

Development of the THESEUS IRT telescope refocusing system

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ABSTRACT

The THESEUS mission [1] is a proposed mission designed to fully exploit the unique and breakthrough potentialities of Gamma-Ray Bursts (GRBs) for investigating the Early Universe and advancing Multi-Messenger Astrophysics, while simultaneously vastly increasing the discovery space of high energy transient phenomena over the entirety of cosmic history. The THESEUS spacecraft includes a payload composed of three instruments, one of them being a 0.7m class Korsch InfraRed Telescope (IRT). The thermo-optical stability of the IRT requires a tight control over the entire thermal operative range of the inter-mirror distance between the primary (M1) and secondary (M2) mirror. This inter-mirror distance is driven by the mechanical characteristics of the truss in which the M2 is integrated. The selected materials for the truss and its structural design quite likely cannot achieve the required optical stability, therefore a refocusing strategy needs to be developed allowing to accurately adjust the M1-M2 distance. Moreover, in-orbit adjustment of the M1-M2 distance is required to compensate the thermal difference between on-ground AIT and in-orbit environment. M1-M2 adjustment capability is also beneficial to neutralize any dimensional variations of the Carbon Fiber Reinforced Polymer (CFRP) structure caused by moisture release in orbit, despite the necessary bake-out procedures performed before AIT. In this paper we report about the development of a refocusing breadboard structures for the secondary mirror of the IRT, including experimental characterization in vacuum.

Keywords: telescope, refocusing, space

1. STATE-OF-THE-ART OF THE IRT TELESCOPE DESIGN

The IRT telescope [2] consists of a Korsch design with three curved mirrors and one folding mirror. The optical aperture of the telescope is 700 mm, and the M1-M2 distance is 675 mm, which are two key design drivers for the truss structure. Given the size of the telescope, there's a truss structure to reduce mass at equivalent structural performance of a tubular structure.

An important element is the selection of the telescope materials; the current baseline is to have Zerodur mirrors with a CFRP structure. Dimensional variability of the CFRP beams can be caused by moisture release in vacuum. This is a known issue of CFRP material and is typically determined by the epoxy adhesive. Characterization and control of the axial properties of the beams is very important in order to have a predictable behavior of the Refocusing Truss System in space.

Moisture effects of the CFRP beams can be mitigated by selecting epoxy resins that have lower Coefficient of Moisture Expansion (CME). Although more advanced epoxy resins can reduce the effective axial CME properties of the beam, they will not eliminate it. For this reason, the residual CME shrinkage of the beam is included in the maximum elongation budget of the Refocusing Beam. In other words, the beam will necessarily shrink in vacuum, therefore a portion of the refocusing range will be used to bring the structure to nominal dimensions.

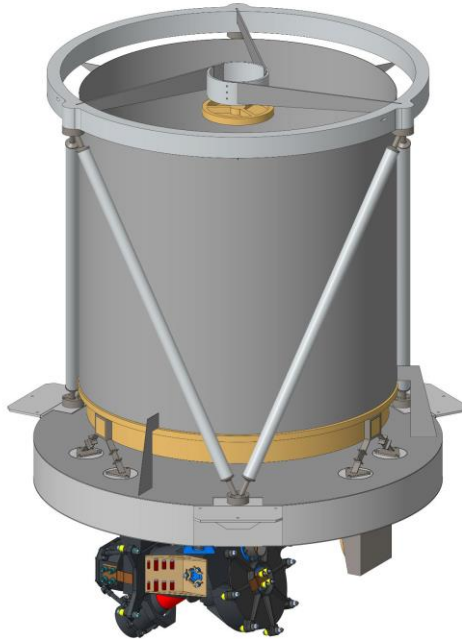


Figure 1. Reference design of the THESUS IRT telescope

The thermo-optical stability of the IRT telescope of THESEUS requires tight control of the M1-M2 distance and an in-orbit refocusing strategy is needed to accurately adjust the M1-M2 distance. Moreover, in-orbit adjustment of the M1-M2 distance will likely be required to compensate the thermal condition differences between on-ground AIT and in-orbit environment. M1-M2 adjustment capability is also beneficial to neutralize any dimensional variations of the CFRP structure caused by moisture release in orbit (CME), despite the necessary bake-out procedures performed before AIT.

The preliminary Thermo-Elastic (TE) analysis performed on the IRT optical system by the scientific team has shown that by compensating M1-M2 distance change allows fully recover the optical quality. The current baseline telescope configuration based on CFRP and Zerodur mirrors requires small displacements, within 10 micrometers, considering some margins and some additional shrinkage due to outgassing, a total maximum displacement of 15 micrometers is considered.

For the THESEUS IRT telescope we have considered different options for a refocusing system capable of controlling the M1-M2 distance. In-orbit refocusing mechanisms have been developed by the space industry for several past and ongoing missions, thus providing state-of-the-art information for the development of a refocusing concept for THESEUS. Adjustment mechanisms controlled by piezoelectric motors or stepper motors (Euclid like) are heavy and contain several single point failure elements. In addition, piezoelectric motors need high voltage drivers and must be latched for launch. As an alternative to the mechanisms, a possibility is to control thermally the M2 mounting elements, changing the axial position of the mirror by changing the temperature and relying on the thermal expansion of these elements. The temperature is controlled by means of heaters and sensors, it can be adjusted to achieve the correct position of M2 and maintained constant thereafter. In this scenario, we are studying a truss structure with an embedded metal insert in a CFRP beam, with the latter engineered with a very low axial CTE. In this solution the metal insert provides accurate thermal expansion control along the axial direction. Such a configuration is power efficient because it fully exploits the low thermal conductance of the CFRP beam.

A refocusing breadboard has been designed and tested to increase the Technological Readiness Level of this proposed system. The activities for the development and characterization of the refocusing breadboards have been organized on two prongs, one for the development and characterization of the single refocusing beam element, the other implementing the refocusing beam in a representative truss breadboard (with six beams) to fully characterize the refocusing functionality, performance and dynamics. The preliminary single beam characterization provides important inputs for the truss design.

2. SINGLE BEAM ELEMENT

The single refocusing beam is designed with a central metallic insert in Titanium Ti-6Al-4V (grade 5). This insert is structurally bonded to the CFRP laminate by means of epoxy EA 9394 from Loctite. The Titanium insert is covered by a thermal heater over its complete length, to increase its temperature and hence control the elongation of the complete strut.

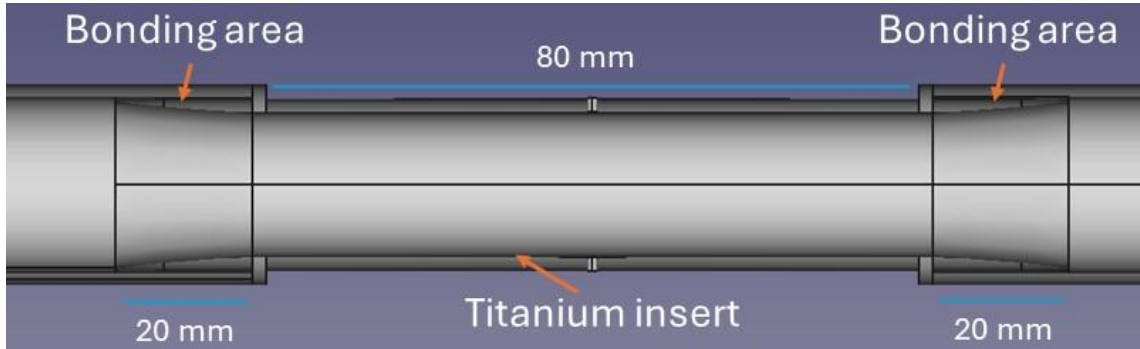


Figure 2. Titanium insert in the middle of the beam

In the sizing of the strut, also the end fittings play a role. The material selected for the end-fittings is Invar 36, so to have good mechanical properties, a small coefficient of thermal expansion and high thermal resistance. Likewise for the Titanium insert, the Invar end-fittings are structurally bonded to the CFRP laminate by means of epoxy inside the CFRP tube, for a length of 20 mm. 30 mm is the length of the Invar end-fitting from the edge of the CFRP tube to their common bracket.

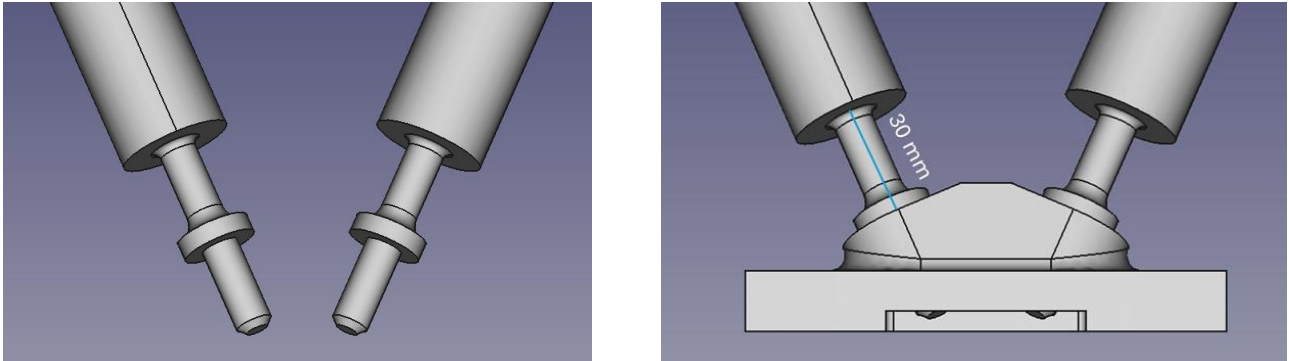


Figure 3. Geometry of the Invar end-fittings; the mechanical interface of the truss is yet preliminary.

The overall length of the strut is 867 mm, the CFRP tubular is 727 mm, the titanium insert is 80 mm, and the end fittings are 30 mm each. The dimensioning of the metallic parts is driven by the thermal compensation requirements and considering the boundaries of upper and lower temperatures of the Cold and Hot case as specified for THESEUS:

- Cold Case: upper end at -90°C; lower end at -59°C
- Hot Case: upper end at -35°C; lower end at -23°C

For the COLD CASE we need bringing the temperature of the Titanium insert to -30°C, requiring a power of:

$$Q_{heatCold} = 2 \cdot \frac{|\Delta T_{COLD}|}{(R_{eq})} = 1.44 \text{ W}$$

For the HOT CASE we need bringing the temperature of the Titanium insert to -17°C, requiring a power of:

$$Q_{heatHot} = 2 \cdot \frac{|\Delta T_{Hot}|}{(R_{eq})} = 0.32 \text{ W}$$

For the fiber filament the baseline material is M55J from Toray and the epoxy adhesive is Araldite LY556 from Huntsman. Both are well-known materials with extensive heritage in space applications.

Table 1. Base material properties of the CFRP beam

	M55 J	LY556
Youngs Module	$E_F = 540 \text{ GPa}$	$E_M = 3.1 \text{ GPa}$
CTE	$\alpha_F = -1.1 \cdot 10^{-6} \text{ K}^{-1}$	$\alpha_M = 57 \cdot 10^{-6} \text{ K}^{-1}$
Density	$\rho_F = 1910 \text{ kg} \cdot \text{m}^{-3}$	$\rho_M = 1196 \text{ kg} \cdot \text{m}^{-3}$
Thermal Conductivity	$k_F = 155 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$	$k_M = 0.3 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$

Starting from the single layer mixture parameters, the CFRP layup is designed based on the following drivers:

- The axial stiffness requirement of $30 \cdot 10^6 \text{ N/m}$
- The axial CTE value shall be close to zero, or slightly negative
- The radial CTE shall also be controlled, to ensure the structural integrity of the bonded joints with the metallic inserts

Concerning internal diameter, 26 mm is selected based on the availability of master tube for the wound. So, the tubular will have internal diameter 26 mm and external diameter 29 mm.

Table 2. CFRP layup

Layer number	Material	Thickness	Orientation
1	M55J-LY556	0.3 mm	$\pm 6^\circ$
2	M55J-LY556	0.3 mm	$\pm 6^\circ$
3	M55J-LY556	0.3 mm	$\pm 80^\circ$
4	M55J-LY556	0.3 mm	$\pm 6^\circ$
5	M55J-LY556	0.3 mm	$\pm 6^\circ$

As summarized in Table 2 the first two layers and last two layers have a fiber angle of $\pm 6^\circ$, the layer in the middle has a fiber with an angle of $\pm 80^\circ$. Each layer is 0.3 mm, giving a total radial thickness of 1.5 mm.

Table 3. Laminate material properties (direction 1 is in the axial direction)

Property	Symbol and value
Tensile Modulus in axial direction	$E_1 = 256 \text{ GPa}$
Tensile Modulus in radial direction	$E_2 = 67 \text{ GPa}$
In plane Shear Modulus	$G_{12} = 5.8 \text{ GPa}$
Poisson coefficient	$\nu_{12} = 1.039 \cdot 10^{-1}$
CTE in axial direction	$\alpha_1 = -7.5 \cdot 10^{-7} \text{ K}^{-1}$
CTE in radial direction	$\alpha_2 = 1.9 \cdot 10^{-5} \text{ K}^{-1}$
Thermal Conductivity in axial direction	$k_1 = 74.4 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$
Thermal Conductivity in radial direction	$k_2 = 19.5 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$
Moisture strain in axial direction	$\epsilon_1 = -1.8 \cdot 10^{-6}$
Moisture strain in radial direction	$\epsilon_2 = -9.8 \cdot 10^{-5}$

The Coefficient of Moisture Expansion (CME) is calculated following the ECSS-E-HB-32-20 Part 1A 20 March 2011, and considering the worst-case saturation scenario of the LY556 adhesive, meaning 10 days immersed in water.

3. TRUSS BREADBOARD

The refocusing truss breadboard structure is composed of six beam struts elements, connected to two plates through six identical mechanical interfaces. On the two plates, two flat mirrors are attached to permit the measurement of their distance with an optical instrument (a differential interferometer).

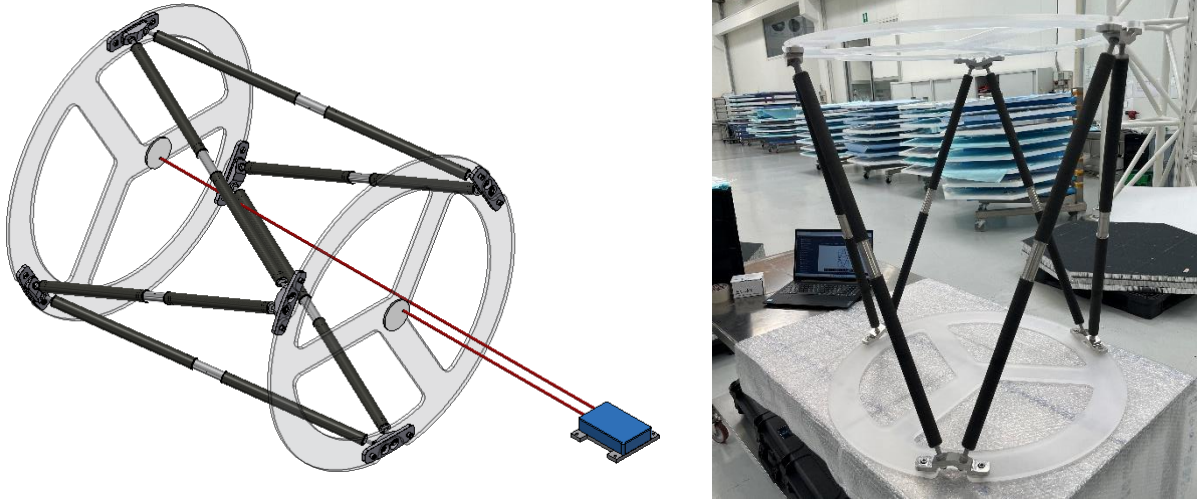


Figure 4. Refocusing truss model and picture (on the right)

The two plates are designed to be lightweight and to bring a low CTE contribute to the overall system. Fused Silica is selected as material of the plates, with a CTE of 0.55 ppm/K.

The mechanical interface is designed to connect two beam-ends to the plates. The material is selected to match the one of the beam-ends fitting (INVAR 36) to not introduce thermal stresses. The mechanical interface is then screwed to the plates through threaded inserts. The threaded inserts are glued to the quartz plates through injection holes by means of epoxy. Three couples of inserts are positioned at an angle of 120° to screw the mechanical interfaces to the glass plates. To control the refocusing truss elongation with temperature, a thermal heater will cover the titanium insert of each beam element over its complete length.



Figure 5. Refocusing truss mechanical interface

Mechanical interfaces are a very important part in the refocusing truss design. Their shape shall be very accurate to give the beams the right inclination during the integration phase. To not introduce thermal stresses, the mechanical interface is made of INVAR 36 to match the material of the beam end fittings.

4. TESTING OF THE TRUSS BREADBOARD

The refocusing system will be tested in the thermal vacuum chamber at Politecnico di Milano campus in Lecco. The testing area of the chamber consists of a cylinder with an internal diameter of 1500 mm, and a total internal length of 1700 mm. An 800-mm-wide plate is in the bottom area, serving as a floor. The supporting Strut will be easily accommodated within this area.

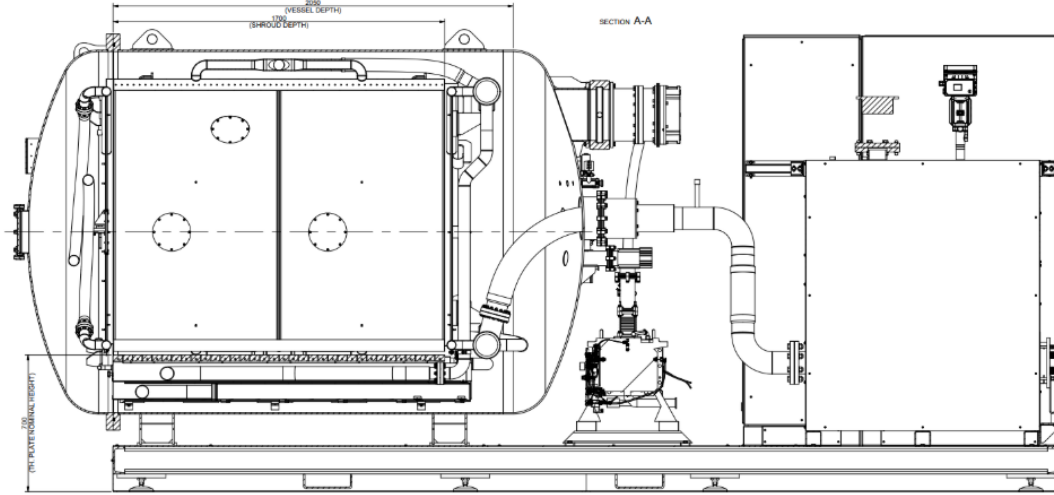


Figure 6. TVAC overview

To ensure the representative testing of the thermal refocusing mechanism, a dedicated GSE structure has been designed to support the assembly inside the chamber.

- Isostatic Support: the integration uses a “Fixed-Sliding” configuration to prevent parasitic mechanical stresses that could affect the sub-micrometric displacement measurements.
- Floating Ends: both the plates are supported by an axially unconstrained interface, with relative displacement between support and Truss accommodated by ball bushings.
- Plate Interfaces: the quartz plates are supported at specific points optimized to minimize gravity-induced deformations.

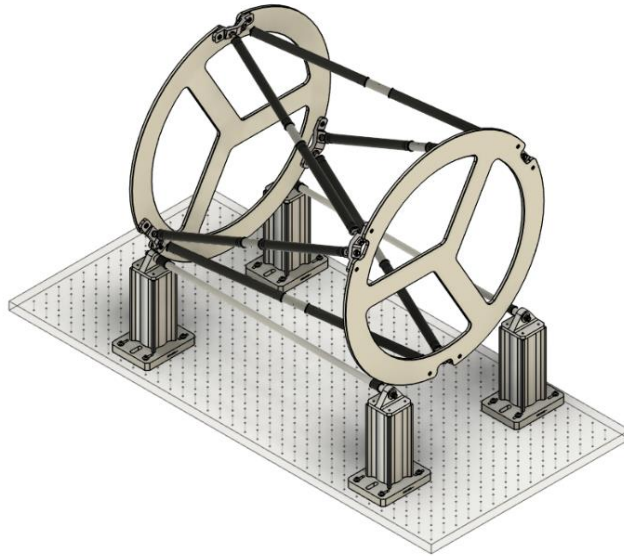


Figure 7. Truss mounted on the TVAC plate with the GSE

To measure the elongation of the refocusing truss with a differential interferometer, with retroreflectors (designed for stable performance in high-vacuum conditions) attached to the two plates. SIOS SP 5000 DI Differential Interferometer with 5 pm (picometer) resolution, sensor head located outside the TVAC chamber. Measurement is performed through a dedicated optical window in the chamber wall.



Figure 8. SIOS SP 5000 DI

The TVAC test is planned for October 2026, with the goal of verifying the following success criteria:

- Possibility to achieve the maximum target elongation $M1-M2 > 15 \mu\text{m}$ by controlling the power injected to the heaters
- Possibility to control the relative displacement with a resolution of $1 \mu\text{m}$ or better
- < 2 Watts per heater (one heater per beam, total of six heaters) to achieve the target elongation

5. SUMMARY

Media Lario and the team of scientific and industrial partners have designed and built a prototype refocussing truss, with the goal of increasing the Technology Readiness Level of the system. The boundary conditions of the proposed mission THESEUS have used for defining the set of requirements, but the technology could also be used in other future missions. The breadboard of the study is ready and waiting for the availability of the TVAC chamber for the final characterization in vacuum and cold temperature, with an expectation for October 2026.

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