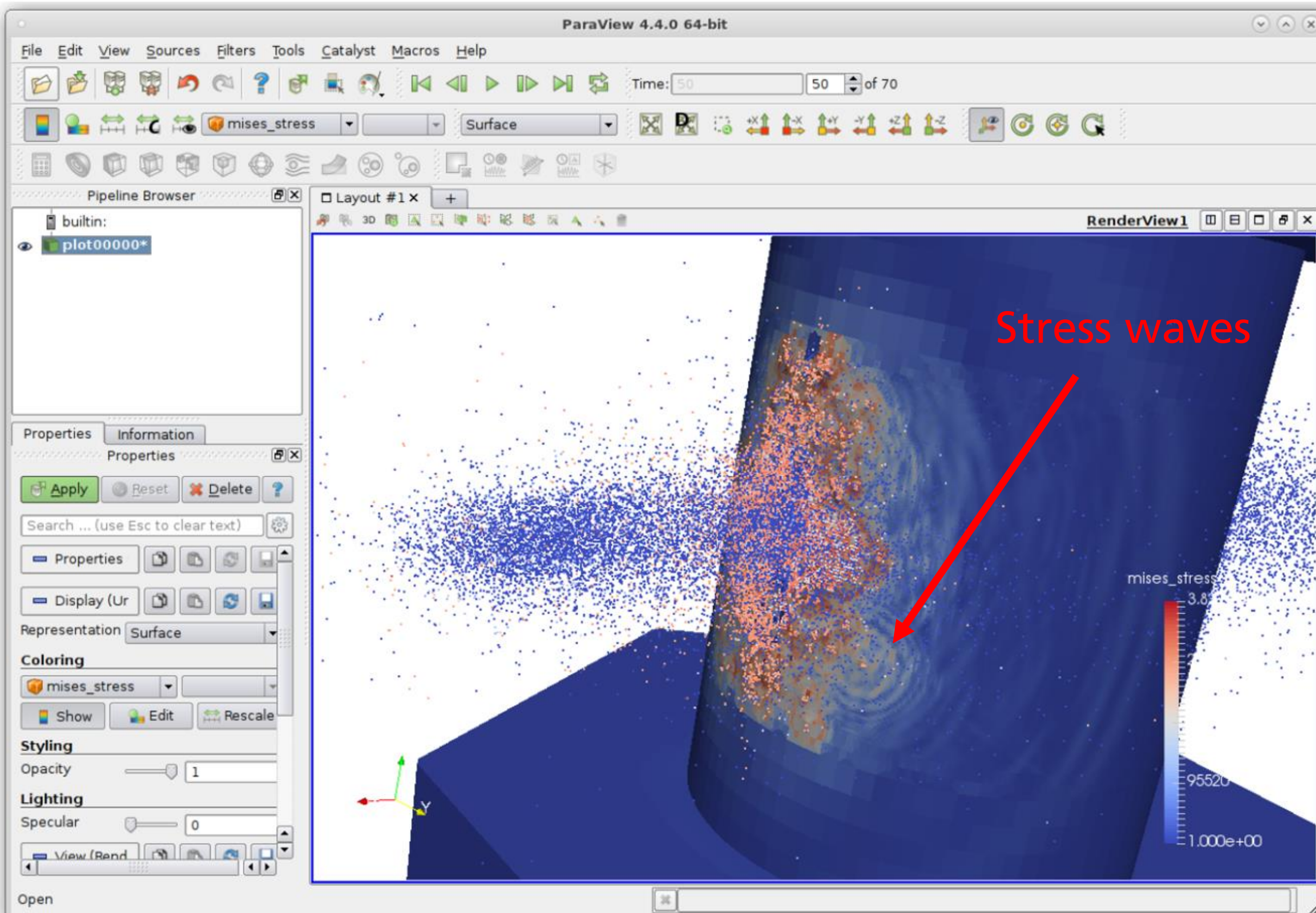
Software tool PHILOS-SOPHIA (WP3000)

Graphical User Interface – Starting Paraview for 3D-visualization



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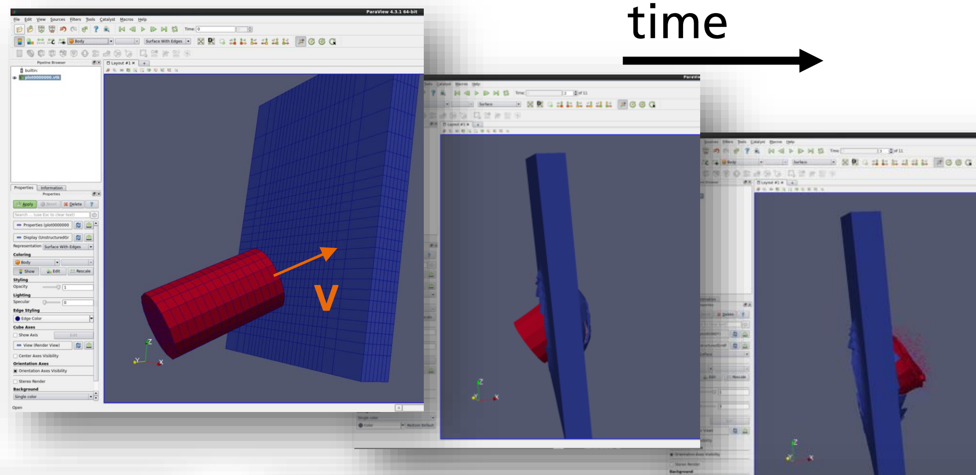
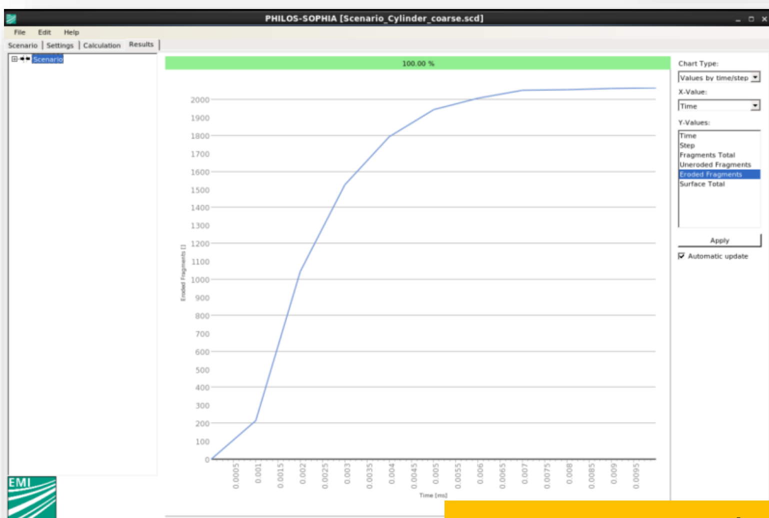
Software tool PHILOS-SOPHIA (WP3000)

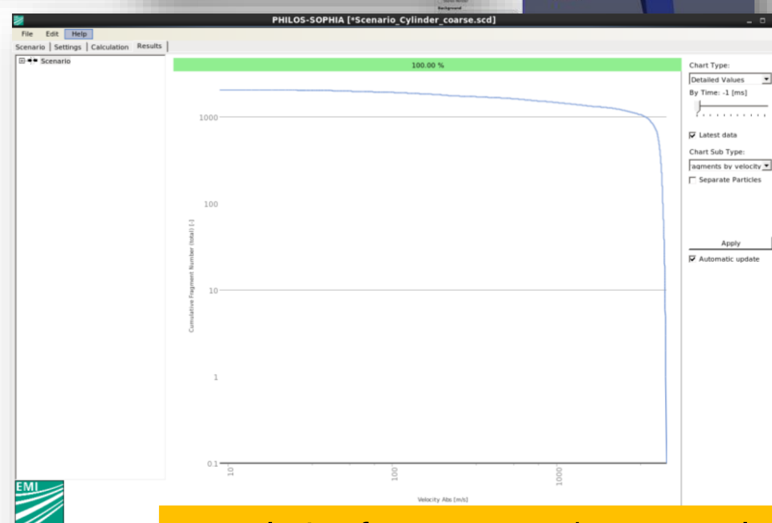
Graphical User Interface – Automated Fragment Analyses

- Exemplary fragment analyses





#Fragments over time



Cumulative fragment number over velocity

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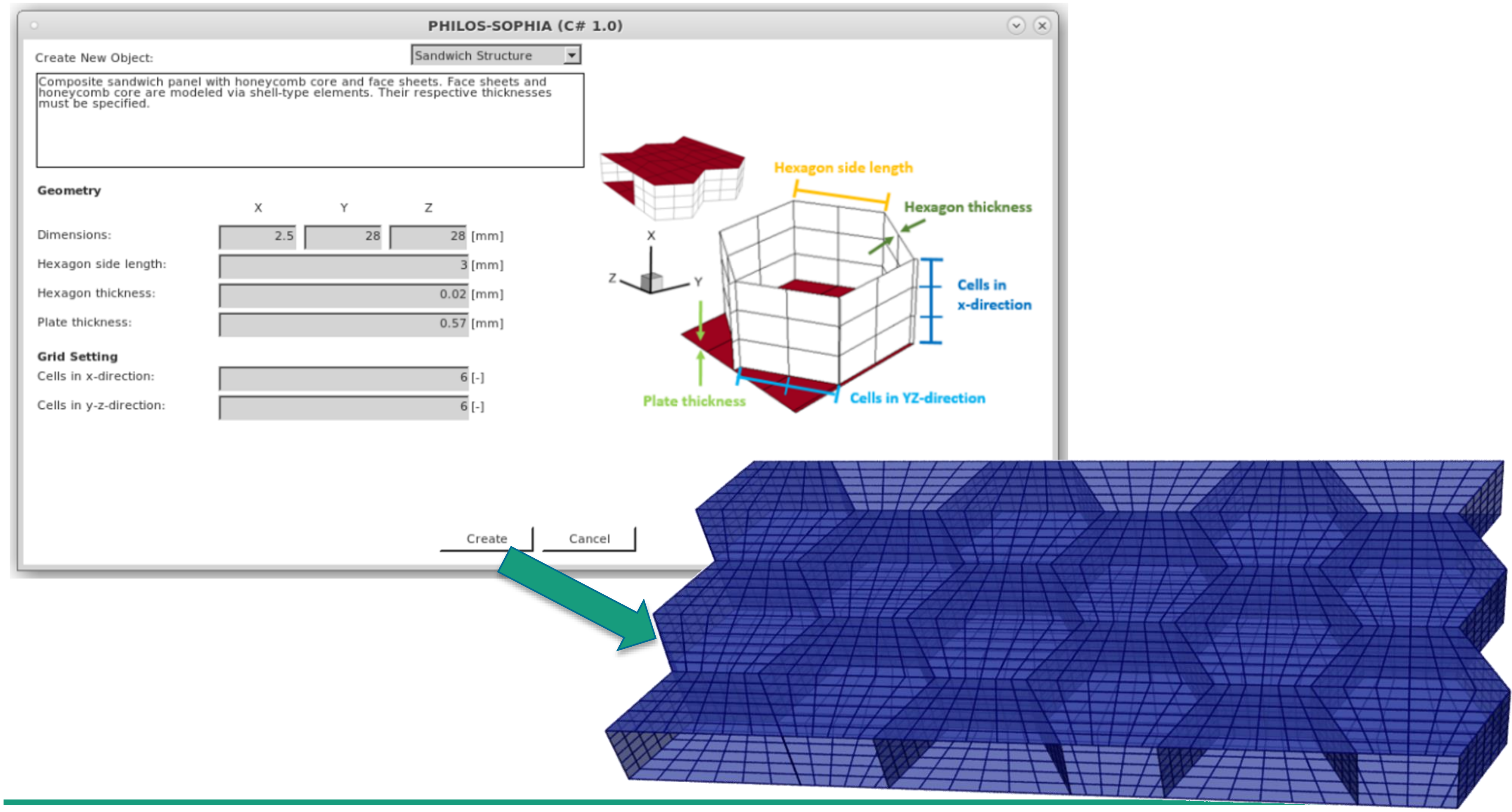
Software tool PHILOS-SOPHIA (WP3000)

Graphical User Interface – Object Modeller



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Software tool PHILOS-SOPHIA (WP3000)
Conclusions

- Software framework established including
  - Graphical User Interface
    - to easily setup, monitor and analyze collision scenarios
  - Model Database
    - with predefined models: LOFT S/C, CubeSats, Generic Satellite Model
  - Object Modeler
    - to create user-defined objects as plates, spheres, cylinders, sandwich panels
  - Hydrocode SOPHIA (temporal license)
    - to perform the collision calculation
  - Automated Fragmentation Analyzer
    - to investigate the fragmentation process

Software tool PHILOS-SOPHIA (WP3000)
Conclusions

- Software tool can be extendend by
  - New (complex) S/C or sub-scale models (database)
  - New Object Modeller capabilities (other object shapes, multi-layer/material objects etc.)
  - New material models in SOPHIA (more complex strenght and failure models, if needed)

NUMERICAL SIMULATIONS FOR S/C CATASTROPHIC DISRUPTION ANALYSIS

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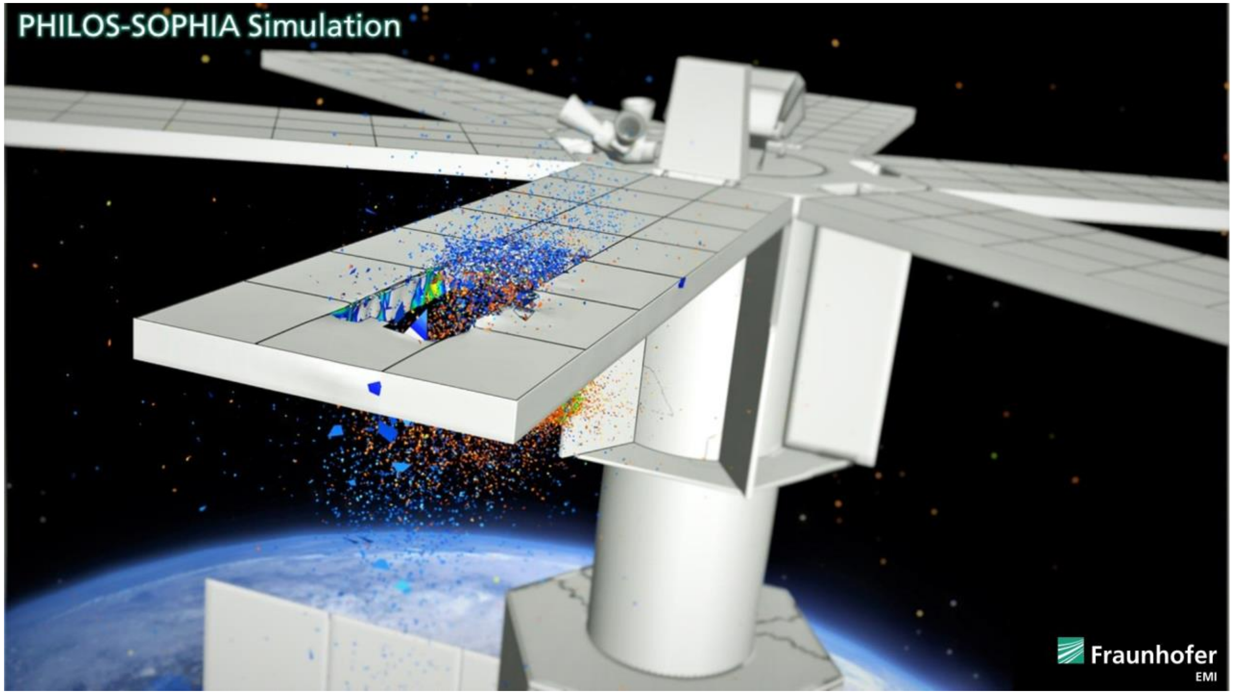
Numerical Simulations

(WP4000)



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Martin Schimmerohn

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Numerical Simulations (WP4000)

Overview

- „Simple Validation“ test cases
  - 4 multi-layer shielding configuration scenarios
  - 15 simulations showing PHILOS-SOPHIA capabilities
- Reproduction of impact experiments for qualitative validation
  - 2 thin-plate impact scenarios with obliquity and impactor shape effect
  - 4 simulations validating PHILOS-SOPHIA against experimental data and general purpose hydrocode ANSYS/AUTODYN
- Complex collisions simulations with ESA LOFT spacecraft
  - 2 LOFT models (regular and refined mesh, mass criteria), 3 impactors
  - 12 simulations for analyzing spacecraft fragmentation behavior and catastrophic disruption criterion

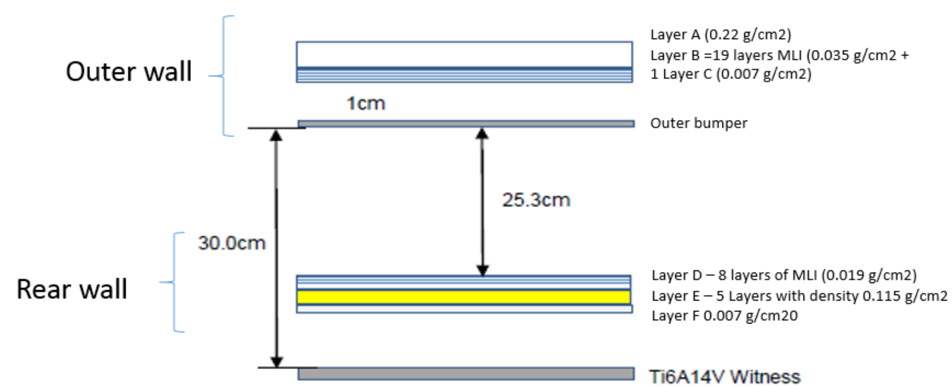
Numerical Simulations (WP4000)

„Simple Validation“ test cases

- Multi-layer spacecraft shielding configurations
  - Show method capability to study impact fragmentation
  - Standardized test cases for comparison with method developed in parallel consortium
- „Simple” → small-scale targets (compared to spacecraft scale)
- “Complex” → complex materials (kevlar, nextel, MLI, sandwich structures)

➡ Using analogous models if needed

➡ New material models can be included in PHILOS-SOPHIA



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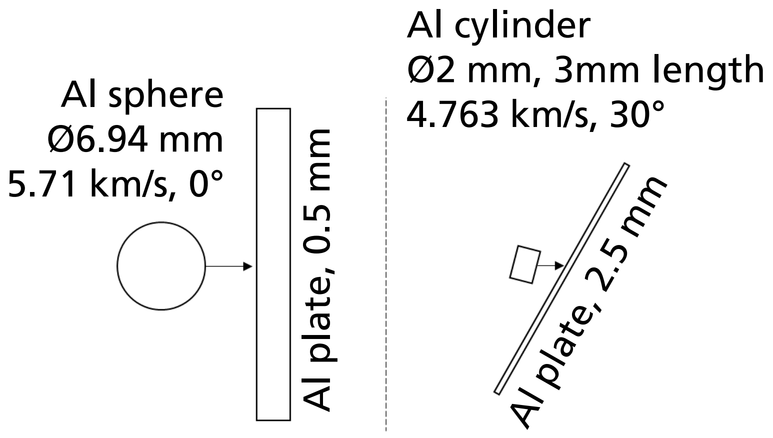
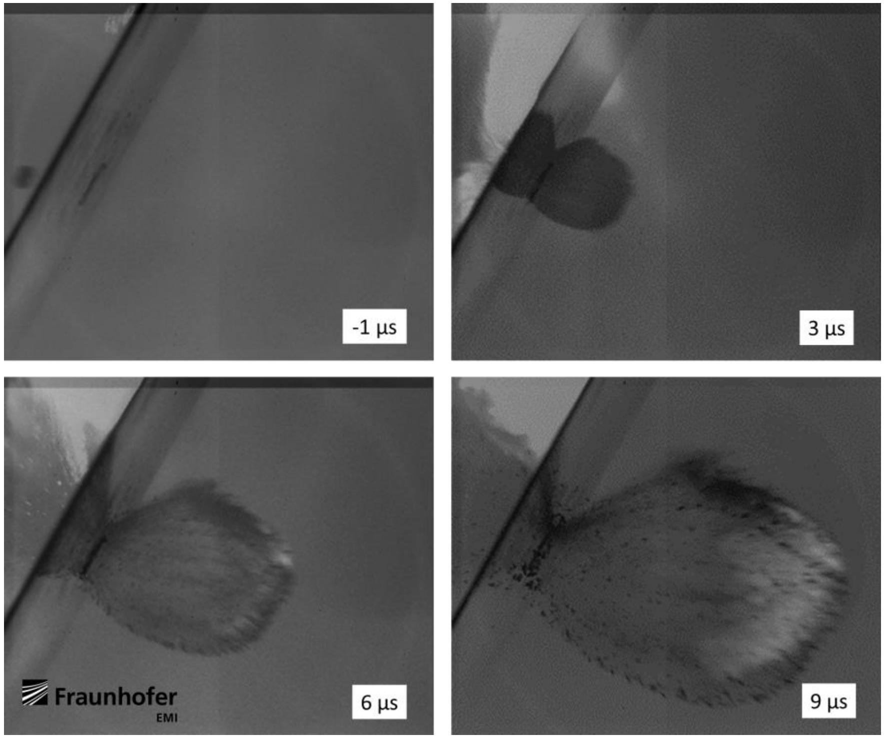
Numerical Simulations (WP4000)

Reproduction of impact experiments

- Qualitative validation using high-speed videos
  - Cloud evolution parameters
  - Including obliquity and impactor shape effects





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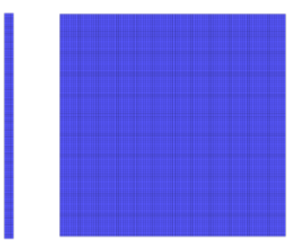
Numerical Simulations (WP4000)

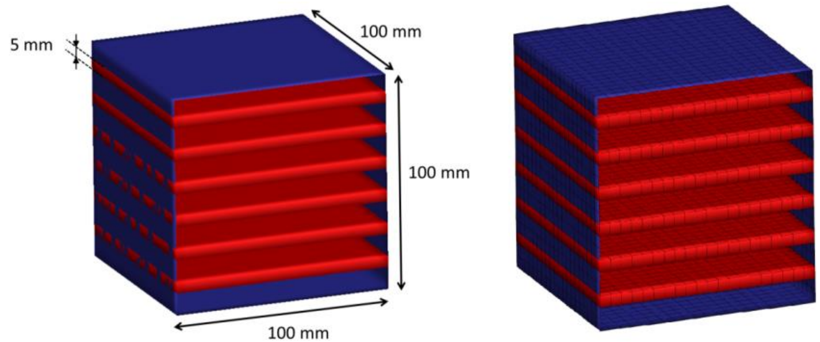
Complex collisions simulations with ESA LOFT spacecraft

- Finite element models of impactors

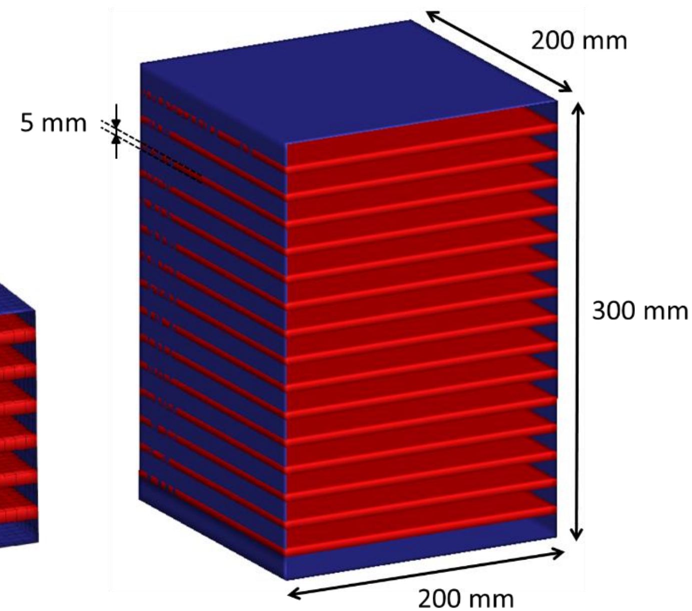
Thin plate,
0.1 kg



1U CubeSat, 1 kg



12U CubeSat, 10 kg



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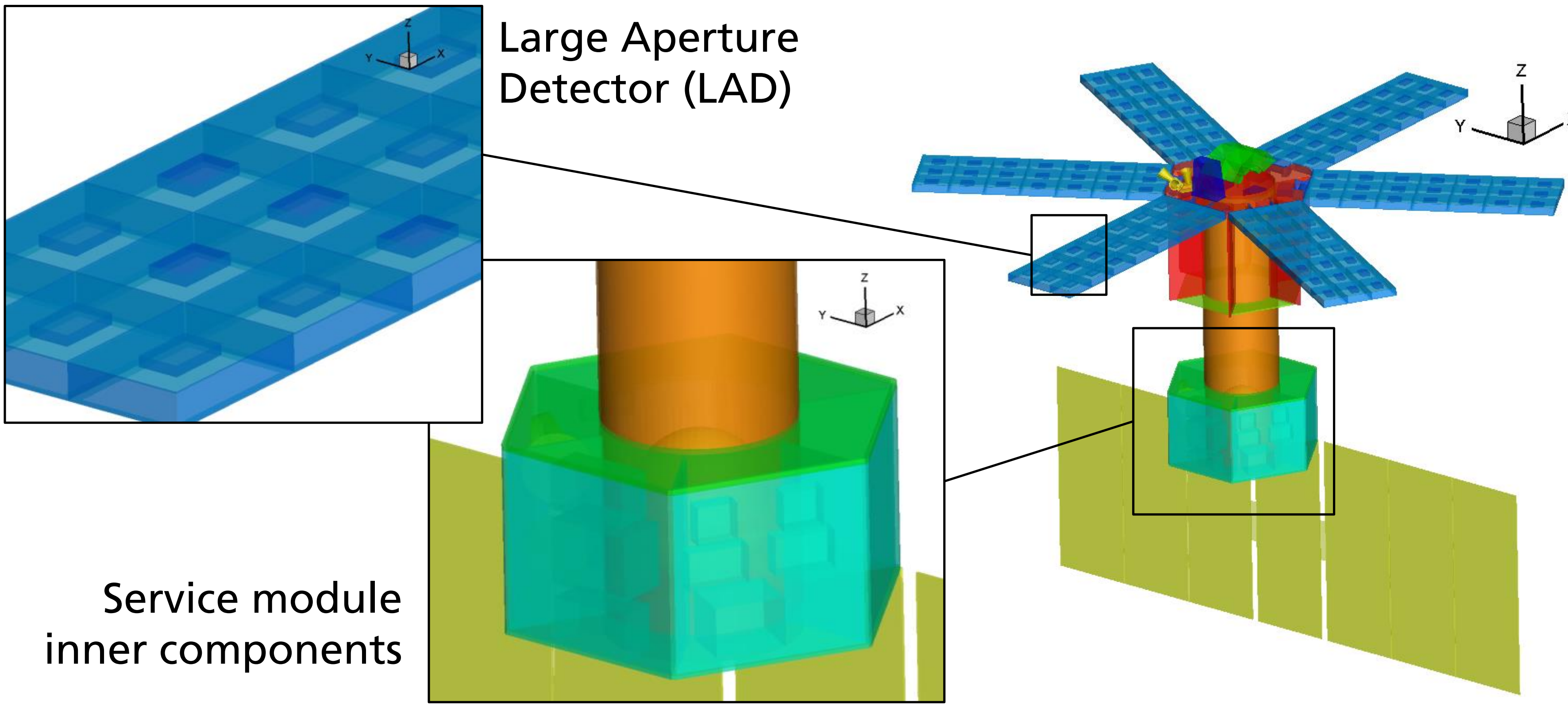
Numerical Simulations (WP4000)

Complex collisions simulations with ESA LOFT spacecraft

- LOFT spacecraft model

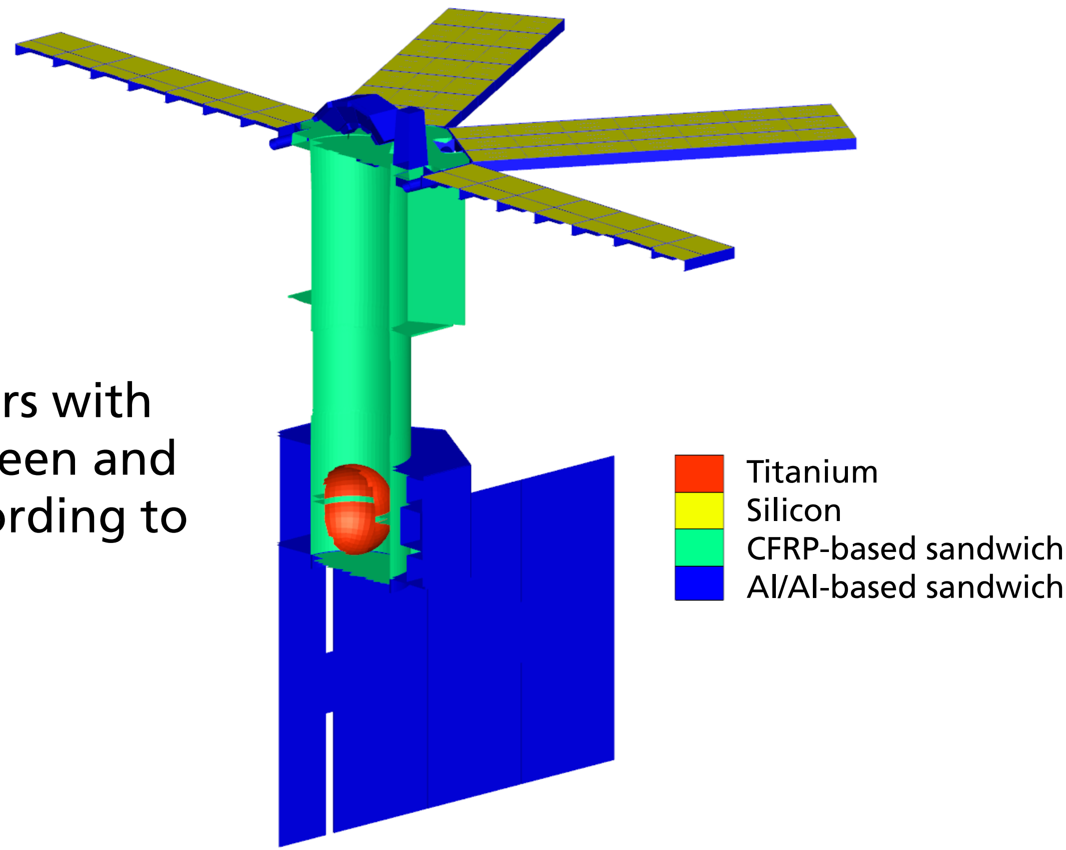


Numerical Simulations (WP4000)

Complex collisions simulations with ESA LOFT spacecraft

- LOFT spacecraft materials
  - analogous (material) models for CFRP- and aluminum-based sandwich structures

➡ Two shell element layers with empty volume in between and thickness adapted according to honeycomb mass

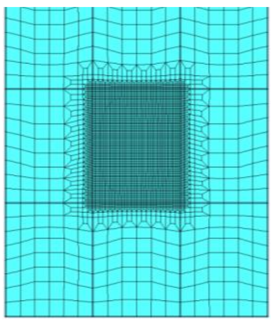


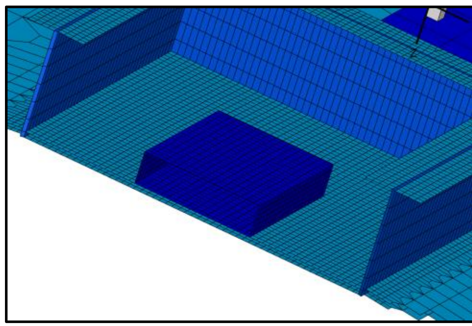
Fraunhofer EMI

Numerical Simulations (WP4000)

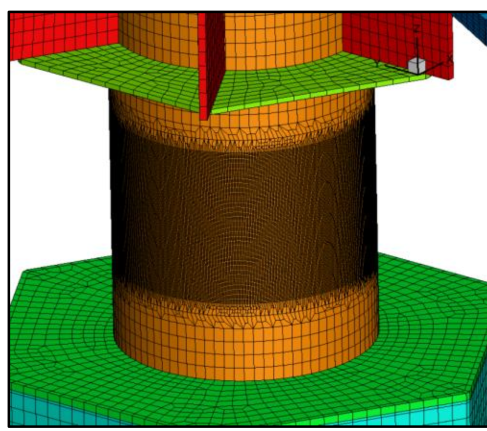
Complex collisions simulations with ESA LOFT spacecraft

- LOFT finite element model

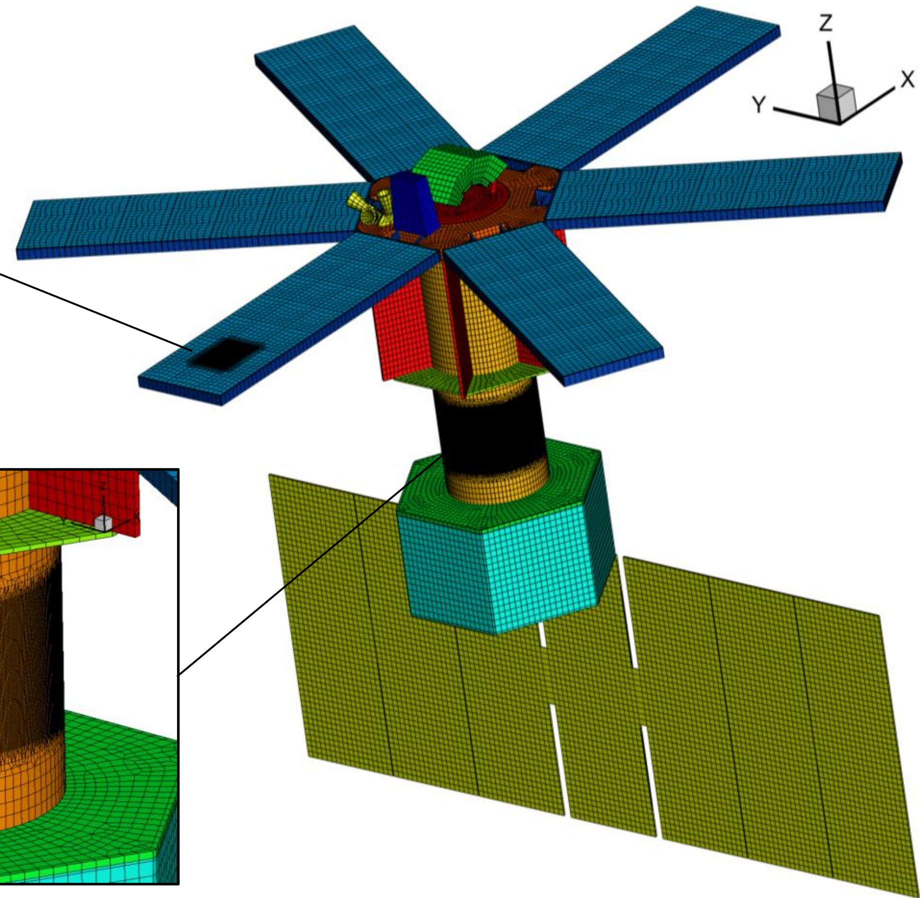




LAD panel details



Mesh refinement
on central tube



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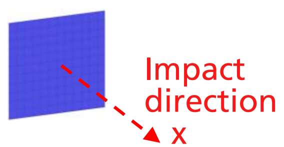
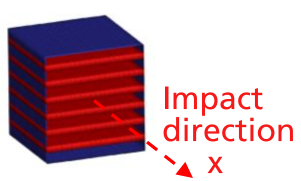
Numerical Simulations (WP4000)

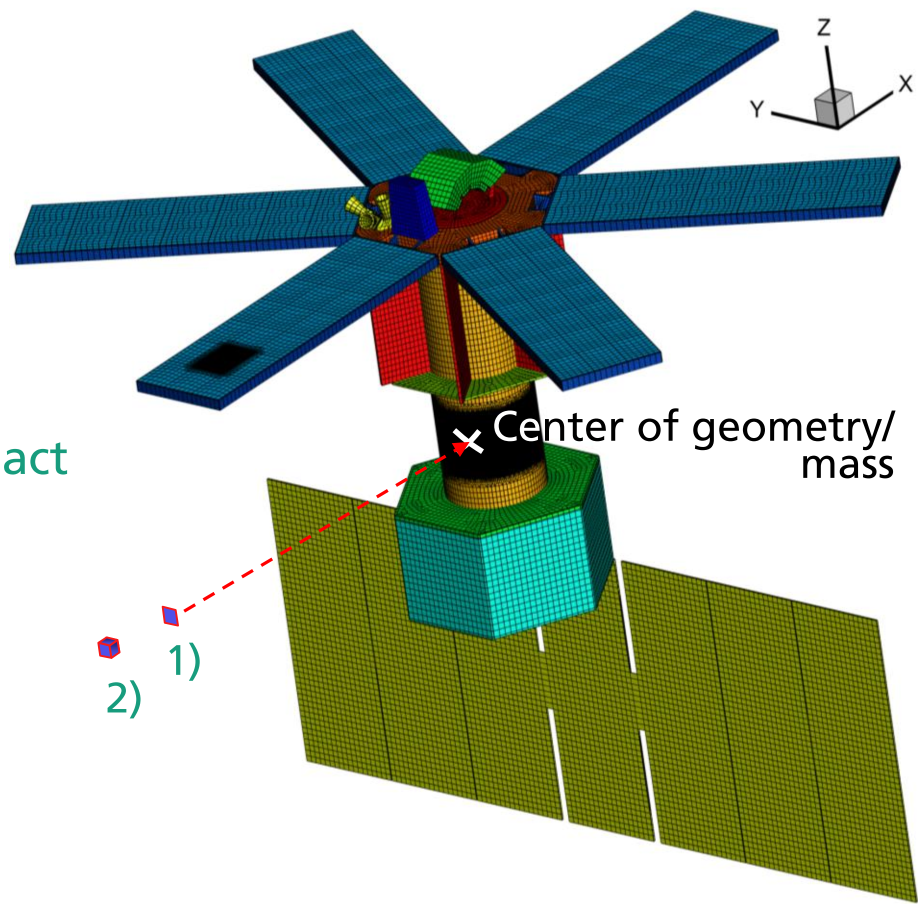
Complex collisions simulations with ESA LOFT spacecraft

1) Plate impactor central impact
   Dimension: 4×100×100 mm³
   Mass: 0.1 kg
   EMR: 3.025 J/G (12.1 J/g)



2) 1U CubeSat impactor central impact
   Dimension: 100×100×100 mm³
   Mass: 1 kg
   EMR: 30.25 J/G (121 J/g)





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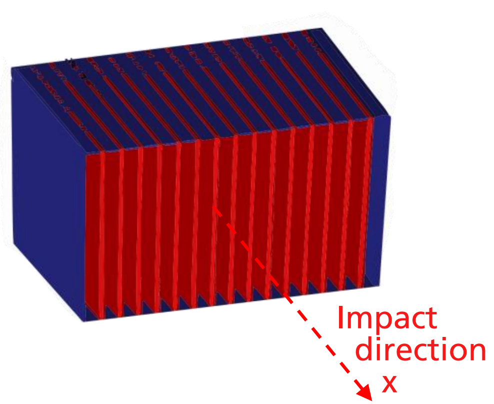
Numerical Simulations (WP4000)

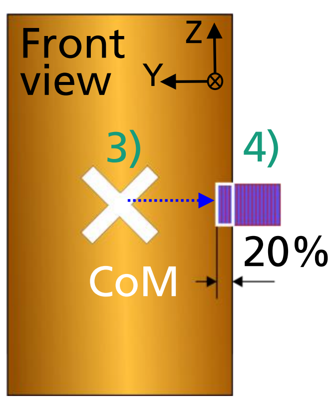
Complex collisions simulations with ESA LOFT spacecraft

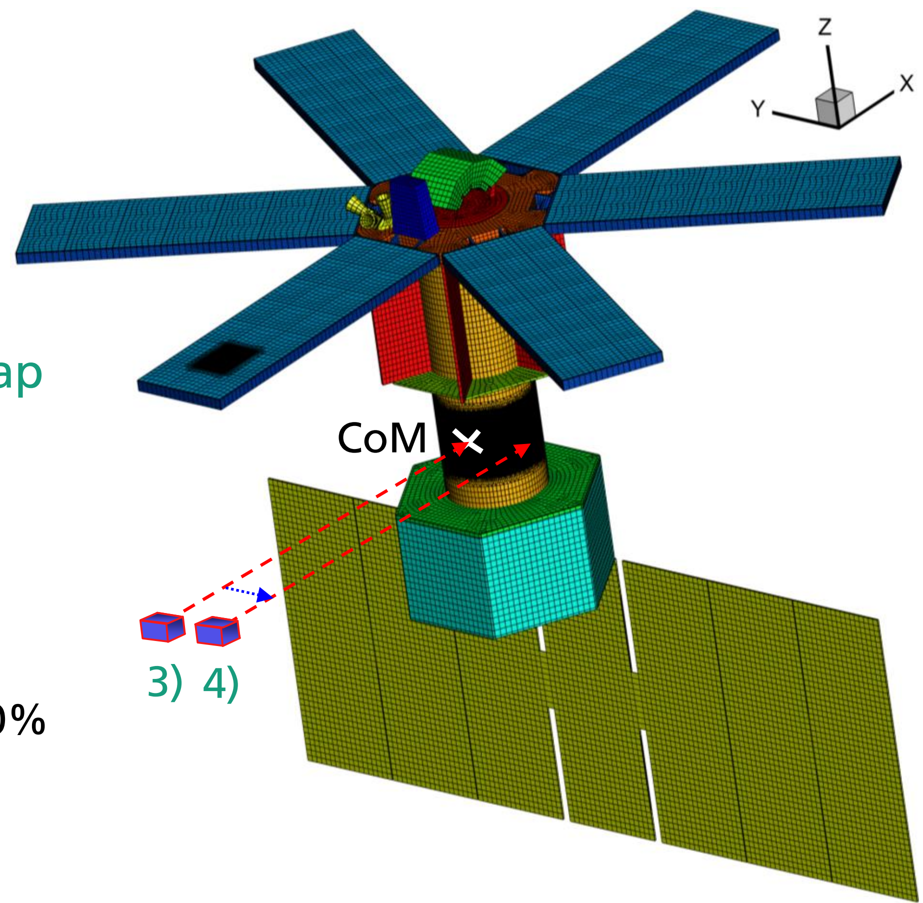
12U CubeSat impactor
Dimension: 200×200×300 mm^3
Mass: 10 kg
EMR: 302.5 J/G (1210 J/g)

3) Central impact on CoM

4) Grazing collision with 20% overlap







Numerical Simulations (WP4000)

Complex collisions simulations with ESA LOFT spacecraft

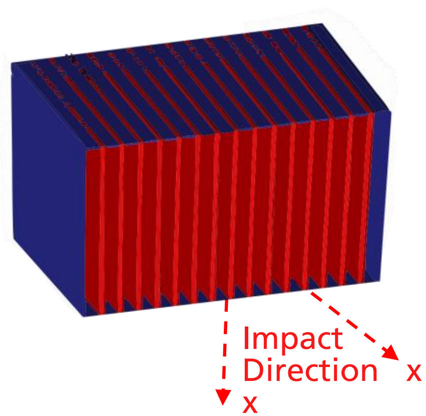
12U CubeSat impactor

Dimension: 200×200×300 mm^3

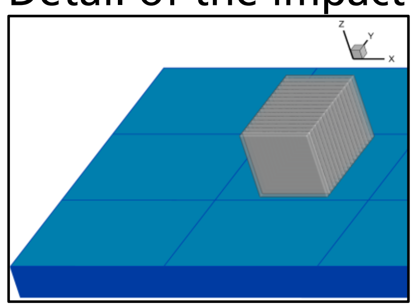
Mass: 10 kg

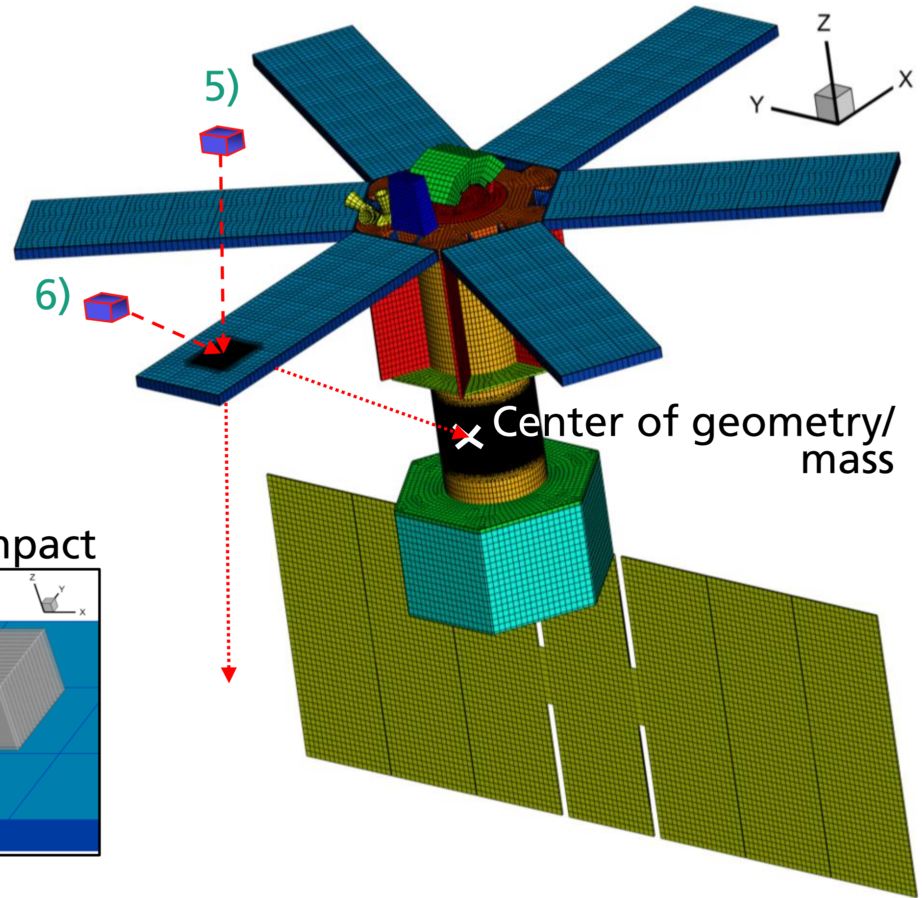
EMR: 302.5 J/G (1210 J/g)

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 (WP4000)
Conclusions

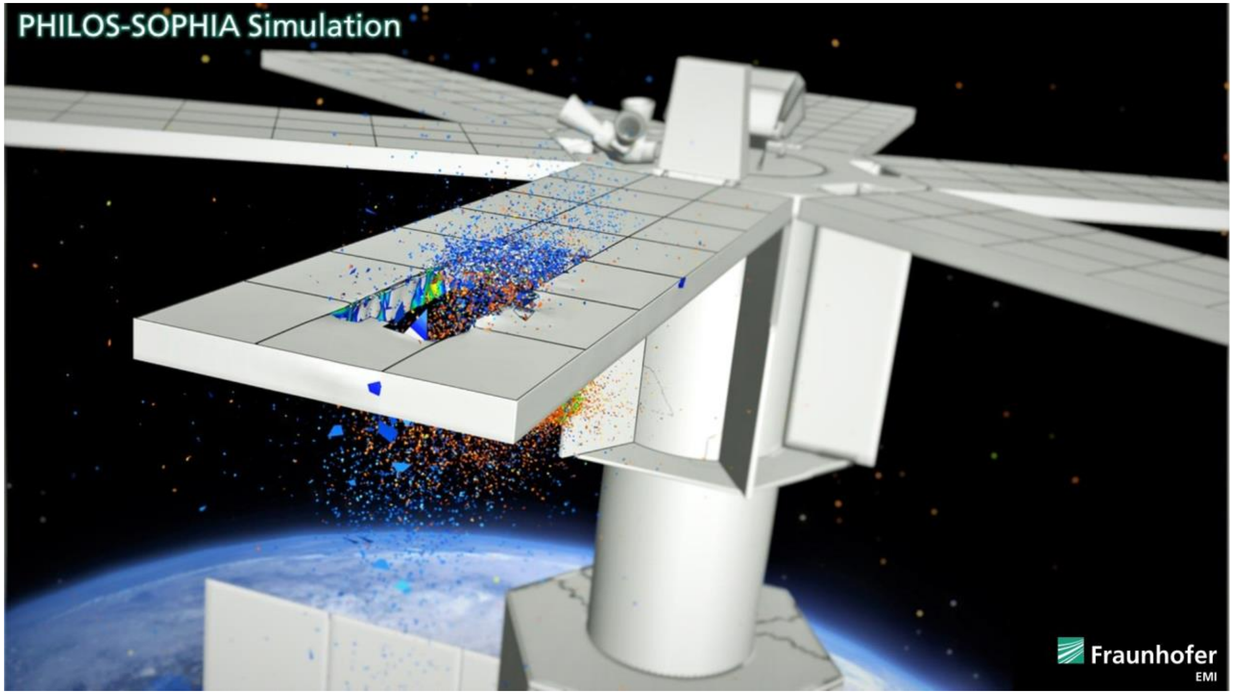
- Various finite element models generated
- Scenarios defined
- More than 30 simulations performed
  - Evaluating tool capabilities → shielding analysis
  - Validating tool output → experiment reproduction
  - Evaluating fragmentation → complex collisions

NUMERICAL SIMULATIONS FOR S/C CATASTROPHIC DISRUPTION ANALYSIS

Final Review - ESA Contract N° 4000119400/16/NL/BJ/zk

Results Evaluation

(WP5000)



Pascal Matura
Martin Schimmerohn

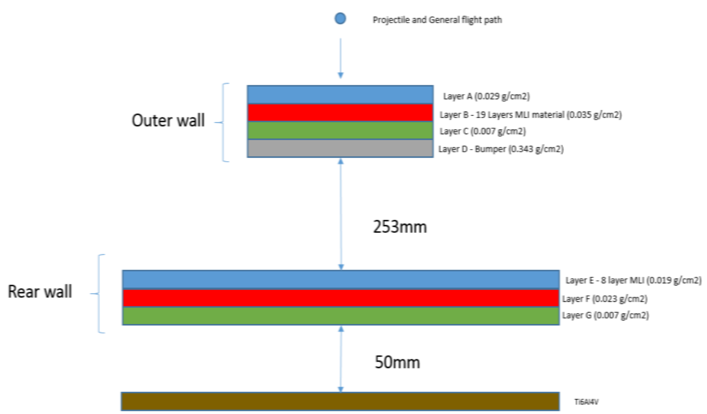
ESTEC, Noordwijk
12 September 2018

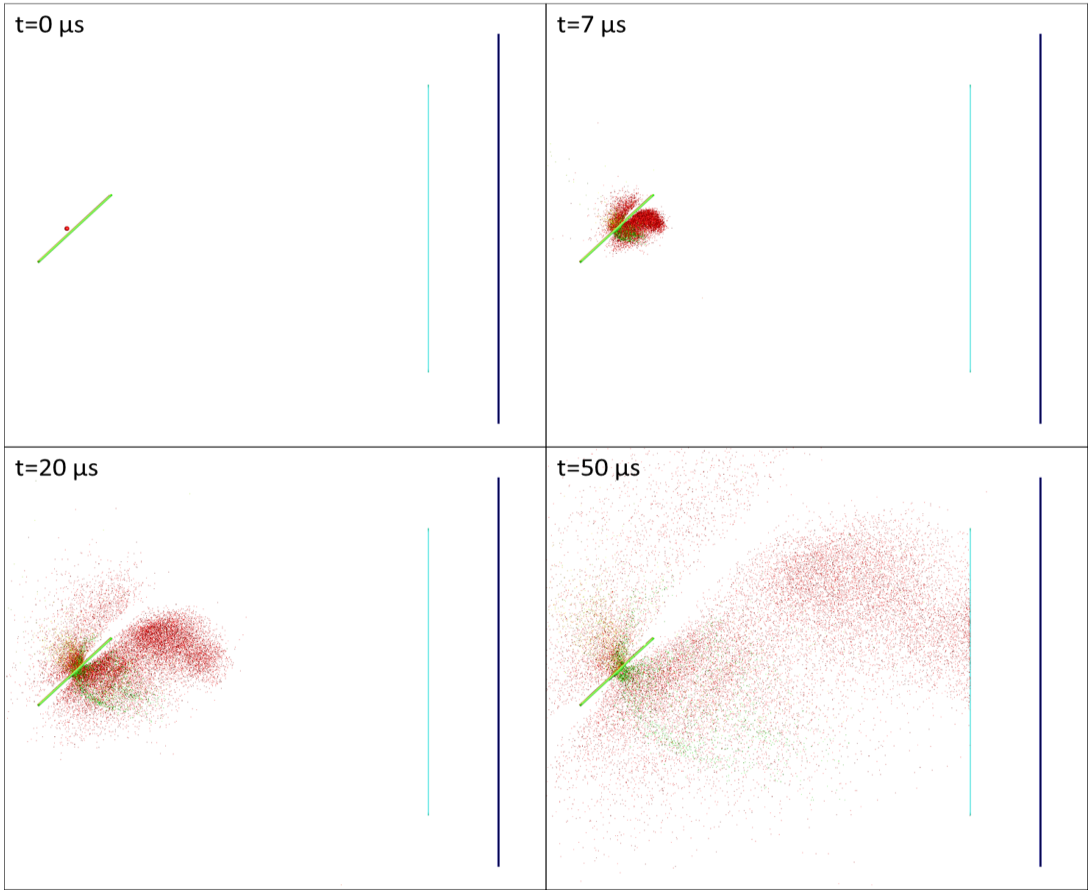
Fraunhofer EMI

Results Evaluation (WP5100)

Simple validation example

- Test case 1b)
  - Ø3.6 mm nylon impactor
  - 6.66 km/s, 45°

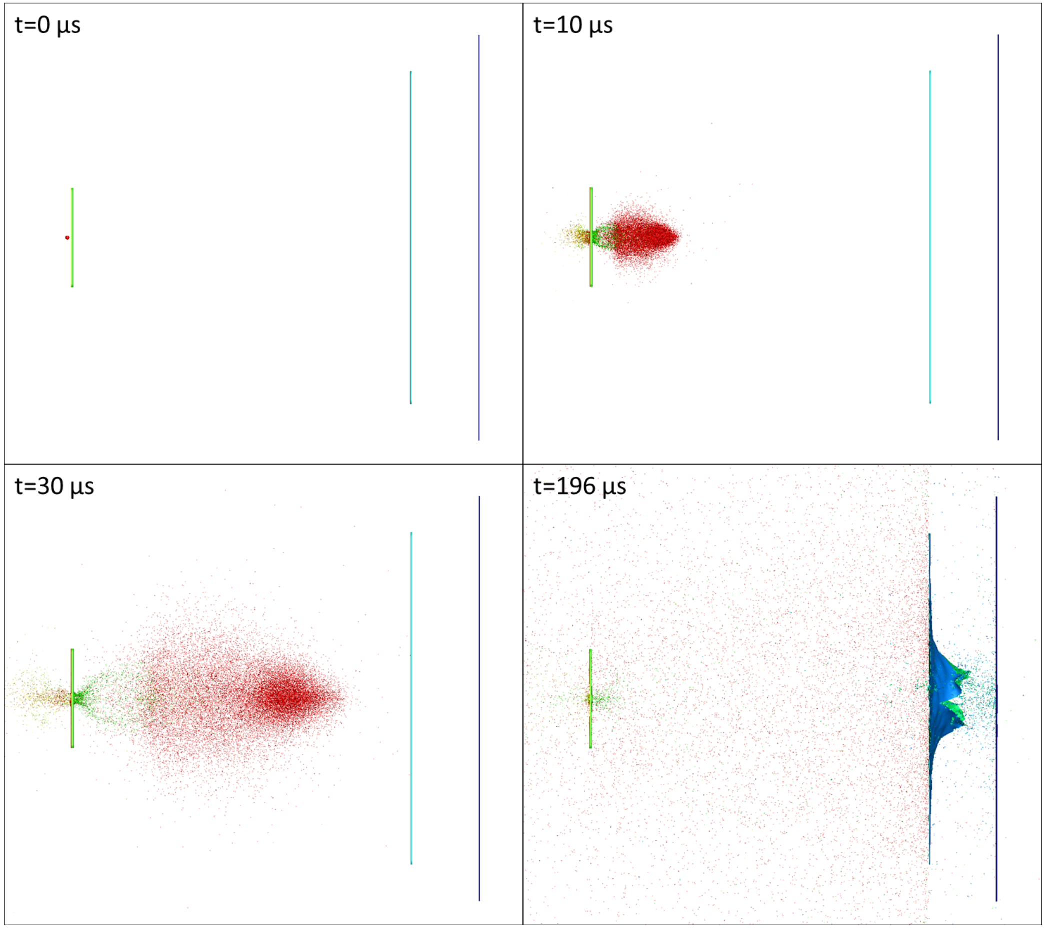


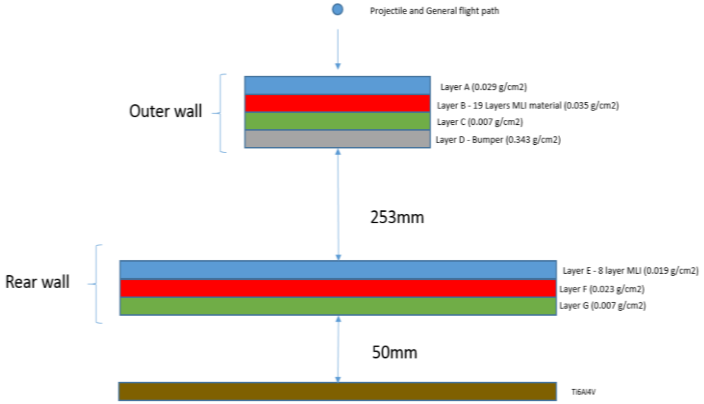


Results Evaluation (WP5100)

Simple validation example

- Test case 1d)
  - Ø3 mm Al impactor
  - 7.11 km/s, 0°



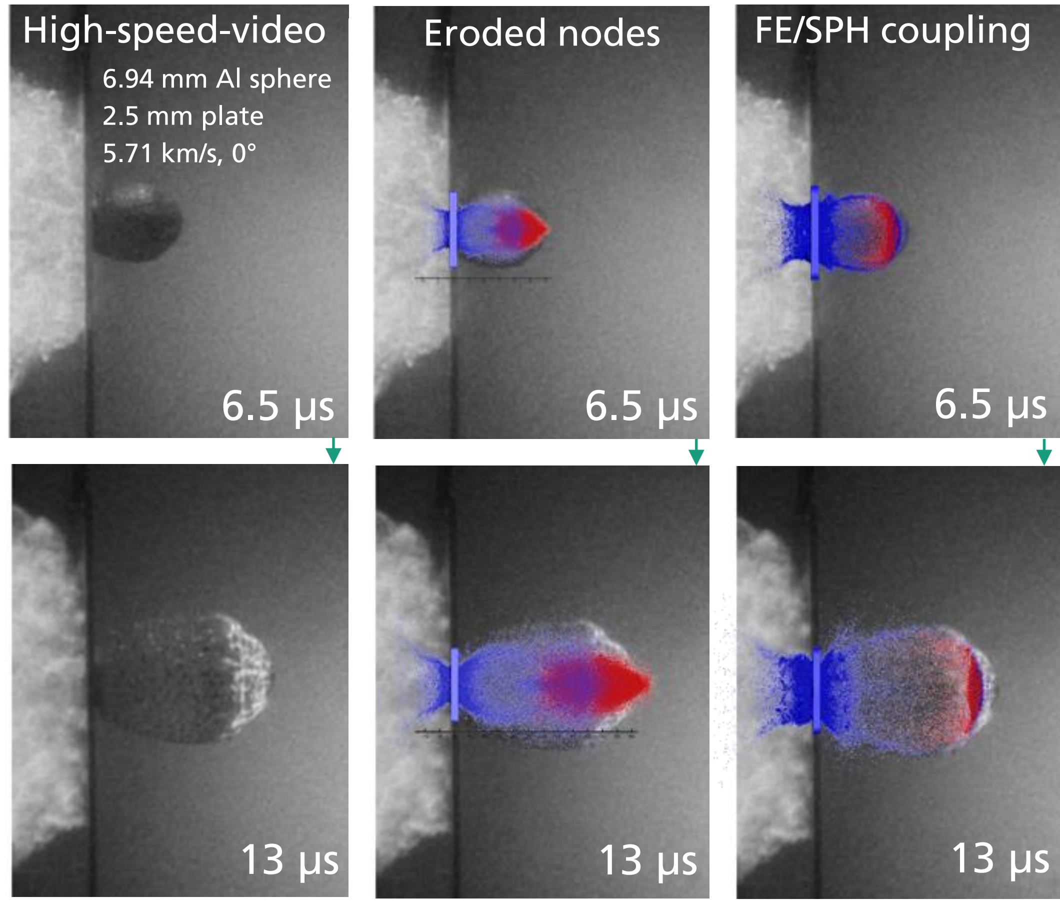


Results Evaluation (WP5100)

Experiment reproduction

- Eroded nodes
  - Reasonable results with 402,216 finite elements
  - 8.7 hours computation
- FE/SPH coupling
  - More precise results with 68,208 finite elements
  - 210 hours computation

➡ Selection of method depends on simulation needs



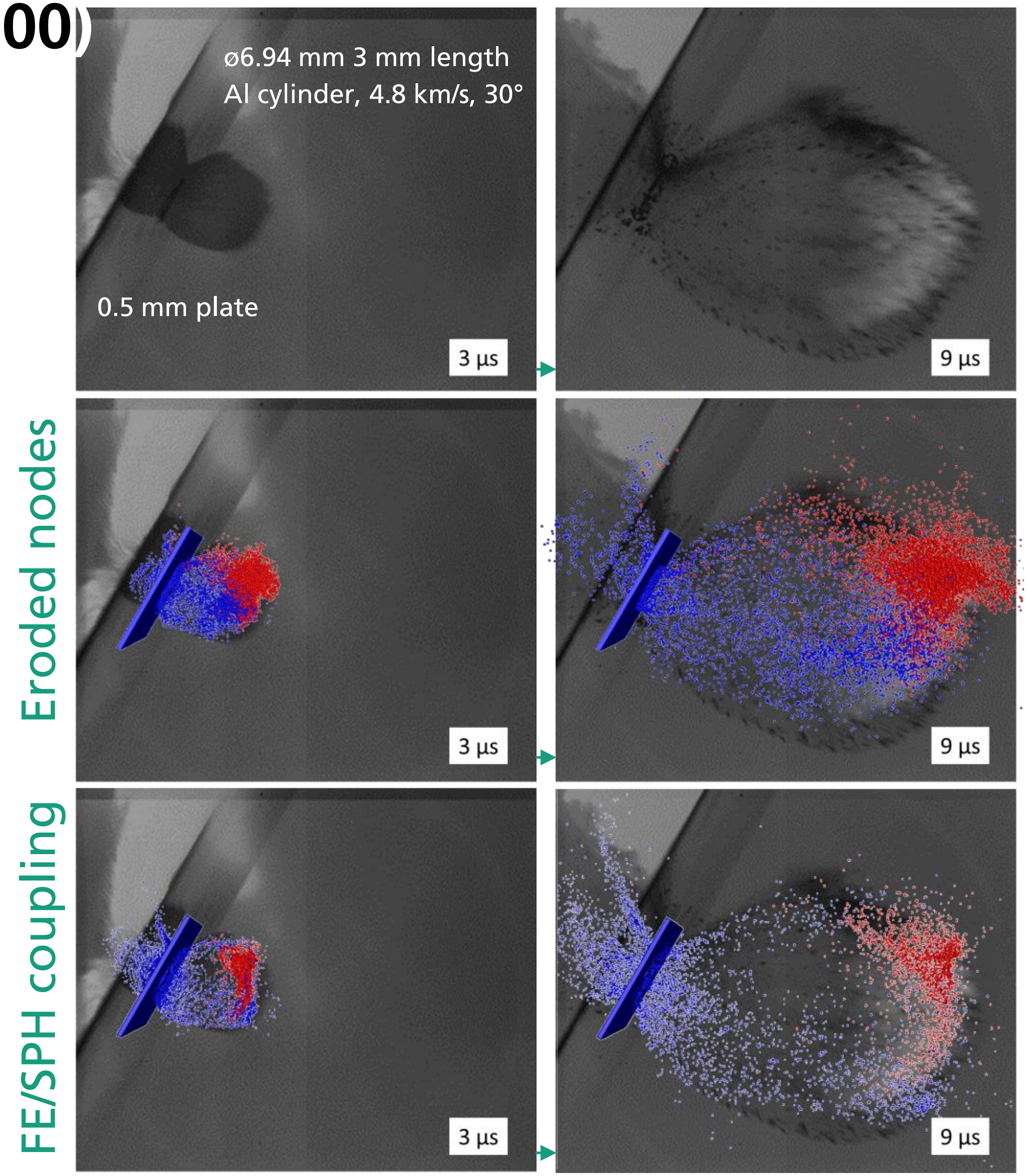
Fraunhofer EMI

Results Evaluation (WP5100)

Experiment reproduction

- Eroded nodes
  - Reasonable results with 102,570 finite elements
  - 5 hours computation
- FE/SPH coupling
  - More precise results with 102,570 finite elements
  - 11 hours computation

➡ Selection of method depends on simulation needs



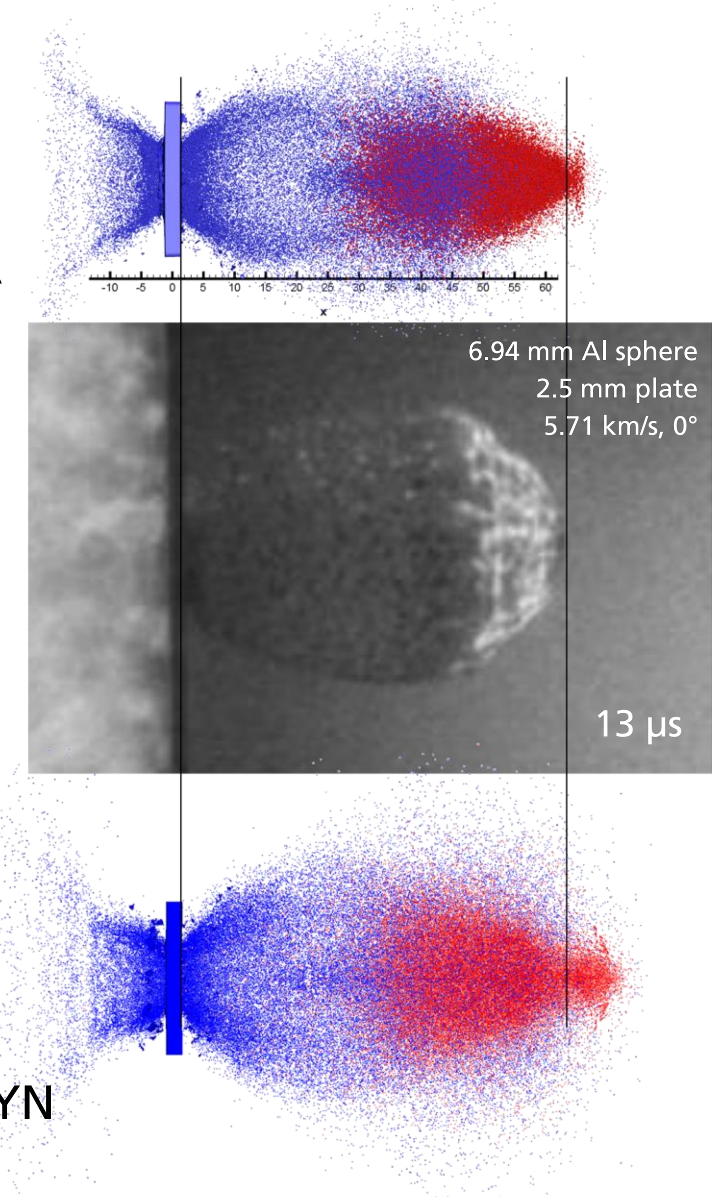
Fraunhofer EMI

Results Evaluation (WP5100)

Experiment reproduction

- Cross-validation with commercial hydrocode
- PHILOS-SOPHIA
  - Similar mass distribution
  - Better velocity distribution
  - 9 hours computation time
- ANSYS-AUTODYN
  - Similar mass distribution
  - 27 hours computation time

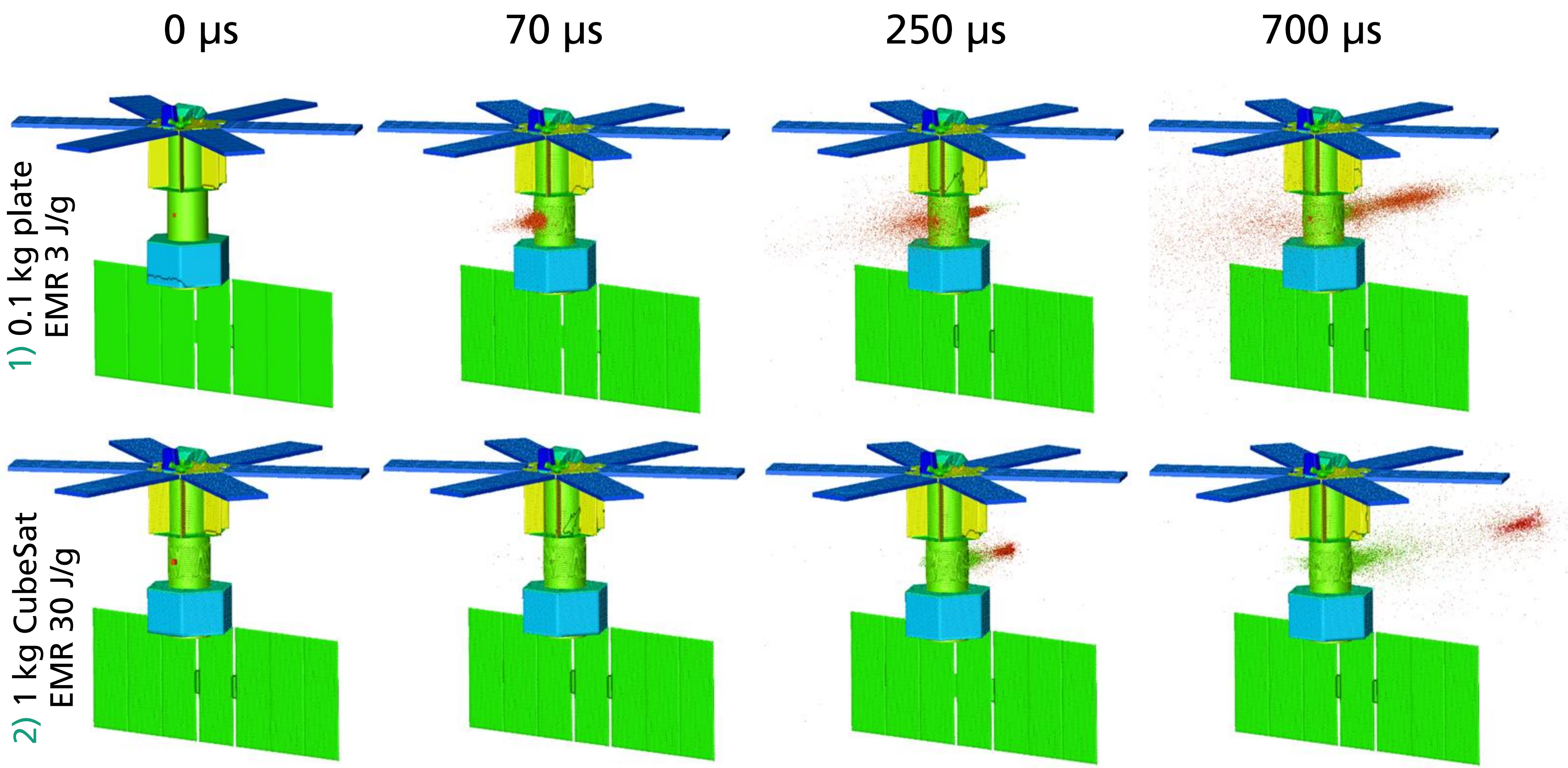
PHILOS-SOPHIA
Eroded nodes



ANSYS-AUTODYN
Eroded nodes

Results Evaluation (WP5100)

Simulation results – Fragmentation process Scenario 1 + 2

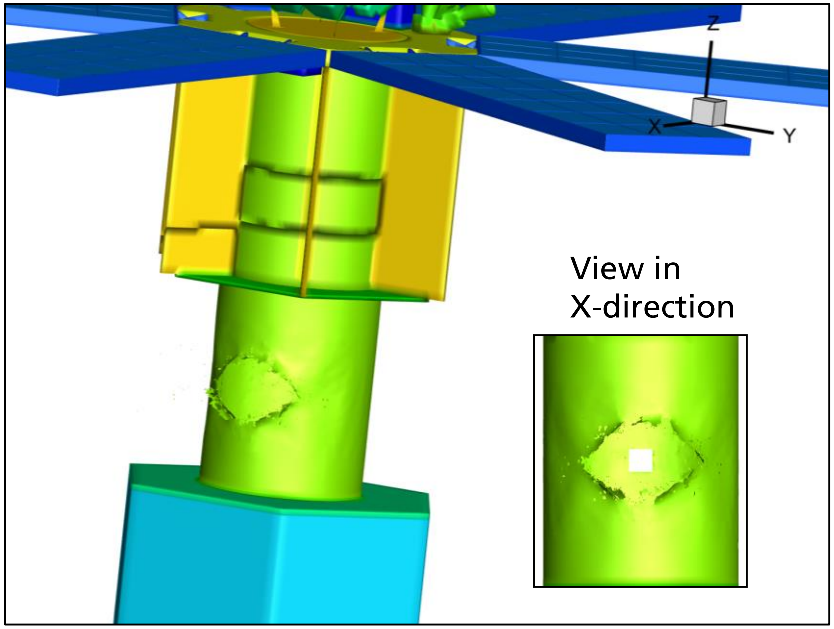


Fraunhofer EMI

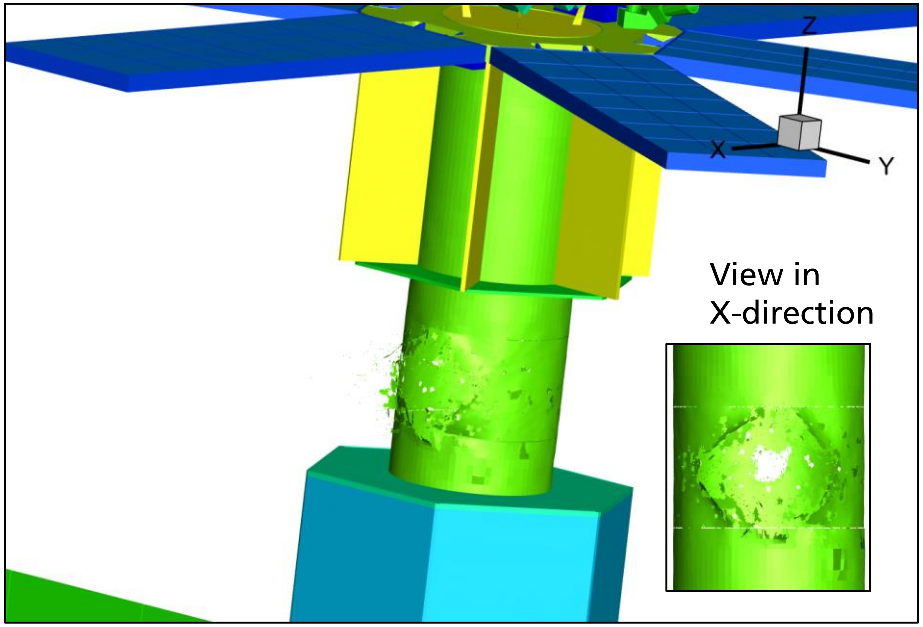
Results Evaluation (WP5100)

Simulation results – Damage non-eroded fragments Scenario 1 + 2

1) 0.1 kg plate, EMR 3 J/g

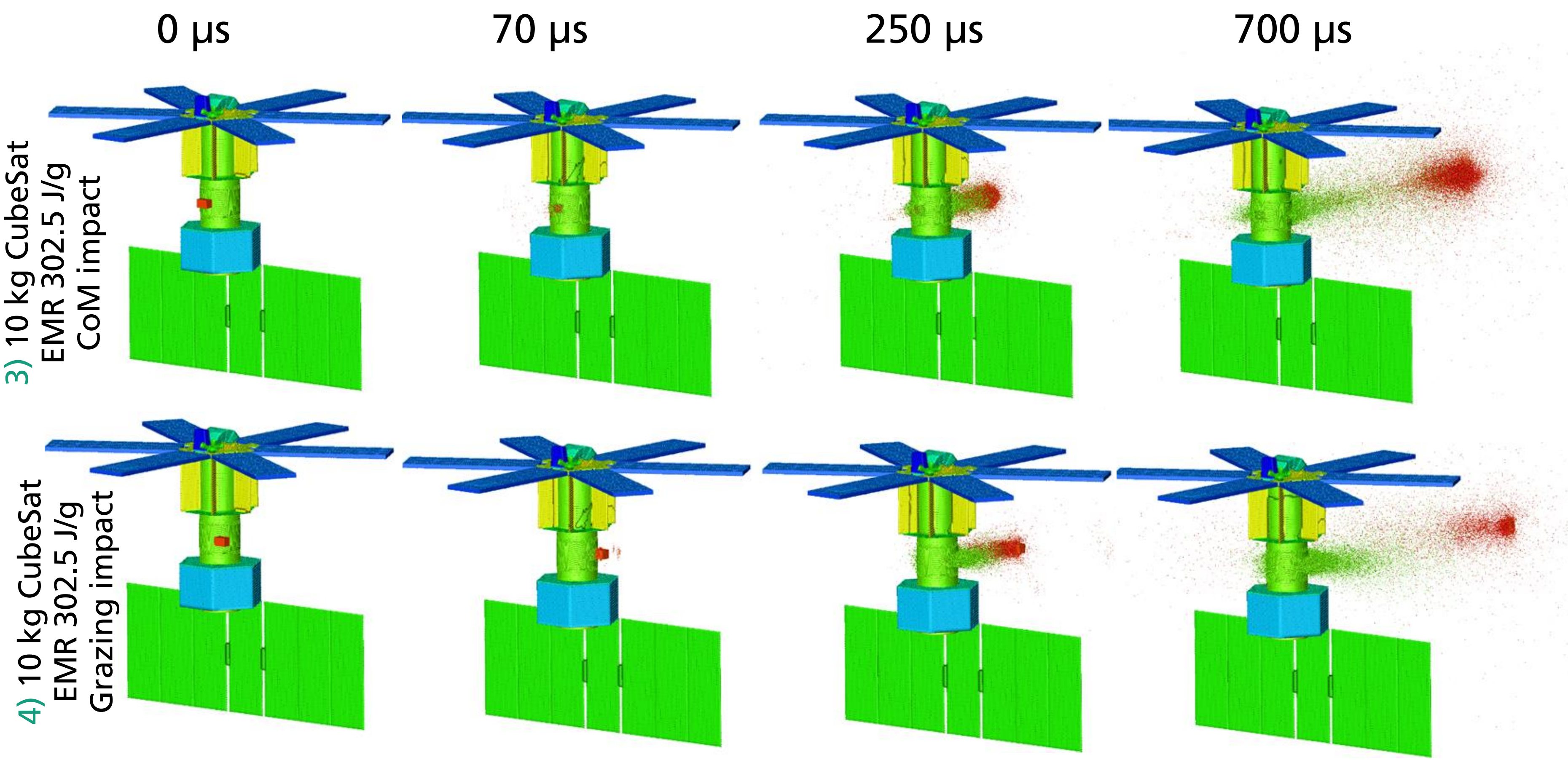


2) 1 kg CubeSat, EMR 30 J/g



Results Evaluation (WP5100)

Simulation results – Fragmentation process Scenario 3 + 4



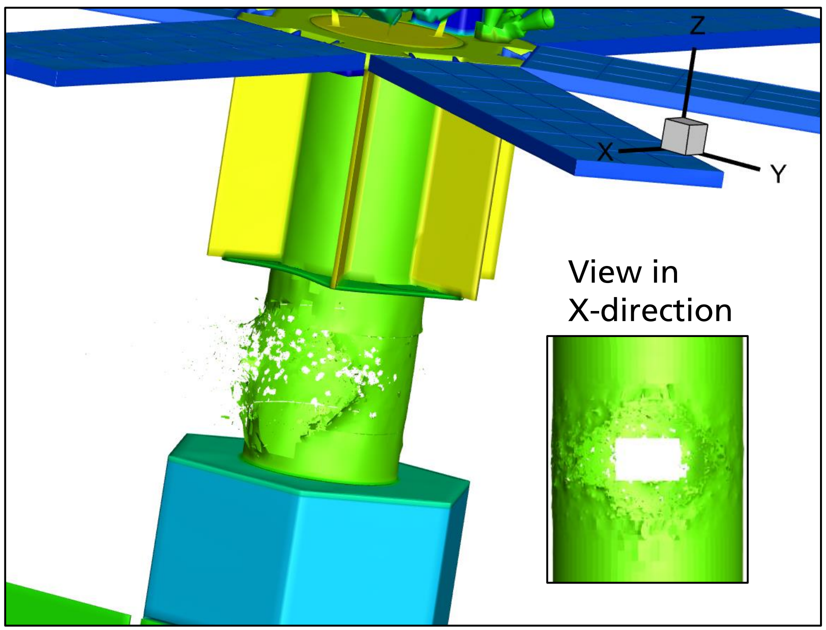
Fraunhofer EMI

Results Evaluation (WP5100)

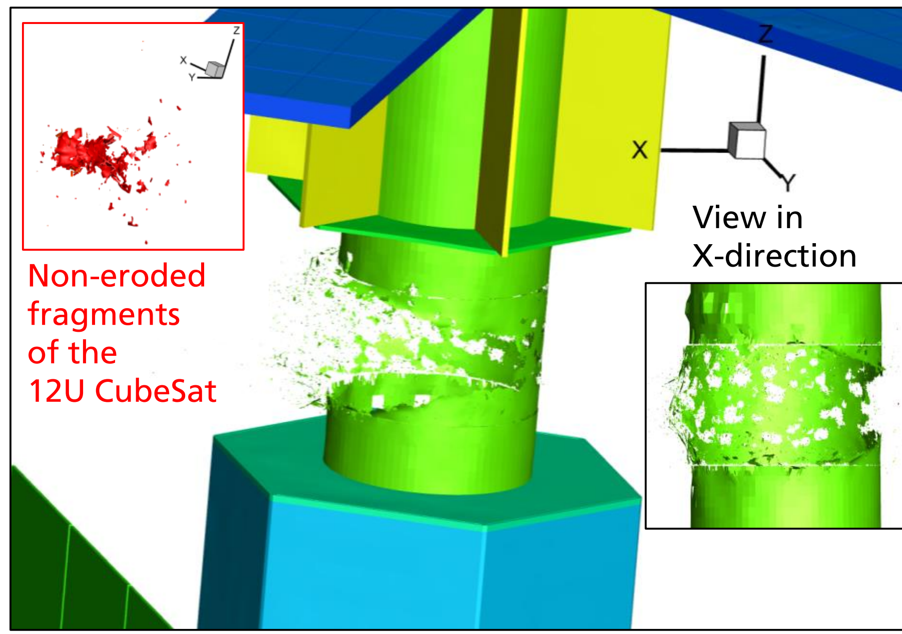
Simulation results - Damage non-eroded fragments Scenario 3 + 4

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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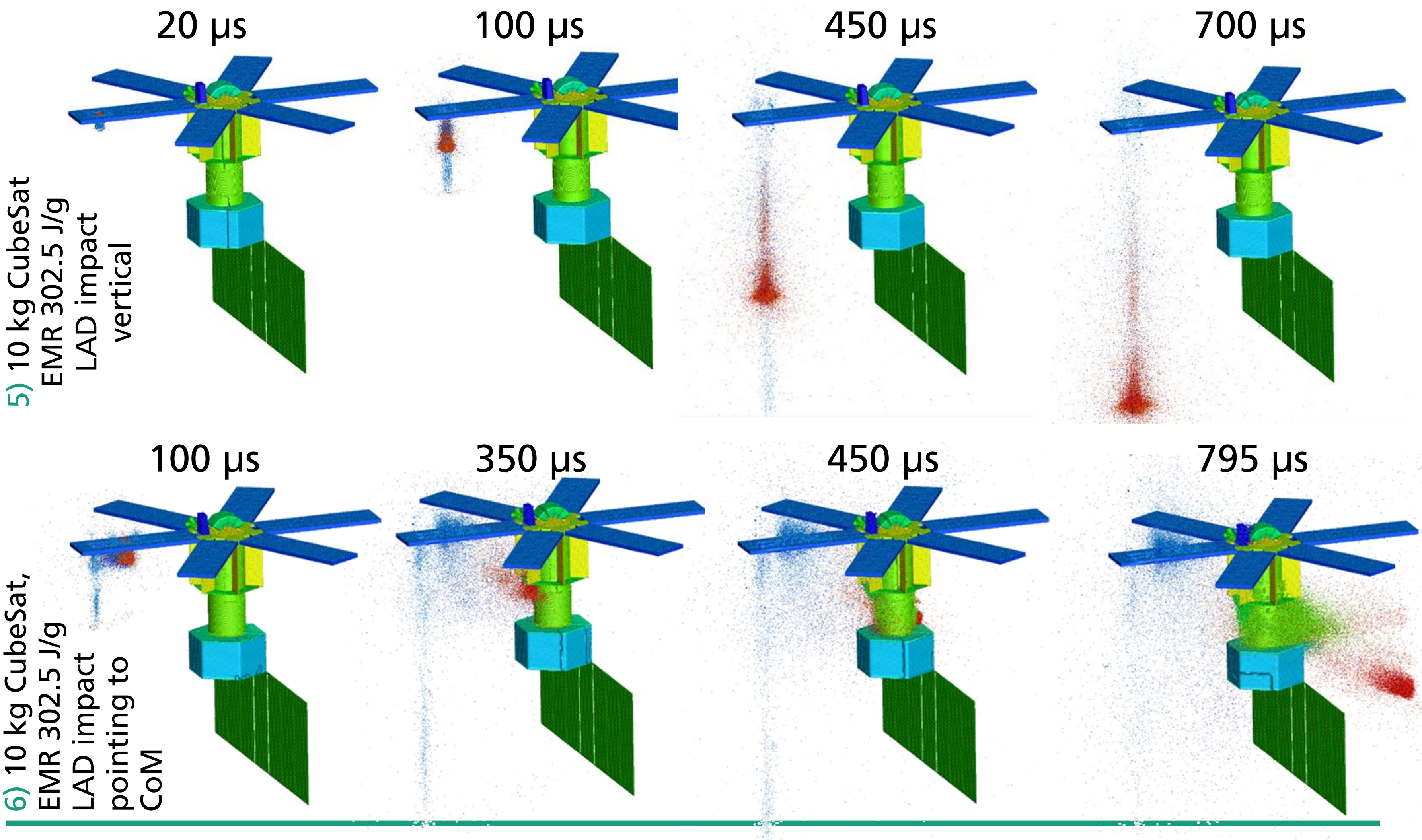
Results Evaluation (WP5100)

Simulation results – Fragmentation process Scenario 5 + 6



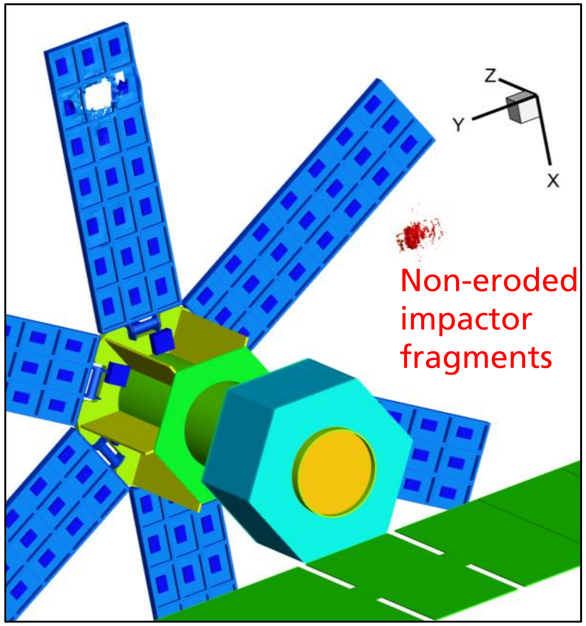
Fraunhofer EMI

Results Evaluation (WP5100)

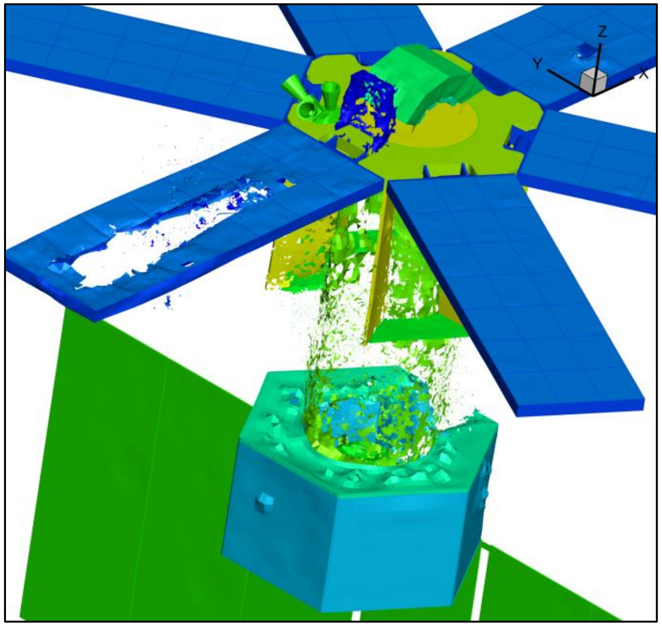
Simulation results - Damage non-eroded fragments Scenario 5 + 6

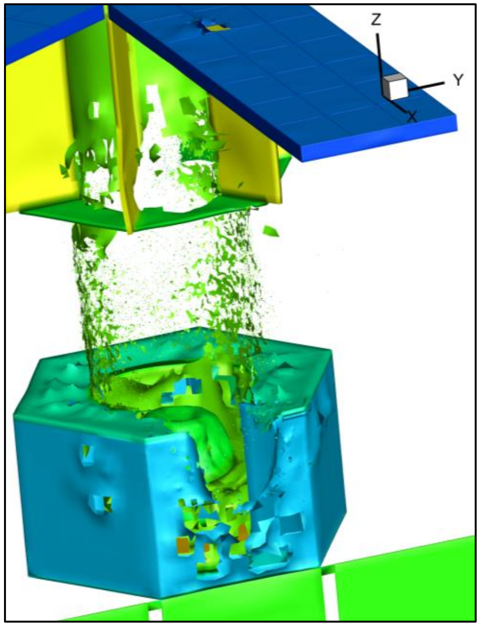
10 kg CubeSat, EMR 302.5 J/g

5) Vertical LAD impact



6) LAD impact pointing to CoM

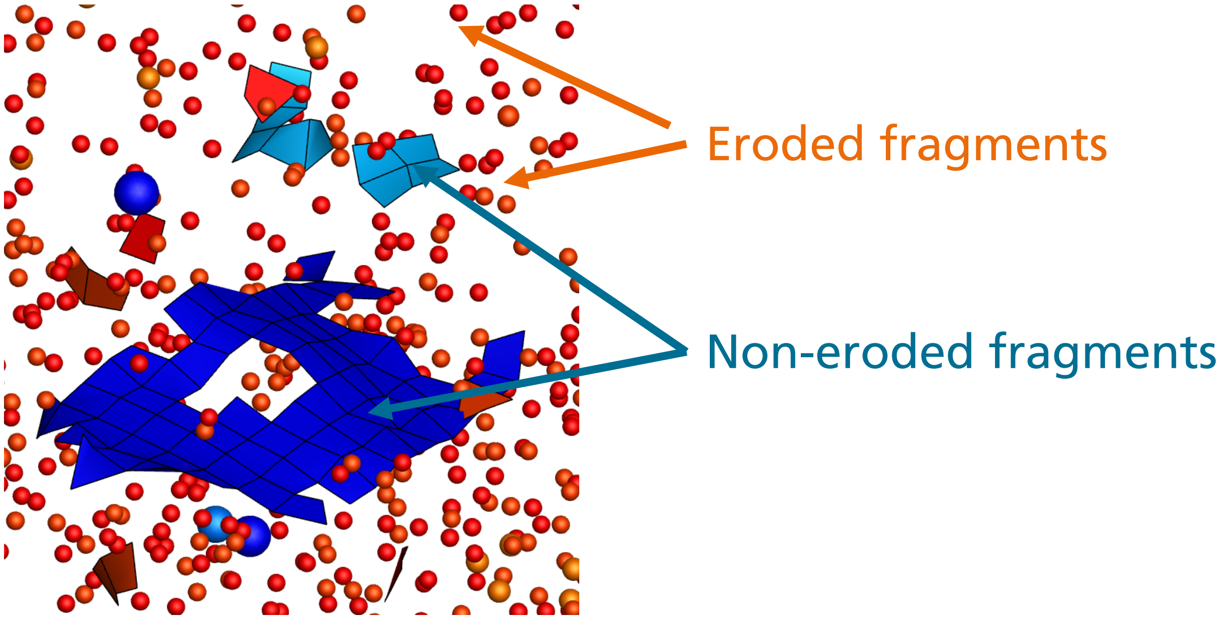




Results Evaluation (WP5100)

Fragmentation Analysis - Approach

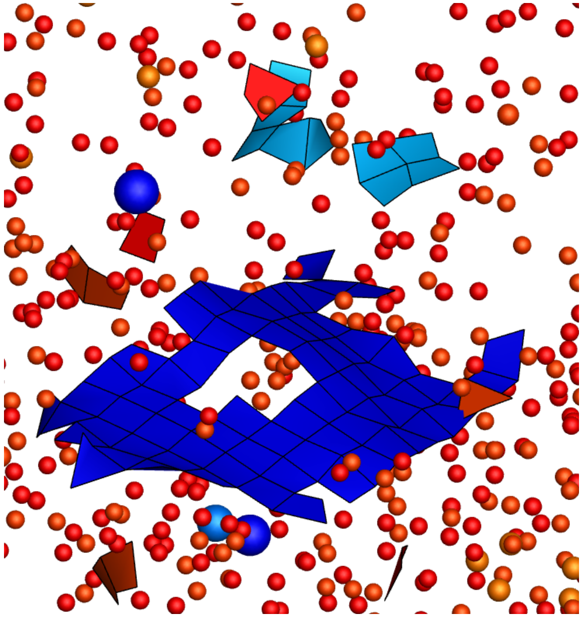
- Two „types“ of fragments to distinguish
  - Non-eroded fragments (coherent finite element mesh)
  - Eroded fragments (deleted finite elements replaced by mass points)

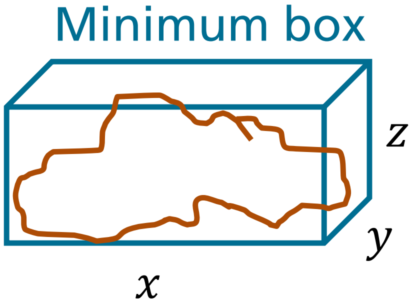


Results Evaluation (WP5100)

Fragmentation Analysis – Fragment properties

- Velocity of center of gravity
- Surface area to mass ratio (A/M)
- Characteristic length $L_c = \frac{x + y + z}{3}$





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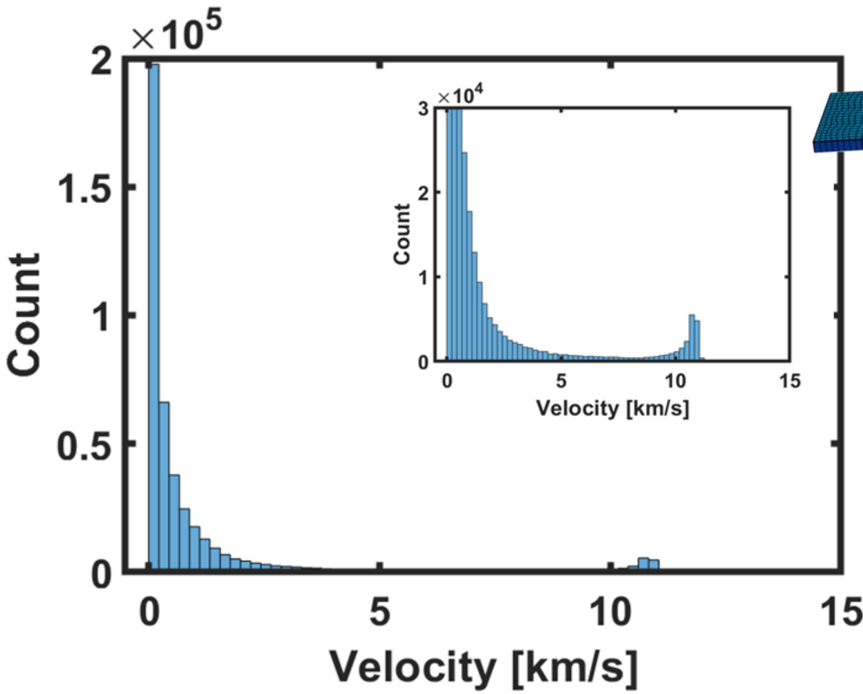
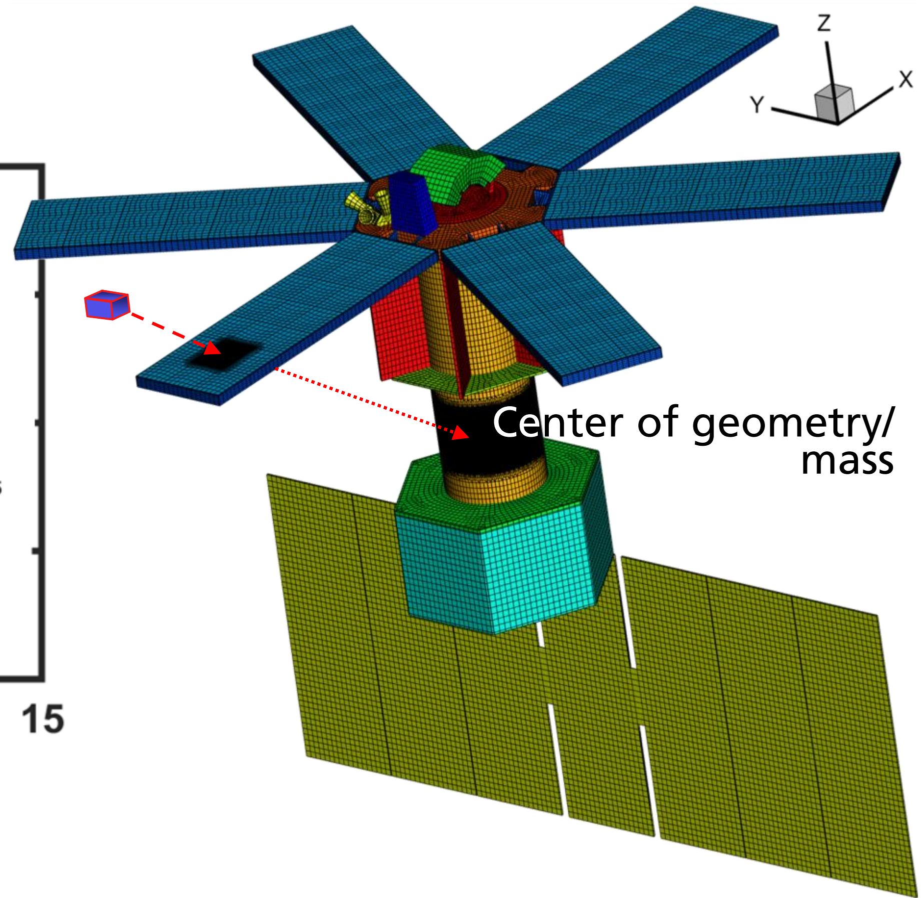
Results Evaluation (WP5100)

Fragmentation Analysis – Scenario 6

- Fragment number over velocity



Eroded and non-eroded fragments,
940 µs after impact



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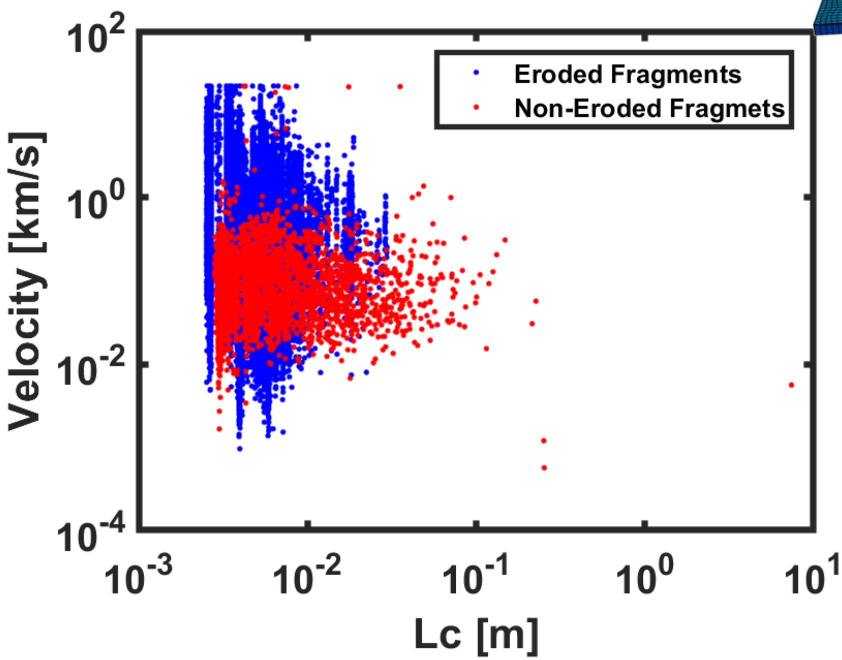
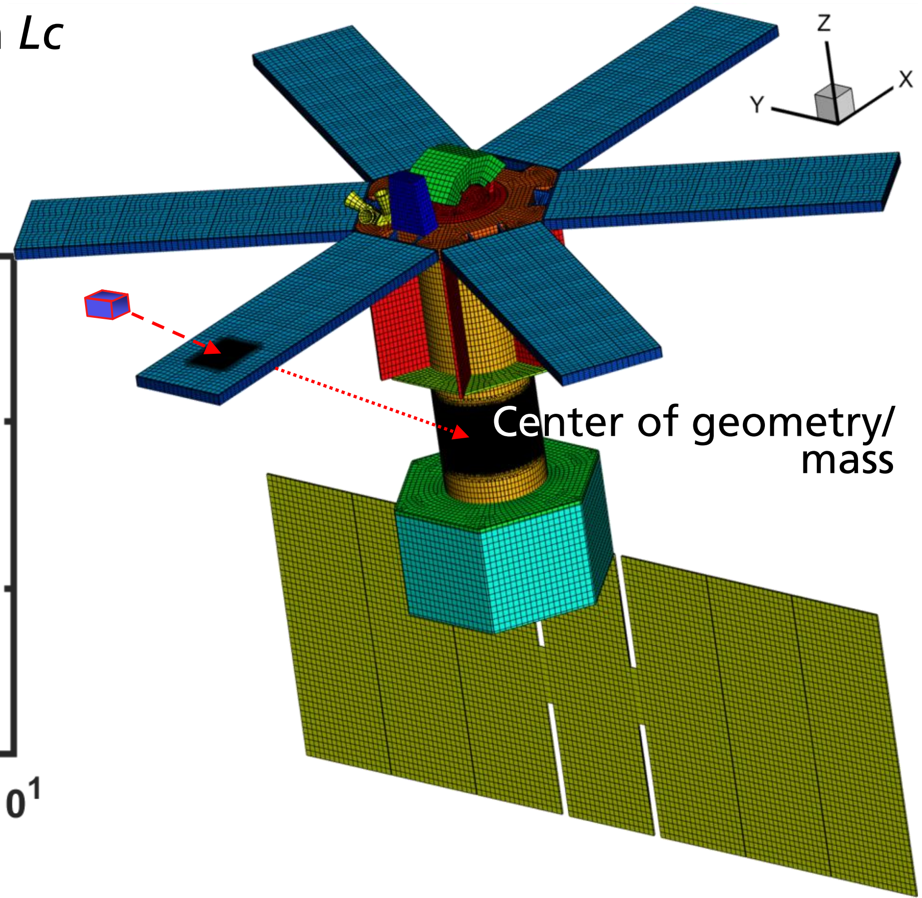
Results Evaluation (WP5100)

Fragmentation Analysis – Scenario 6

- Velocity over characteristic length *Lc*





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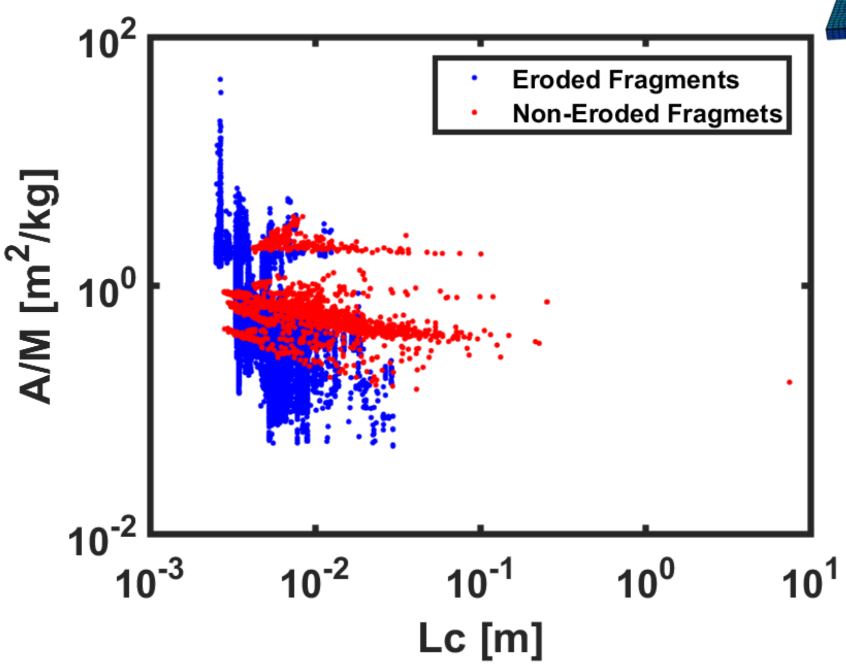
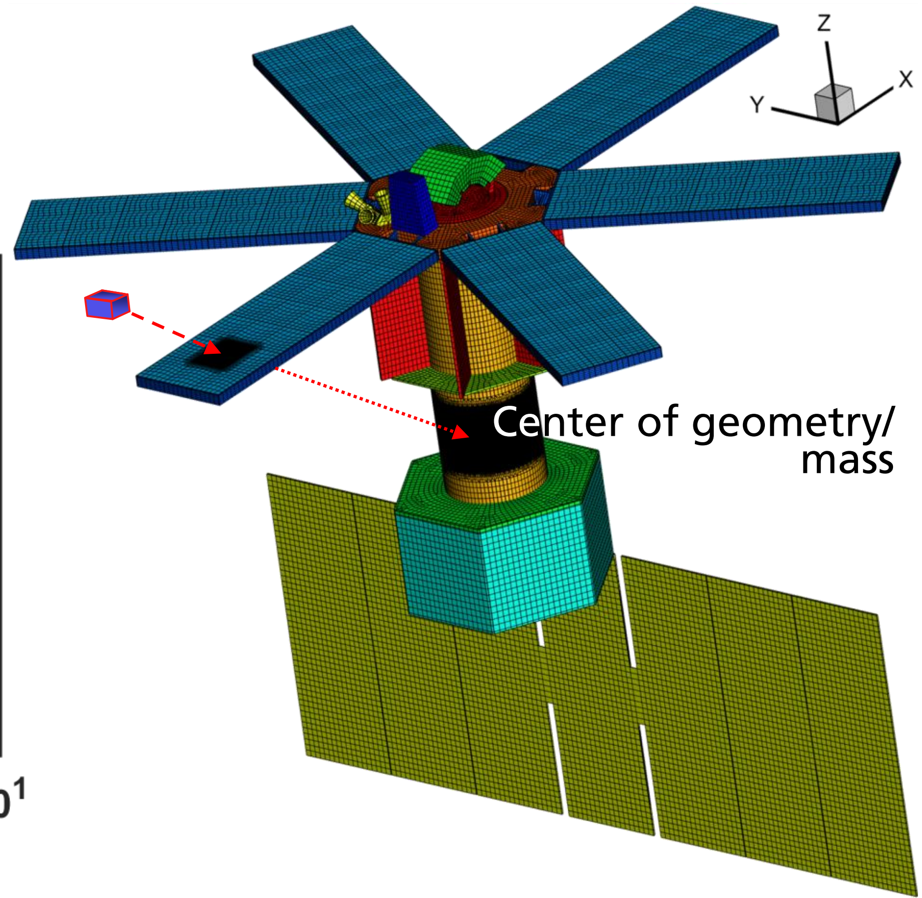
Results Evaluation (WP5100)
Fragmentation Analysis – Scenario 6

- *A/M* over characteristic length *Lc*





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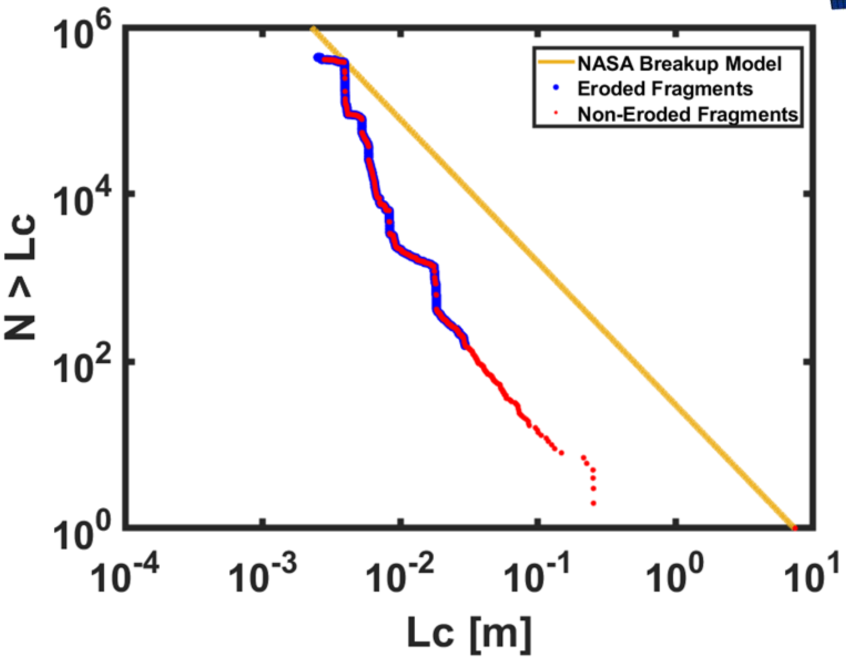
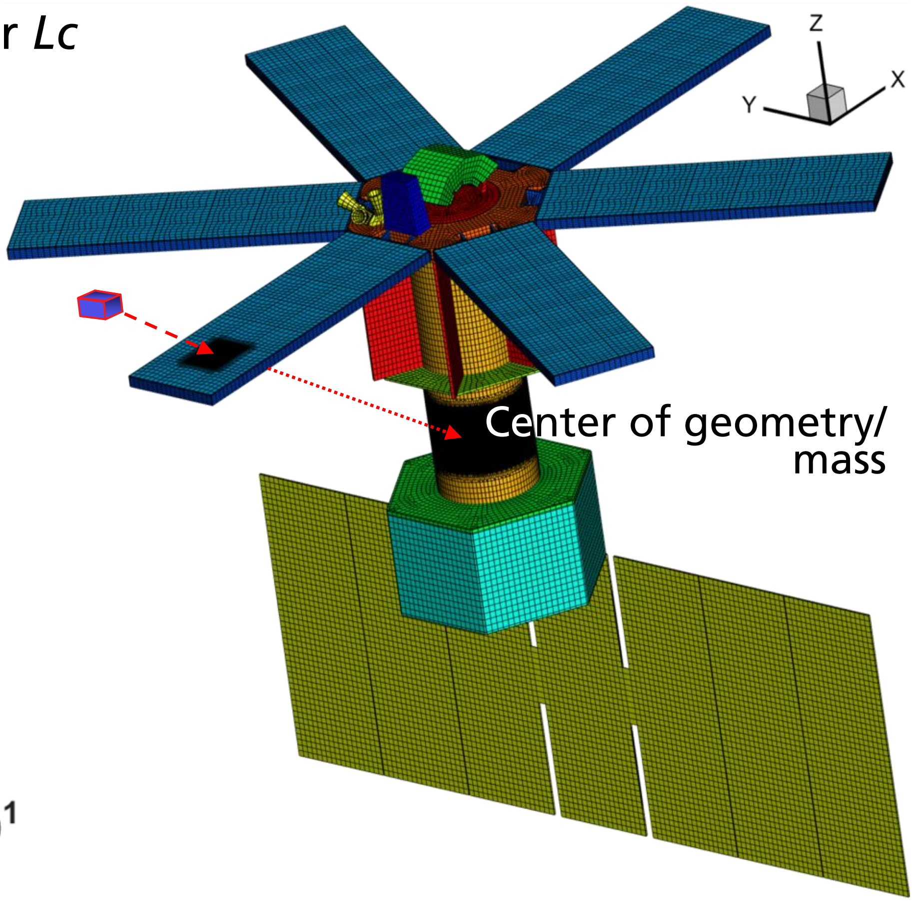
Results Evaluation (WP5100)

Fragmentation Analysis – Scenario 6 – Comparison with NASA SSBM

- Cumulative fragment number over *Lc*

$$N(L_c) = 0.1(M)^{0.75} L_c^{-1.71}$$





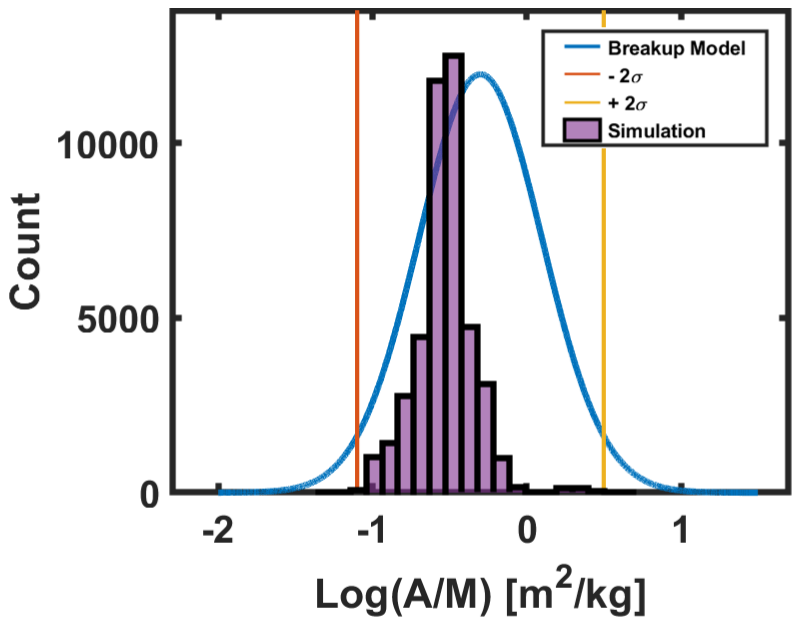
Results Evaluation (WP5100)

Fragmentation Analysis – Scenario 6 – Comparison with NASA SSBM

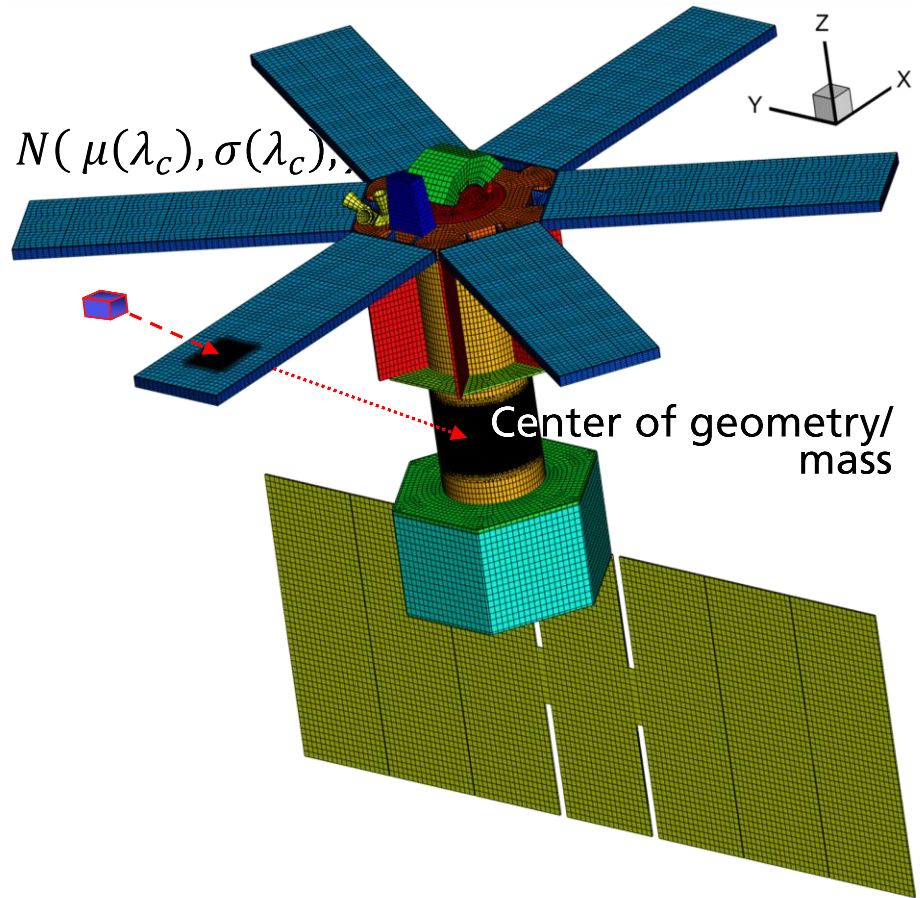
- *A/M* distribution

* $D_{A/M}(\lambda_c, \chi) = N(\mu(\lambda_c), \sigma(\lambda_c), \ldots$

$\lambda_c = \log_{10}(L_c),\ \chi = \log_{10}(A/M)$



5.6 mm < *Lc* < 17.8 mm ($-2.25 < \lambda_c < -1.75$)



* for fragments < 8 cm

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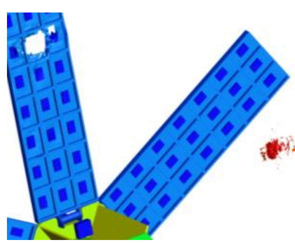
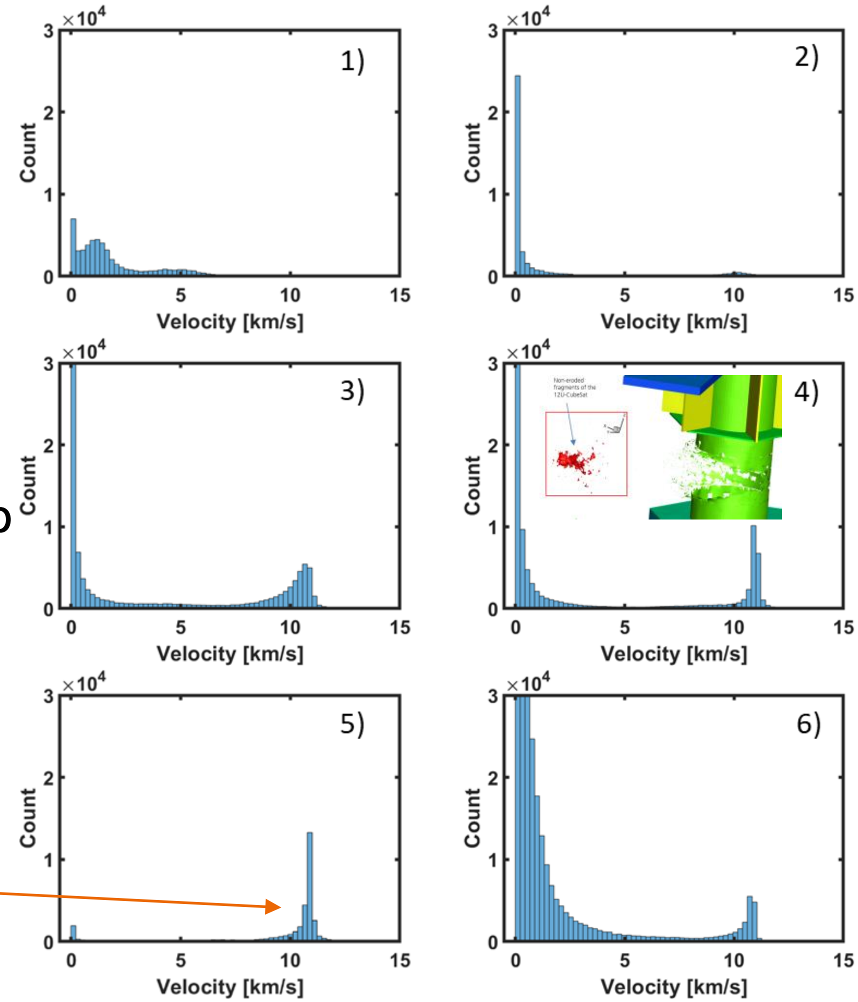
Results Evaluation (WP5100)

Fragmentation Analysis – Scenario Comparison

- Fragment count over velocity for scenarios 1) to 6):
  - 1) Plate, Center of Mass (CoM)
  - 2) 1U-CubeSat, CoM
  - 3) 12U-CubeSat, CoM
  - 4) 12U-CubeSat, CoM with overlap
  - 5) 12U-CubeSat, LAD perp.
  - 6) 12U-CubeSat, LAD oblique





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Results Evaluation (WP5100)

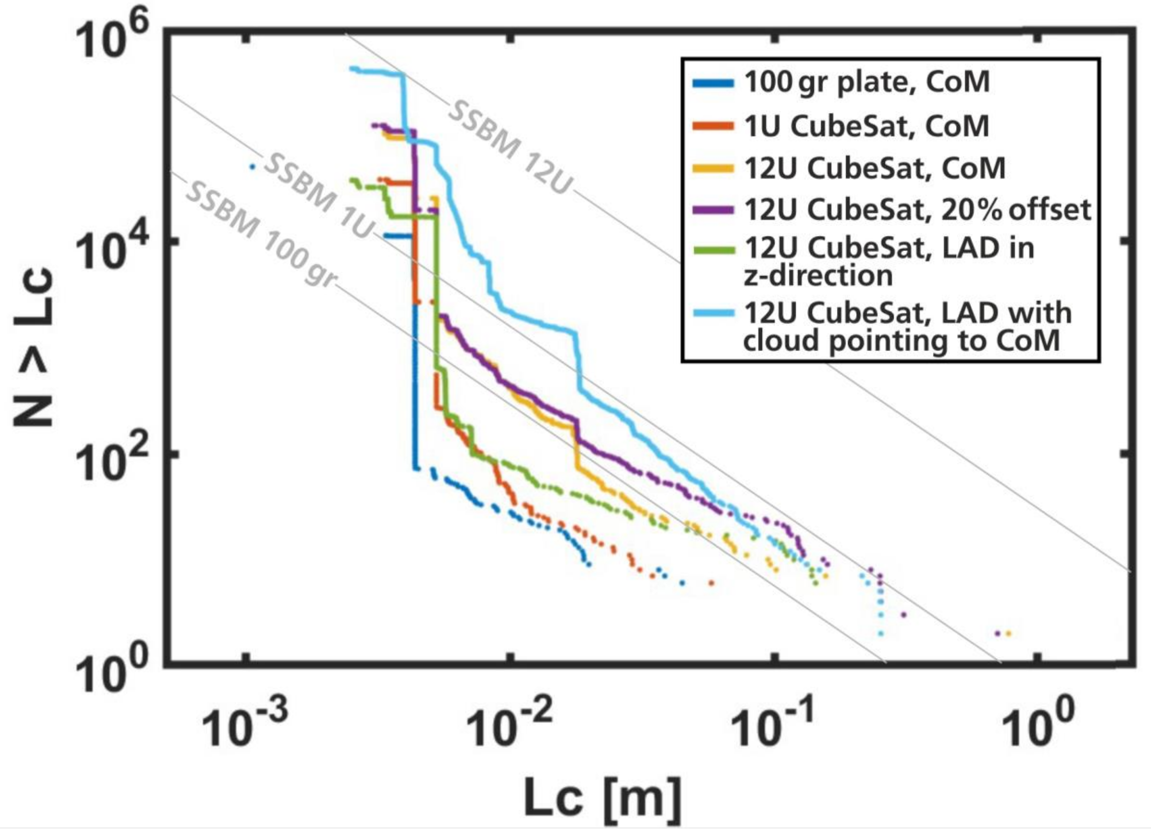
Fragmentation Analysis – Scenario Comparison

- Cumulative fragment number over *Lc* for scenarios 1) to 6)

➡ Agreement and deviations to NASA Breakup Model

➡ Fragmentation strongly depends on collision configuration

➡ EMR-criteria does not reflect fragmentation complexity



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Results Evaluation (WP5200)

Experimental techniques for validation - Proposal

Dedicated experimental validation needed for fidelity

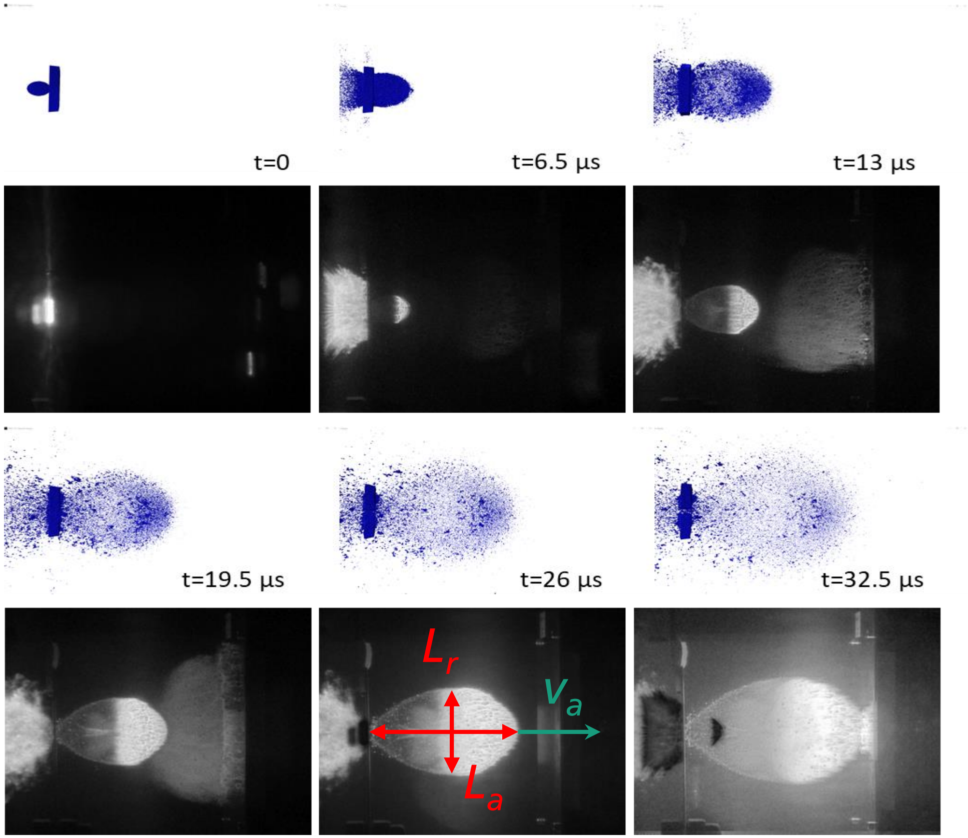
- Impact tests on representative targets (CFRP sheets, sandwich, harness)
  - Fragmentation analysis for standard materials
  - Development of simple analogous material models for full scale simulations
- Generic targets with well-known dynamic material models
  - Direct validation of effects of obliquity and impactor shape/design/material

➡ Acquisition of in-situ data for quantitative validation needed

Results Evaluation (WP5200)

Experimental techniques for validation – State of the art

- Comparing cloud expansion in high-speed videos
- Comparing damage patterns



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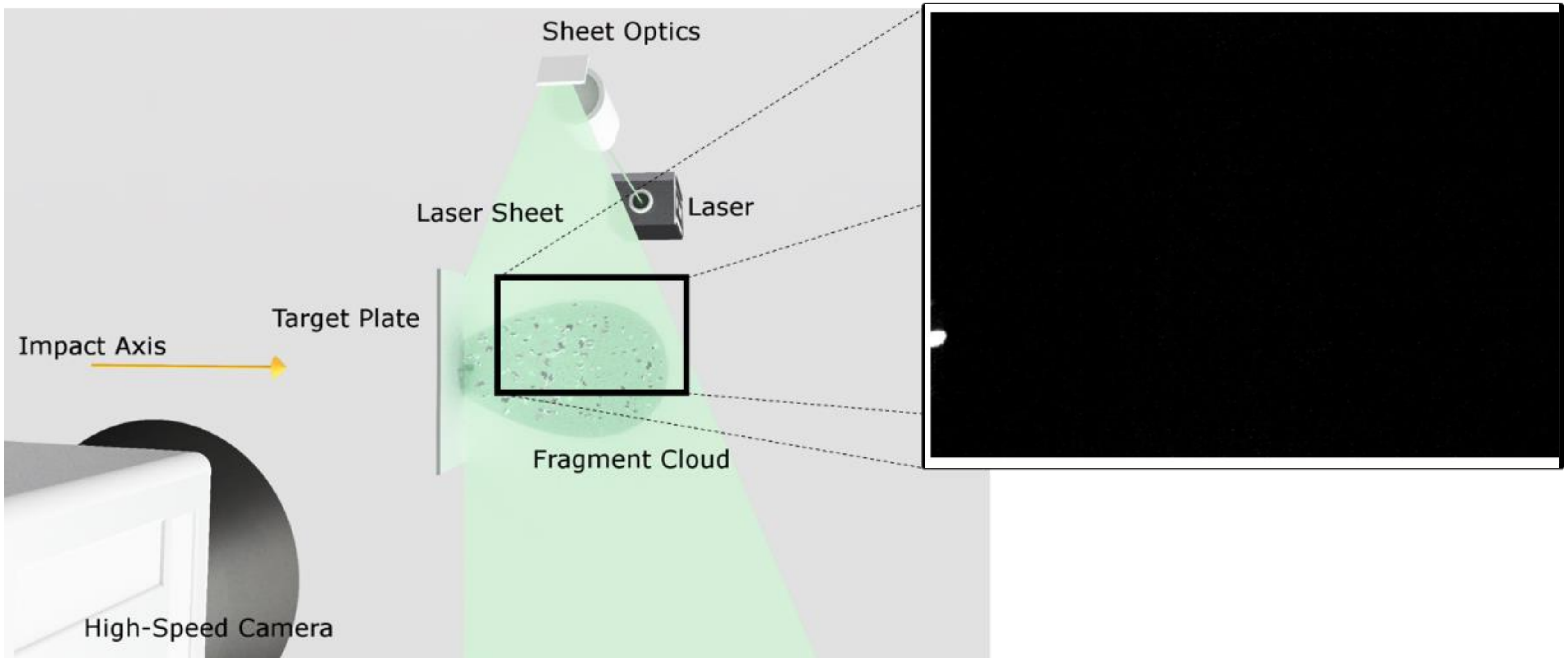
Results Evaluation (WP5200)

Experimental techniques for validation – new approach

Measuring spatio-temporal fragment characteristics



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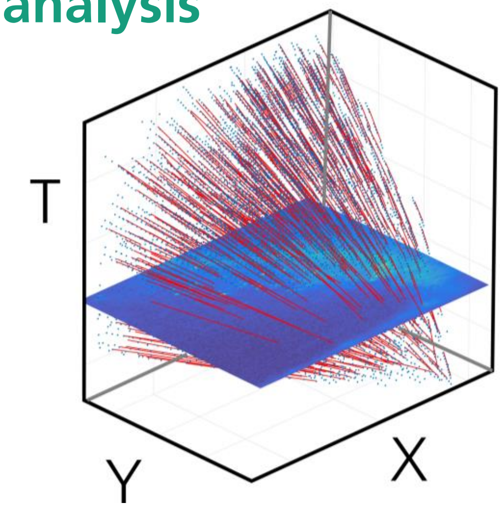
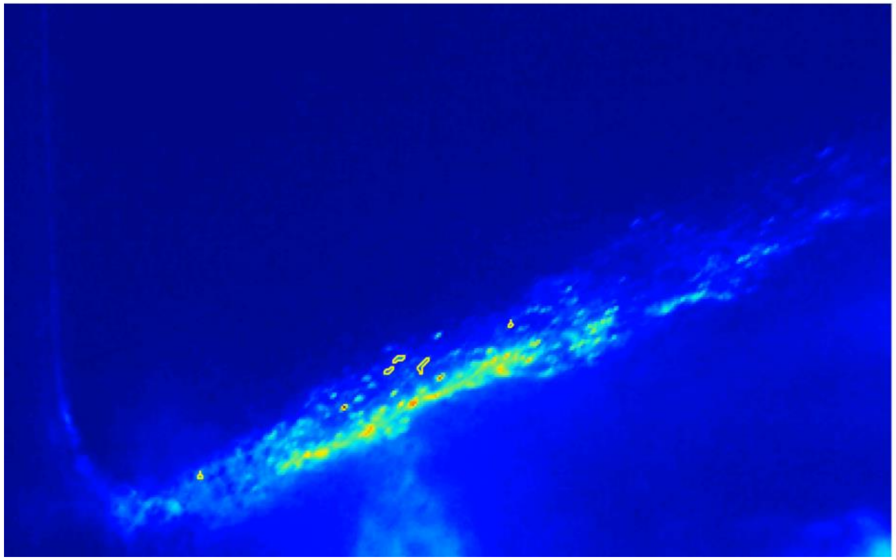
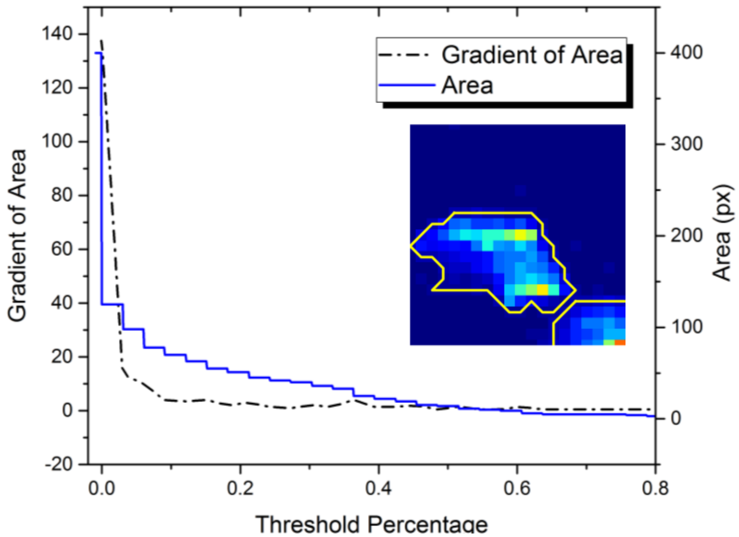
Results Evaluation (WP5200)

Experimental techniques for validation – Image analysis

- Specific algorithms to identify and track fragments
  → fragment contour, trajectory and velocity
- 3D-analysis possible







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Results Evaluation (WP5000)

Conclusions

- Demonstrated PHILOS-SOPHIA capabilities to numerically simulate complex spacecraft collisions
- Evaluation of impact processes and damages
  - fragmentation and incurred damages strongly depend on collision geometry and configuration
- Detailed analysis of fragment characteristics:
  - both agreements and clear deviations to the semi-empirical NASA Standard Satellite Breakup Model
  - EMR-criteria for catastrophic breakups does not reflect collision complexity
- Specific experiments with new particle tracking methods may allow for quantitative validation
  - increasing fidelity of numerical tool for powerful breakup analyses

AGENDA – FINAL REVIEW

10:00
- Welcome and Introduction
- Management Report (WP1000)
- Final Report
  - Introduction
  - Review, Trade-off, Methodology Selection (WP2000)
  - Software Tool PHILOS-SOPHIA (WP3000)
  - Numerical Simulations (WP4000)
  - Results Evaluation (WP5000)
- Project Finalization

17:00
- End of Meeting

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