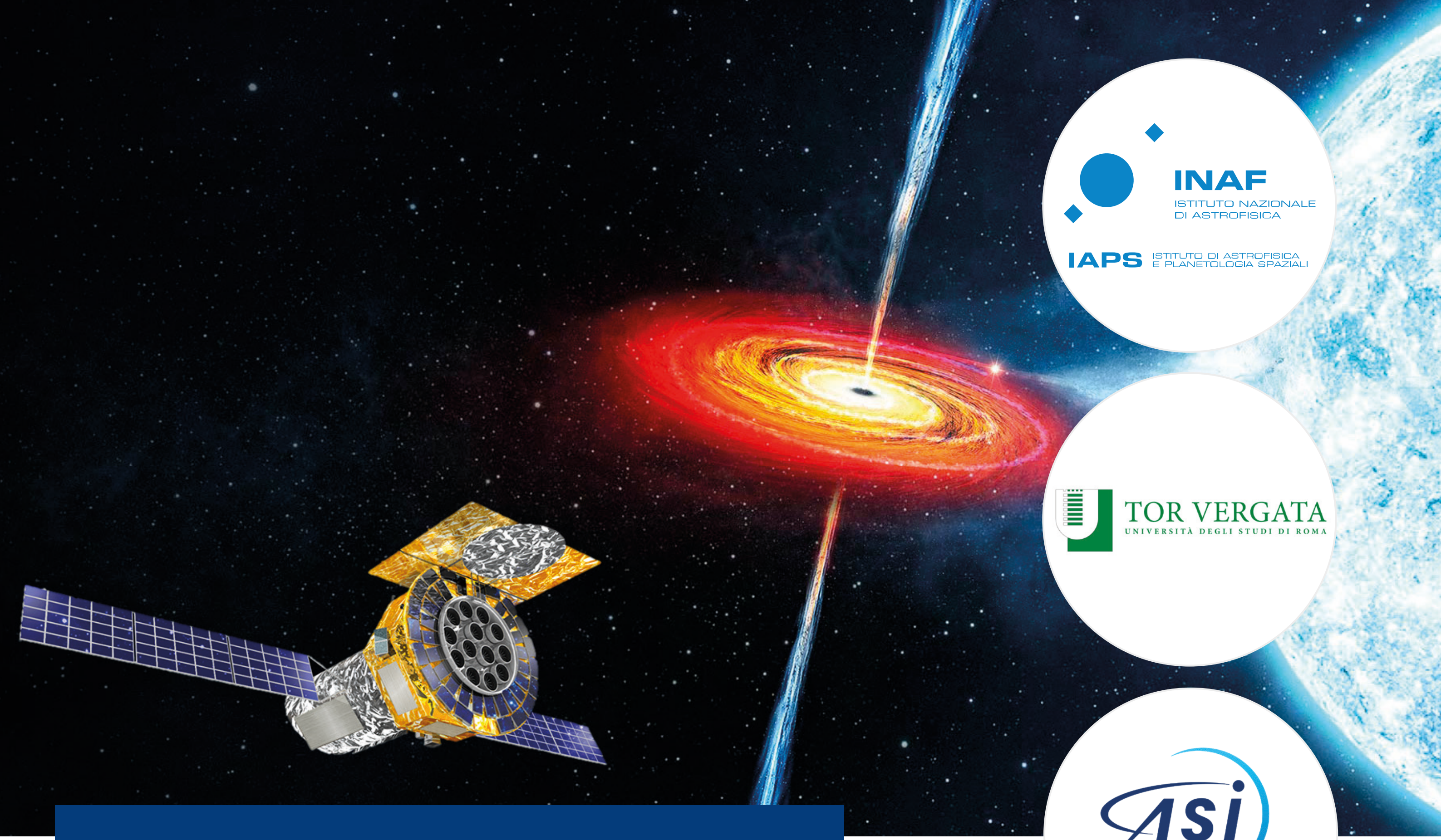

# Preliminary thermo-mechanical design, simulation and optimization of LAD on board the eXTP space mission

**by Giovanni Lombardi[1], Marco Evangelos Biancolini[2], Raffaele Piazzolla[3] and Marco Feroci[1]**
1. INAF/IAPS of Rome, 2. University of Rome Tor Vergata, 3. ASI (Italian Space Agency)

A major project of the Chinese Academy of Sciences (CAS) and the China National Space Administration (CNSA), the eXTP (enhanced X-ray Timing and Polarimetry) mission is currently conducting a phase B study and proposal for launch in 2027. The eXTP scientific payload includes a suite of instruments that offer simultaneous wide band X-ray timing and unprecedented polarimetry sensitivity. A large European consortium is contributing to the eXTP study and will provide key hardware elements, including the Large Area Detector (LAD) consisting of 40 modules with a total effective area of 3.2m$^2$ at 8.0keV.

This article describes the preliminary study resulting in the design solutions adopted for the LAD module's most important thermo-mechanical drivers, which were developed and used to demonstrate compliance with the system requirements at the spacecraft level. More specifically it describes the mechanical design of the module and its components, the results of a static, dynamic, and thermo-elastic finite element analysis of a simplified parametric model with accurate mesh processing, and the preliminary optimization of a critical component: the bipod.

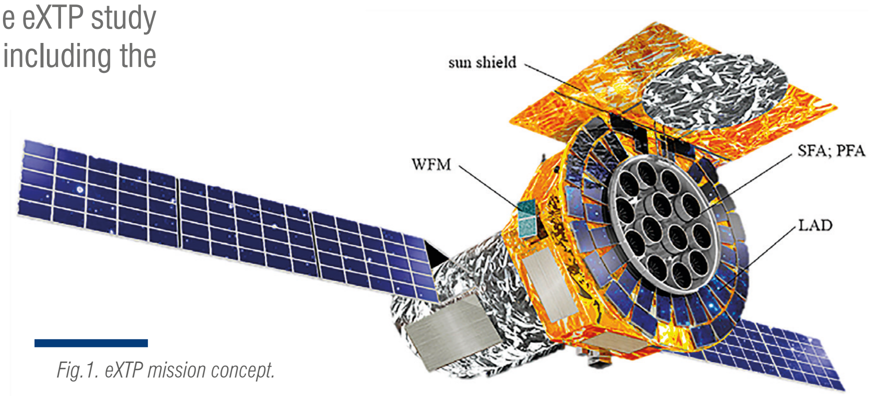


*Fig.1. eXTP mission concept.*

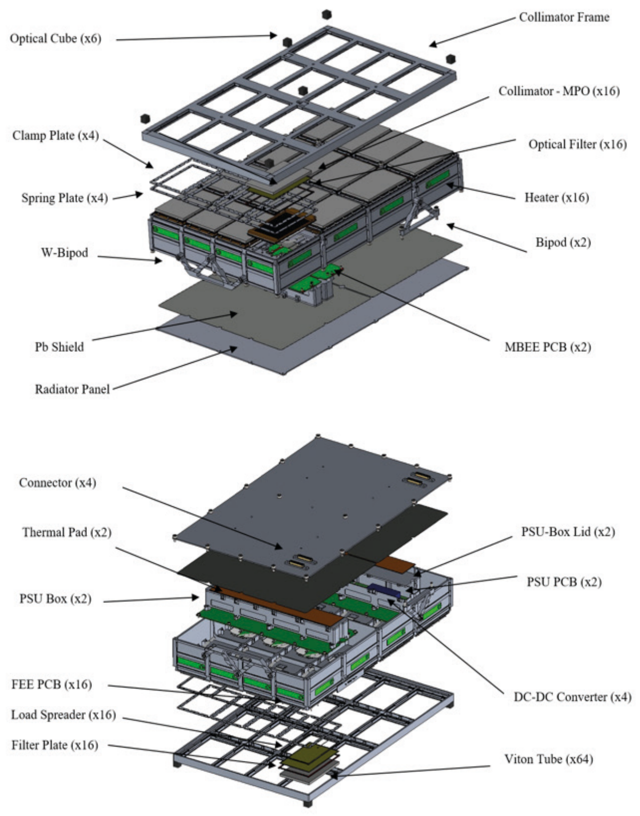


*Fig. 2. Exploded view of the module.*

The enhanced X-ray Timing and Polarimetry (eXTP) mission is a flagship Chinese project, with a large contribution from a European consortium, including institutions in Italy, Spain, Austria, the Czech Republic, Denmark, France, Germany, the Netherlands, Poland, Switzerland and Turkey. This mission is designed to address the science of understanding the behaviour of matter under extreme conditions of gravity, density, and magnetism.

The eXTP aims to determine the equation of state of ultra-dense matter inside neutron stars, study the dynamics of matter near neutron stars and near the event horizon of black holes where the theory of General Relativity predicts large distortions of space-time with respect to Newton's law, and study the effects on photon propagation of the ultra-critical magnetic fields hosted in magnetar sources.

The eXTP satellite's scientific payload consists of four scientific instruments: a Spectroscopic Focusing Array (SFA), Polarimetry Focusing Array (PFA), Wide Field Monitor (WFM), and a Large Area Detector (LAD) – the subject of this study.

The 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 able to deploy an effective area of 3.2m$^2$ – at 8keV – in space, adopting a modular configuration. The LAD is organized as a modular instrument, consisting of 40 co-aligned modules, each housing a set of 16 large-area silicon drift detectors (SDDs) and 16 corresponding capillary plate collimators.

The module contains:

- An aluminium alloy Collimator Frame with 16 co-aligned MPO tiles (in positions corresponding to the 16 SDDs), clamped to the frame;
- A thin Kapton film (~1$\mu$m), coated with ~100nm aluminium on each side, is housed under each collimator (MPO) tile and the detector;
- A detector frame containing 16 SDD+FEE. Each SDD has 224 anodes. Each FEE has 30 ASICs;
- Module Back End Electronics (MBEE). Control the ASICs and HV PSUs and read the digitized events; the MBEE are housed in the same mechanical and electrical structure as the detector frame;
- HV/MV/LV PSU. The power supply for the SDDs; the PSU is housed in the same mechanical and electrical structure as the detector frame;
- A 300$\mu$m lead back-shield, to reduce background events in the SDDs;
- A radiator to dissipate heat from the module (a lower SDD temperature improves energy resolution);
- A heating belt around the module. The heating process during annealing, which heats the model up to 50°C, alters the crystalline structure of the silicon, repairing the damage induced by particle irradiation.

The LAD is conceived as a classical collimated experiment: the need to acquire X-ray events with high temporal and spectral resolution and high statistical significance led to the LAD instrument, made possible by the development of large-area silicon detectors and micro-collimator structures. The effective area requirement leads to a geometric area of ~6m$^2$, the LAD's field of view will be limited to <1 degree by X-ray collimators.

The objective of this study was to obtain a parametric optimization of the design of the bipods, the critical element that supports the module and connects it to the truss, with the aim of increasing the first natural frequency of the system by a margin of 15% to achieve the target value of 120Hz, the mission requirement. Since the bipod connects the frame to the LAD Module, it will absorb all the same inertial and thermal loads to which the LAD is subjected, making it a critical structural component.

The purpose of this study is firstly to present the preliminary thermomechanical design of the LAD module in its entirety and then to focus on the bipod, which is the subject of the optimization and parameterization. Subsequently, after explaining the method and approach used, the tools used and the results obtained will be illustrated.

## Preliminary design and structural analysis of the Bipod

The CAD (computer aided design) model of the module was generated using SolidWorks 2022 software, but the shapes were reconstructed and simplified using the standard functionality of Ansys SpaceClaim software.

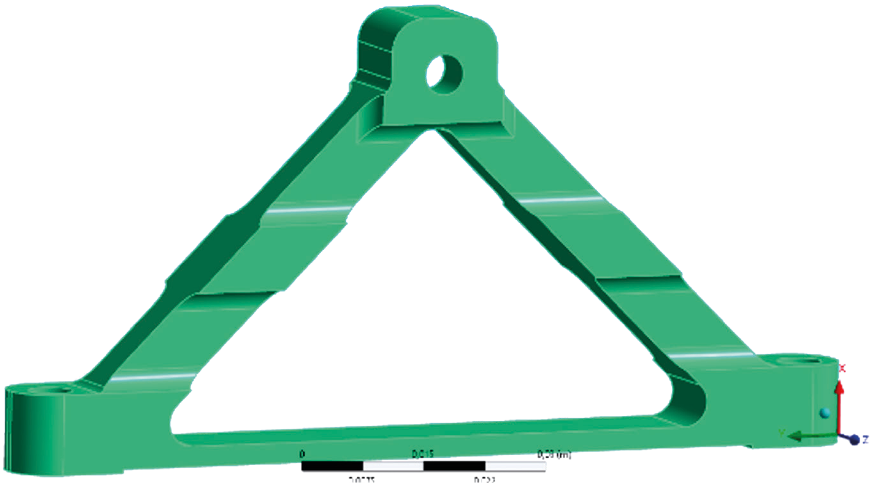

*Fig. 3. Bipod.*

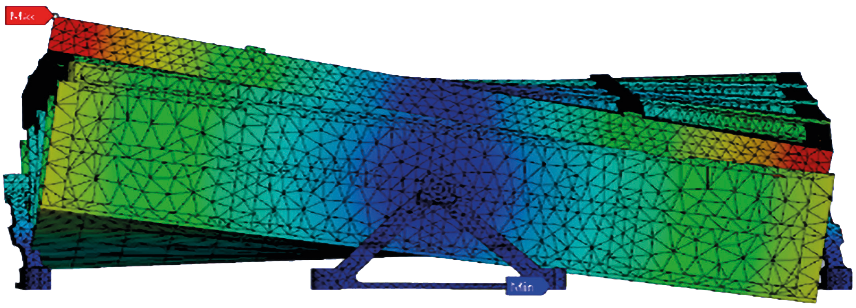

*Fig. 4. Modal analysis.*

The following steps were used towards the final goal:

- Creation of a complete CAD model of the preliminary design of the module meeting the mission requirements and export of the model to Ansys SpaceClaim to obtain a simplified defeatured model compliant in terms of mass and volume;
- Re-processing and parameterization of the CAD geometry of the bipod using the Ansys RBF Morph tool;
- Structural optimization of the Bipod using optiSLang.

In order to generate a mesh that provided adequate results it was necessary to make some changes to the settings, defining not only a global mesh value (thus defining a general element size), but also specific values for surfaces and bodies.

The default mesh was defined using the general settings and controls to define the mesh on critical surfaces. For each of these parameters the optimal value was identified and then the optimal mesh was calculated. Optimization of the mesh was carried out through the use of response surface, an Ansys tool that allows values to be changed by parameterization.

The optimization constraints were the total number of nodes as a compromise between the available computing power and the need for a very dense mesh and constrained the first natural frequency above 120Hz (system requirement) by a value at which the bipod frequency size ratio was almost convergent.

Starting from the geometry shown in Fig. 3, the modal analysis returned the minimum natural frequency value of 122.69Hz. The deformed configuration, relative to the same mode, is also shown, the analysis of which proved useful in determining areas where an increase in stiffness could be decisive. In particular, observing the displacements undergone, it can be seen that the two lateral bipods undergo bending around the y-axis while the front one twists around it.

Three different configurations were considered, hereafter labelled A, B, and C, to increase the natural frequency of the system, considering the mass of the system relative to the cost of the mission.

In solution A only the thickness of the two sides of the bipod was modulated by a parametric variation of the heights and a horizontal insert was added.

This horizontal insert was retained in solutions B and C, while a vertical element was added to solution B to increase the bending stiffness. In solution C a reticular structure was realized by placing two

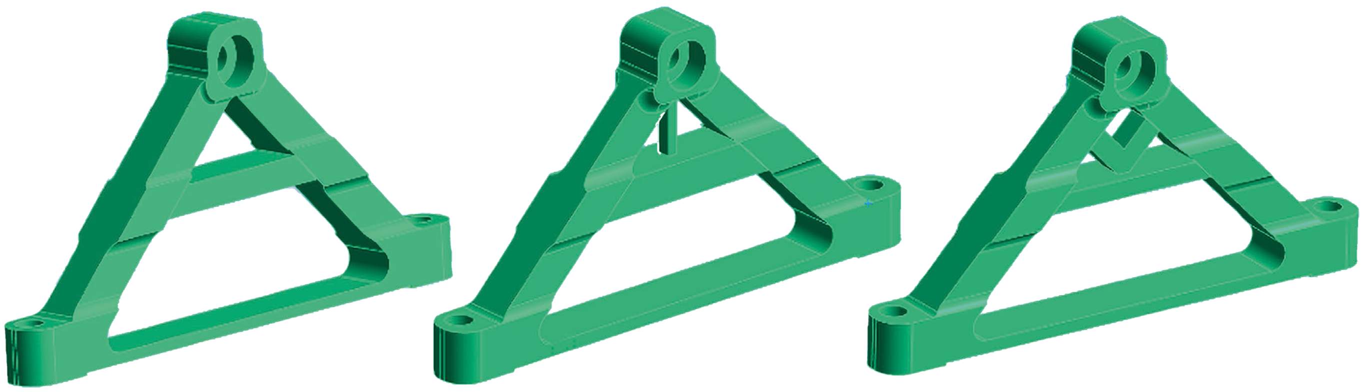

*Fig. 5. Configurations of solutions A, B, and C.*

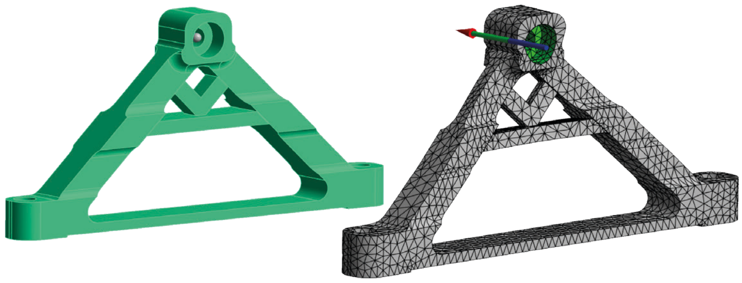

*Fig. 6. Bipod design with morphing.*

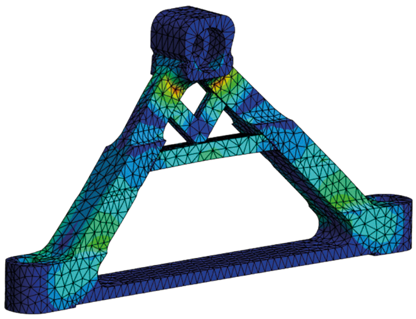

*Fig. 7. Optimized equivalent stress.*

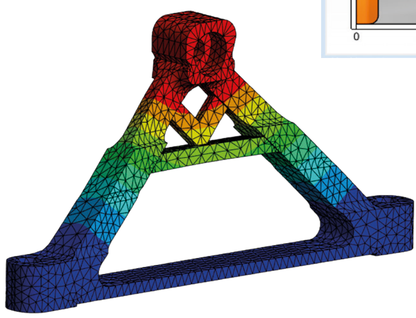

*Fig. 8. Optimized modal frequency.*

oblique symmetrical elements on this insert.

The mass of the initial geometry of 58.858g is increased in favour of an increase in the first natural frequency. Configuration C was therefore chosen as it is less heavy in terms of weight.

The RBF Morph tool, which allows the shape of a computational grid to be adapted to a new one by updating the position of all its nodes, was used to perform a geometric parameterization that implements shape modifications directly to the computational domain. The new geometric configurations resulted from the displacement of a mesh

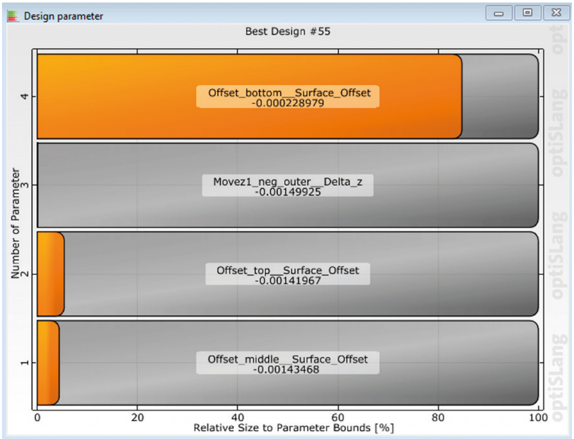


*Fig. 9. optiSLang design parameters.*

region that smoothly propagated the displacement imposed on the surrounding volume using RFB-based algorithms.

A single bipod was considered and two types of simulations were performed to achieve an optimization with the optiSLang tool: a static one representing the thermal loads on the bipod and a modal one with concentrated mass. As seen above the constraints of the optimization were mass minimization through maximum stress and minimum frequency.

The optimized design was then compared, in terms of performance of interest, to the original design. In order to improve the strength and limit the mass of the bipod, the optimization tool was run for about four days on two different workstations and returned the following optimal design:

This design achieved a mass reduction of approximately 18% with the optimized shape.

Subsequently the study continued analysing the stress state of the shape during certain phases of the operation, carrying out static structural analyses with which the equivalent stresses due to quasi-static loads during the launch phase and those due to the temperature difference of the various components between the assembly temperature and the operating temperature in orbit were evaluated.

The analysis of the effects of the launcher stresses was conducted using acceleration

| Time [s] | X [mm/s²] | Y [mm/s²] | Z [mm/s²] |
|---|---|---|---|
| 1 | 9.44e+005 | 2.59e+005 | 41200 |
| 2 | 8.03e+005 | 1.04e+006 | 79400 |
| 3 | 79400 | 23500 | 6.06e+005 |

*Table 1. Launch accelerations.*

| Time [s] | Design Stock | | | Design Optimized | | |
|---|---|---|---|---|---|---|
| | Minimum [MPa] | Maximum [MPa] | Average [MPa] | Minimum [MPa] | Maximum [MPa] | Average [MPa] |
| 1 | 0.21068 | 272.26 | 33.075 | 0.39206 | 251.73 | 30.436 |
| 2 | 0.92793 | 265.65 | 42.324 | 0.34609 | 220.47 | 41.167 |
| 3 | 0.8321 | 551.74 | 54.98 | 0.68228 | 711.92 | 46.577 |

*Table 2. Bipod short side equivalent stress.*

| Time [s] | Design Stock | | | Design Optimized | | |
|---|---|---|---|---|---|---|
| | Minimum [MPa] | Maximum [MPa] | Average [MPa] | Minimum [MPa] | Maximum [MPa] | Average [MPa] |
| 1 | 0.17531 | 251.28 | 29.705 | 9.7448e-002 | 259.37 | 26.822 |
| 2 | 0.87321 | 524.57 | 59.505 | 0.6182 | 536.14 | 55.358 |
| 3 | 1.5234 | 677.57 | 72.895 | 1.4364 | 677.11 | 61.444 |

*Table 3. Equivalent long side stress.*

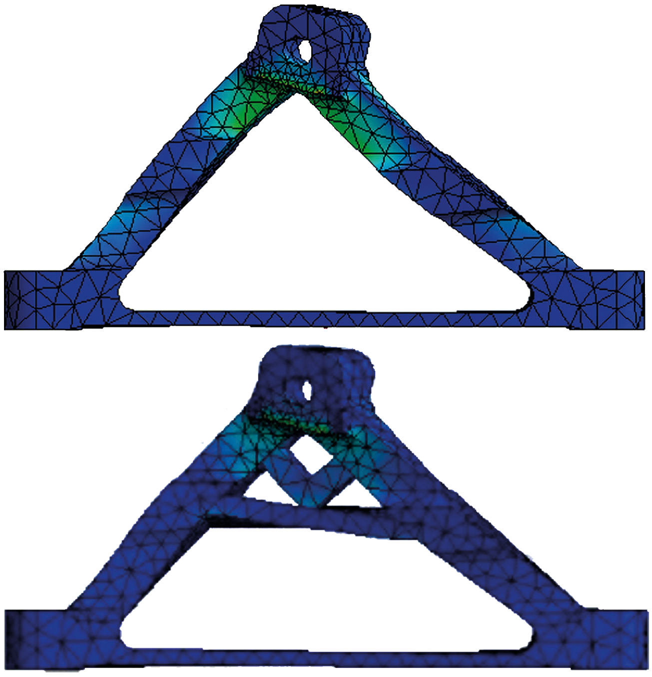

*Fig. 10. Bipod short side equivalent stress, before and after optimization.*

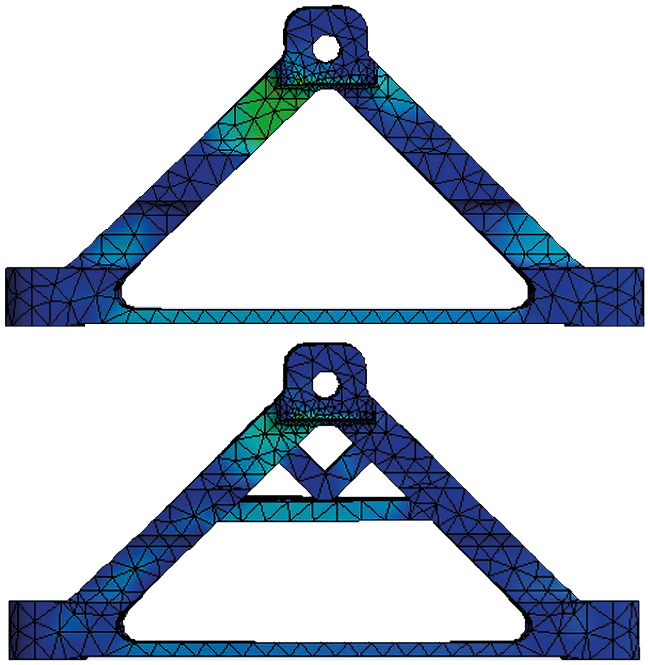

*Fig. 11. Bipod short side equivalent stress, before and after optimization.*

data during the launch phase in the three directions and then by evaluating the effect in terms of equivalent stress. Instead, for the thermoelastic stress analysis a simplified treatment that assigned temperatures to the individual components was used. In both cases the equivalent stress values were extracted according to Von-Mises theory.

Table 2 shows the minimum, average, and maximum values for the equivalent stress for the bipod along the short side of the module, while the following figures graphically represent the time instant 3s, which is the most onerous for the bipod.

On the long side, however, the trend of the stress state in the three cases analysed is as in Table 3.

To assess the thermo-elastic deformations and verify the strength of the structure, the temperatures of the most severe thermal case, the cold case shown in the table, were imported into the FEM model (Table 4).

| | |
|---|---|
| I/F Bipod - Truss | 20 °C |
| I/F Bipod - DF | -48 °C |
| Short Side | -67.3 °C |
| Detector Frame | -52 °C |
| Blades | -61 °C |
| Central Bolt | -55.5 °C |

*Table 4. Temperature profile of cold case.*

| Case | Short side | | Long side | |
|---|---|---|---|---|
| | Maximum [MPa] | Average [MPa] | Maximum [MPa] | Average [MPa] |
| Cold Case (stock) | 458.85 | 52.432 | 312.07 | 30.198 |
| Cold Case | 588.75 | 58.13 | 299.67 | 32.6 |

*Table 5. Thermo-elastic stress.*

The reference temperature for the assembly of the components was set at 20°C. Table 5 shows the average and maximum equivalent stress values obtained through the static structural analysis due to the thermal loads applied to the module components in both the original and optimized design cases.

## Results

The shape of the bipods was optimized to meet the frequency requirements of the first vibrating mode and, through the evaluation of different designs, this work sought to obtain a design that, while meeting the requirements, would limit the increase in weight of the object.

The frequency requirement for the first significant vibration mode was 120Hz with a margin of 15-20%. This work started with a natural frequency of 122.69Hz to 149Hz (+15%) with a preliminary mass increase of 10g per bipod (+16%) reduced with a morphing optimization to 16g per bipod (-18%).

Subsequently, the stress state of the new layout was checked and it was found that, being optimized for the frequency requirement, some hotspots formed that increase the maximum and average stress values compared to the original design. In any case, the results obtained are well below the yield strength limits of the material, which is therefore not in danger of going out of the elastic range.

## Conclusions

The study presented began with an analysis of the CAD model provided, which was simplified to facilitate the initial simulations. A mesh convergence analysis was then carried out, from which the dimensions of the elements were defined, which allowed simulations to be conducted in a short time, but with an acceptable degree of detail.

The study of the bipod was conducted by imposing the required minimum natural frequency of vibration as a constraint, adding a safety margin of 15-20%. The initial design had a natural frequency of about 122Hz, a value quite far from the imposed constraint, so it was decided to modify the topology of the support by introducing material in the areas where the component was more flexible.

The candidate topology presents an increase in mass with respect to the initial design of 16%, so it was decided to carry out an optimization procedure based on FEM analysis and mesh morphing to find a shape compromise between the original configuration and the optimized configuration with the 18% mass reduction. In future, another optimization with a greater computational time budget could be considered to redistribute the initial mass, moving it from the areas that participate less in the frequency response, to those that participate more consistently, thus attempting to maintain the weight of the object constant.

Once the candidate topology was defined, it was successfully verified for all required load conditions. As expected, compared to the initial design, in the thermal load and launch load conditions, the addition of material to the bipod resulted in reduced stresses that never exceeded the yield point of the material.

For more information:
Giovanni Lombardi - INAF
giovanni.lombardi@inaf.it

## About INAF

The National Institute of Astrophysics (l'Istituto Nazionale di Astrofisica, INAF) is the main Italian research institute for the study of the universe.
It promotes, implements, and coordinates research activities in the fields of astronomy and astrophysics. In addition, it designs and develops innovative technologies and state-of-the-art instrumentation for the study and exploration of the cosmos and promotes the dissemination of scientific culture through educational and outreach projects in astronomy aimed at schools and society. The Institute of Astrophysics and Space Planetology (l'Istituto di Astrofisica e Planetologia Spaziali, IAPS), an INAF institute distributed across Italy, is based in Tor Vergata in Rome and represents INAF's main structure for astrophysics and planetological research in space. It collaborates intensely with the main international space agencies (NASA, ESA, ASI, JAXA, CSA), with the Italian Space Agency (l'Agenzia Spaziale Italiana, ASI), and other national and international research bodies in the sector.
In addition to the design and realization of space missions in the field of relativistic astrophysics, theoretical, and experimental research, the development of advanced equipment and technologies, and observations from Earth form part of the scientific activities and projects. 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.