The payload design of the CUbesat Solar Polarimeter (CUSP), for Space Weather and Solar flares X-ray polarimetry.

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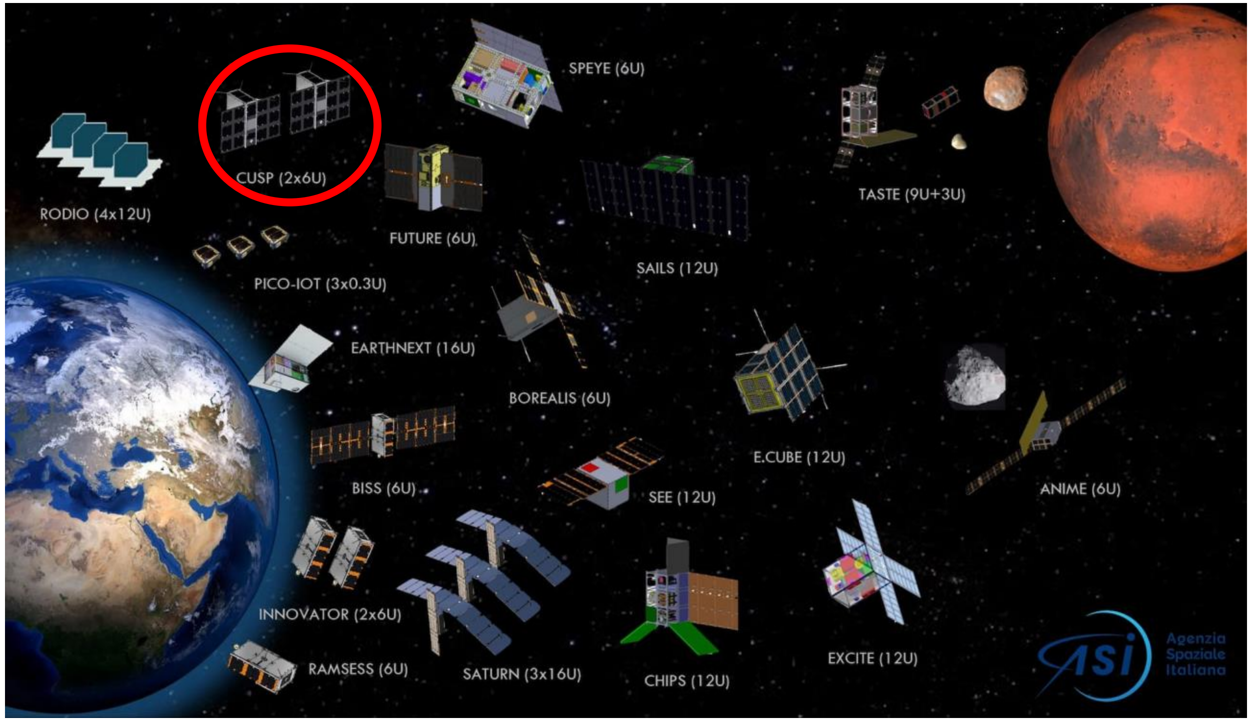
CUSP – Cubesat Solar Polarimeter

The **CUSP** project is funded by the Italian Space Agency (ASI) in the framework of the Alcor program implemented by ASI to develop innovative **CubeSats**. CUSP involves both public and private entities, including research institutes, Universities and Small and medium-sized enterprises (SMEs).

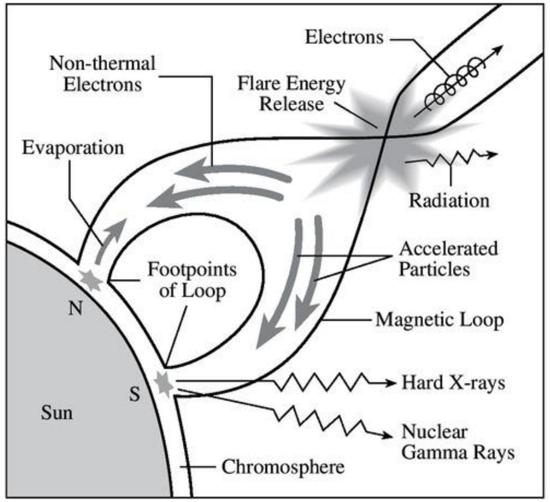
It is approved for a **Phase B** study to start in September.

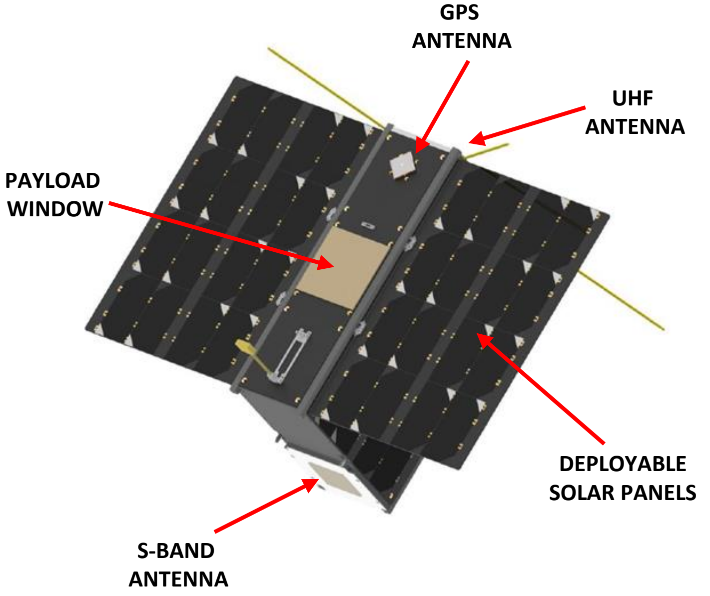


INAF-IAPS research institute leads the project and will design and assemble the scientific payload.

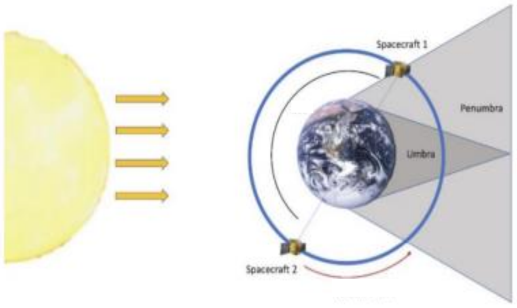
Main Mission Objectives

The CUSP is a constellation of two CubeSats orbiting around the Earth to measure the linear polarization of hard X−rays of **solar flares** in order to improve the knowledge of these violent phenomena involving magnetic re−connection, the particle acceleration on the Sun.



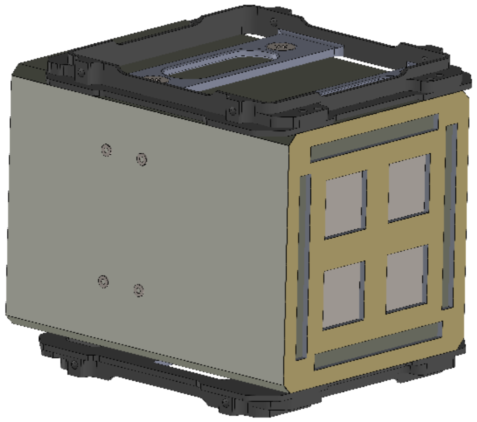


Also, the mission concept, allows the monitoring of the solar activity, for a large fraction of time >68% during the 3 years nominal lifetime, useful for **Space Weather** strategies.

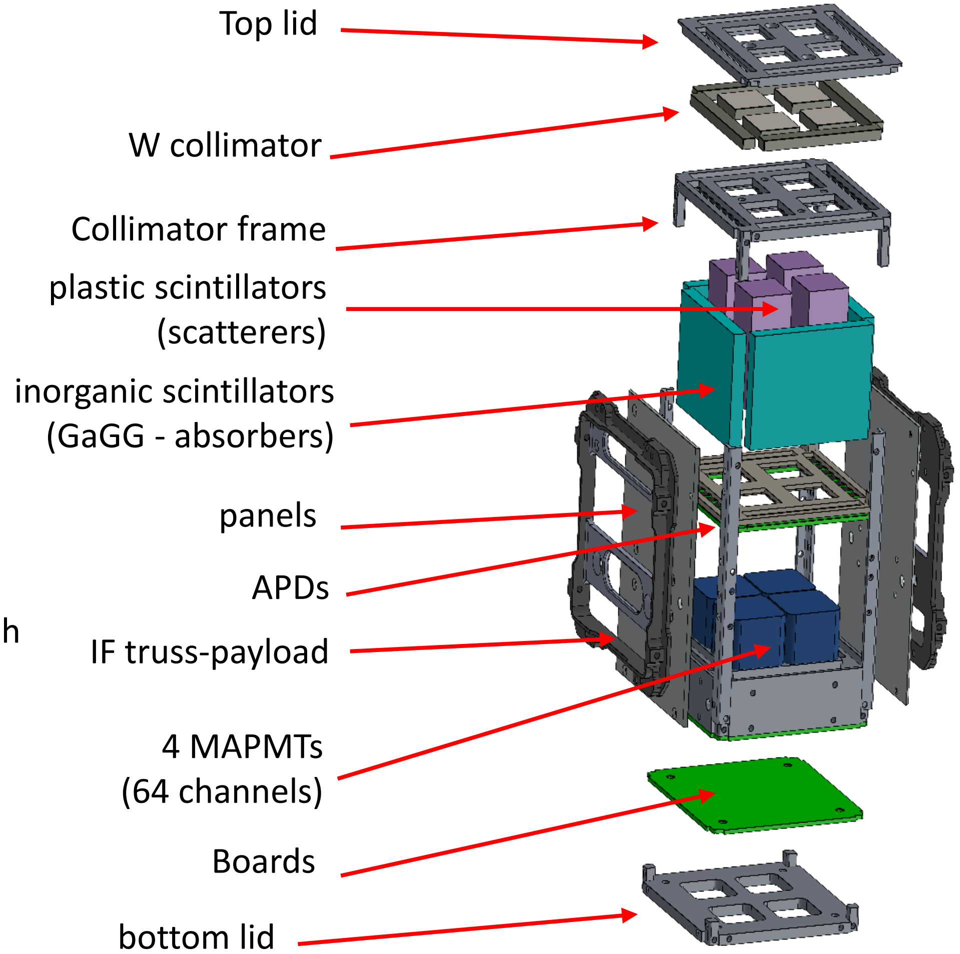


The Payload

- **Payload**:
  - Compton scattering polarimeter
  - W collimator
  - A/D conversion
  - Micro HVs (0.5" x 0.5" x 0.5")
  - Payload computer
- **Absorber** / **scatterer** coincidences (dual-phase scattering polarimeter)



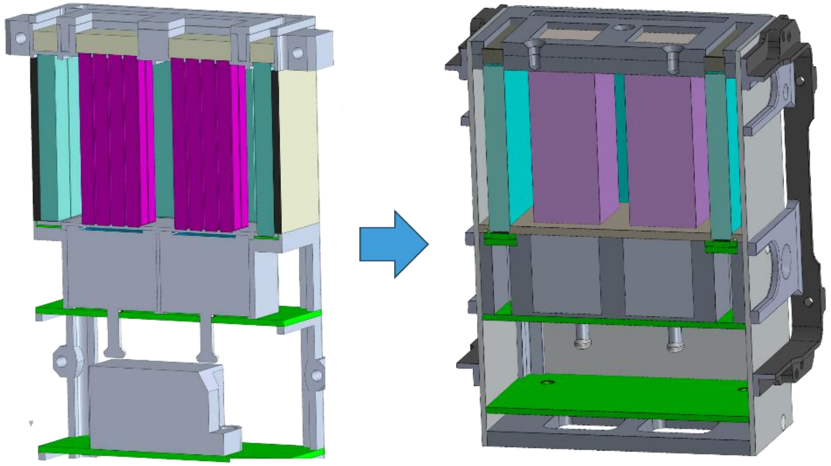
- Scattering stage:
  Multi-anode Photomultipler Tube coupled with plastic scintillator elements
- Absorption stage:
  GAGG readout with APD silicon sensors

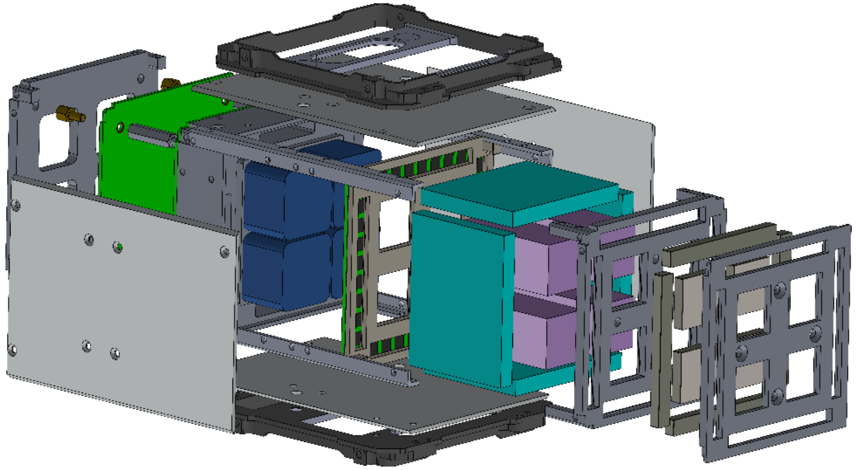


The Payload

The mechanical design, from the inception of **Phase A**, was represented in detail since the sensors and sensitive elements of the payload had already been identified.

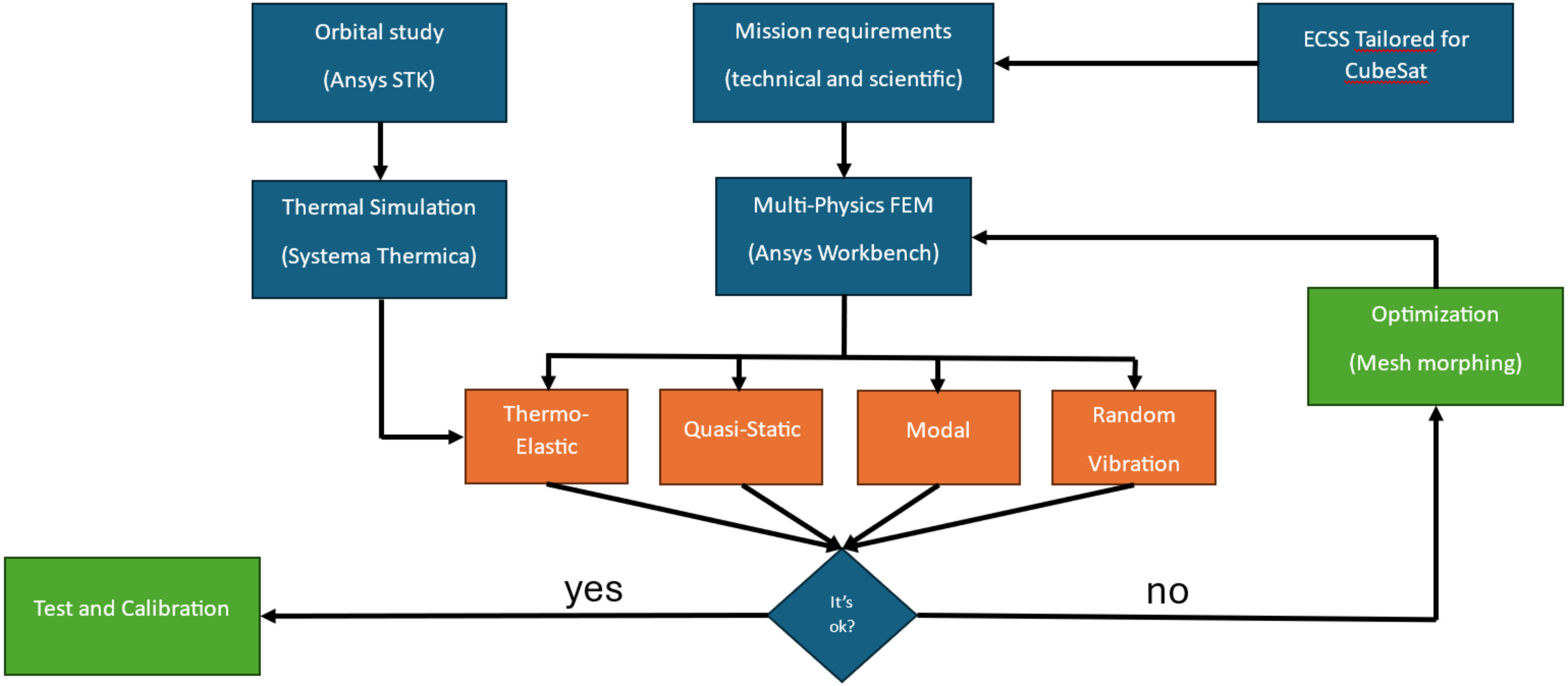
The **technology readiness level (TRL)** of the instrument's core is **very high** due to the long heritage of these components.





The **Phase B** of the mission will coincide with an in-depth examination of the individual mechanical components, the interfaces among these components, and their integration with the overall platform.
A thorough analysis of the available space for the central unit of the CubeSat allowed a **redefinition** of the **mechanical design.**

Multi-Physical Simulation


Orbital study

(Ansys STK)

Mission requirements

(technical and scientific)

ECSS Tailored for CubeSat

Thermal Simulation

(Systema Thermica)

Multi-Physics FEM

(Ansys Workbench)

Optimization

(Mesh morphing)

Thermo-Elastic

Quasi-Static

Modal

Random Vibration

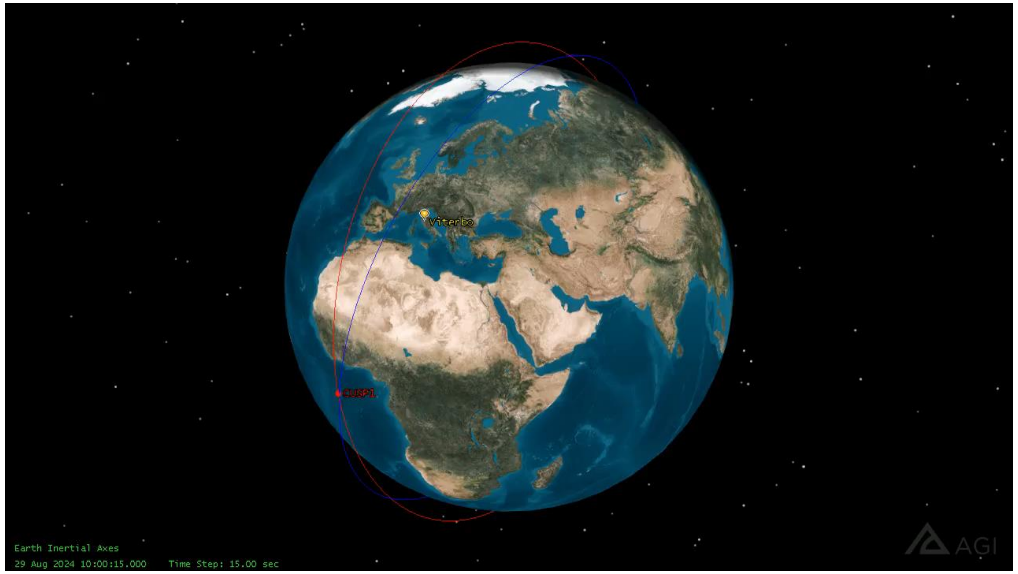
Test and Calibration

yes

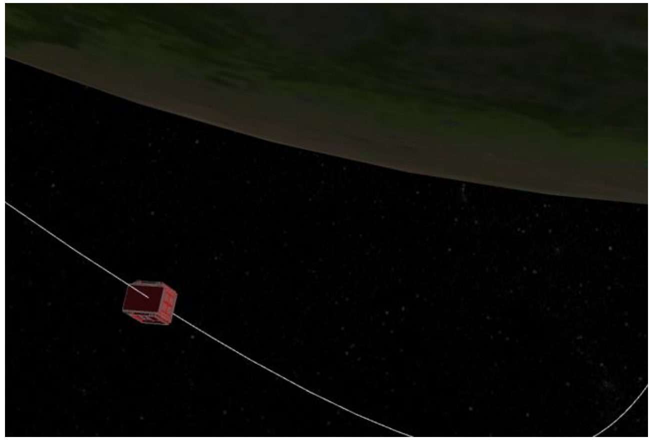
It's ok?

no

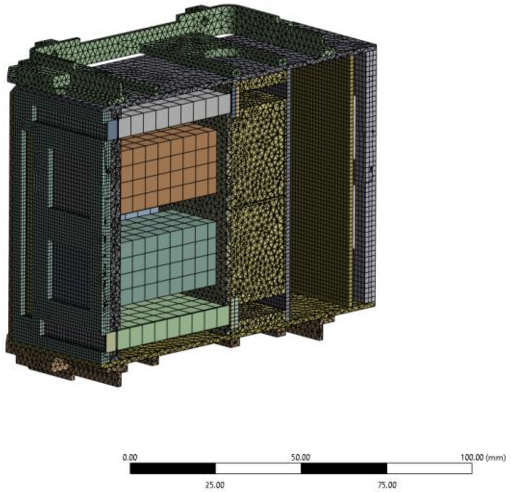
Numerical Simulation



The evolution of the mission design is followed by the implementation of a **simplified model**, without rounds and attachment points in **shell** and **3D solid** parts, which **validates** the **design choices** through a set of **numerical multi-physical simulations** based on mission requirements and the tailored European ECSS standard for CubeSat missions.



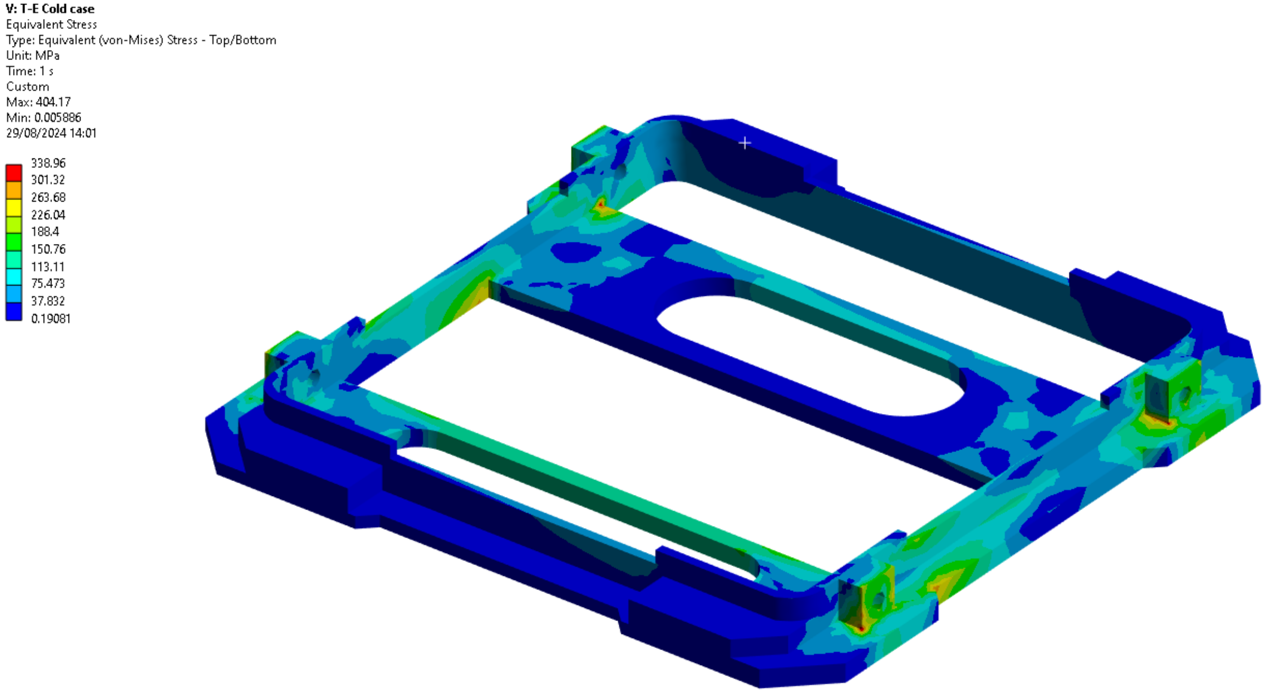
SSO orbit
(~500-600 km)



Nodes: 508566
Elements: 249421

Case study: Thermo-Mechanical Optimization

- During the orbit the **Cubesat payload** is subject to different **thermo-mechanical** load condition.
- The cold-case is chosen for the optimization as more critical condition.
- Eyelets and thickness optimization through mesh morphing.



I/F payload-platform
Cold case
Max stress: **338,94 MPa**
Weight: **37,74 gr**

RBF - Methods

Mesh Morphing - RBF (Radial Basis Function)

$$f^x(x) = \sum_{i=1}^{m} \boxed{\gamma_i^x \phi(\|c_i - x\|)} + \boxed{\beta_1^x + \beta_2^x x_1 + \beta_3^x x_2 + \beta_4^x x_3}$$
$$f^y(x) = \sum_{i=1}^{m} \boxed{\gamma_i^y \phi(\|c_i - x\|)} + \boxed{\beta_1^y + \beta_2^y x_1 + \beta_3^y x_2 + \beta_4^y x_3}$$
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Weight and radial function

Polynomial term

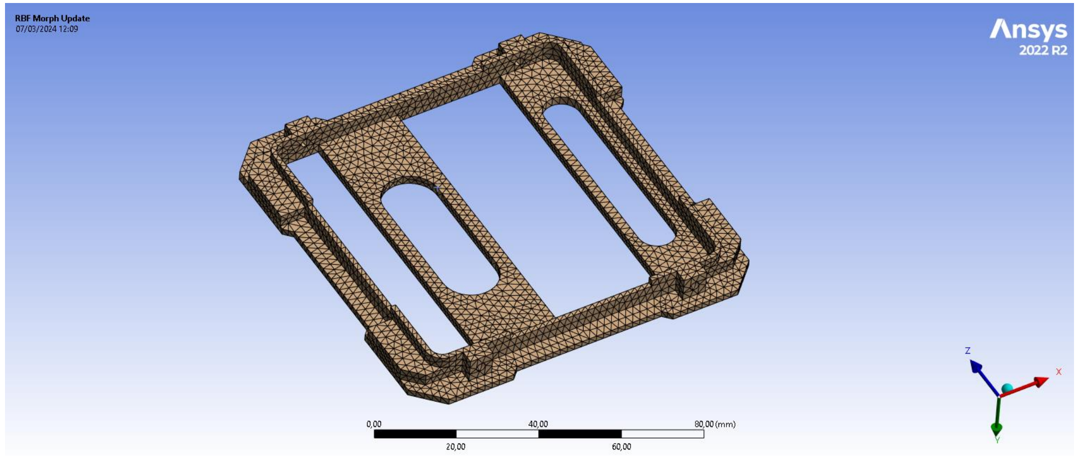
$$\boxed{\begin{gathered}\begin{bmatrix} M & P \\ P^T & 0 \end{bmatrix} \begin{Bmatrix} \gamma \\ \beta \end{Bmatrix} = \begin{Bmatrix} g \\ 0 \end{Bmatrix} \\ With \quad M = \phi(\|c_i - c_j\|) \\ P_j = [1 \ \ x_1 \ \ x_2 \ \ \dots \ \ x_n] \end{gathered}}$$

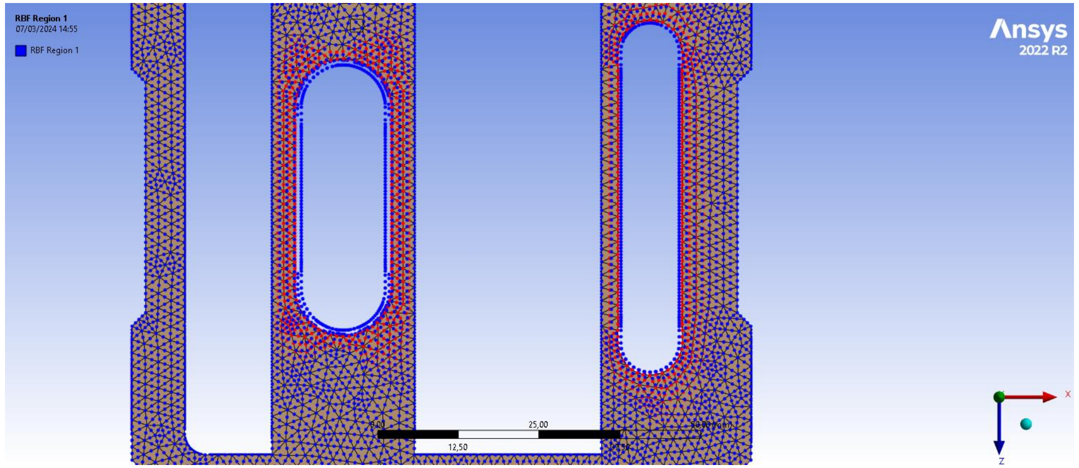
Boundary conditions

	Classic				RBF		
I	Geometry	Meshing	Solving	I	Geometry	Meshing	Solving
…	Geometry	Meshing	Solving	…		Morphing	Solving
n	Geometry	Meshing	Solving	n		Morphing	Solving

Case study: Thermo-Mechanical Optimization

- Geometric parameterization by **mesh morphing.**
- The principle is to take the control on a set of point and to transfer the deformation to the whole mesh.
- **Eyelets** and **thickness** of the internal part are selected for morphing.





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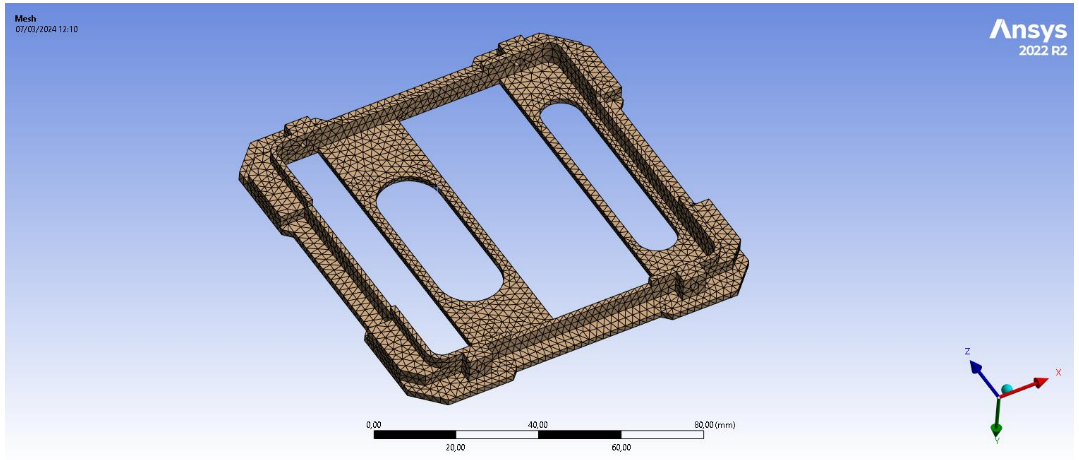
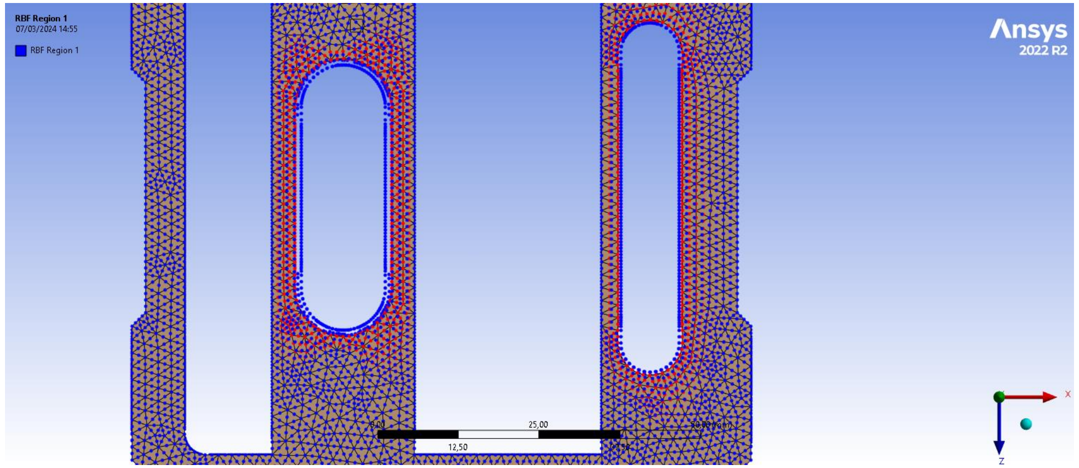




Optimization workflow – response surface

Baseline | Parameters | DOE | RS | Optimum

- Linear Regression:

$$y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \varepsilon_i$$

$$y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i1}^3 + \beta_4 X_{i2}^2 + \varepsilon_i$$

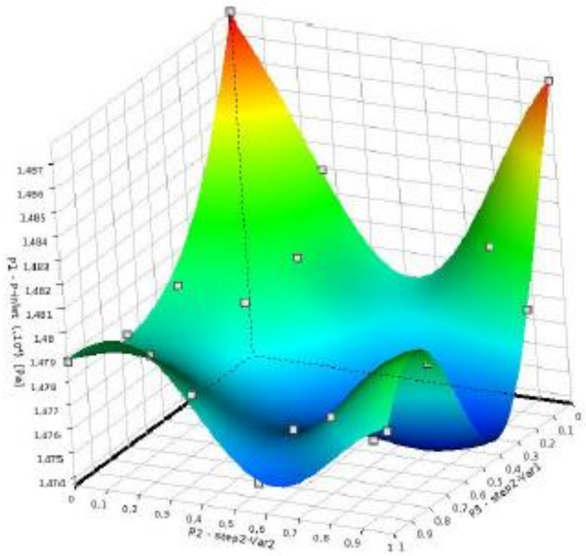
$$y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i1} X_{i2} + \beta_4 \log X_{i3} + \varepsilon_i$$

- A weighted linear combination of RBF functions

$$f(x) = \sum_{1}^{n} \omega_i \phi(\|x - c_i\|)$$

- Neural network
- …

Fitting



Case study: Thermo-Mechanical Optimization

- **DoE optimization** set to minimize **thermal stress** and **mass.**
- **80 snapshots** are collected.
- First **ROM evaluation** on Twin Builder.
- ROMs: **Mesh, Stress, Temperature.**
- ROM exported as **FMU.**
- **VR dashboard**

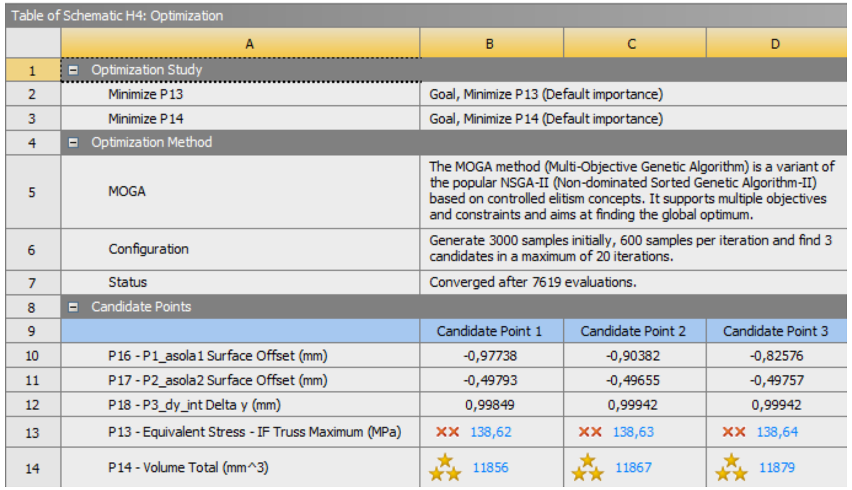
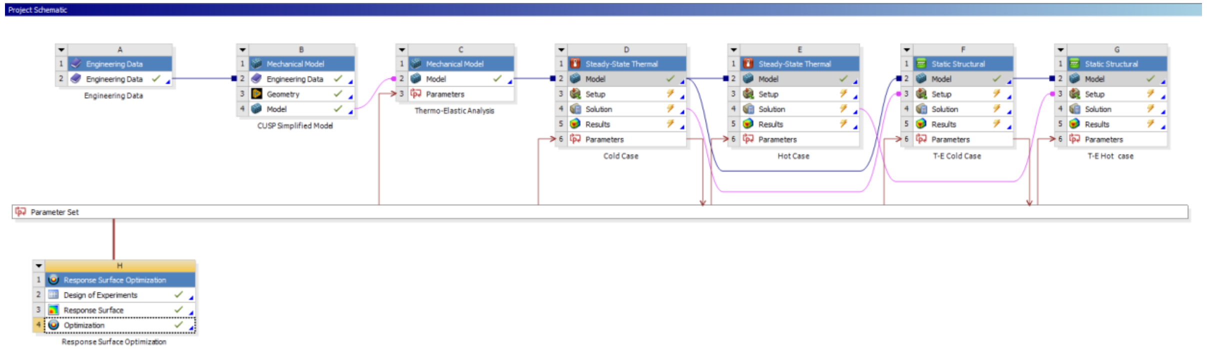


Table of Schematic H4: Optimization

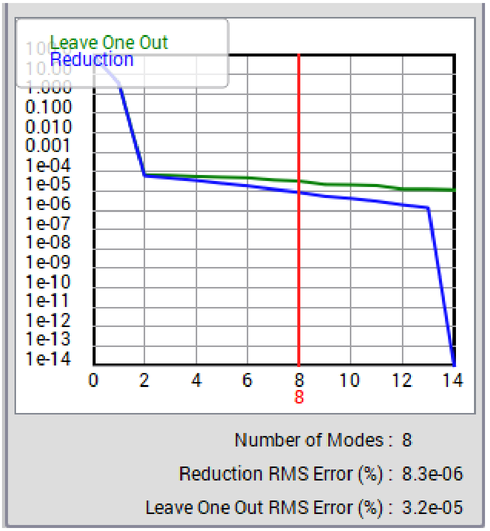
	A	B	C	D
1	⊟ Optimization Study			
2	Minimize P13	Goal, Minimize P13 (Default importance)		
3	Minimize P14	Goal, Minimize P14 (Default importance)		
4	⊟ Optimization Method			
5	MOGA	The MOGA method (Multi-Objective Genetic Algorithm) is a variant of the popular NSGA-II (Non-dominated Sorted Genetic Algorithm-II) based on controlled elitism concepts. It supports multiple objectives and constraints and aims at finding the global optimum.		
6	Configuration	Generate 3000 samples initially, 600 samples per iteration and find 3 candidates in a maximum of 20 iterations.		
7	Status	Converged after 7619 evaluations.		
8	⊟ Candidate Points			
9		Candidate Point 1	Candidate Point 2	Candidate Point 3
10	P16 - P1_asola1 Surface Offset (mm)	-0,97738	-0,90382	-0,82576
11	P17 - P2_asola2 Surface Offset (mm)	-0,49793	-0,49655	-0,49757
12	P18 - P3_dy_int Delta y (mm)	0,99849	0,99942	0,99942
13	P13 - Equivalent Stress - IF Truss Maximum (MPa)	✕✕ 138,62	✕✕ 138,63	✕✕ 138,64
14	P14 - Volume Total (mm^3)	★★★ 11856	★★★ 11867	★★★ 11879



Methods – Digital Twin

Digital twin development: SVD + ROM

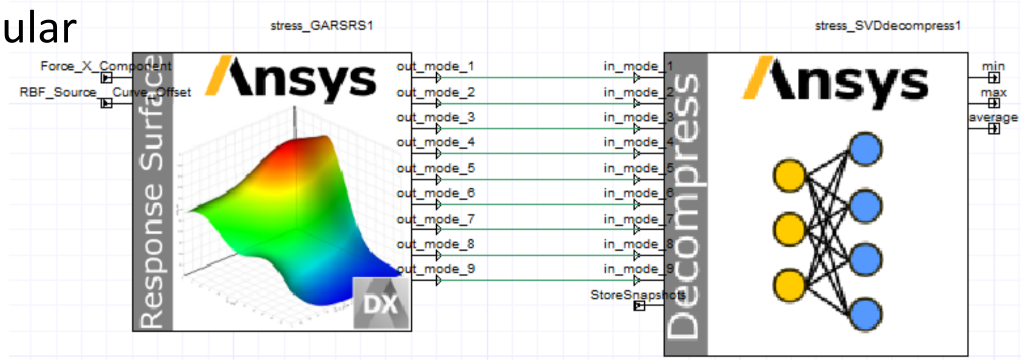
- One of the best-known applications of SVD is Principal Component Analysis (PCA);
- Given a matrix A ∈ R m x n and given p = min(m, n), a singular value decomposition (SVD) of A is a factorization of the form:
  $A = U\Sigma^{t}V$
- U = (u_1 … u_m) ∈ R m x m and V = (v_1 … v_n) ∈ R n x n are orthogonal and Σ ∈ R m x n is (pseudo)diagonal with diagonal elements $\sigma_1 \geq \ldots \geq \sigma_p \geq 0$
- $\sigma_1, \ldots, \sigma_p$ are the singular values of A
- A can be rewritten as: $A = \sum_1^k \alpha_i U_i$, where k are the principal singular values
- Finally, to construct the ROM it is necessary to find a correlation between input parameters and mode weights, and several interpolation methods can be used (RBF, Polynomial/Gaussian Regression, neural networks)



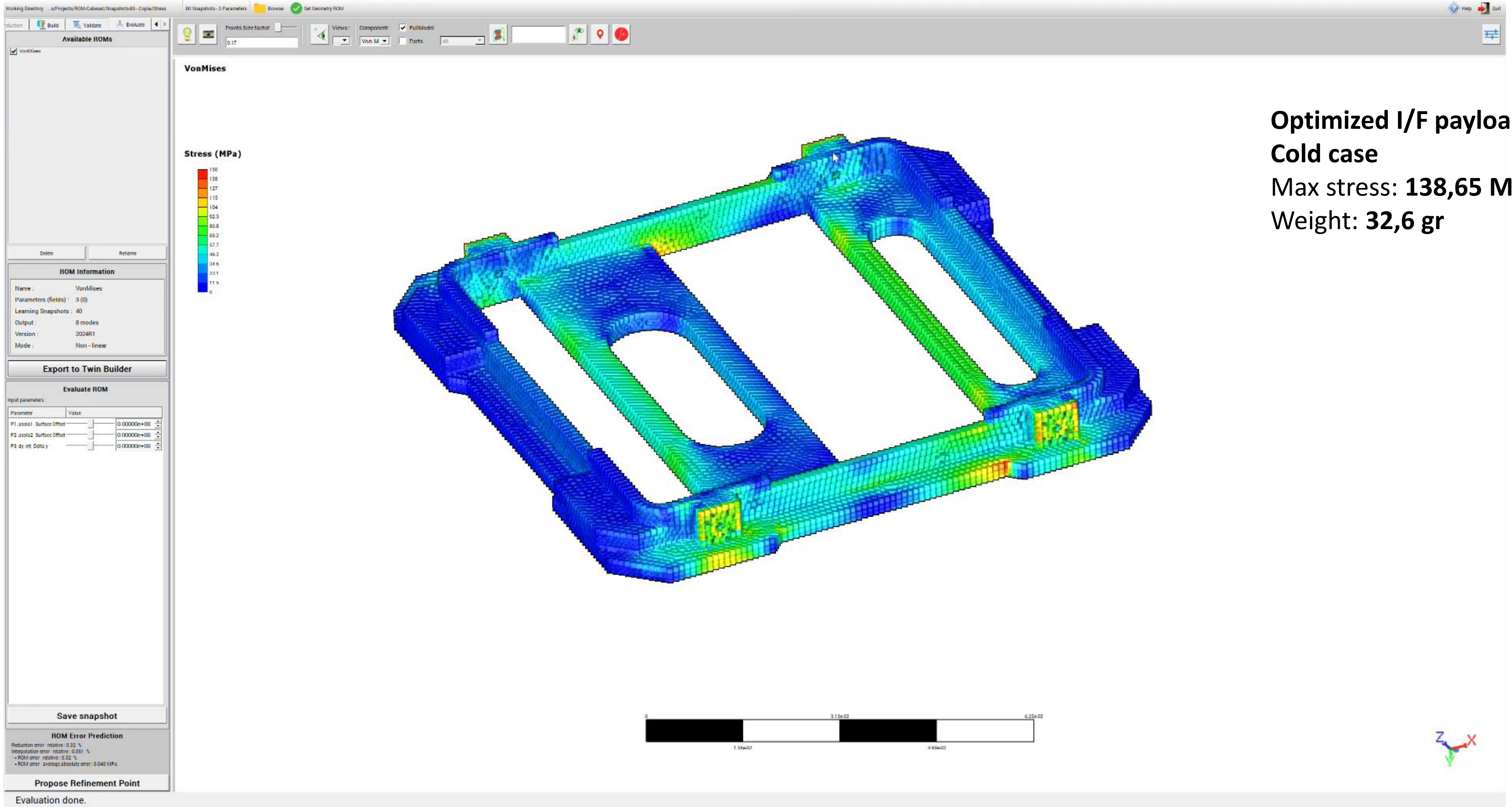
Number of Modes : 8

Reduction RMS Error (%) : 8.3e-06

Leave One Out RMS Error (%) : 3.2e-05



Case study: Thermo-Mechanical Optimization



Working Directory: ...s/Projects/ROM-Cubesat/Snapshots-80 - Copia/Stress

Points Size factor: 0.17

Component: Von M

ROM Information

Name : VonMises
Parameters (fields) : 3 (0)
Learning Snapshots : 40
Output : 8 modes
Version : 2024R1
Mode : Non - linear

Evaluate ROM

Input parameters :

Parameter	Value
P1 asola1 Surface Offset	0.00000e+00
P2 asola2 Surface Offset	0.00000e+00
P3 dy int Delta y	0.00000e+00

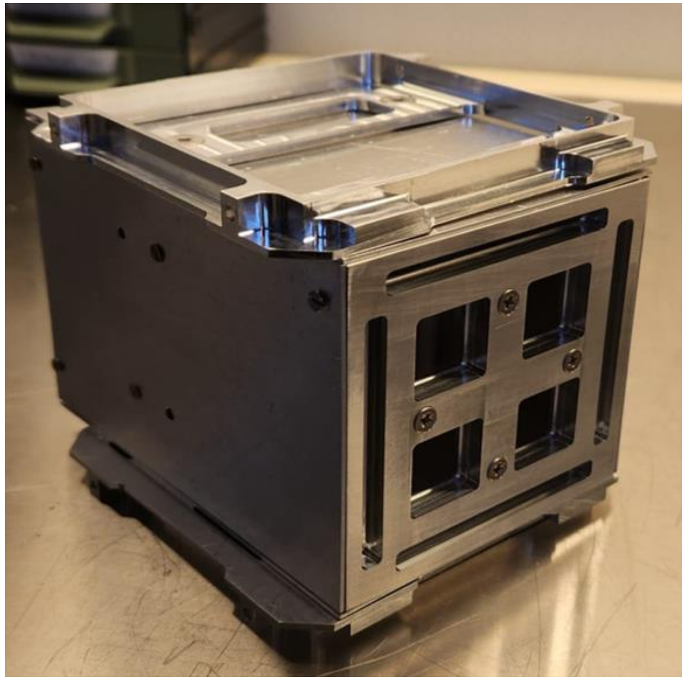
ROM Error Prediction

Reduction error - relative : 0.32 %
Interpolation error - relative : 0.061 %
- ROM error - relative : 0.32 %
- ROM error - average absolute error : 0.040 MPa

Evaluation done.

Optimized I/F payload-platform
Cold case
Max stress: **138,65 MPa**
Weight: **32,6 gr**

Results



The sequence of processes, mentioned above, has been iterated several times until reaching **optimal values**, balancing mechanical and thermal **requirements**.

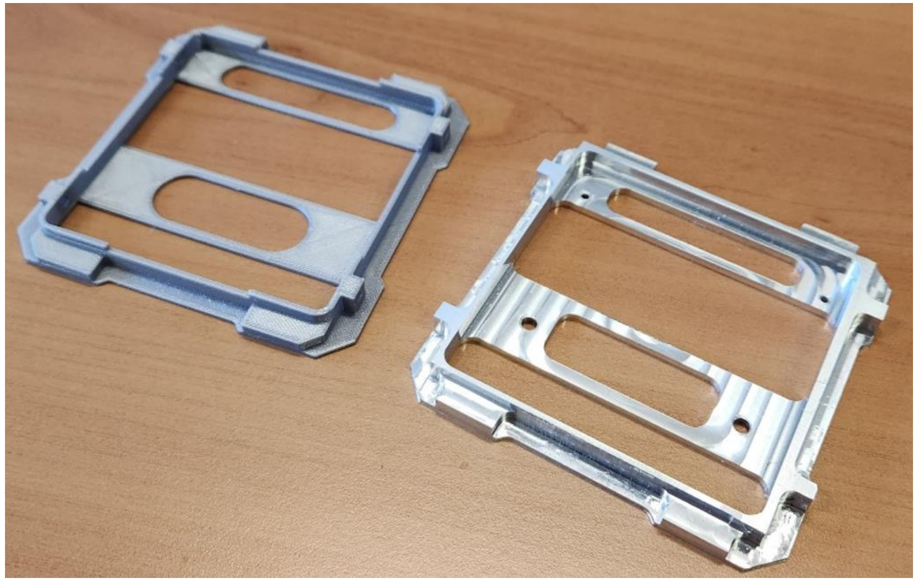
Particularly, the critical area of the **I/F between the payload and the platform** has been refined and improved using advanced **mesh morphing** techniques.

This has led to a **notable decrease in applied stresses** and thermo-mechanical loads, along with a **reduction in mass** percentage, while still maintaining the minimum reference value of 120 Hz for the first mode of modal analysis.

Conclusion and Future Goals

The CUSP mission has reached a **critical phase** in its development, with upcoming objectives focused on refining and integrating every aspect of the project:

- precise **optimization** of mechanical systems, following the explained processes for other critical areas of the spacecraft. This includes verifying **tolerances**, **reducing vibrations**, and **refining** every moving and structural component.
- **rapid prototyping** and VR/mixed reality environments will be employed. The first allows for quick testing and iteration of design solutions, the **VR/mixed** reality environment provides an immersive experience, allowing designers to visualize and interact with the system in three dimensions.



Finally, to validate the generated model, **environmental tests** will be performed in 2025 on a technological demonstrator.

Thank you for your attention!

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