THE ROLE OF HIGH FIDELITY CAE MULTI-PHYSICS DESIGN AT INAF

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INAF
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DI ASTROFISICA

The National Institute of Astrophysics (**INAF**) is the main Italian research institute for the study of the universe.

The Institute of Astrophysics and Space Planetology (**IAPS**), an INAF institute, is based in Tor Vergata in Rome and represents INAF's main structure for astrophysics and planetological research in space.

One of the Institute's scientific objectives is understanding the structure of the **Universe**, from its birth to its evolution, through the study of **celestial objects** in the various bands of the **electromagnetic spectrum**.
Much attention is also paid to the study of our **solar system** in all its aspects, from the formation and evolution of the **planets** to the relationships between our planet and the **sun**, the study of **star formation**, and the verification of relativity and the law of universal gravitation that governs the motion of all bodies.

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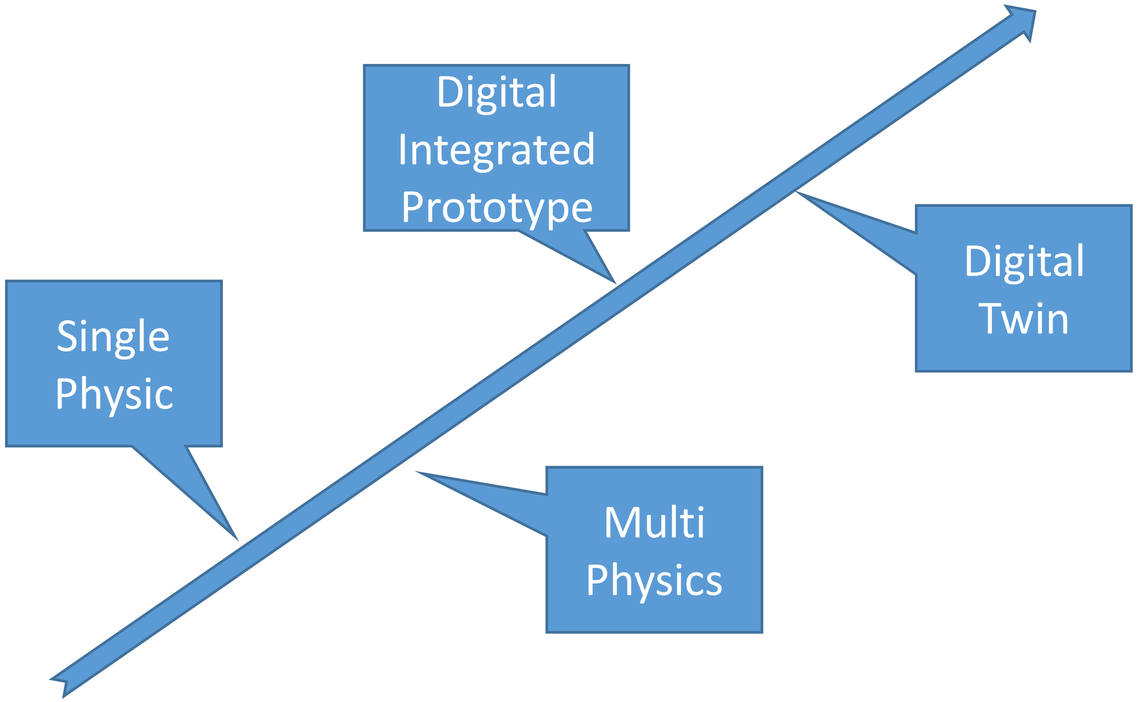
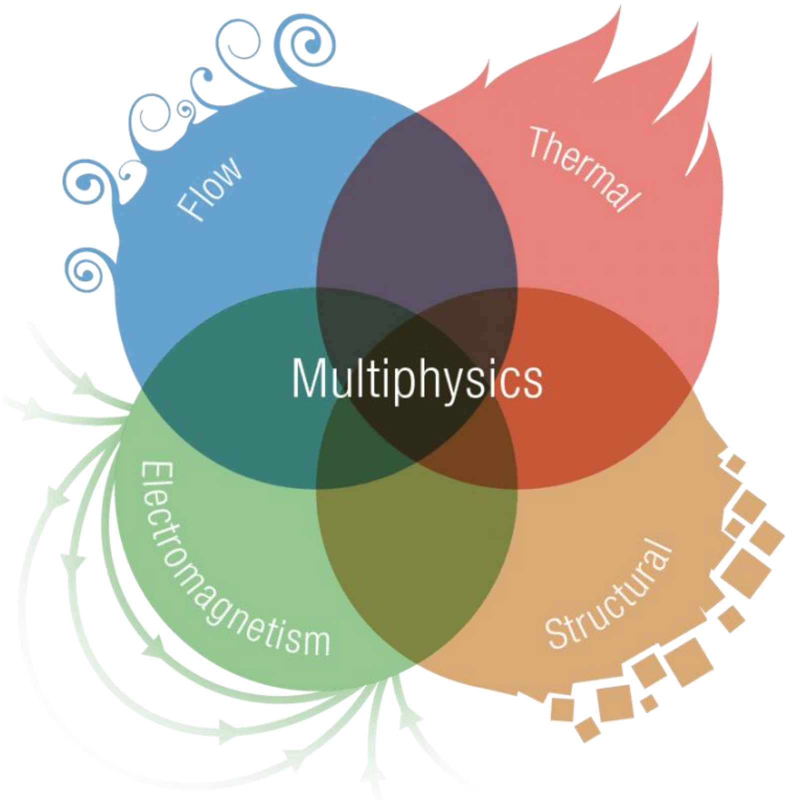


The route of the **CAE** in aerospace sector at IAPS/INAF is focused on the following topics:

- **Multifunctional materials**
- **Process automation**
- **Topological optimization and additive manufacturing**
- **Innovation and confidence**

In order to accurately model a design to meet the requirements imposed by the space mission and the spacecraft operating environment, **multiphysics** simulation has become a necessity since, compared to the traditional approach, gives the possibility to couple any number of physical phenomena.

Accurate multiphysics models consider a wide range of possible physical conditions and effects, making it possible to use the models to understand, design, and optimize processes and devices for realistic operating conditions.



(rbf-morph)™
Welcome to the World of Fast Morphing!

The challenge is to employ **cross-platform** and **cross-solver** tools and methodologies for CAE-based design, **reducing** the design process duration and make **feasible** some applications even with **high-fidelity** models.

Engineers and designers of the Institute are working on aimed at developing an integrated numerical platform and methodology to efficiently face the most demanding challenges of spacecraft and satellite design and **optimization**.

The basic idea is to make the numerical model parametric through the use of a **mesh morphing** technique founded on radial basis functions (**RBF**) mathematical framework, a class of mathematical interpolation functions.

RBF are in CAE applications, such functions can be used to drive mesh morphing (smoothing) of computational nodes applying predefined displacements to source points.

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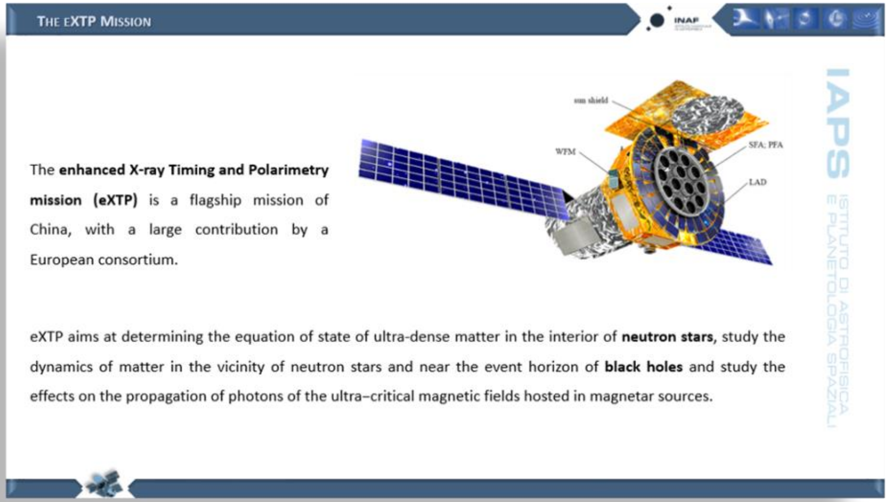
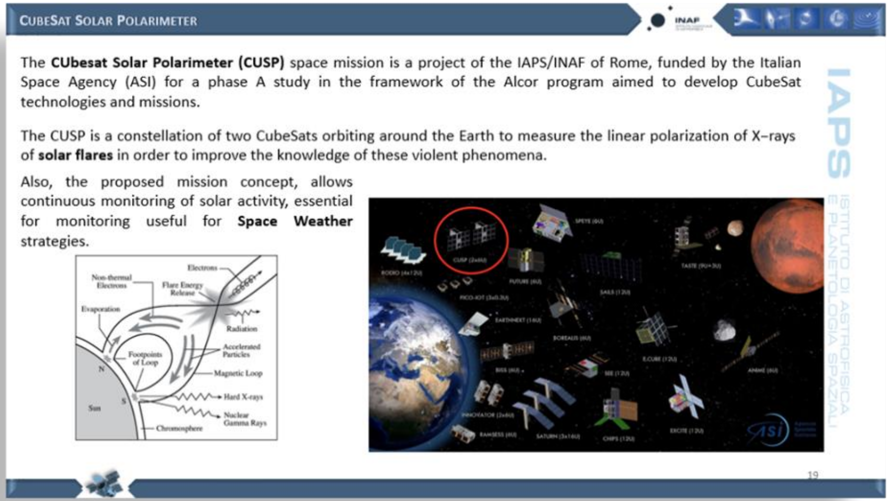
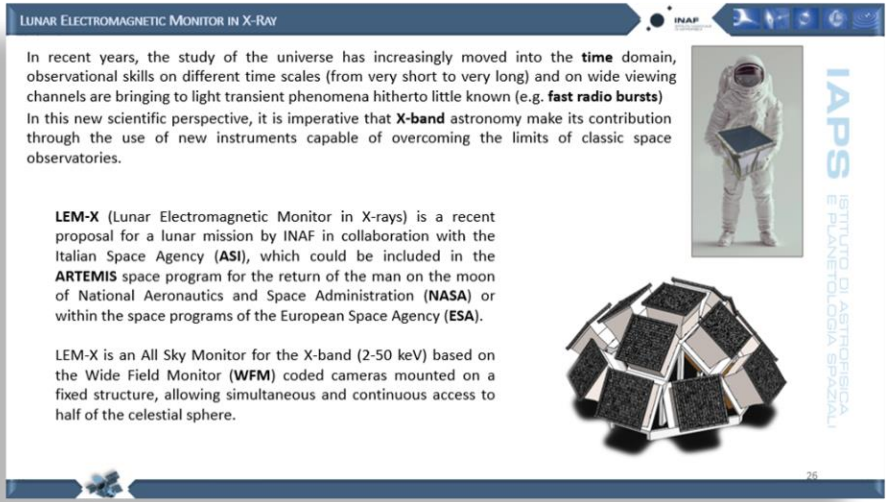
- eXTP Mission



- CubeSat Constellation: CUSP



- The Institute on the Moon: LEM-X



- Conclusion

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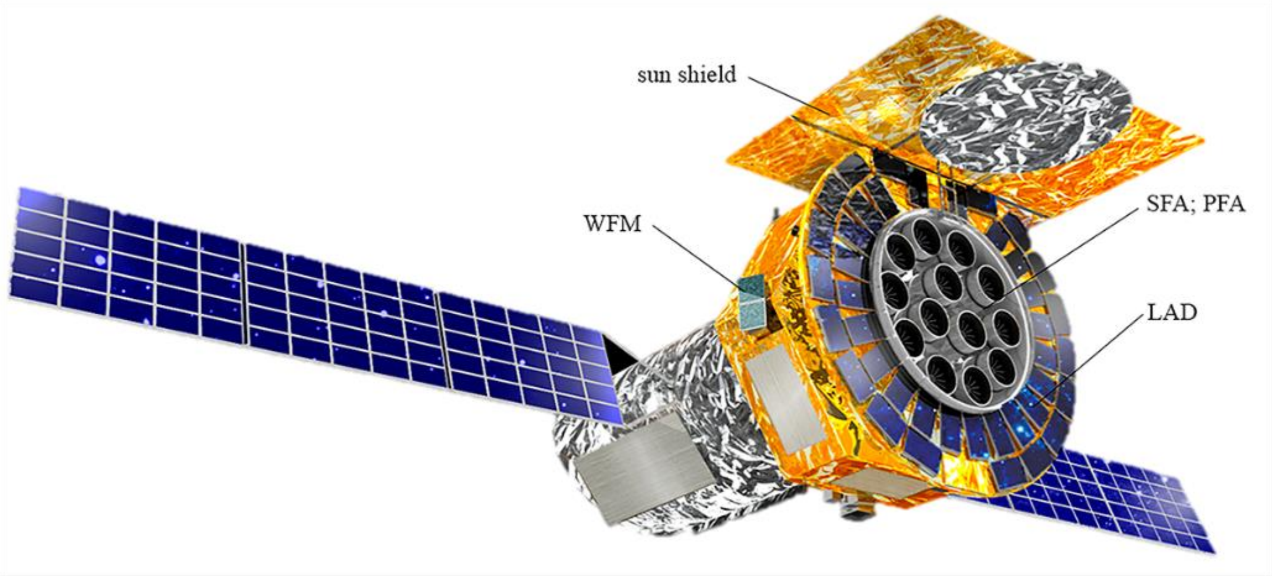
The **enhanced X-ray Timing and Polarimetry mission (eXTP)** is a flagship mission of China, with a large contribution by a European consortium.



eXTP aims at determining the equation of state of ultra-dense matter in the interior of **neutron stars**, study the dynamics of matter in the vicinity of neutron stars and near the event horizon of **black holes** and study the effects on the propagation of photons of the ultra−critical magnetic fields hosted in magnetar sources.

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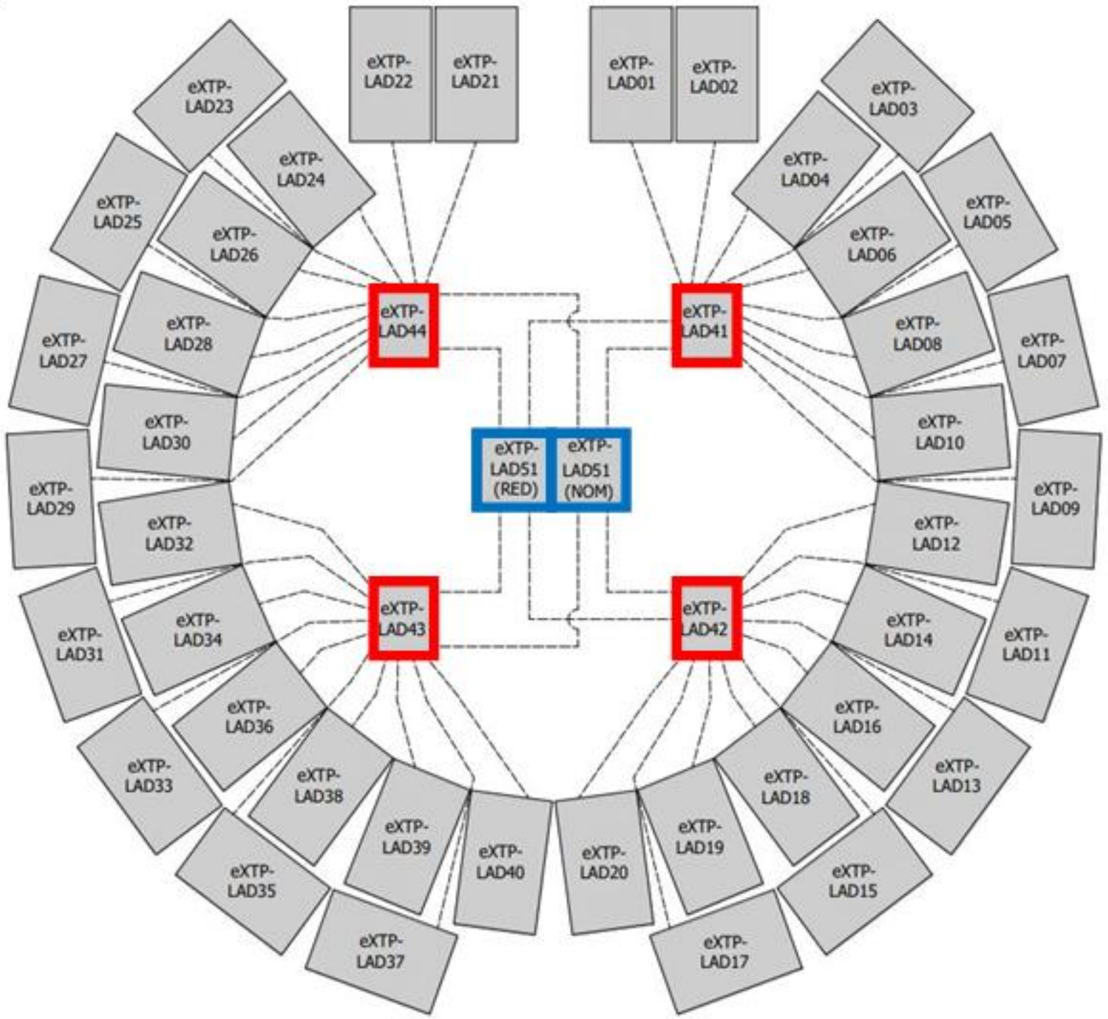
Large Area Detector



The **Large Area Detector (LAD)** is designed to be the most sensitive spectral-timing instrument for bright Galactic and extra galactic sources to date, an innovative and highly efficient technology and design allow to deploy in space an effective area as **large** as 3.2 m^2 – class with a modular configuration.

The LAD is organized as a modular instrument, composed of 40 coaligned **Modules**, each one hosting a set of 16 **Silicon Drift Detectors (SDDs)** and 16 corresponding capillary plate **collimators (MPO).**

The Modules are hierarchically interfaced by a set:

- four **Panel Back End Electronics (PBEE)**;
- **Instrument Control Unit (ICU).**

LAD MODULE – OVERVIEW

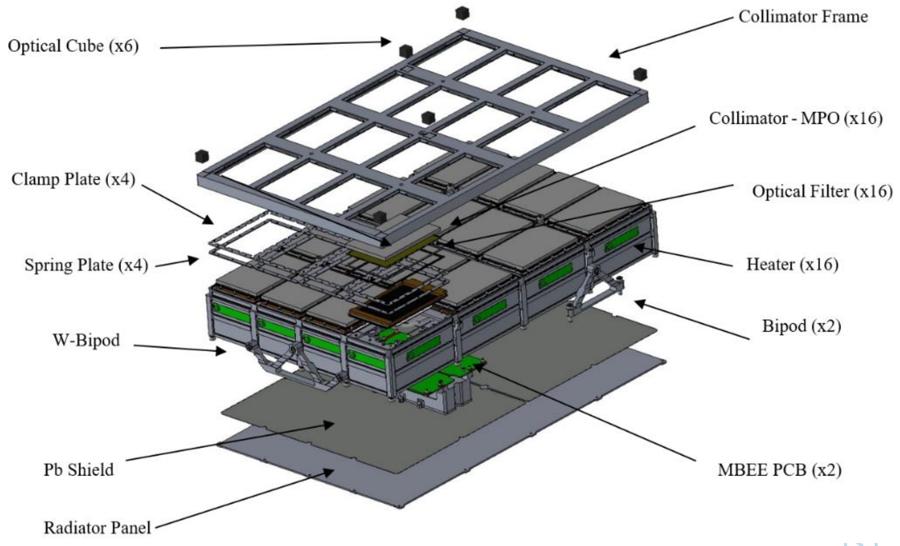
The module consists of:

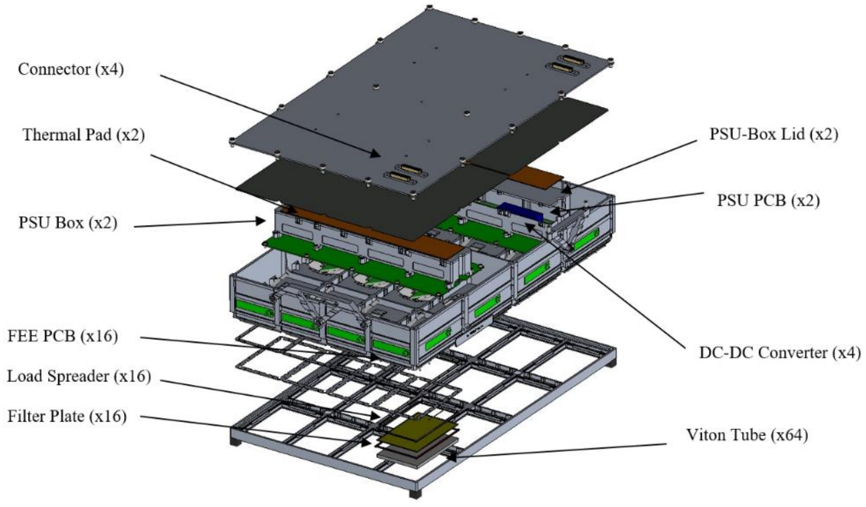
A **Collimator Tray**, including:

- an aluminum alloy **collimator frame**;
- 16 co-aligned **MPO** collimator tiles (one per SDD), clamped to the frame;
- 16 **optical filters**, under each MPO;

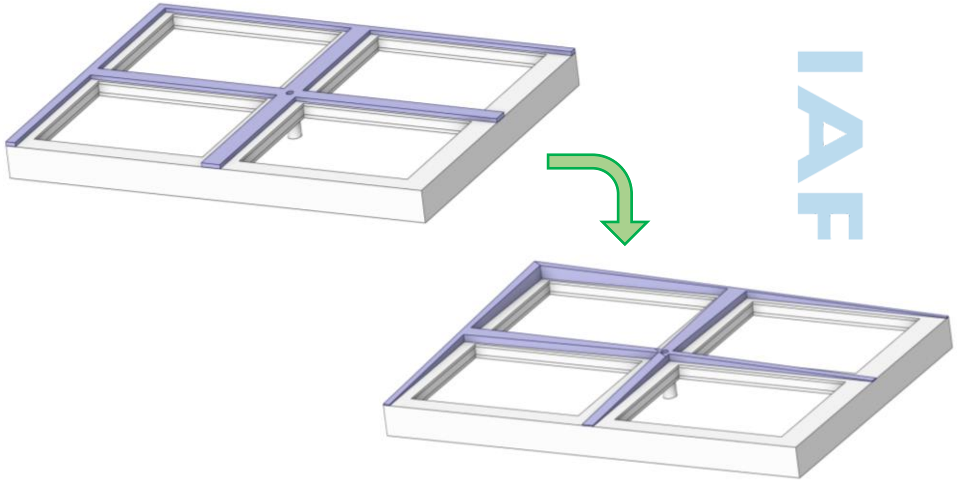
A **Detector Tray**, including:

- an aluminum alloy **detector frame**;
- 16 detector assemblies, each including a **SDD** and a **FEE**. Each SDD has 224 anodes, each FEE has 30 ASICs, to read out the signals from the anodes. The ASICs amplify and digitize the anode charge pulses resulting from X-ray events;
- Two Module Back-End Electronics (**MBEE**) boards, which control the ASICs and HV PSU, read out the digitized events, format and timestamp each event, and transmit it to the Panel Back-End Electronics (PBEE);
- Two HV/MV/LV Power Supply Unit (**PSU**) boards for the SDDs and MBEE;
- An aluminum alloy back panel, including 300 µm **lead shielding** to reduce the background, and acting as a **radiator** dissipating heat from the module;
- A **heater** belt around the module, to maintain the module in the operating and survival temperature ranges, and to allow the annealing of the SDDs, a heating process (up to 50°C) which alters the silicon crystal structure, recovering the damages induced by particle irradiation.

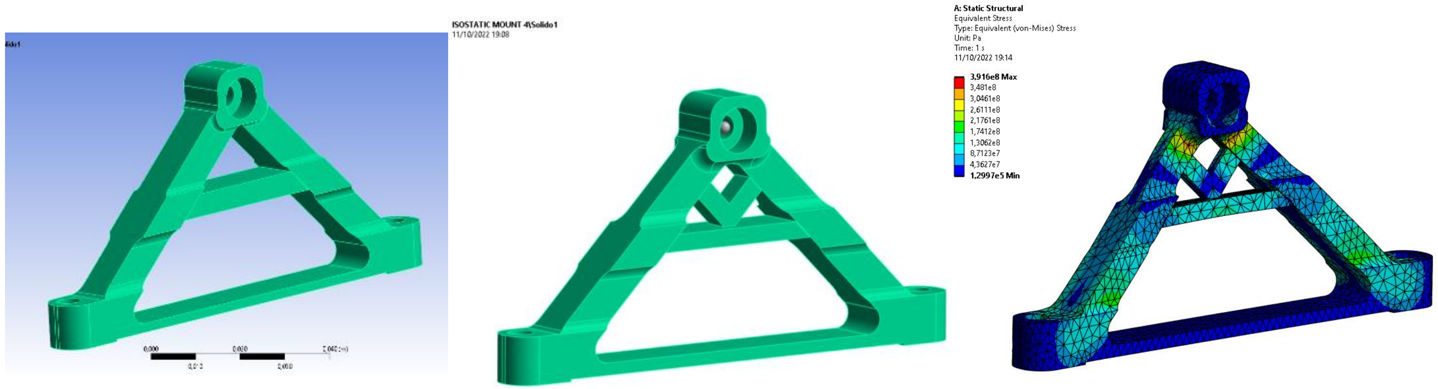




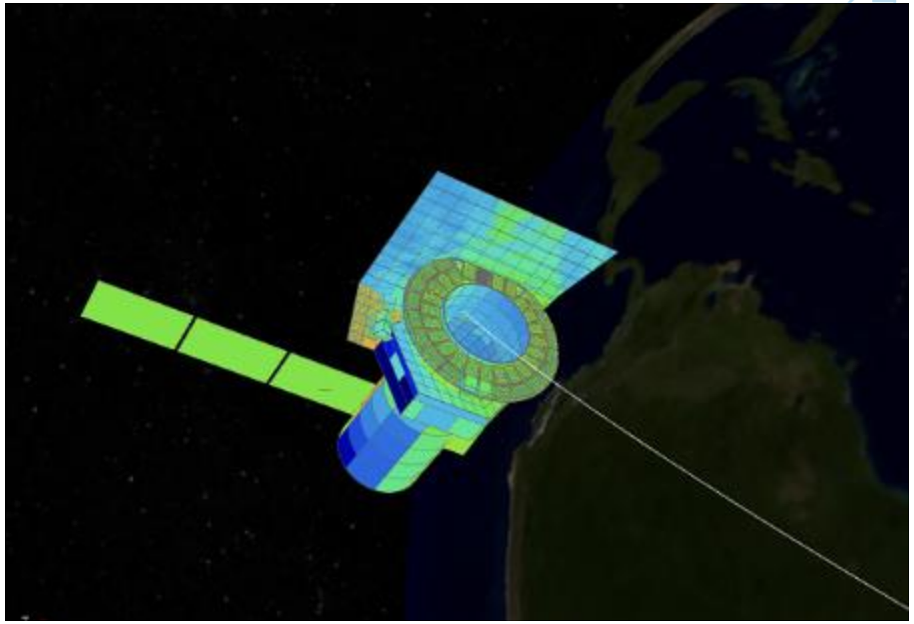
1. illustrate two mechanical optimization for critical elements:
   - **collimator frame**, where the parameter of merit to be minimized was the angle that describes the misalignment of the collimator with respect to the frontal direction;
   - **bipod** to increase the first natural frequency of the system and reduce the mass.
2. explain the **thermal analysis** conducted into the extreme hot and cold cases of the eXTP mission (single module detailed and whole satellite) studied in order to obtain the thermal response of the LAD instrument



Section of collimator frame

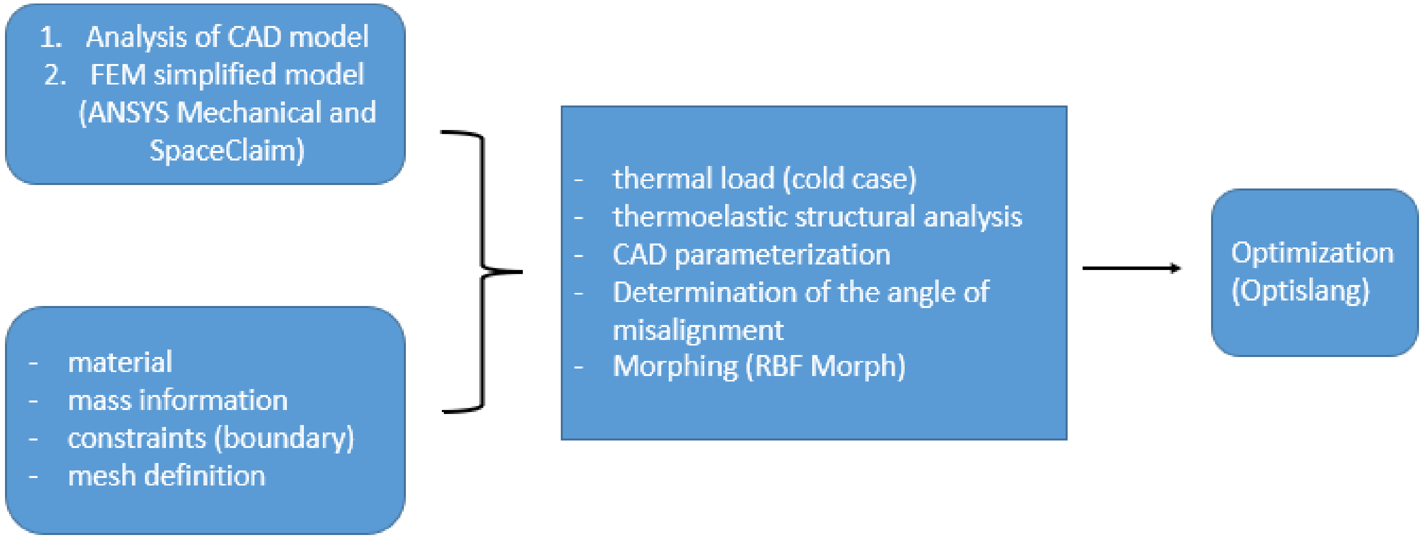


Bipods



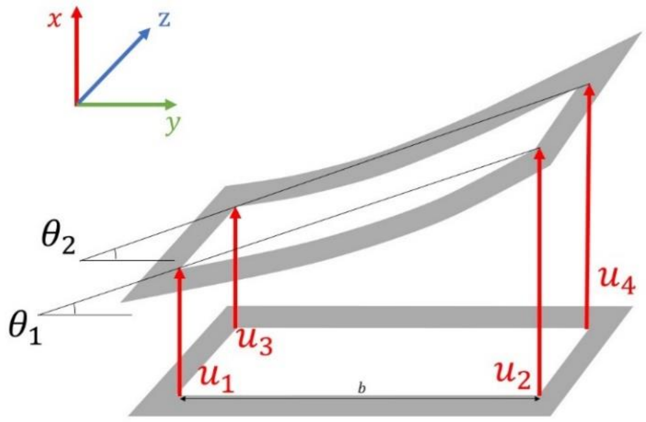
Optimization – Collimator Frame

Due to the different **thermophysical** properties of the materials, the components during thermal cycles deform causing a misalignment of the 16 Collimators and, since the structure is not free to deform due to the presence of internal and external constraints, they become tensioned.



Optimization of Collimator Frame

Starting from the evaluation of the thermo-elastic deformation of a simplified collimator frame, modified with ribs. The results of a static structural simulation of a **parametric** model with an accurate mesh allows an optimization, throught some **mesh morphing** tools.



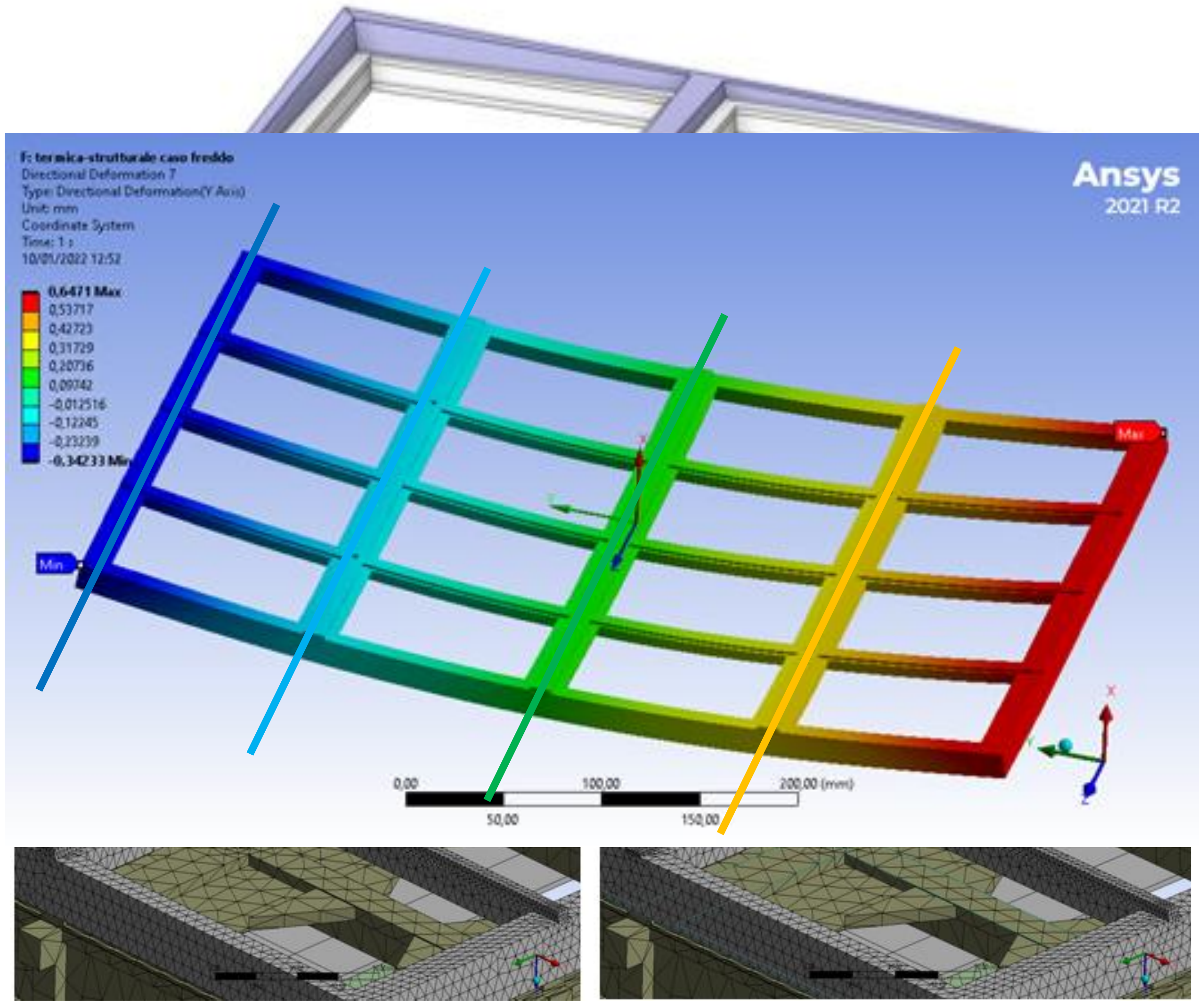
Following equation was used for calculate each angle of a single quadrant into the collimator frame, expressed as a function of the **displacements** along all directions:

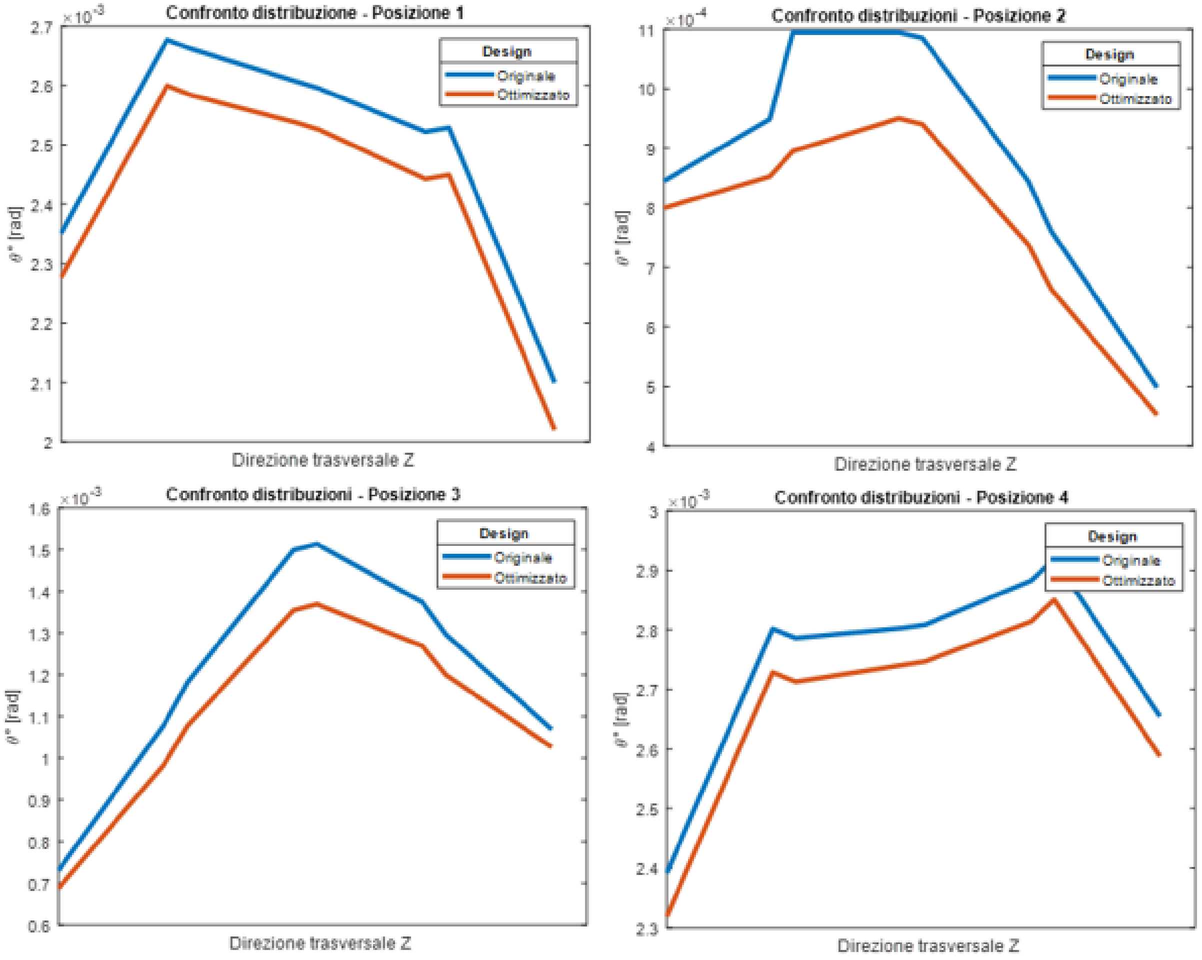
$$\theta = atan\left(\frac{u_{max} - u_{min}}{b}\right)$$

$$\theta^* = mean(\theta_1, \theta_2, \ldots \theta_{32})$$

Θ∗ represents the value of the **misalignment** calculated into the original configuration, it is a necessary condition for the success of the optimization to obtain an angle Θ≤Θ∗.

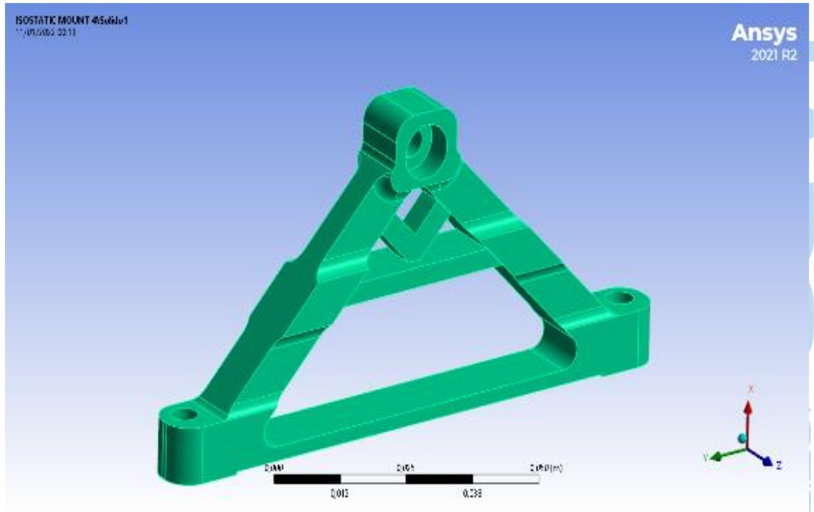
The distribution of misalignment's is better overall, the study produced a reduction in misalignment of approximately **5%**.

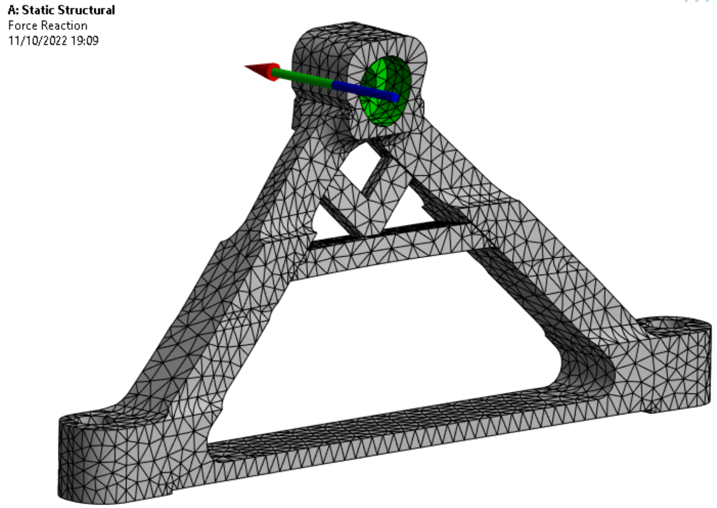




Optimization of **bipod**, critical element that supports the module and connects it to the truss:

- preliminary design of the module in a complete CAD model meeting the requirements of the mission and export of the model in ANSYS SpaceClaim obtaining a simplified defeatured model but compliant in terms of mass and volume;
- Re-processing and **parameterization** of the CAD geometry of the bipod through the ANSYS RBF Morph tool;
- **Structural optimization** of the Bipod through OptisLang.

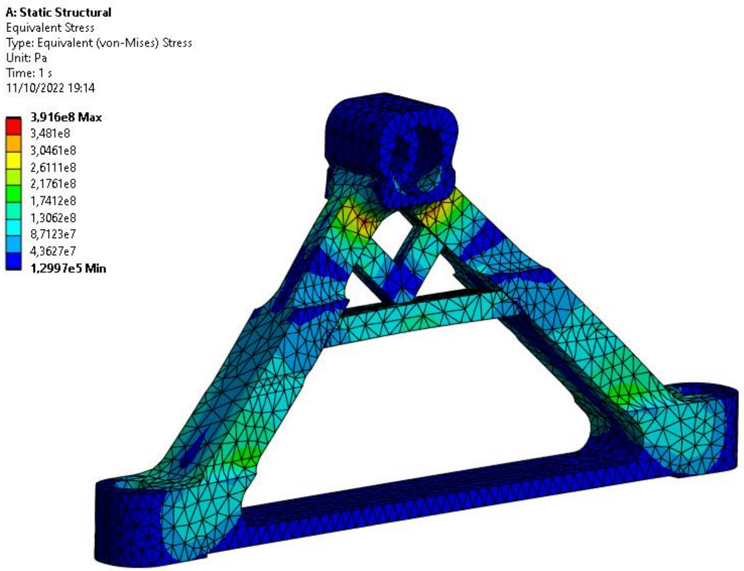


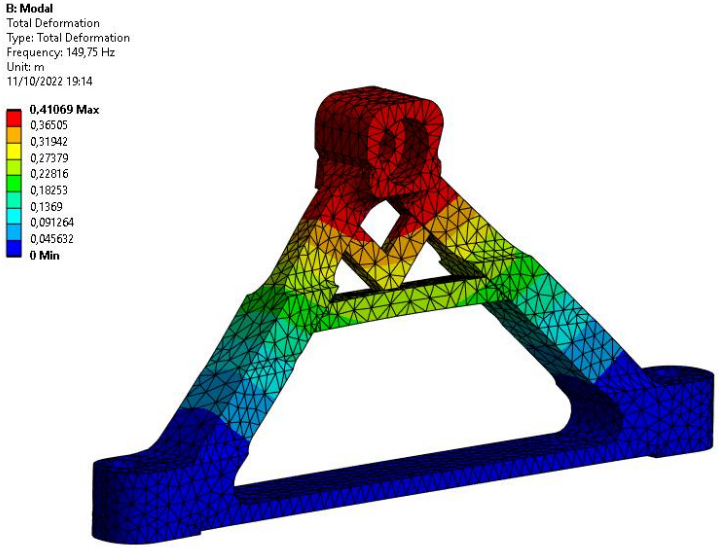


Objectives:

1. increase the first natural frequency of the system and make it higher, by a margin of 15-20%, the target value of 120 Hz, requirement of mission;
2. minimize the mass.

Optimization – Bipod



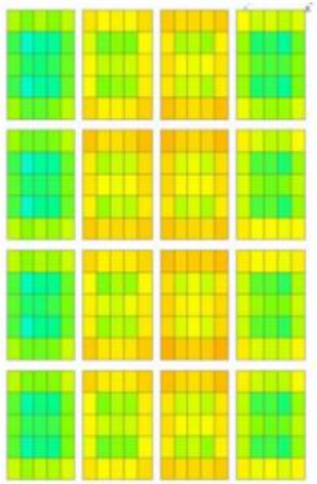


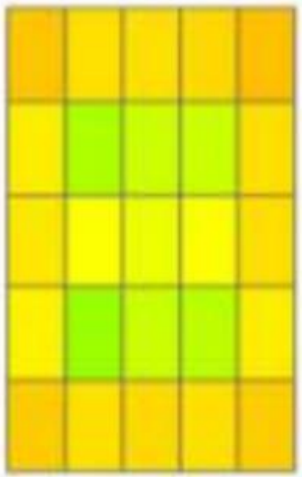
Starting with a natural frequency of **122.7 Hz** to **149 Hz** (+ 15%) with an preliminary increase in mass of 10 g each bipod (+ 16%) reduced with a morphing optimization of 16 g for bipod **(- 18%).**

Subsequently, the stress state of the new layout was verified and it was verified that, being optimized for the frequency requirement, we witness the formation of some hotspots that increase the maximum and average stress values compared to the original design.

In the conditions of **thermal** and **launch load**, the addition of material in the component resulted in a reduction of the tensions compared to the initial design, which never exceed the yield stress of the material.

LAD MODULE – THERMAL DESIGN





The thermal analysis focused on two specific points of the eXTP mission trajectory, were studied in order to obtain the thermal response of the LAD instrument, where the satellite is expected to have the hottest and coldest temperatures: the **extreme hot** and **cold** cases of the eXTP mission.

HOT CASE: particular interest since the SDD can’t heat up more than −32 °C (due the thermal property of silicone). The moment considered is the Winter Solstice, which is one of the days where the Earth is the closest to the Sun.

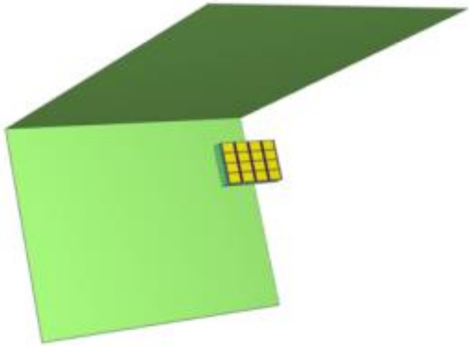
COLD CASE: considered to occur on the Summer Solstice (the day that the Earth is the farthest to the Sun), when the instrument is faced at an angle of 90° to Earth.

ANNEALING CASE: the instrument is heated up for a short period of time in order to extend its lifetime by removing defects into silicone lactice structure. The requirement for the annealing process to succeed is about having an equivalent module temperature of +49 °C for one hour.

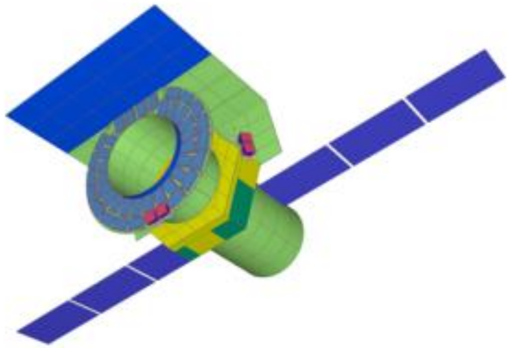
THERMAL MODELS

GEOMETRIC MODELS

1. Only one module with the sunshield – a preliminary design to study some features of the thermal response. It has the advantage of being a simpler module, saving computational time;
2. whole satellite with detailed model for the analysis on the forty module.

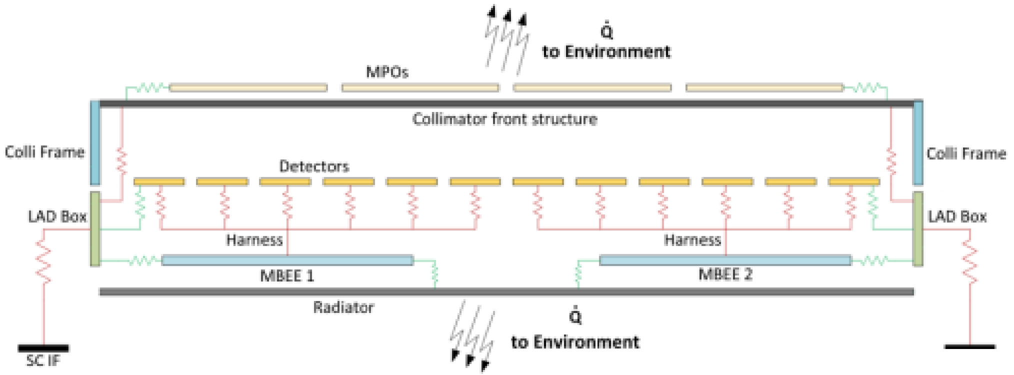


1- Simplified model



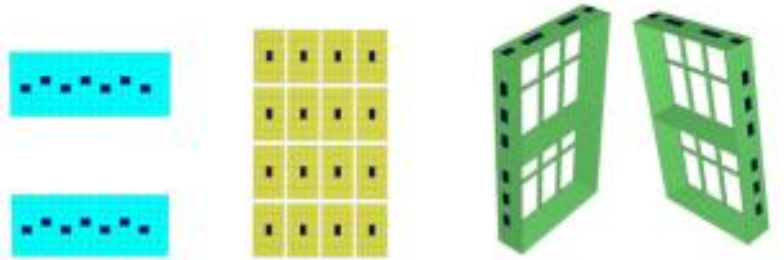
2- Detail model into spacecraft

THERMAL LINKS



Thermal links

DISSIPATION

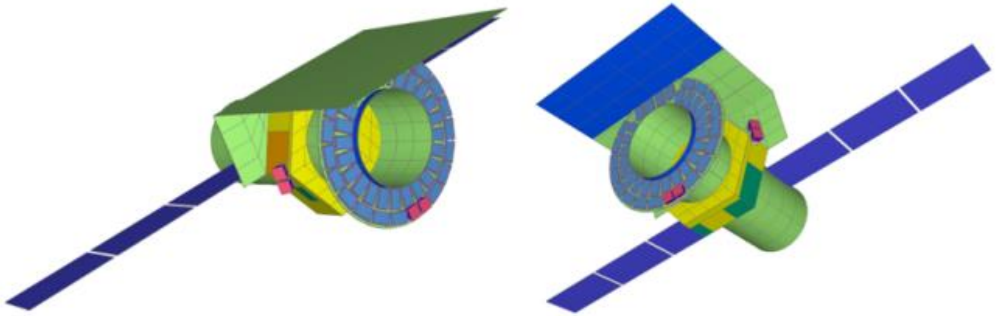


Thermal dissipation nodes

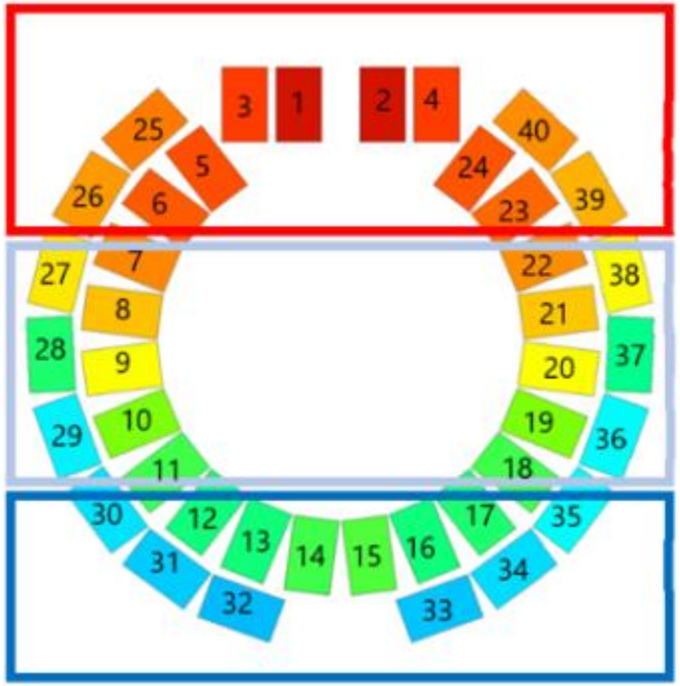
MATERIAL THERMO-OPTICAL PROPERTIES

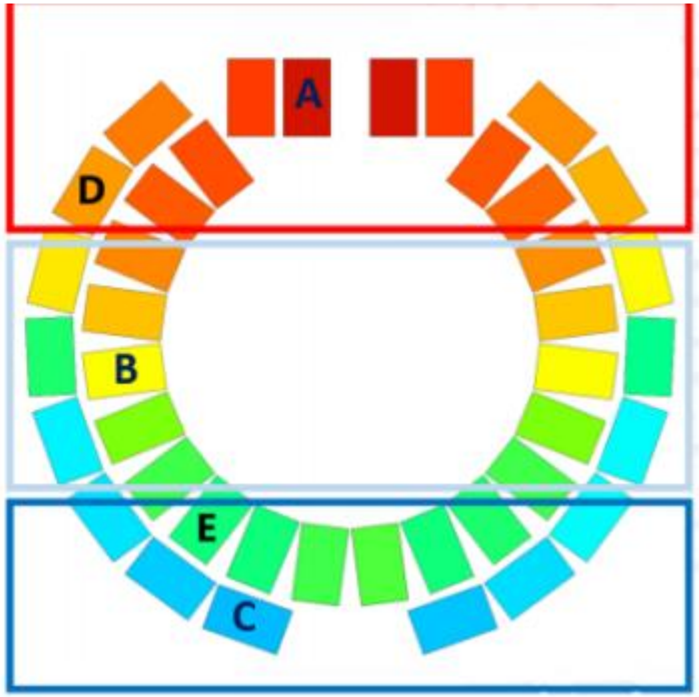
ORBITAL PARAMETERS OF THE EXTP MISSION

KINEMATICS

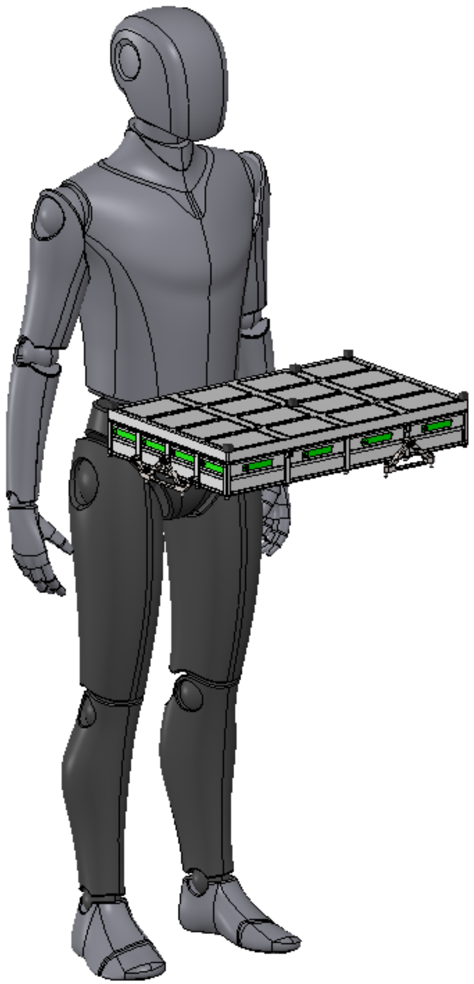


One **detailed module** at each simulation and simplify the remaining 39 modules in terms of mesh refinement (the number of nodes of each component was reduced), with a consequent simplified features for thermal links and dissipations





The thermo-mechanical design of the LAD module is **progressing** accompanied by different design studies. Especially, the Collimator, the Detector frame and the truss I/F are complex subsystems that require compromise and design adaptation.



In the study of the **collimator frame**, a thermo−elastic structural analysis was first carried out for the cold thermal case. Then, through a CAD parametric optimization, was defined the collimator misalignment angle as a parameter of merit in order to perform a topological optimization.
The candidate point has been successfully verified in terms of misalignment, obtaining a value of about **5% less** than the initial angle.

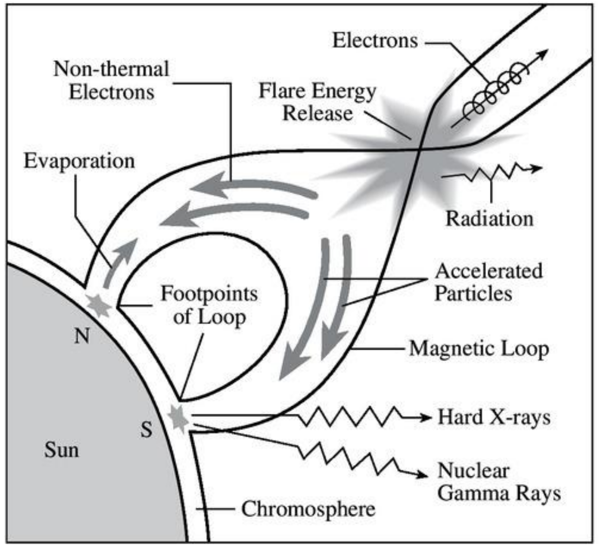
Also, the **bipod** optimization study was conducted by imposing the minimum required natural vibration frequency and the mass reduction as a constraint, obtaining a minimum threshold value of **149 Hz** and a reduction of mass near **-18%.**

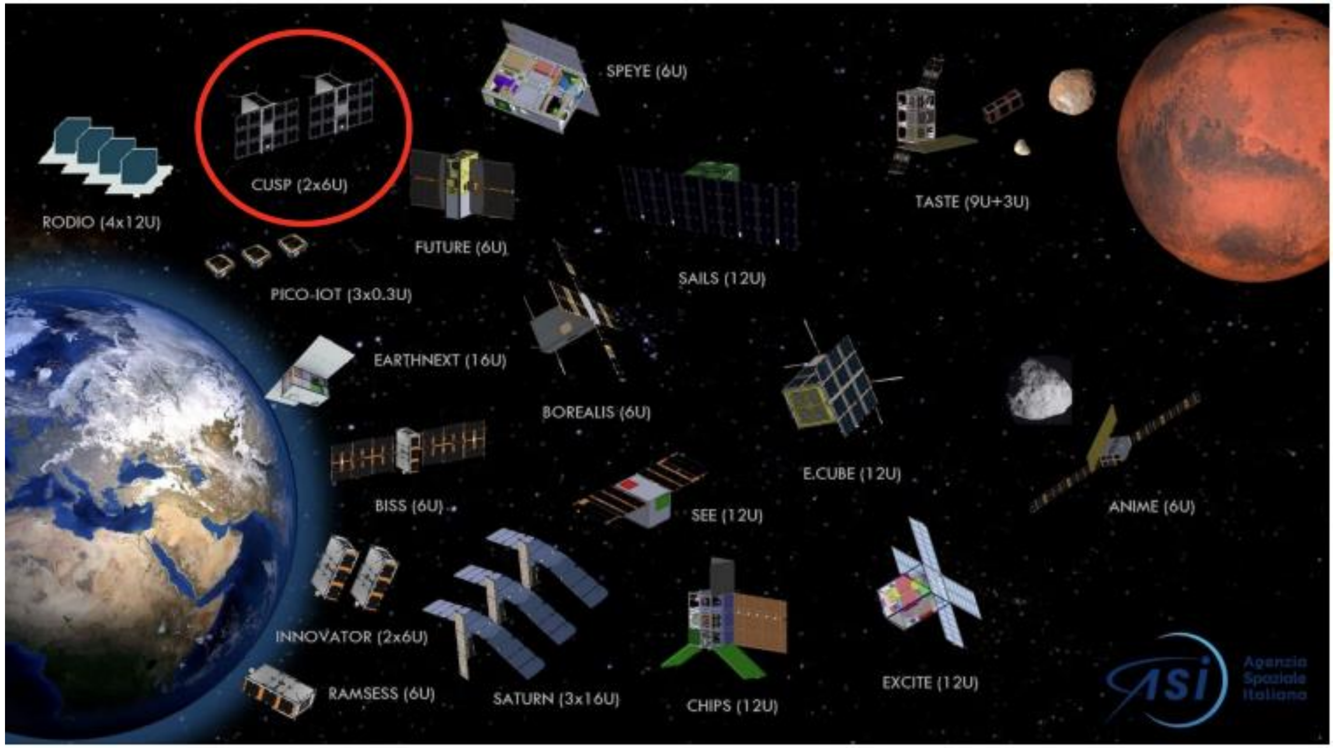
Future work will be dynamic vibrations and better **multi-physical analyzes** that will show potential **optimization** in the instrument frame, reducing the later stage of the eXTP mission.

The **CUbesat Solar Polarimeter (CUSP)** space mission is a project of the IAPS/INAF of Rome, funded by the Italian Space Agency (ASI) for a phase A study in the framework of the Alcor program aimed to develop CubeSat technologies and missions.

The CUSP is a constellation of two CubeSats orbiting around the Earth to measure the linear polarization of X−rays of **solar flares** in order to improve the knowledge of these violent phenomena.

Also, the proposed mission concept, allows continuous monitoring of solar activity, essential for monitoring useful for **Space Weather** strategies.





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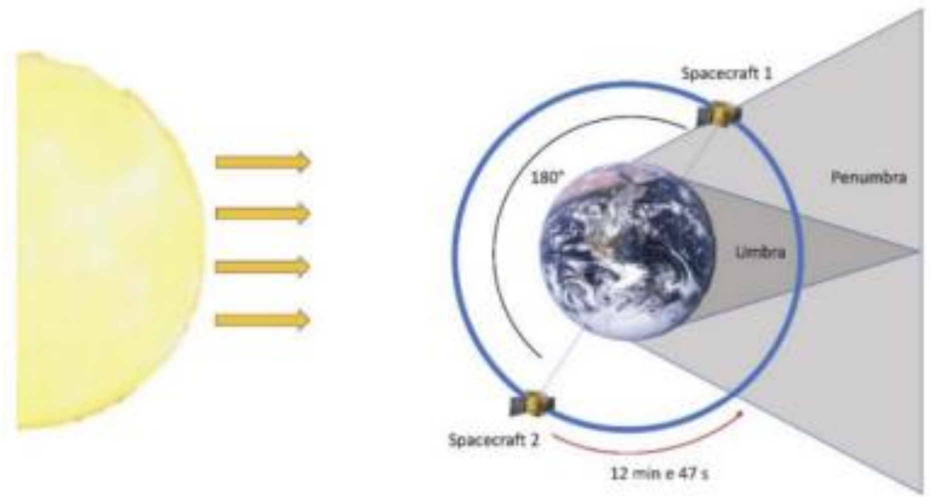
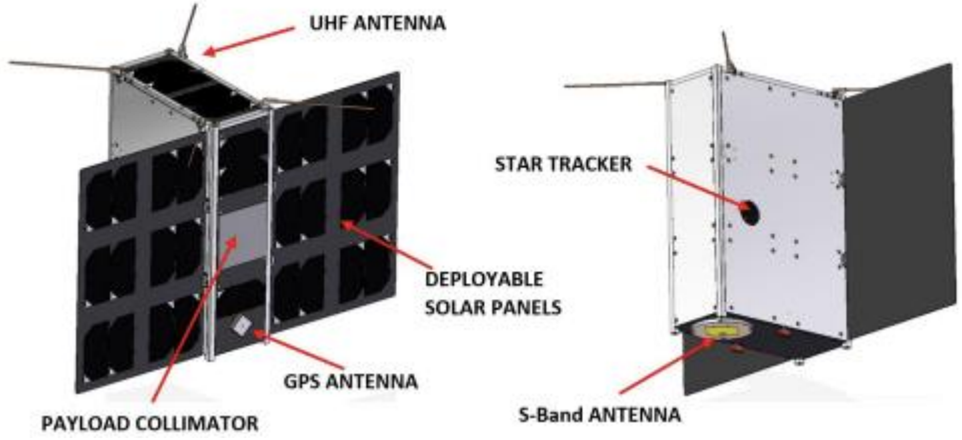
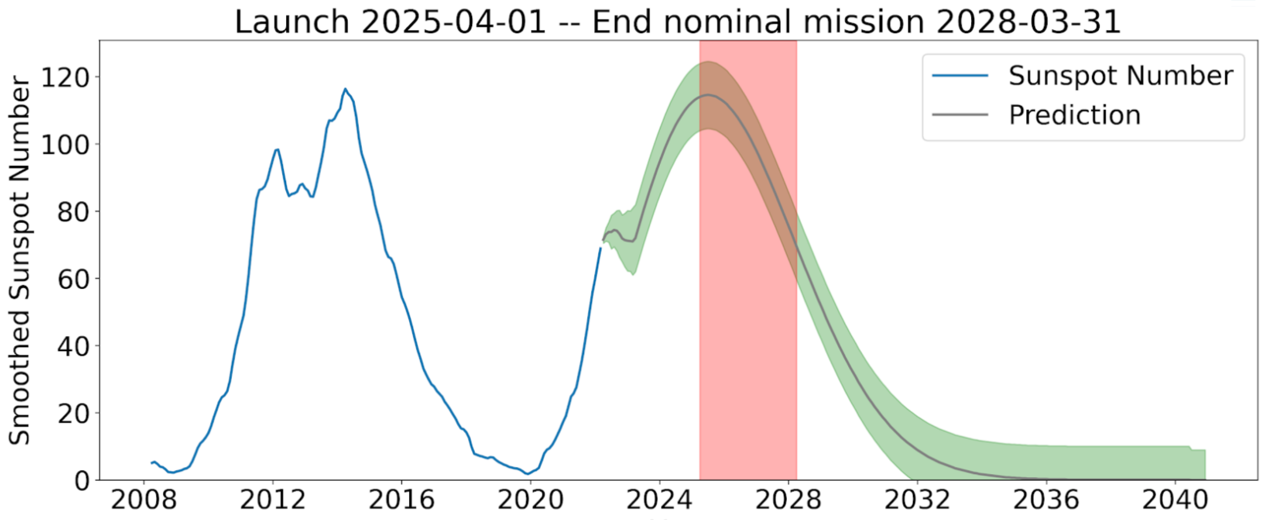
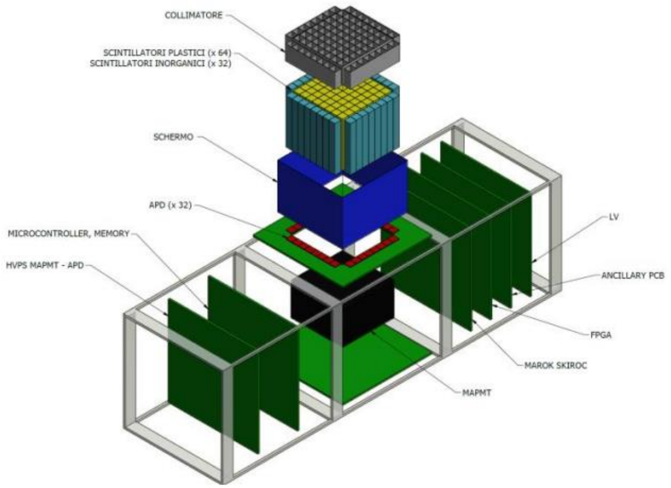


The two small satellites travel at 180° phase difference along the orbit, this configuration ensures **continuous monitoring** of the **Sun**.
This configuration allows to have always at least one satellite of the constellation in daylight for observing the Sun.

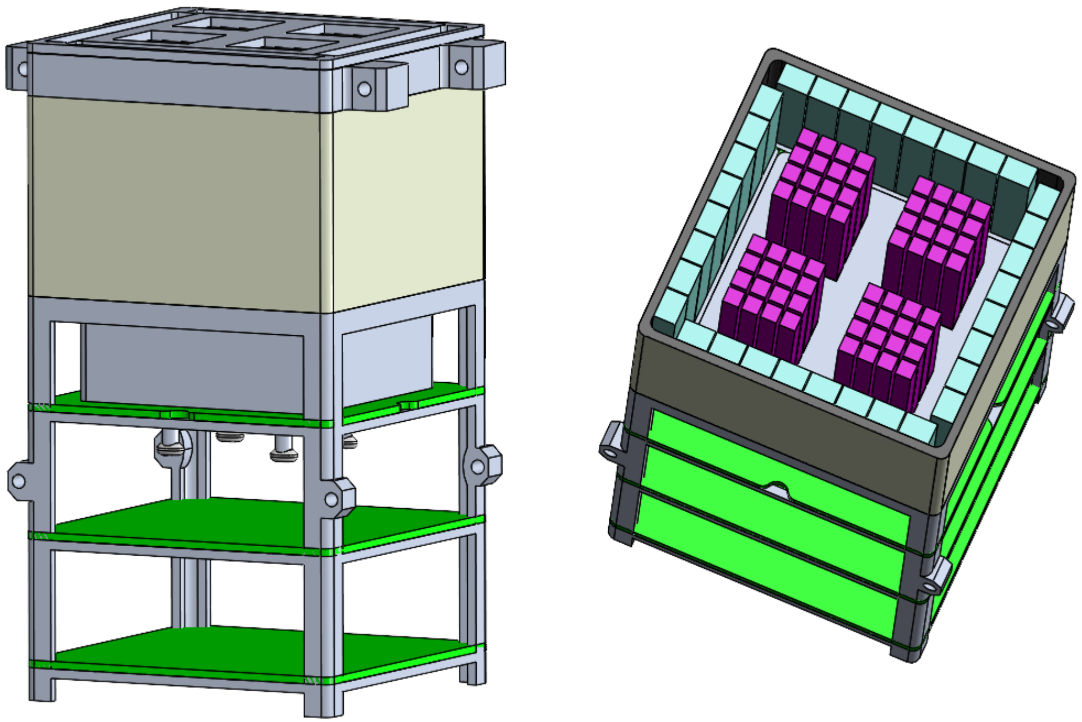




In the project proposal at ASI, the polarimeter of the CUSP project was represented by a **dual phase Compton** diffusion polarimeter, whose concept (exploded view) is shown here:



Starting with a simplified concept, based on a first survey on the sensors, with the acceptance of the proposal by the Italian Space Agency, a detailed mechanical design was developed:

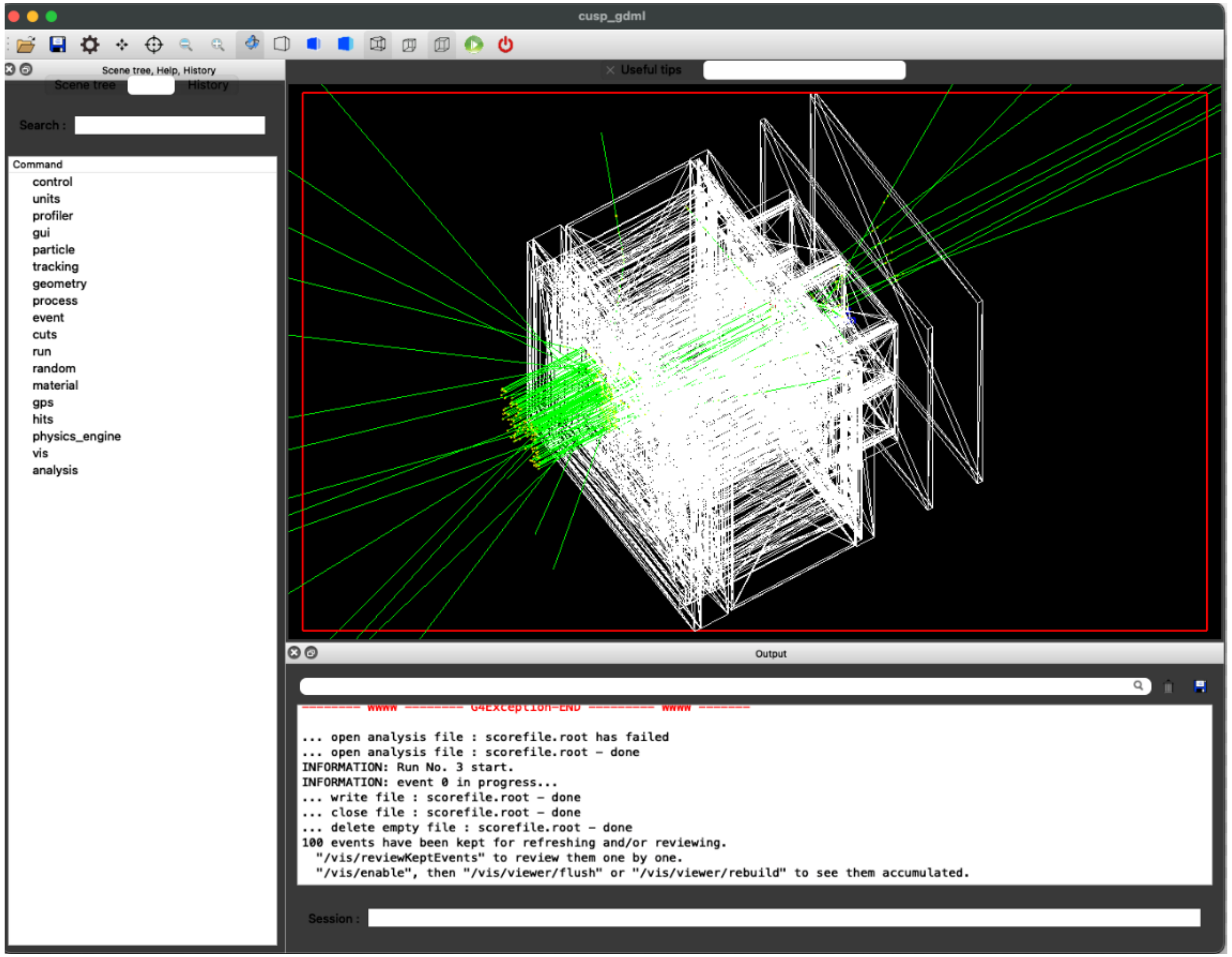


This design is very advanced for an "A" mission phase because the team have identified which sensors will be used and these sensors (which have a long heritage) have imposed a limitation on the sensor geometry.

After the rough definition of the mechanical design it was necessary to develop a simplified CAD model to be used on the **GEANT4**, high energy physics **simulator**, in order to study the **scientific performance** of the instrument.

Typically, when building the GEANT4 simulation platform, the operator had to draw manually the geometry with a waste of time and resources.

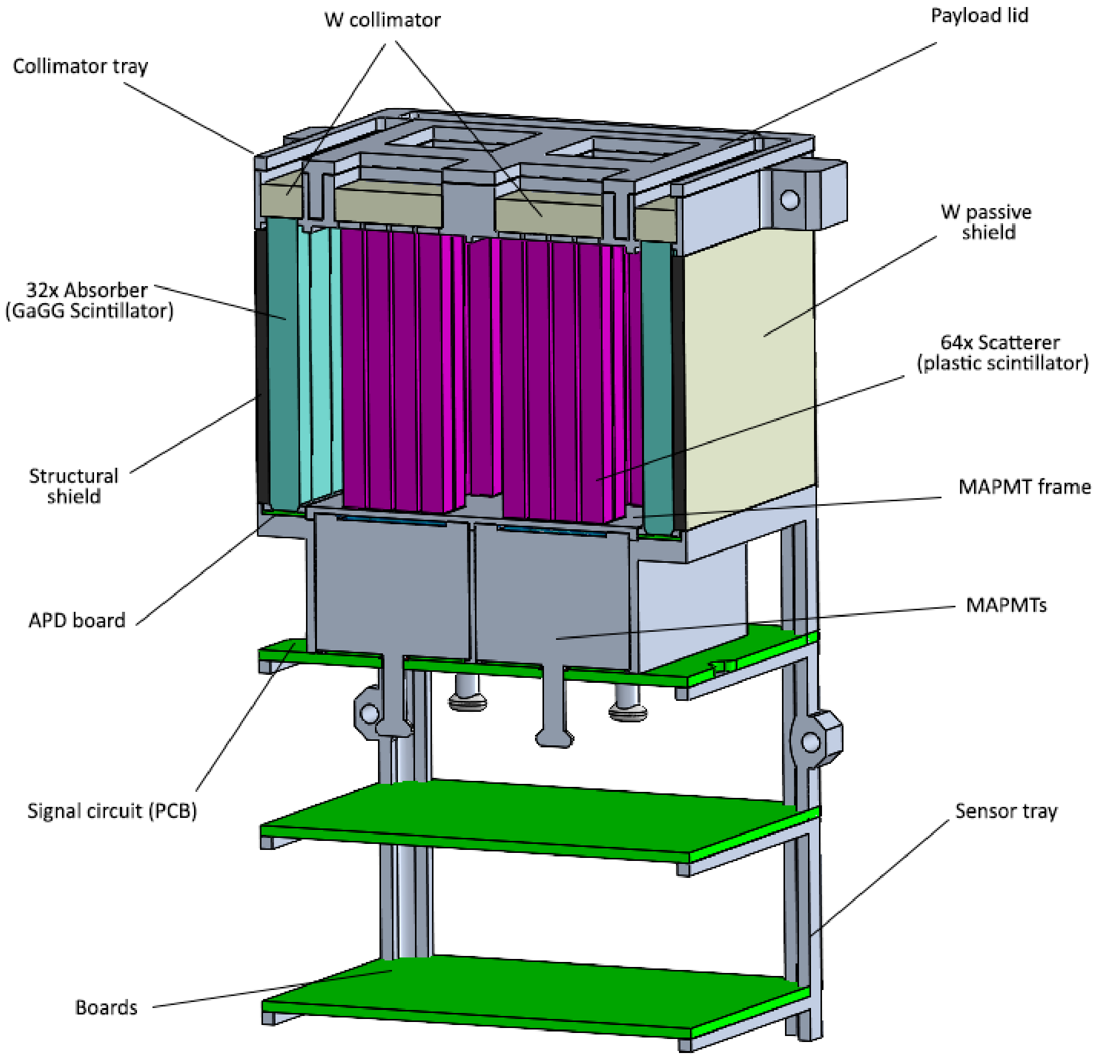
In this case, was developed a **methodology**, through dedicated tools on CAD software, which allowed to directly insert a mass model in GEANT4, in gdml format, allowing the developer to **keep** the **two models aligned** by simulating exactly the payload.



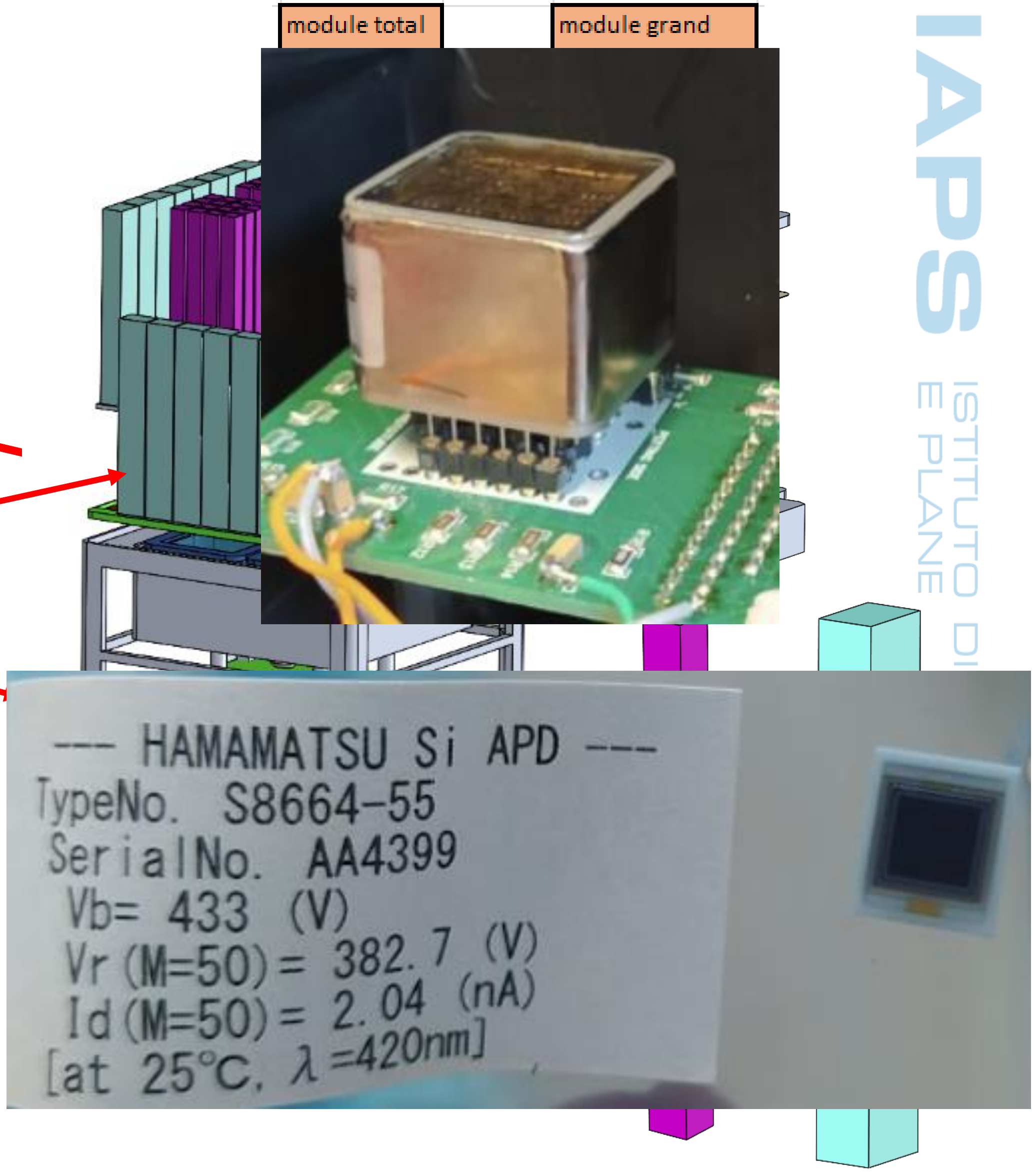
The **payload** contains:

- An aluminium alloy **lid** and a **collimator tray** with a passive tungsten thin film clamped to the tray;
- The collimator tray contain 4 **collimator** for the scatterer and 4 collimator for the absorber realized with a tungsten alloy;
- 32x **Absorber** made from GaGG scintillator hosted on **APD board**;
- In the same mechanical and electrical framework of the Sensor tray are located 64x **Scatterer** made from plastic scintillator (EJ404) and leaned on the **MAPMT frame**;
- **High Voltage** (HV), micro power supply, and other electronics parts are hosted on the boards, one of these is linked to the **MAPMT**.

In the mission phase "A" are missing all the mechanical and electrical feature, like connector, threads and screws.



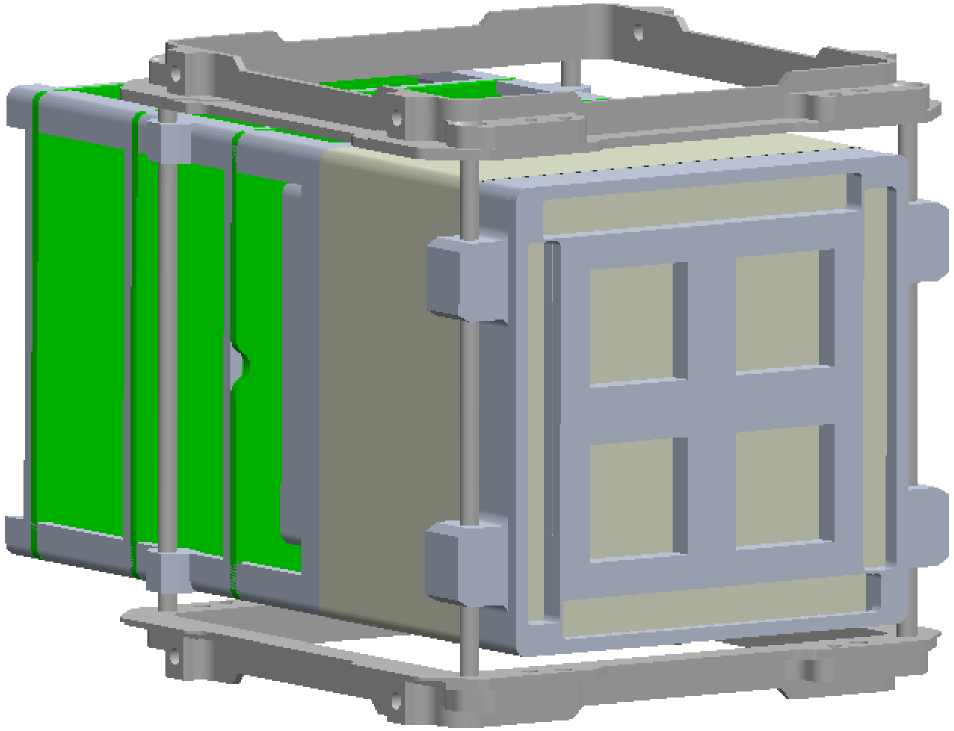
Full name	Material	Qty per Module	CBE (g)	Method	Total CBE (g)	DMM (worst case)	CBE + DMM (g)	Note
PAYLOAD		1						
Collimator Frame		1			**361,13**		**433,36**	
Collimator Tray	EN AW 7075	1	55,78	Estimated	55,78	20%	66,94	
MAPMT Collimator	Tungsten	4	30,78	Estimated	123,12	20%	147,74	
APD Collimator	Tungsten	4	38,75	Estimated	155	20%	186,00	
Lid	EN AW 7075	1	23,53	Estimated	23,53	20%	28,24	
Top T Film	Tungsten	1	3,7	Estimated	3,7	20%	4,44	
Detector Frame		1			**672,3**		**806,71**	
Sensor Tray	EN AW 7075	1	75,74	Estimated	75,74	20%	90,89	
MAMPT Frame	EN AW 7075	1	8,32	Estimated	8,32	20%	9,98	
APD Frame	EN AW 7075	4	0,52	Estimated	2,08	20%	2,50	
APD	Silicone	32	0,14	Estimated	4,48	20%	5,38	S8664-55
MAPMT	Composite	4	50	Datasheet	200	20%	240,00	
Scatterer	EJ404	64	0,61	Estimated	39,04	20%	46,85	
Absorber	GaGG	32	10,2	Estimated	326,4	20%	391,68	
Optical Coupling	Silicone	60	0,27	Estimated	16,2	20%	19,44	
CUSP Electronic		1			**142,05**		**170,46**	
MAPMT PCB	FR-4	1	14,83	Estimated	14,83	20%	17,80	
APD_PCB	FR-4	1	2,38	Estimated	2,38	20%	2,86	
PCB	FR-4	5	15,08	Estimated	75,40	20%	90,48	
UMHV	Composite	8	4,10	Datasheet	32,80	20%	39,36	UMHV0520N
Thermal pad	LAIRD Tflex-p340	4	0,47	Datasheet	1,88	20%	2,26	
Connector	TBD	6	2,46	Estimated	14,76	20%	17,71	
Other Items					**75,18**		**90,22**	
Shield box	ABS (TBC)	1	23,89	Estimated	23,89	20%	28,67	
Screws	Stainless steel	40	0,50	Estimated	20,00	20%	24,00	
Elastomer Spring	Silicone	20	0,02	Estimated	0,40	20%	0,48	
PCB long spacer	Aluminiu 6082	24	0,81	Estimated	19,44	20%	23,33	
Film	Tungsten	1	11,45	Estimated	11,45	20%	13,74	



This work presented:

- analysis of the preliminary **mechanical design** of CUSP;
- Multi-physics study between the mechanical design and the **GEANT4** physical simulation.

Future static, dynamic **numerical simulation** and thermal (steady and elastic) analyzes will show potential optimization in structural frames and connectors.
A future work for the CUSP project will be a **thermal simulation** with specific software containing one detailed module and the structure of the CubeSat 6U.



Furthermore, through the use of techniques based on **morphing** it will be possible to conduct more accurate analyzes and optimizations aimed at developing such a small payload. Finally, the INAF engineering team would like to develop a digital twin to allow continuous improvement and monitoring of the CubeSat constellation.

In recent years, the study of the universe has increasingly moved into the **time** domain, observational skills on different time scales (from very short to very long) and on wide viewing channels are bringing to light transient phenomena hitherto little known (e.g. **fast radio bursts**)

In this new scientific perspective, it is imperative that **X-band** astronomy make its contribution through the use of new instruments capable of overcoming the limits of classic space observatories.

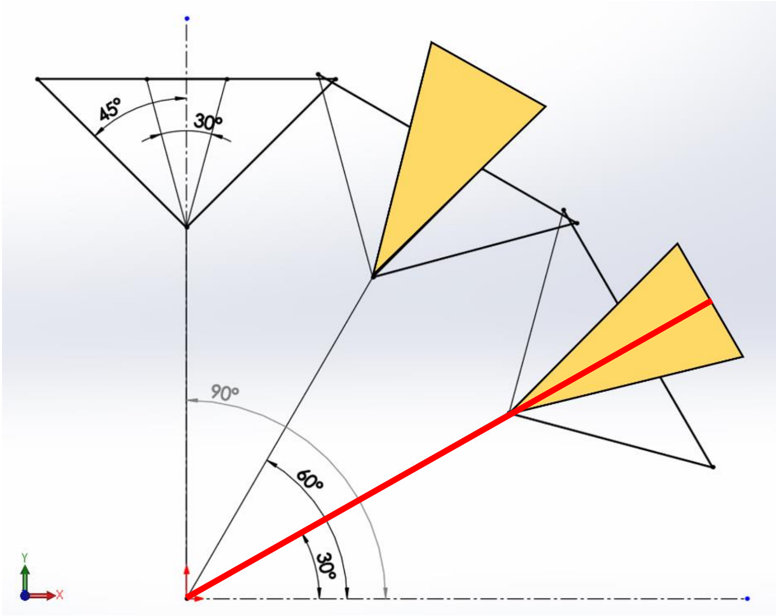
LEM-X (Lunar Electromagnetic Monitor in X-rays) is a recent proposal for a lunar mission by INAF in collaboration with the Italian Space Agency (**ASI**), which could be included in the **ARTEMIS** space program for the return of the man on the moon of National Aeronautics and Space Administration (**NASA**) or within the space programs of the European Space Agency (**ESA**).

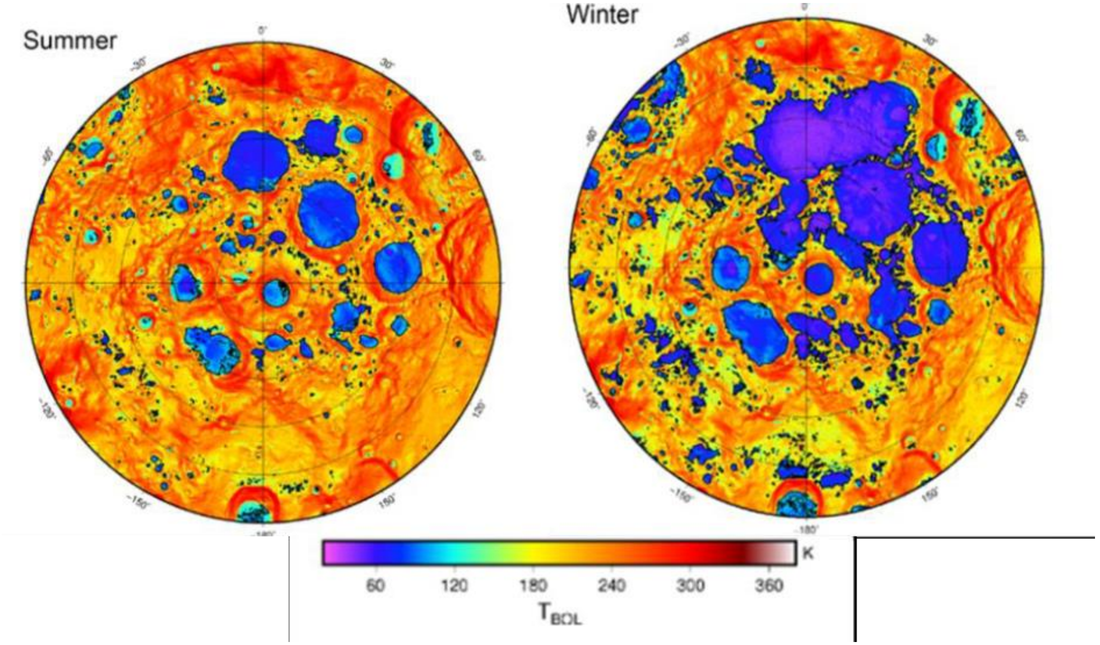
LEM-X is an All Sky Monitor for the X-band (2-50 keV) based on the Wide Field Monitor (**WFM**) coded cameras mounted on a fixed structure, allowing simultaneous and continuous access to half of the celestial sphere.

In this mission, one of the most complex engineering challenges, is the design of a structure capable of supporting the WFM chambers, maintaining a degree of **alignment** between the frame and the chamber of **1 arcmin** in the environmental conditions of the Moon.

Lunar environment:

- absence of atmosphere;
- gravity lower than Earth's (1/6);
- high termal excursions;
- Regolith (lunar dust).





To visualize the celestial sphere in an optimal way, the rows of WFM chambers are spaced each apart by **30°**.

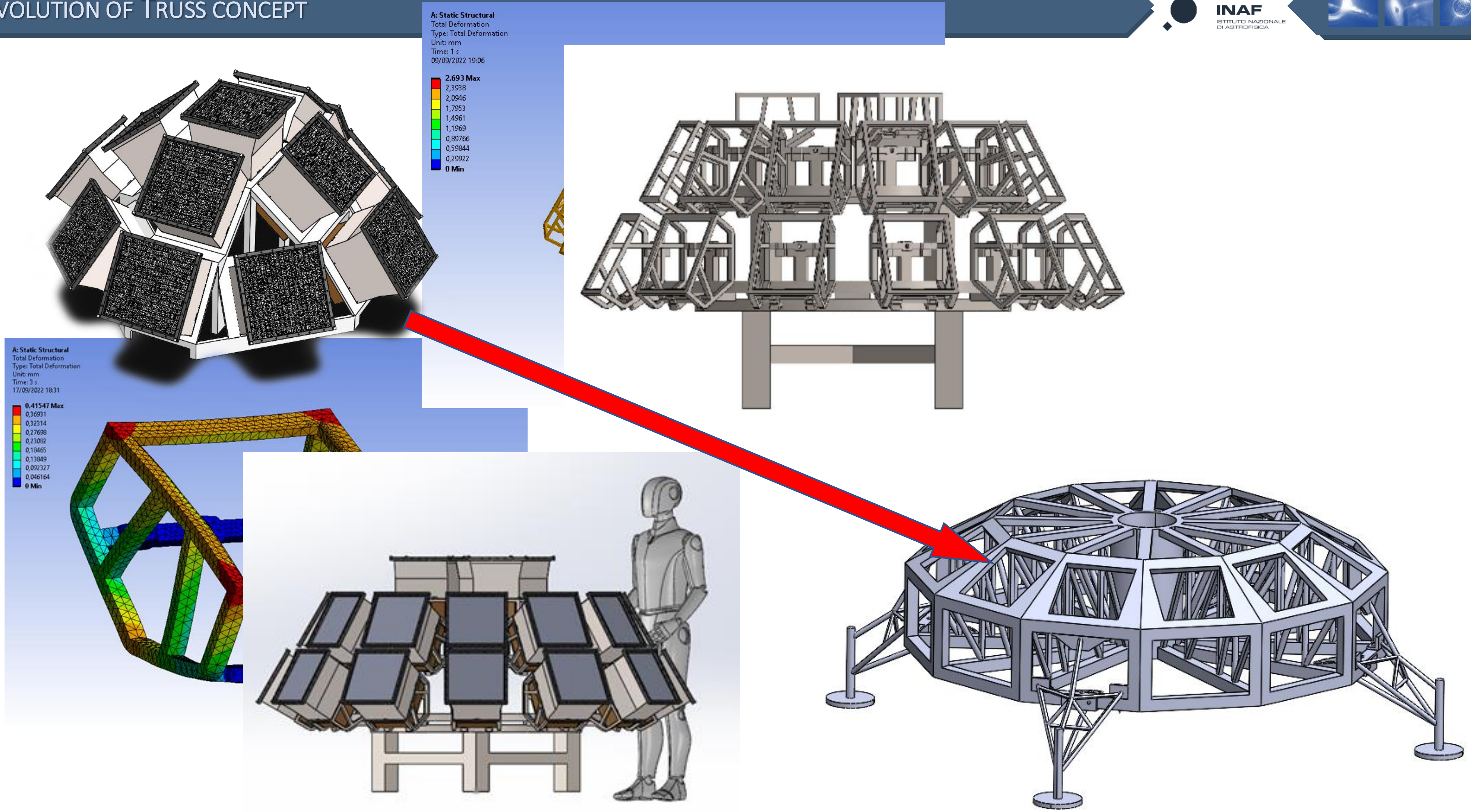
In the preliminary design phase of the structure, the following factors are considered:

- different **temperature** distributions, based on the place foreseen for the positioning of the experiment (e.g. Shackleton crater);
- different types of **material**, from aluminum for space applications to titanium alloys and composite materials;
- the **launch loads** foreseen by the different types of launchers currently in use by Space Agencies;
- the possibility of having **different** structures with WFM oriented on different angles (30°, 60° and 90°) or of having a single all-encompassing structure.

	T [K]	T [°C]
T_max	136,03	-137,12
T_min	41,50	-231,65
T_mounting	293,15	20

Alloy	α [K^(-1)]	Density [Kg/m^3]	E [GPa]	TUS [MPa]
Ti6Al4V	8,79E-06	4429	111	918
Al 7075 T6	2,30E-05	2770	71	310
Al 6061 T6	2,28E-05	2713	69	306
Steel	1,7E-05	7750	193	586

EVOLUTION OF TRUSS CONCEPT



The goal of being able to place a scientific experiment on the **lunar surface** is a dream for every scientist of this sector. The challenges are many and the use of the latest technologies and finite element simulation systems, such as the **rbf morpghing**, will facilitate the optimization and design work of **LEM-X**.

Currently, the approach used made it possible to return a possible **design** of the structure through the creation of the CAD, subject to revisions and optimizations with the use of finite element software.
In order to maintain the requirements, work has been done on the **geometry** and on the choice of **material**, looking for deformations of the chambers mounted on the frame that allow to meet the **misalignment** requirement of 1 arcmin.

Future works will be:

- consider different **geometries**, assuming a single structure for a single angle orientation of the chambers;
- make the structure hollow and optimized in terms of **mass**;
- introduce **composite materials** specifically designed for this application;
- create a realistic **simulation environment** and test the structure.

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THANK YOU
FOR YOUR ATTENTION!

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