A Low-Fidelity Tool for Aero-Thermal and Re-entry Analyses

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4th International Workshop on Space Debris Re-entry

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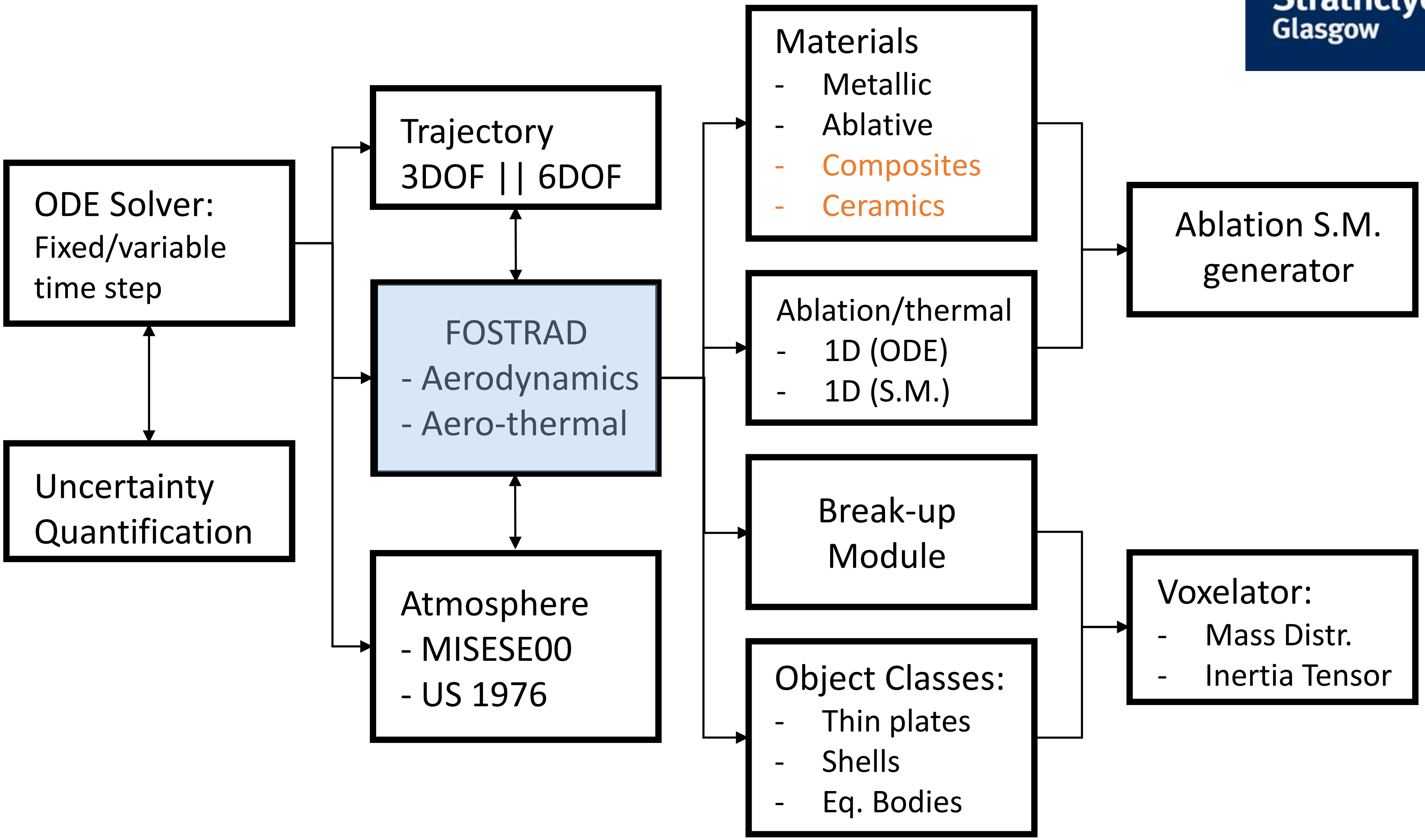
OUTLINE

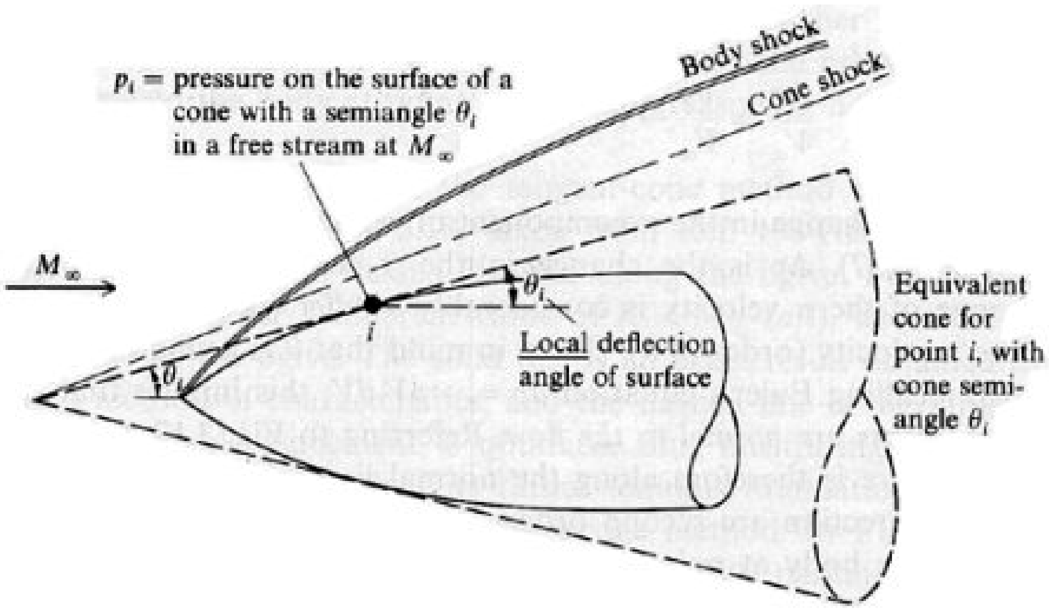
- Core module Introduction
- Previously studied cases
- Block Diagram description
- Mock satellite test case
- Conclusions and future works

A Low-Fidelity Tool for Aero-Thermal and Re-entry Analyses



Introduction: FOSTRAD

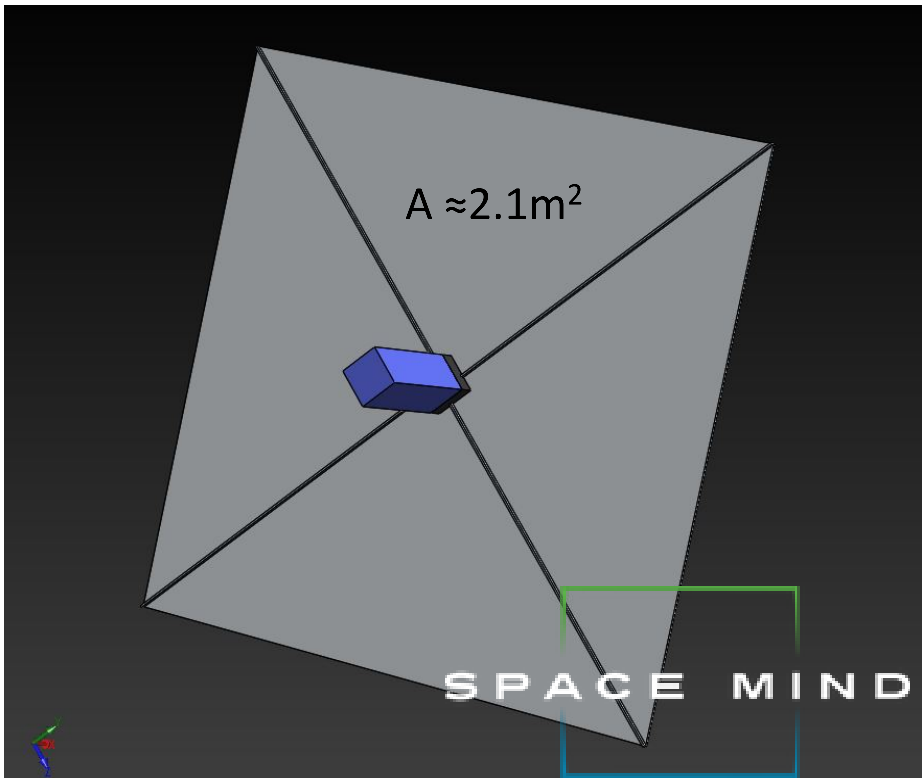
- Basic Aerodynamics Module
  - Based on the Local Panel Inclination Method
  - Continuum: Modified Newtonian Theory
  - Free Molecular: Schaaf and Chambre

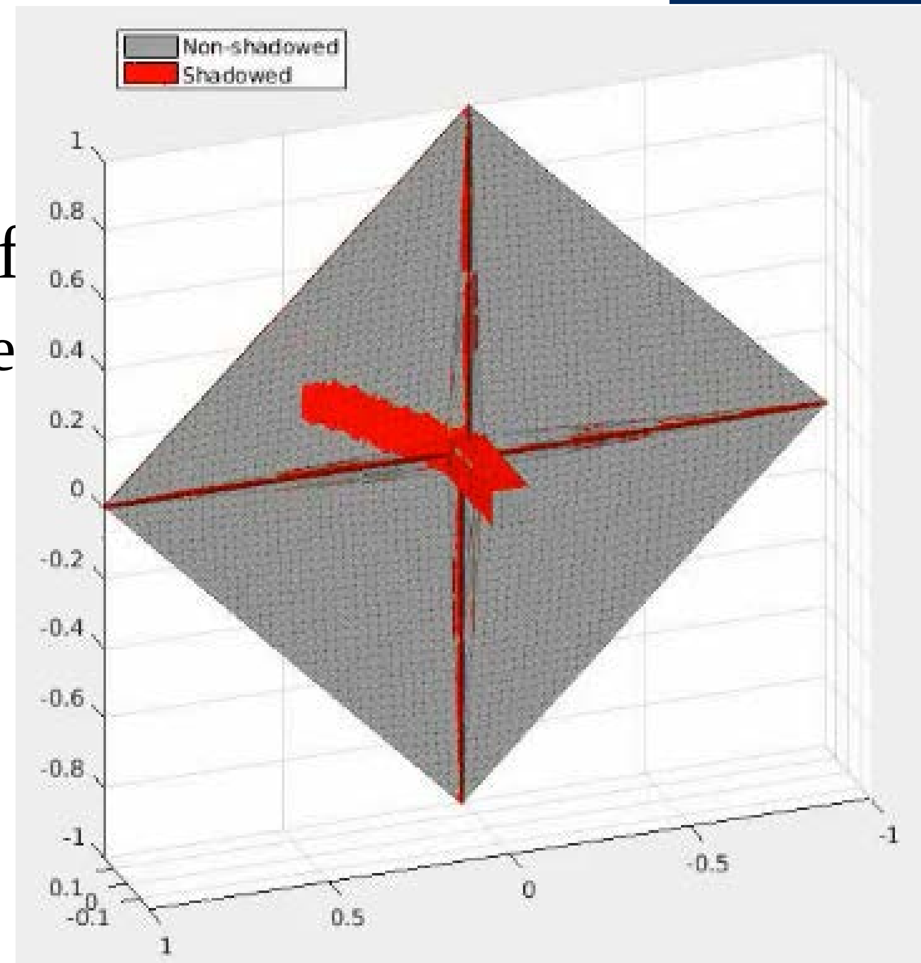


FOSTRAD Aerodynamics

- Based on two graphical rendering techniques:
  - Back-face culling

3U CubeSat – Solid 3D model





[1] Falchi, A., Minisci, E., Vasile, M., Rastelli, D., and Bellini, N. (2017b). Dsmc-based correction factor for low-fidelity hypersonic aerodynamics of re-entering objects and space debris. EUCASS 2017

FOSTRAD Aerodynamics[1]

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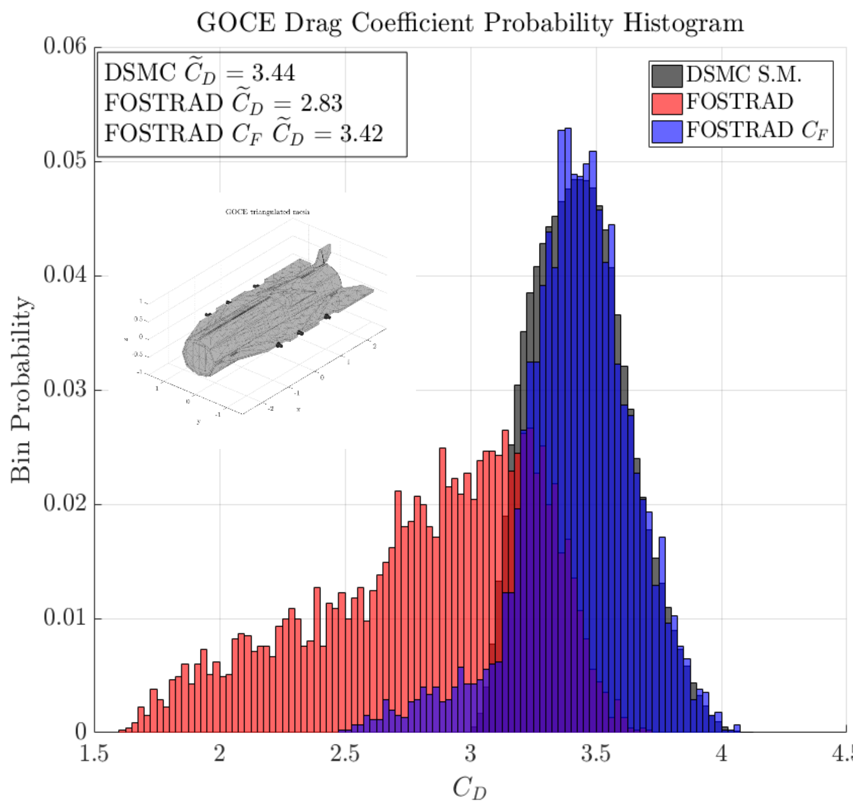
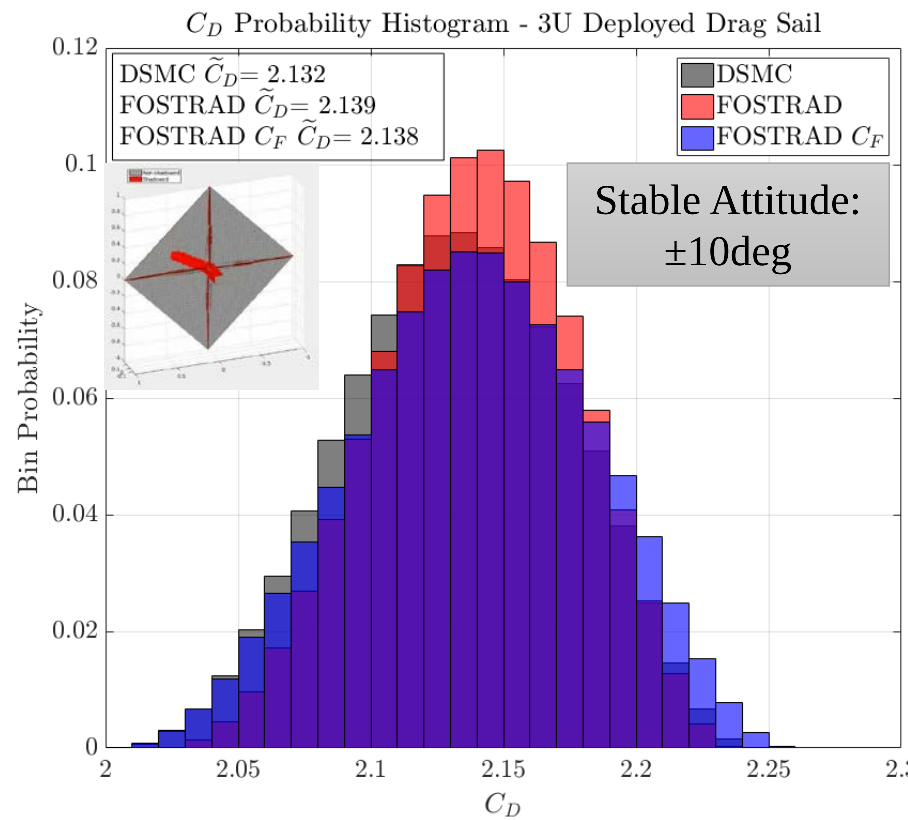
GOCE Re-entry Aerodynamics



CubeSat: Deployed Drag Sail

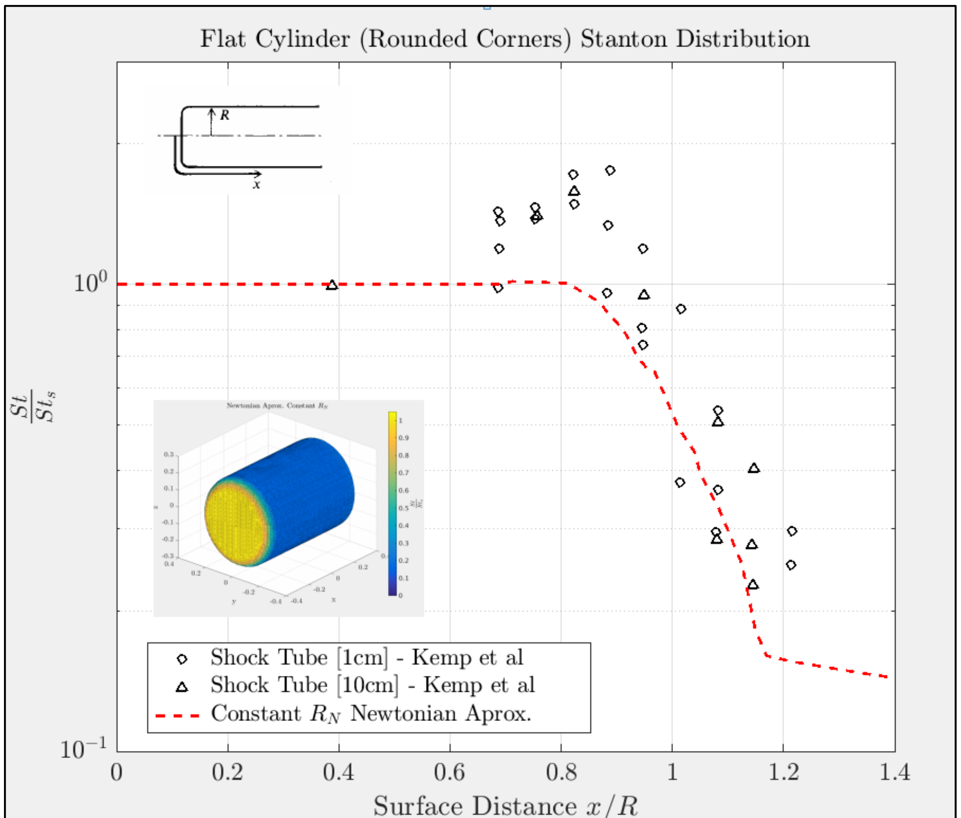


[1] Falchi, A., Minisci, E., Vasile, M., Rastelli, D., and Bellini, N. (2017b). Dsmc-based correction factor for low-fidelity hypersonic aerodynamics of re-entering objects and space debris. EUCASS 2017

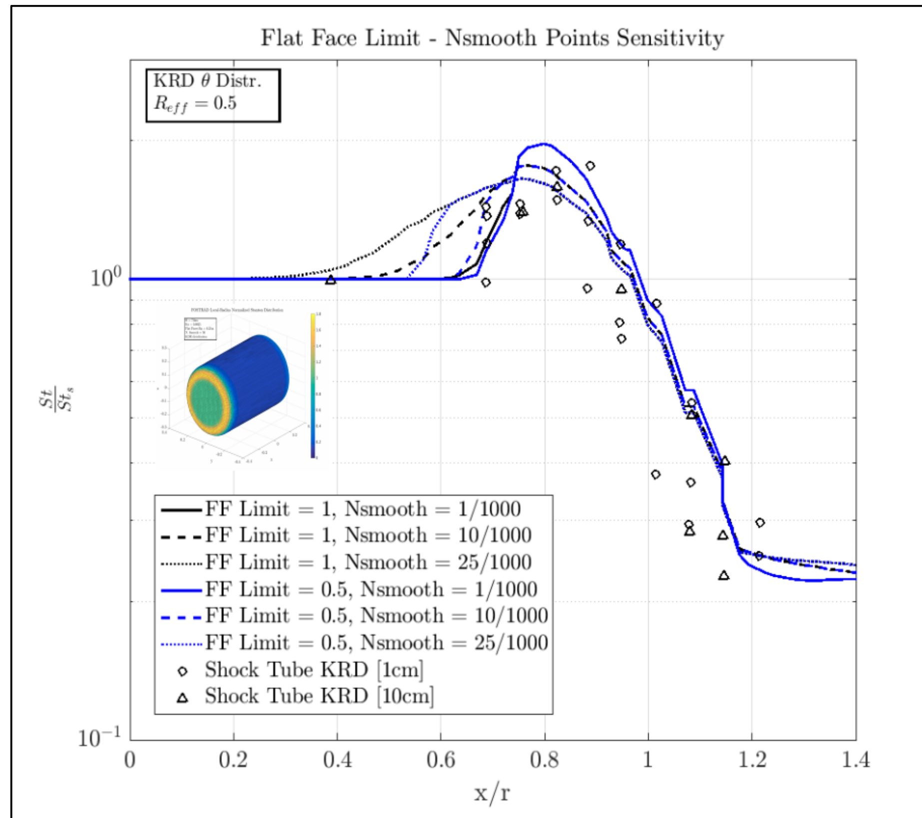
FOSTRAD Aerothermodynamics[2]

Heat flux: Local Radius Formulation

Standard Local Panel Inclination



FOSTRAD with Local Radius Formulation



[2] Falchi, A., Renato, V., Minisci, E. and Vasile, M., 2017. FOSTRAD: An Advanced Open Source Tool for Re-entry Analysis. Reinventing Space Conference, Glasgow 2017

Uncontrolled Space Debris Re-entry

Technical changes required by:

1. Importance of uncontrolled attitude dynamics
2. Significant ablation/recession velocity
3. Different object classes (shells/thin geom.)
4. Different accuracies required in different phases
5. Various materials ablation models

1. Uncontrolled attitude dynamics

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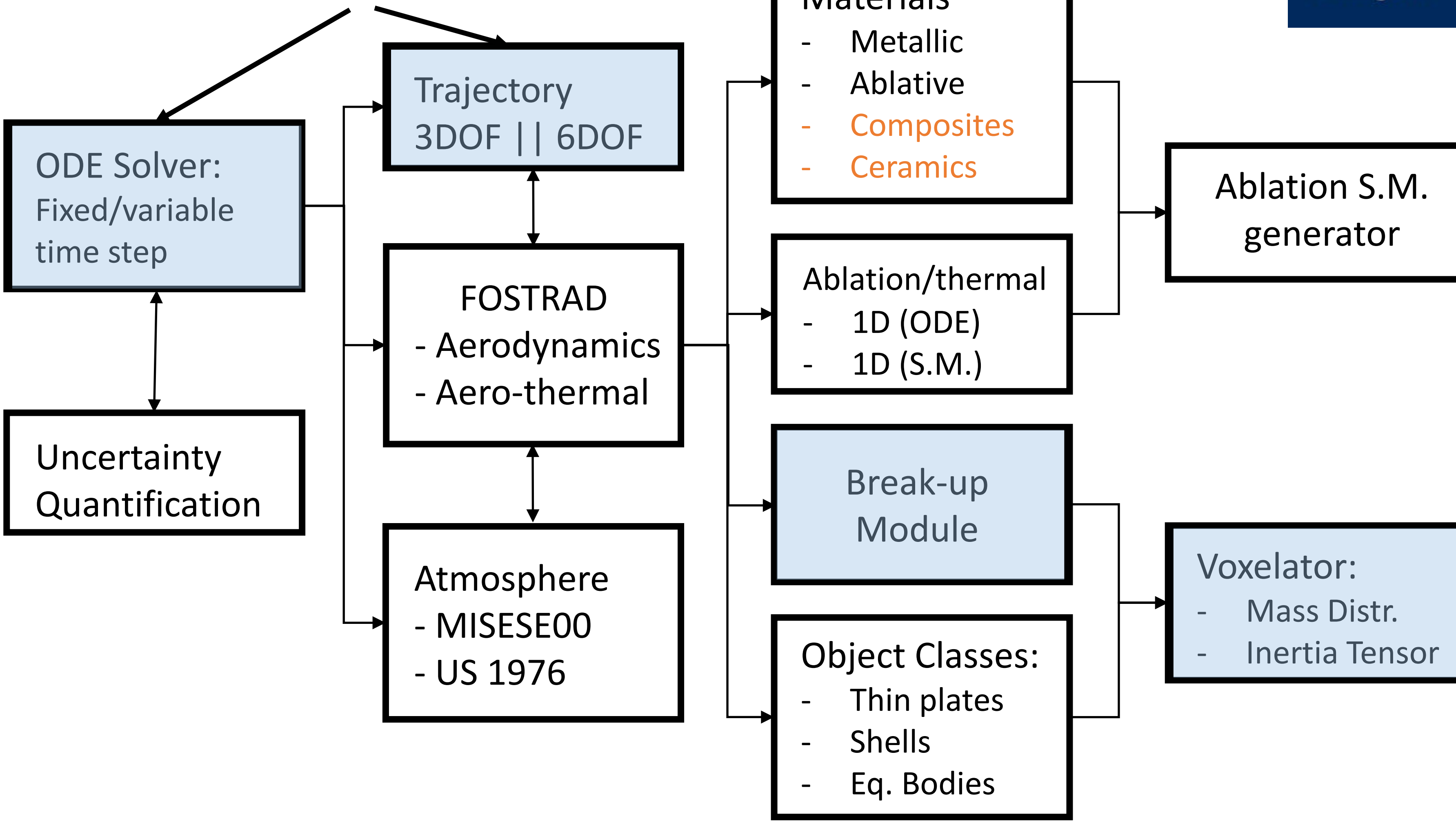
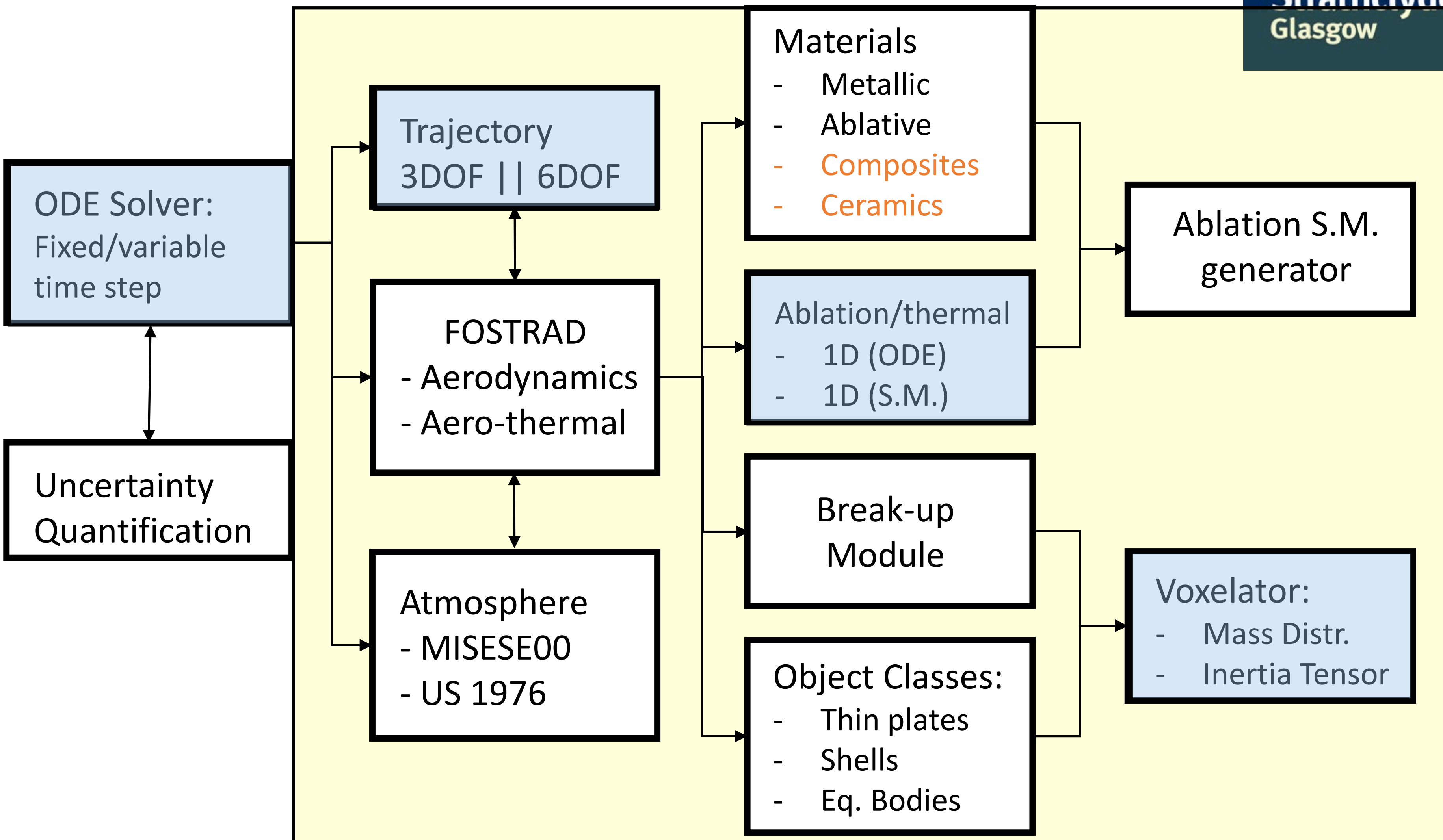
The capability to distinguish a stable from an unstable/tumbling attitude



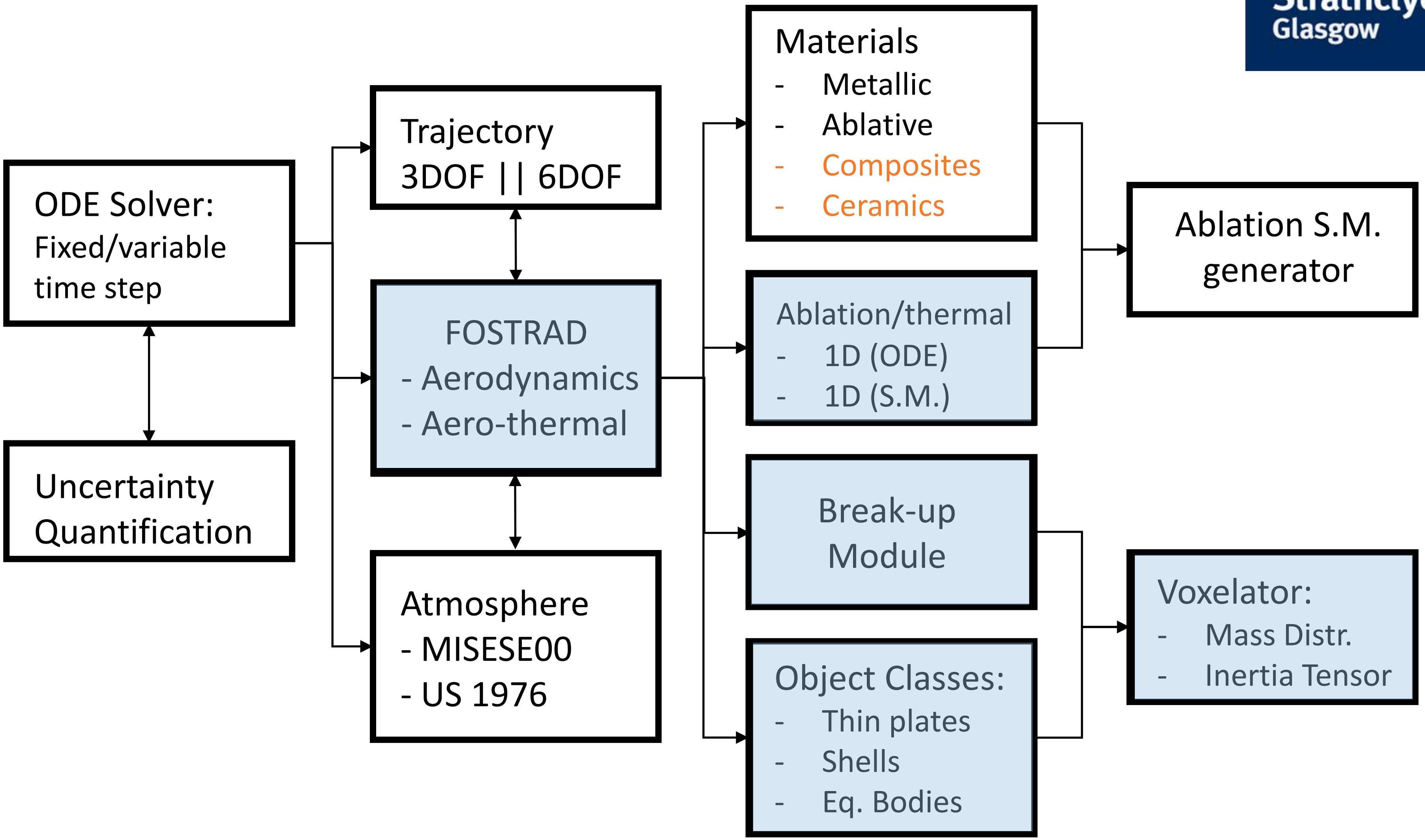
2. Significant ablation/recession velocity

The entire problem is solved with a RK4 method



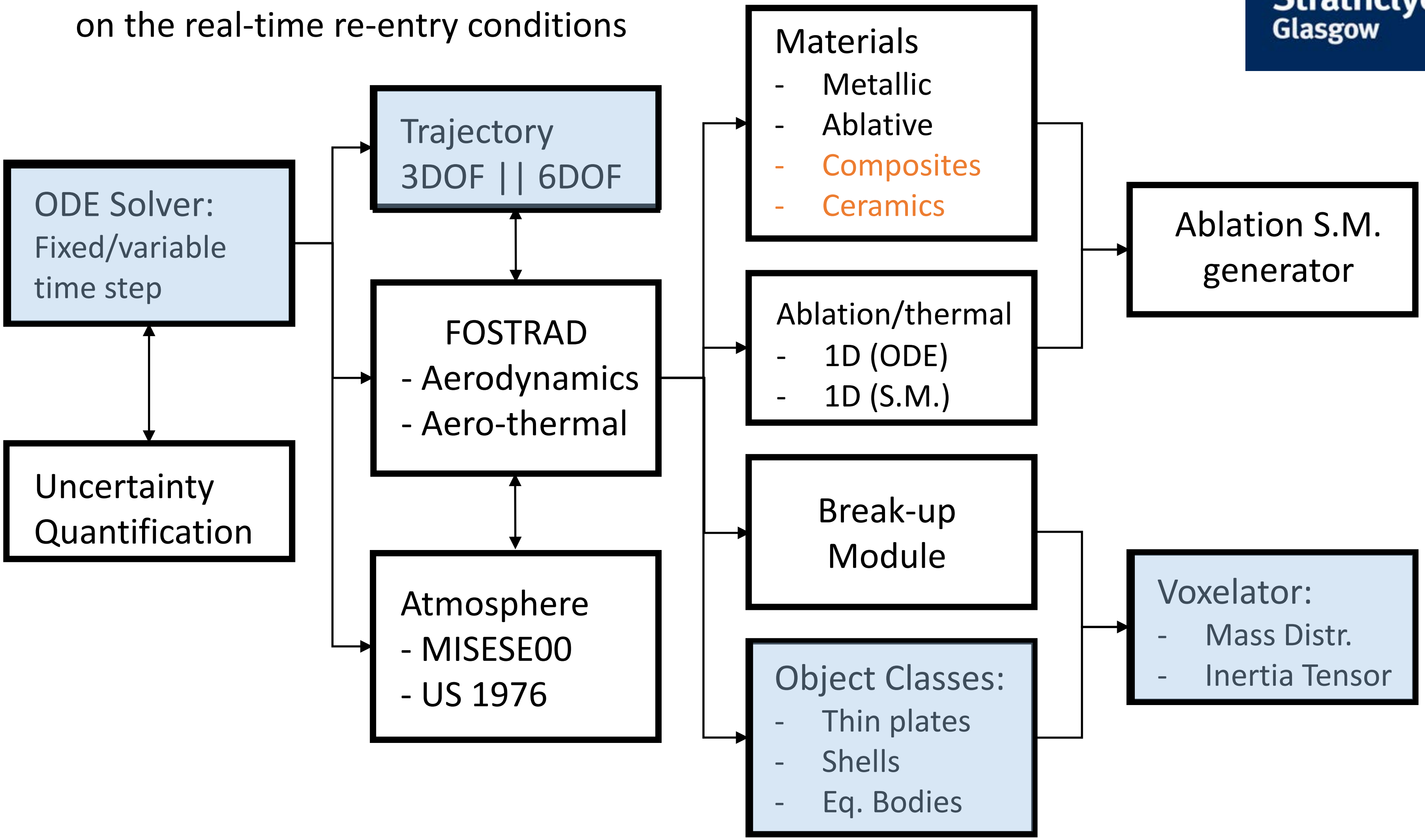
3. Different object classes (shells/thin geom.)

Different recession modes for each class



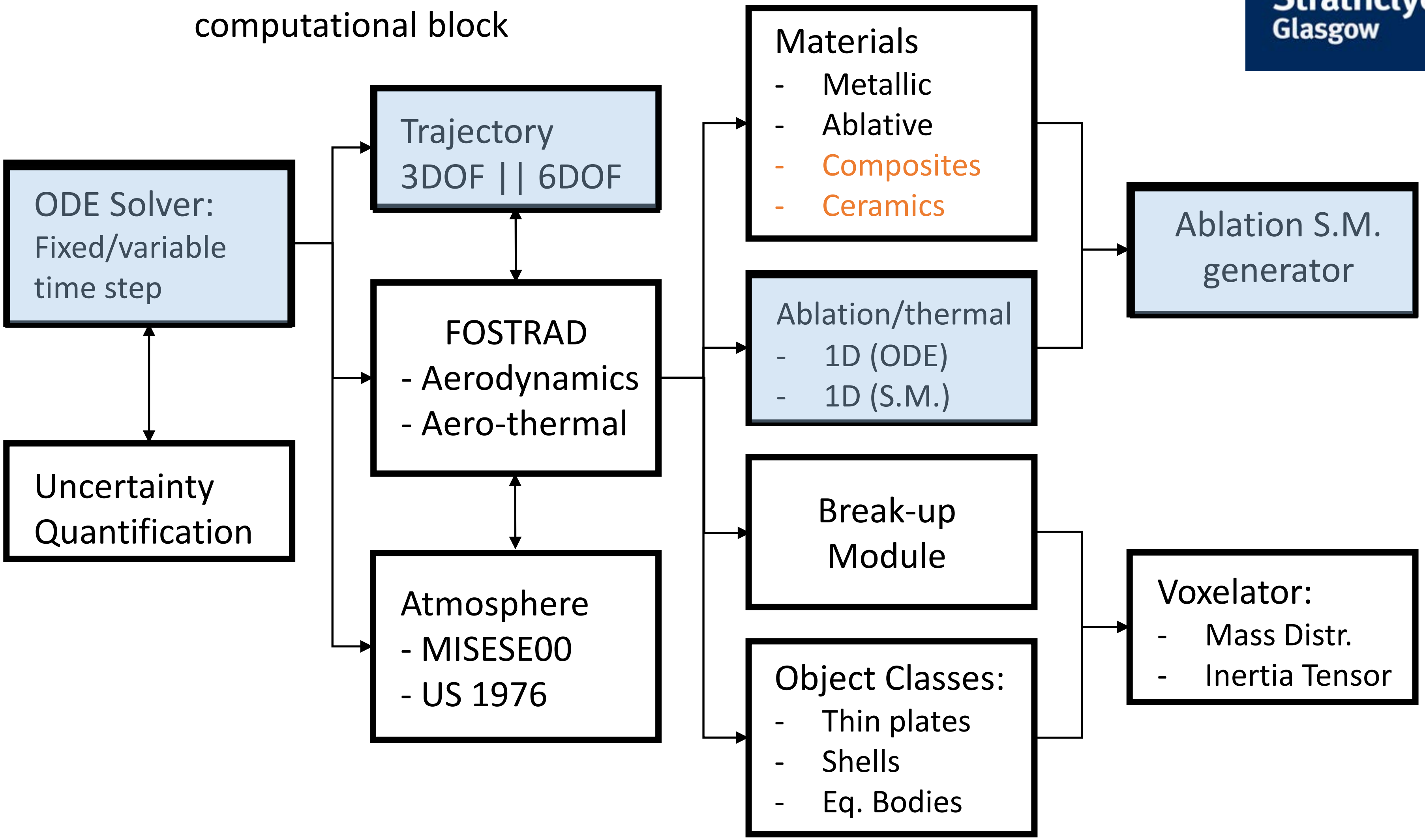
4. Different accuracies required in different phases

Switching on/off different modules depending on the real-time re-entry conditions



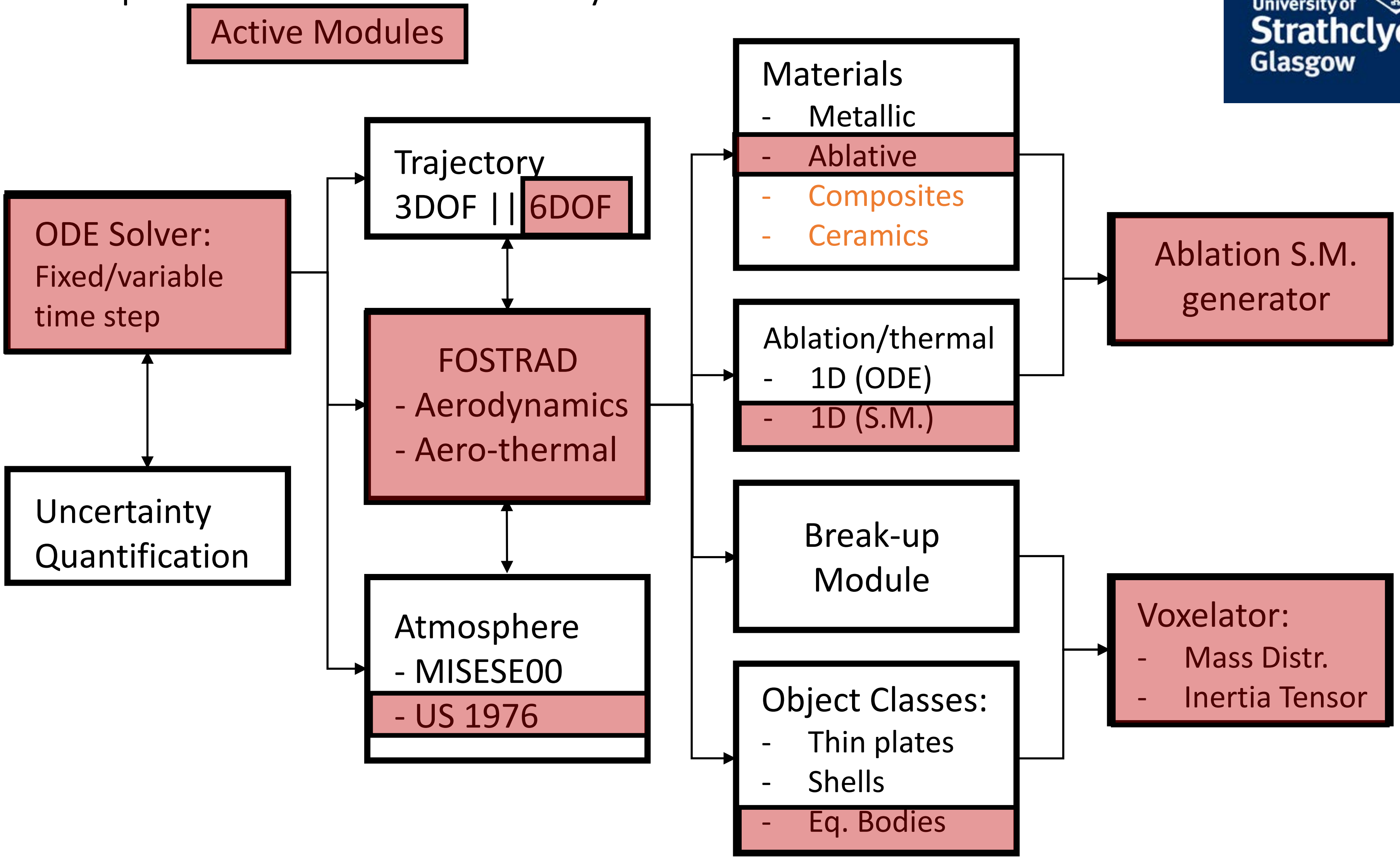
5. Various materials ablation models

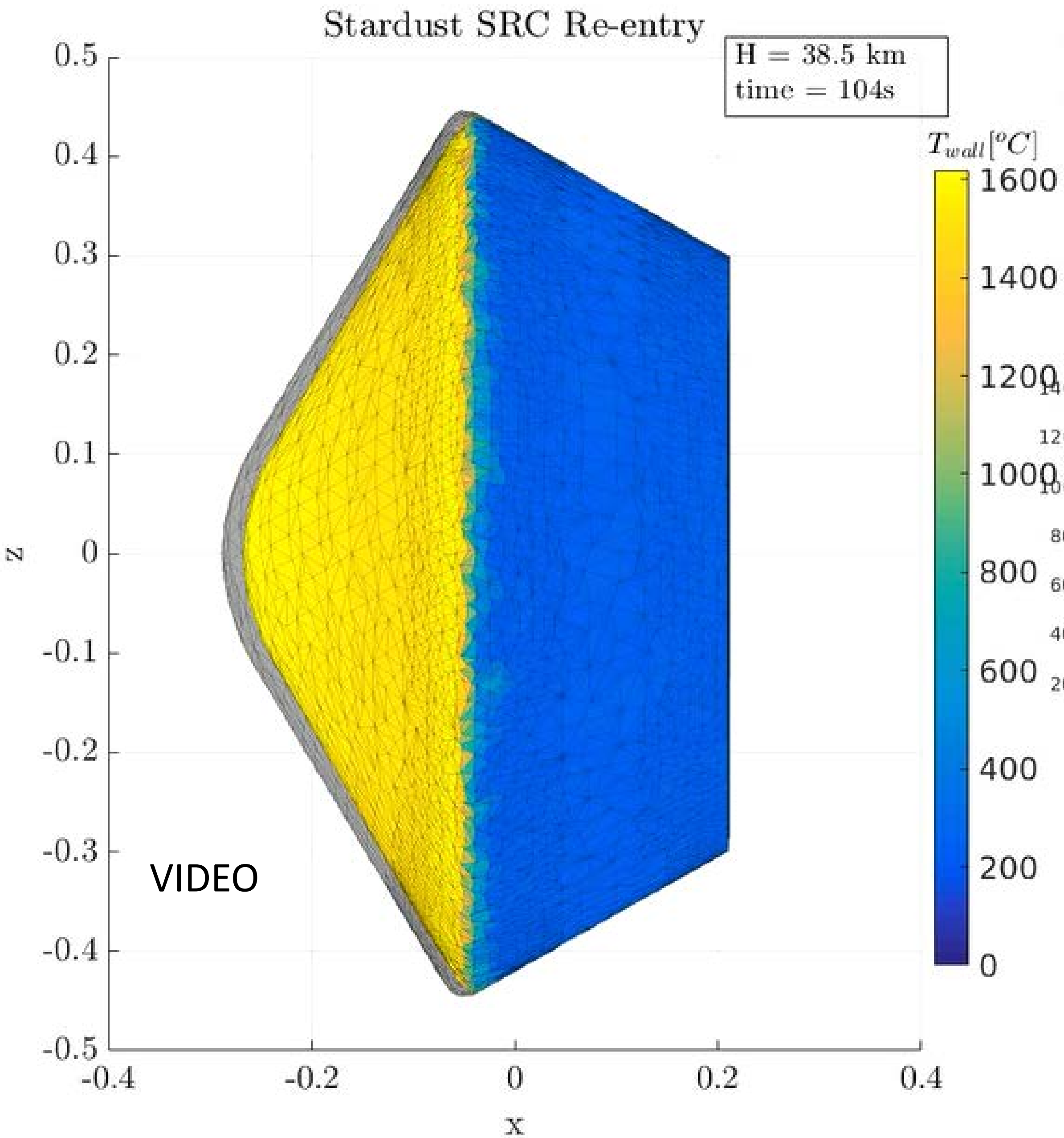
Each material has its own S.M. or ablation computational block



Example: Stardust SRC 6DOF case

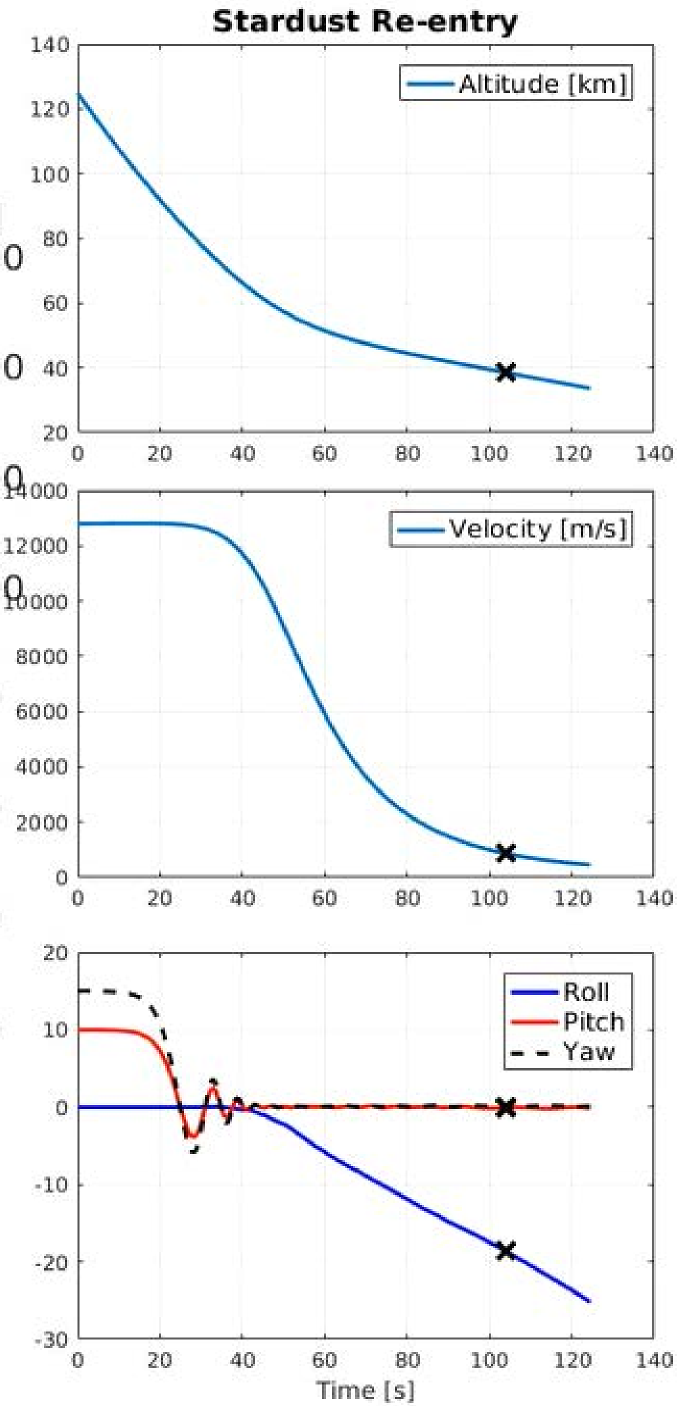
Example For the Software Modularity:





Stardust SRC Re-entry
H = 38.5 km
time = 104s
T_wall [°C]
x
z

VIDEO



Stardust Re-entry
Altitude [km]
Velocity [m/s]
Roll
Pitch
Yaw
Time [s]

Ablation and Material module

Thermal/ablation module:

- Convective, conductive, radiative (ext. cooling)
- 1D multi-layer Runge-Kutta 4th order[3]
- 1D multi-layer Surrogate Model (conservative)

Recession computation:

- Vertex-to-barycenter recession (ODE or S.M.)
- Vertex-to-Normal recession (ODE or S.M.)
- Aspect Ratio-based recession (ODE or S.M.)

[3] Renato, V., Scanlon, T. and Brown, R., 2017, June. Multi-dimensional ablation and thermal response program for re-entry analysis. In *31st International Symposium on Space Technology and Science (ISTS)*.

Trajectory and Atmosphere

Trajectory propagation:

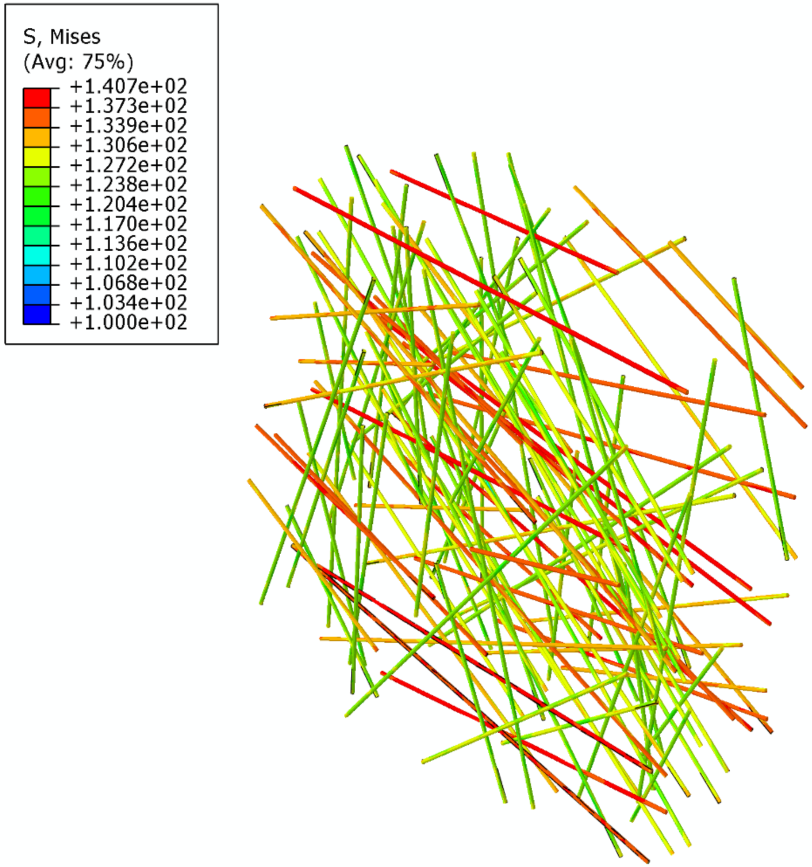
- 6DOF propagation before the break-up
- 3DOF propagation[4] (random tumbling phase)

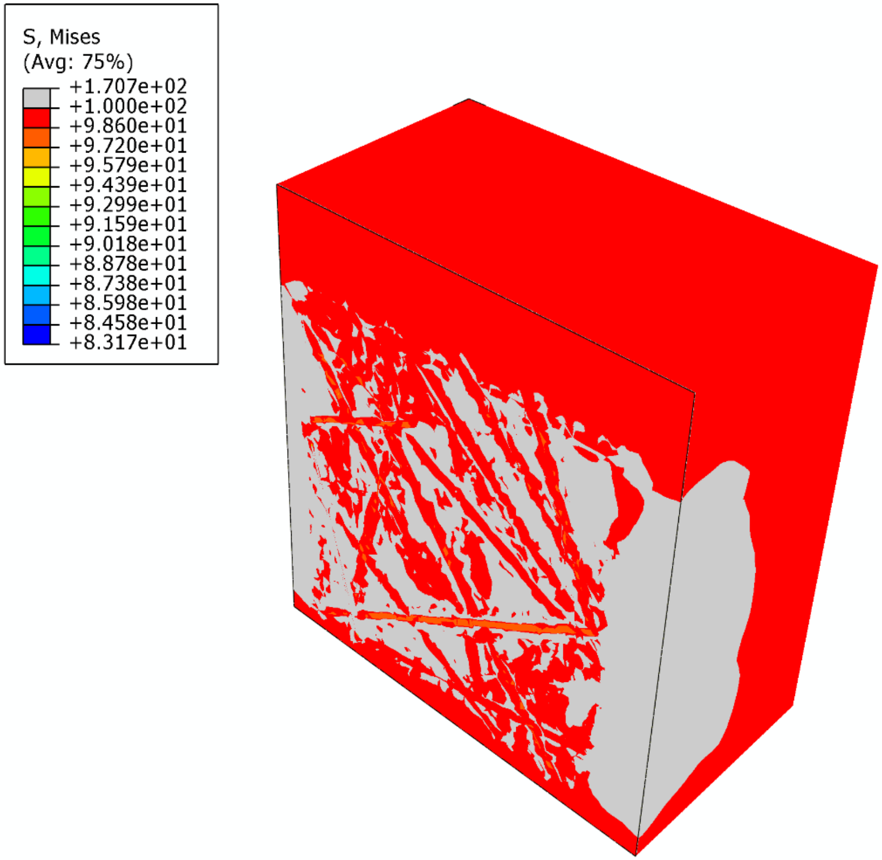
Atmospheric model:

- U.S. 1976 standard
- MSISE-00
- User-Defined Atmospheric model

[4] Toso, F. and Maddock, C., 2017. Return and abort trajectory optimisation for reusable launch vehicles. In *21st AIAA International Space Planes and Hypersonics Technologies Conference* (p. 2250).

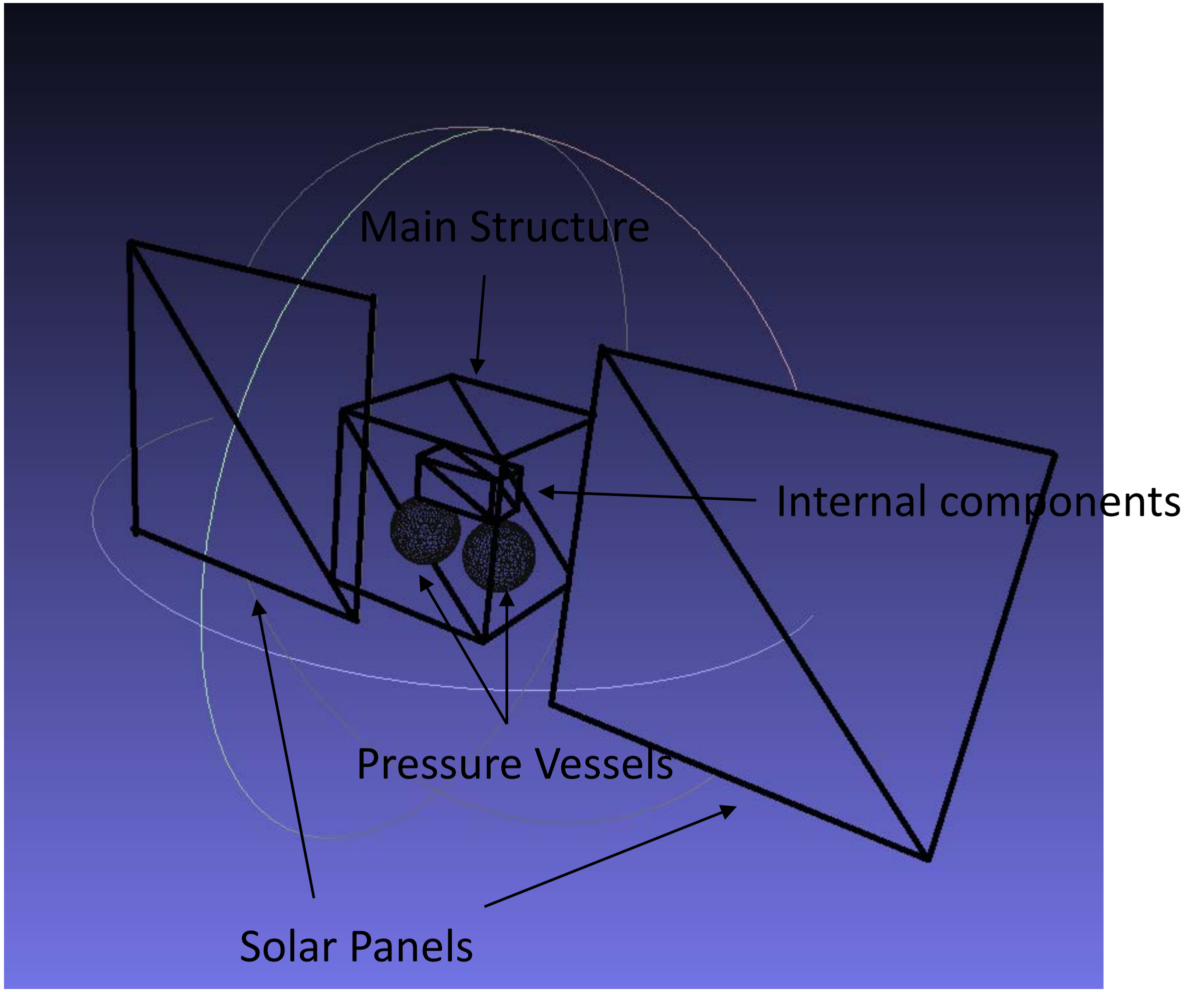
Materials and Ablations models

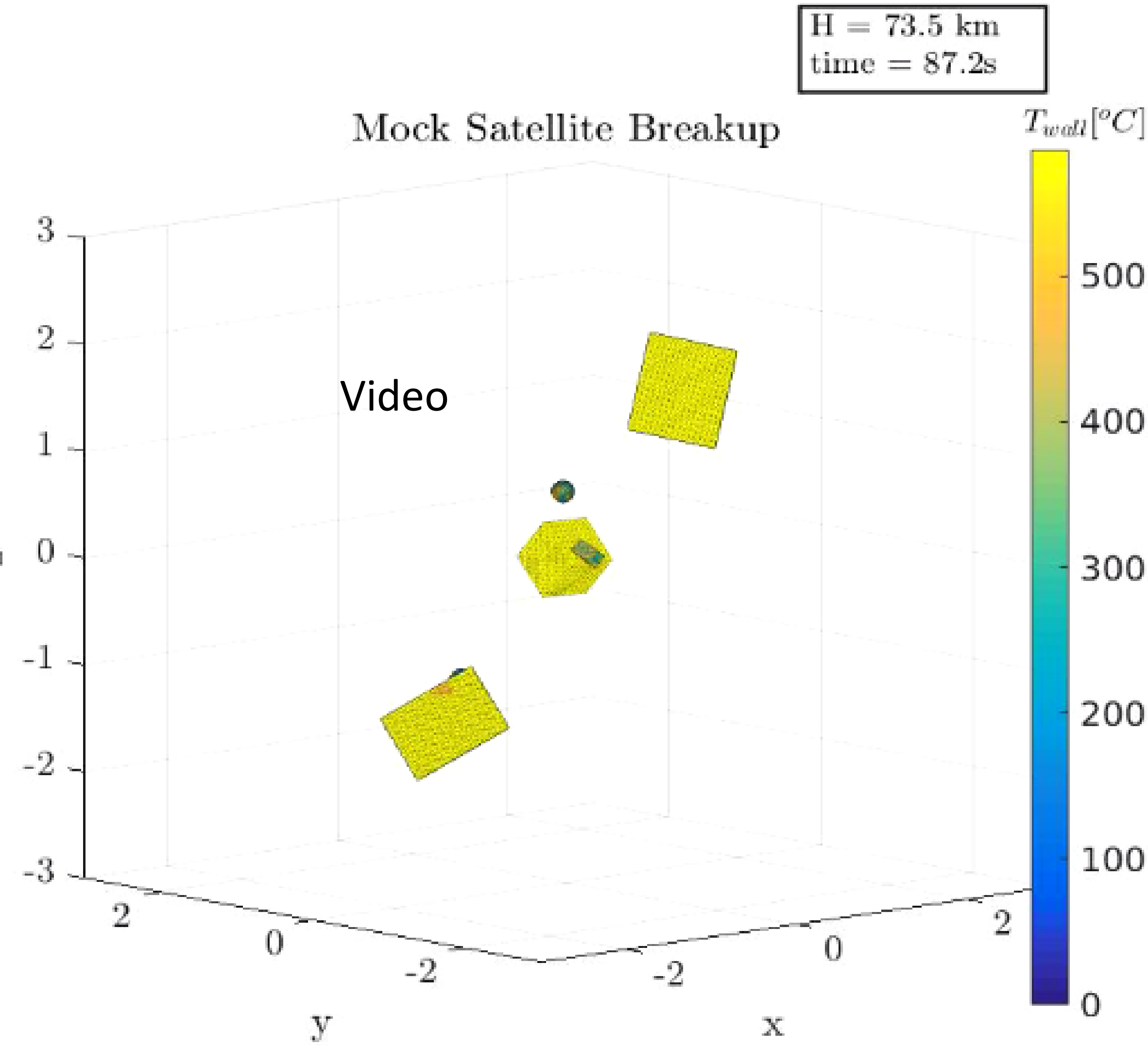


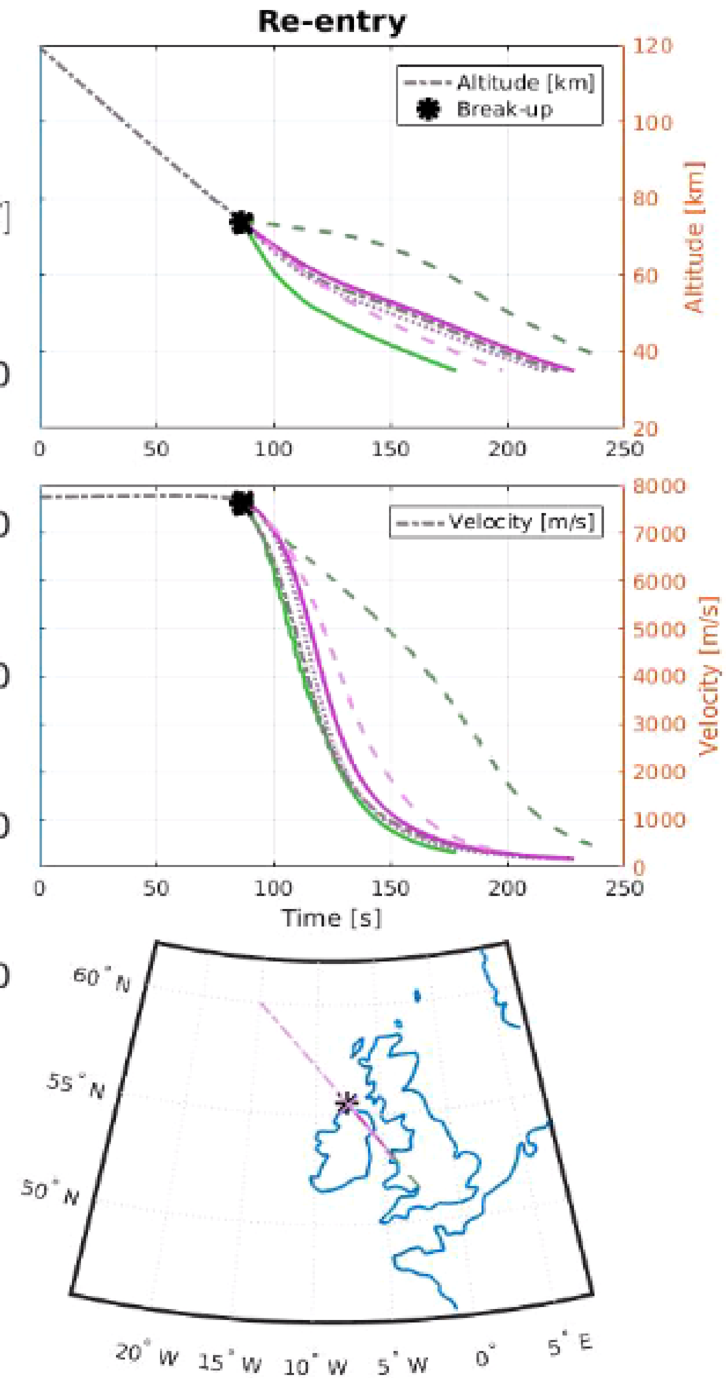


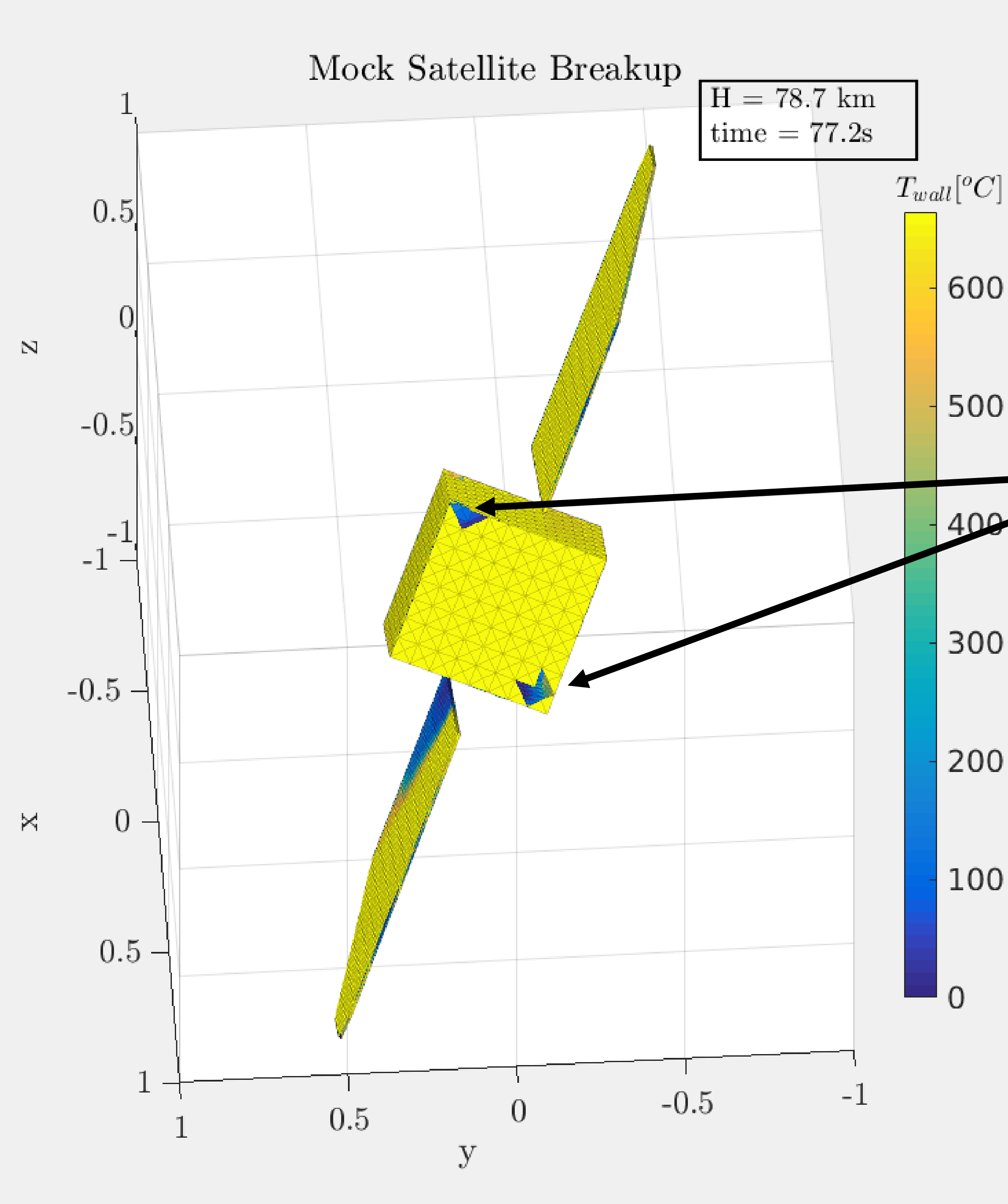
[5] Giugliano, D., Barbera, D. and Chen, H., 2017. Effect of fiber cross section geometry on cyclic plastic behavior of continuous fiber reinforced aluminum matrix composites. *European Journal of Mechanics-A/Solids*, *61*, pp.35-46.

Uncontrolled Re-entry Benchmark

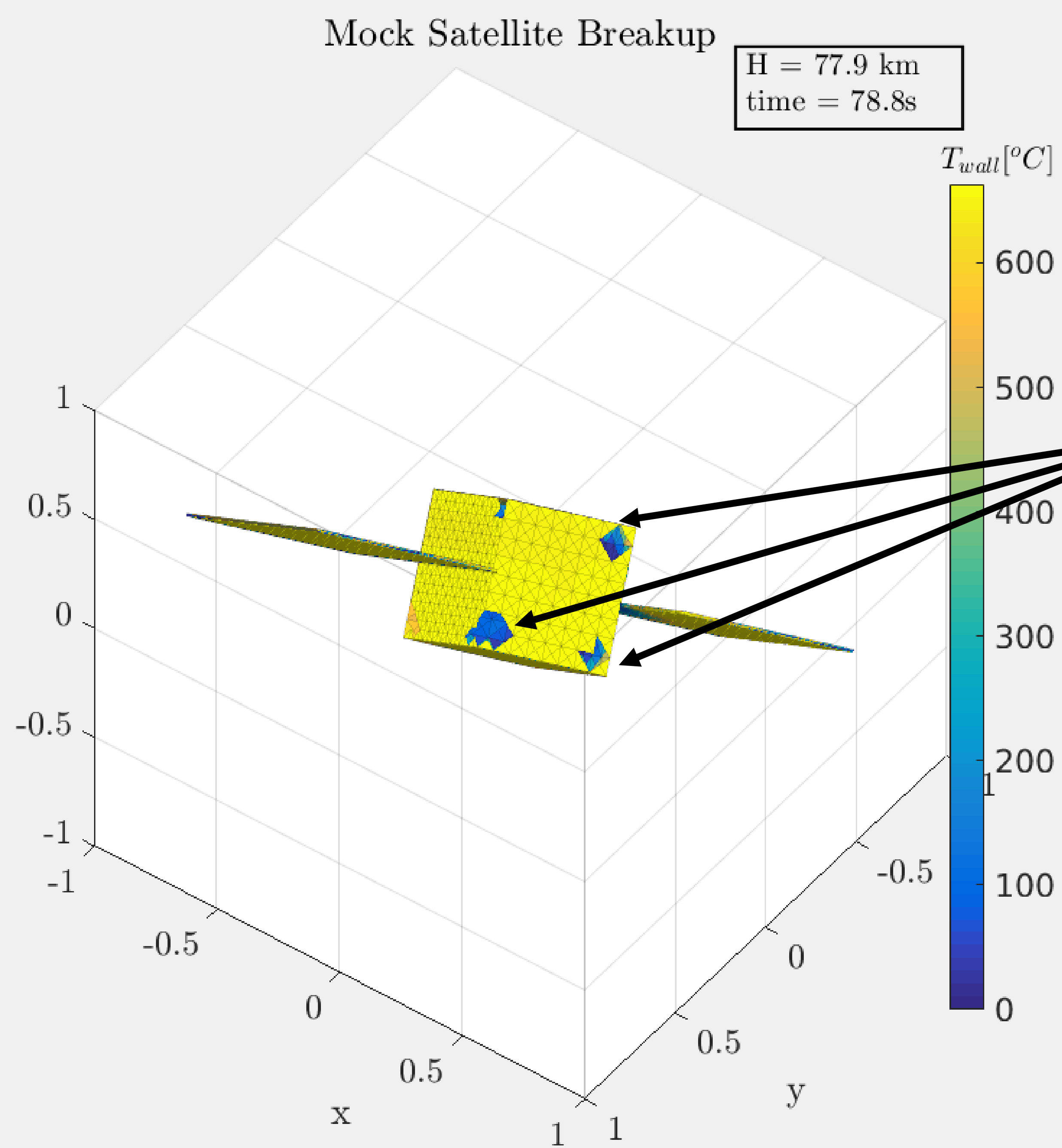



H = 73.5 km
time = 87.2s
Mock Satellite Breakup
Video
$T_{wall} [^oC]$
500
400
300
200
100
0
3
2
1
0
-1
-2
-3
2
0
-2
y
-2
0
2
x


Re-entry
Altitude [km]
Break-up
120
100
80
60
40
20
Altitude [km]
0
50
100
150
200
250
Velocity [m/s]
8000
7000
6000
5000
4000
3000
2000
1000
0
Velocity [m/s]
Time [s]
60° N
55° N
50° N
20° W
15° W
10° W
5° W
0°
5° E



Ablation begins at the corner



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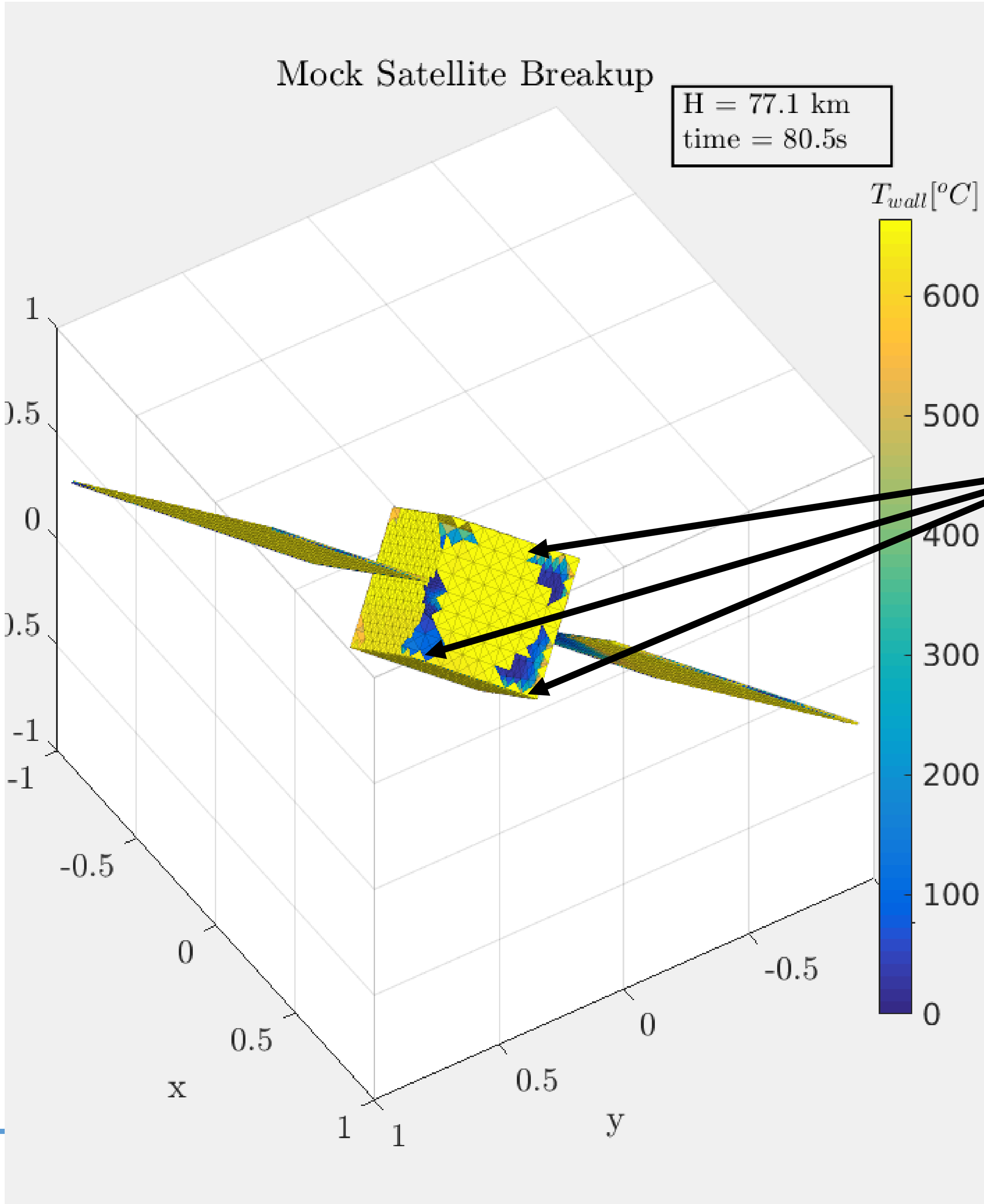
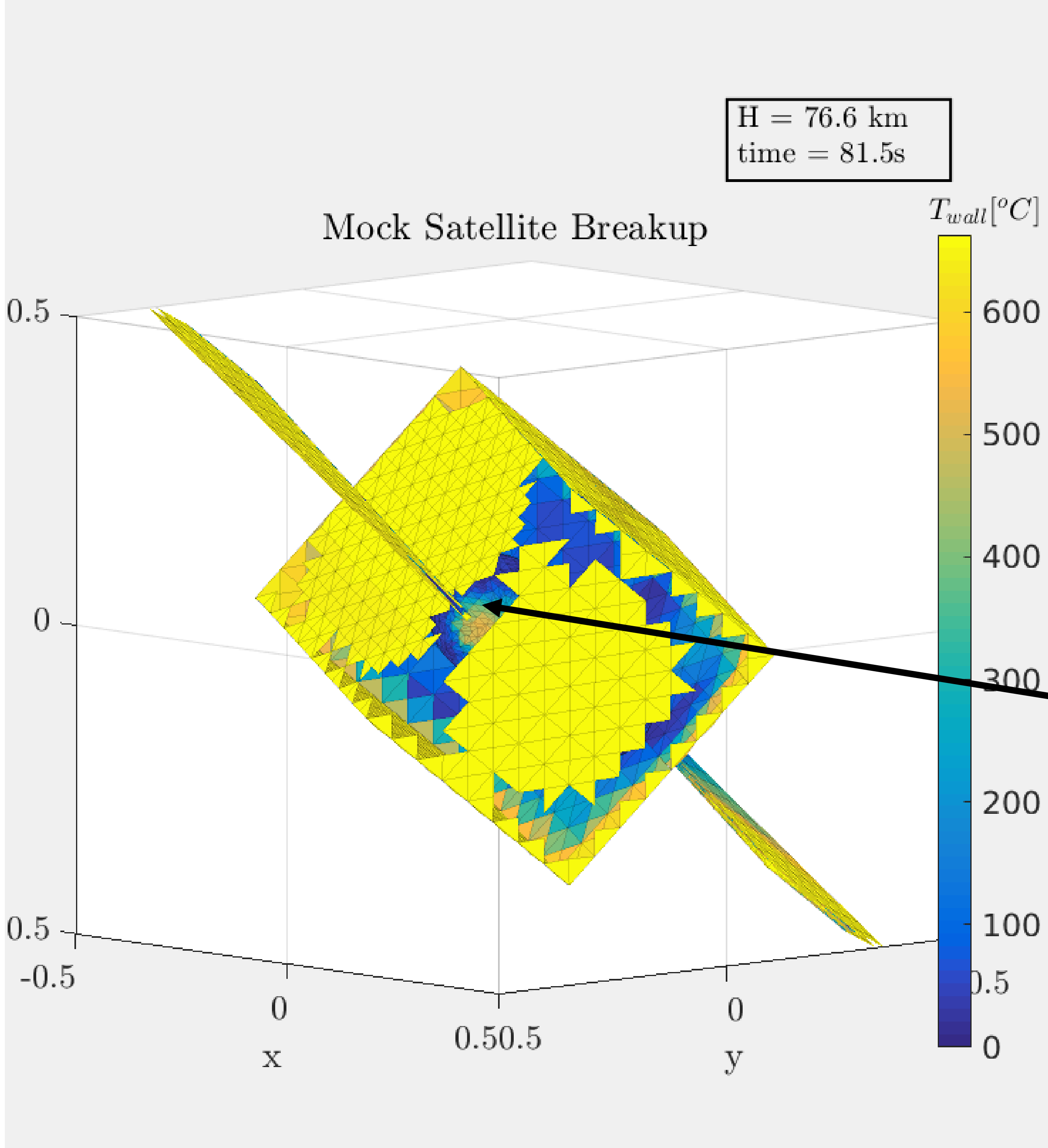
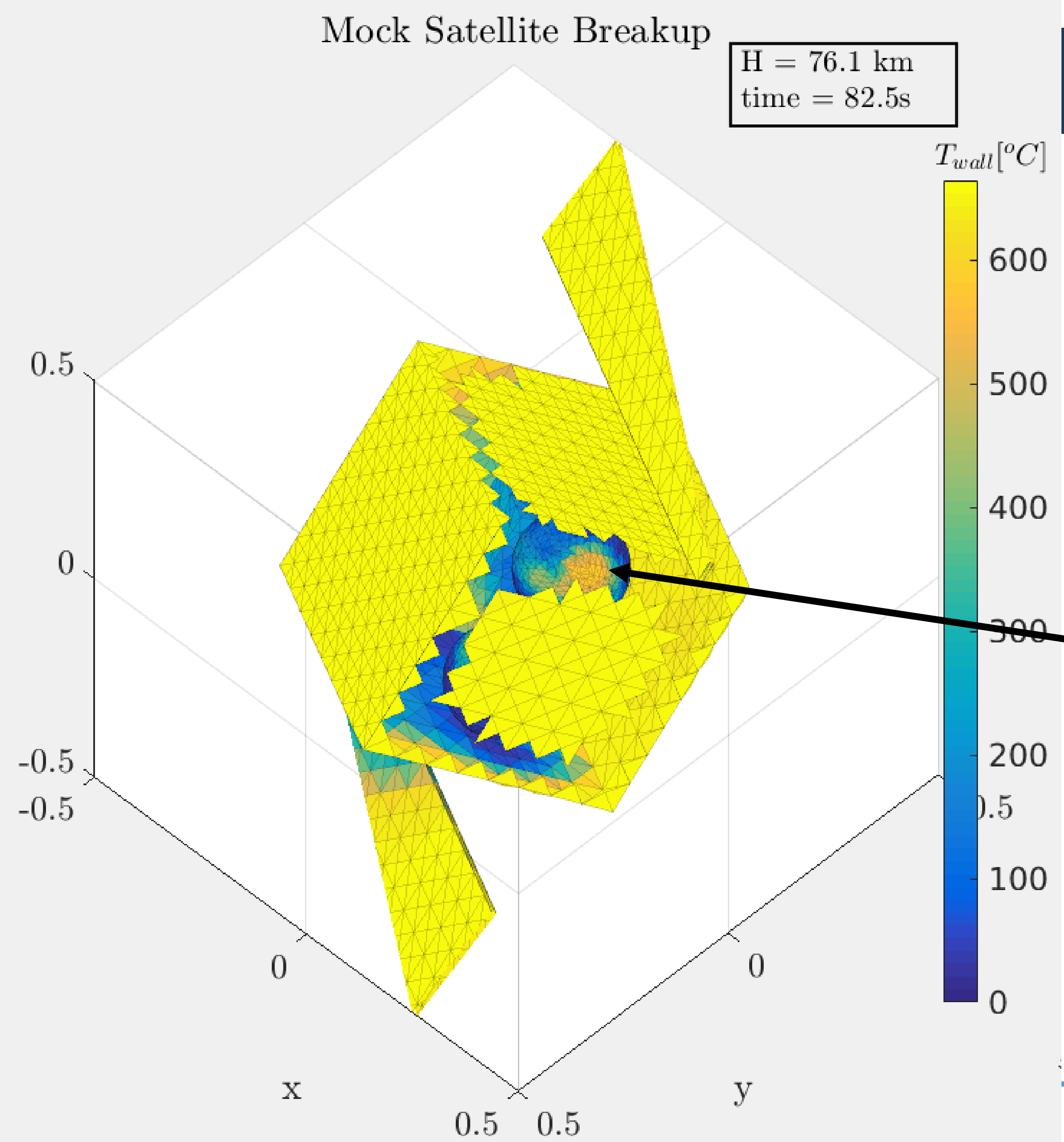


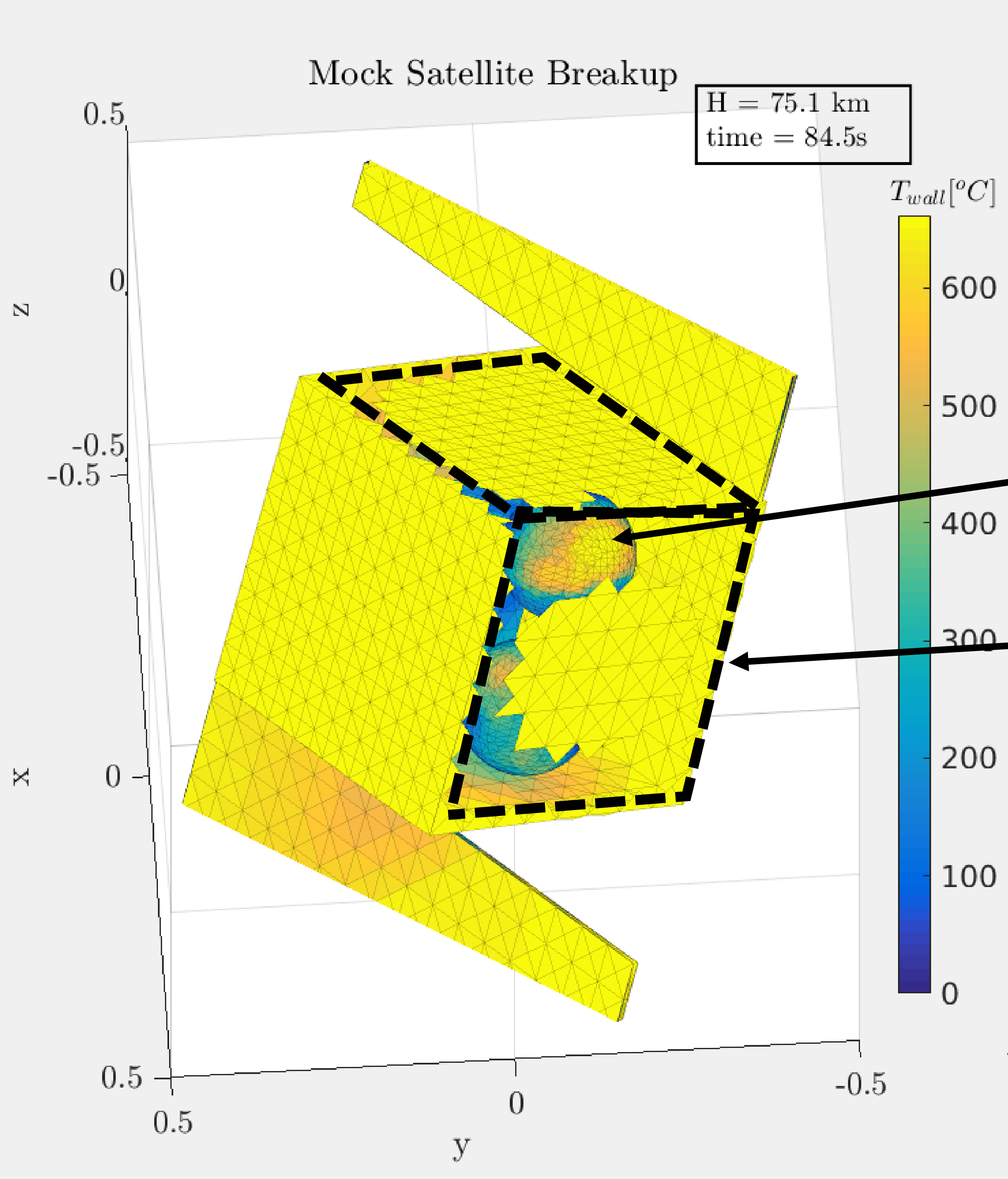
Ablation begins at the corner



Internal components exposed to aero-thermal heating



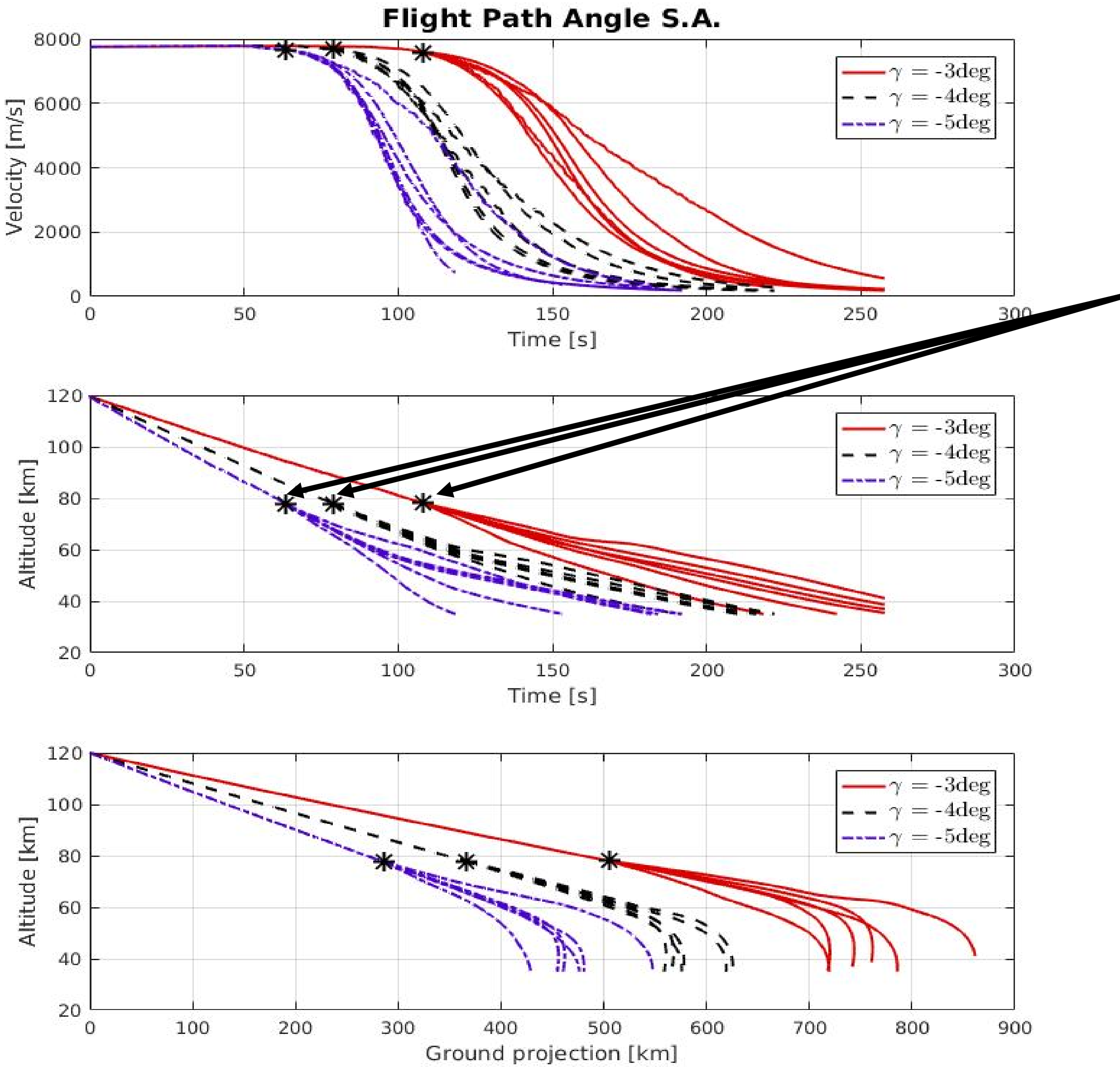
Temperature significantly increases



Melting temperature

Sides totally ablated

Sensitivity Analysis: flight path angle



Fixed breakup altitude: 78km

Simulation stopped at 35km or t = 260s

Conclusions

- FOSTRAD modules successfully implemented in a re-entry break-up framework
- Preliminary analyses of a single break-up mode
- Preliminary evaluation of S.M. use for ablation est.
- Occlusion culling for detecting internal components
- Flexible modular structure (controlled/uncontrolled re-entry)

Future Work

- Integration of progressive break-ups
- Integration of HF micro scale-based ablation S.M. for composite and ceramic materials
- Complete the testing of the UQ module

Thank you for the attention

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