

LISA CAS OPTICAL HEAD DESIGN AND EM DEVELOPMENT

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ABSTRACT

LISA (Laser Interferometer Space Antenna) is the first Space mission designed to observe the universe via gravitational waves, ripples in the fabric of space time caused by the acceleration of massive objects in the universe. The LISA observatory consists of 3 spacecrafts forming an equilateral triangular constellation of 2.5 million km side-length, in trailing orbit with respect to the Earth at about 50 million km. The constellation of the three spacecraft operates as a large interferometer. The passage of a gravitational wave results in a modulation of the length of the arms formed by the three spacecrafts.

Since beginning 2025, Thales Alenia Space in Switzerland (TAS-CH) is developing the Optical Head of the Constellation Acquisition System (CAS) for the LISA project. LISA is a large interferometer with arms extending between its satellites. The laser beam must be acquired by the receiving satellite and stabilized before being injected into the interferometer part of the system. This critical function is performed by the CAS. The CAS requires a relatively large Field of View (FoV) combined with an extremely precise measurement of the incoming beam's pointing direction. For reference, the FoV is ± 30.4 mrad, and the required pointing accuracy is 20 μ rad. Both values are specified after the magnification by the LISA telescope. The pointing accuracy is driven by the sensor, Signal-to-Noise Ratio (SNR), and image quality. The opto-mechanical design itself is driven by the stringent stability requirements. During operation, the pointing measurement must remain stable within a few microradians.

The design has progressed up to PDR and an Engineering Model (EM) model of the CAS has been integrated. The development timeline will be presented as well as the development approach as the requirements were consolidated through extensive co-engineering for this project.

Once integrated, the EM did undergo testing before delivery to the customer. Testing has verified the optical performances of the model, including Wave Front Error (WFE) and pointing accuracy. The design solution and test results will be presented accordingly.

Keywords: Space, LISA, Laser Interferometer, constellation, acquisition. Optical Head

1. INTRODUCTION

This paper describes the work done by Thales Alenia Space in Switzerland (TAS-CH), in collaboration with Teledyne, on the LISA CAS Optical Head (LISA CAS-OH) project, addressing key technical challenges such as designing a very compact optical system into a thermally stable structure, while ensuring high image quality, efficient heat dissipation and very accurate angular measurement.

The successful development of the unit enables the three LISA satellites to acquire each other laser beams and establish the link needed to measure distortions of the space-time fabric in the order of 10 pm induced by gravitational waves.

2. MAIN DESIGN DRIVERS

This section details the primary technical drivers for the LISA CAS-OH design, encompassing both optical and thermo-mechanical requirements.

A. Optical Requirements

The optical subsystem is responsible of focusing the receiving light from the telescope, to measure the field angle with

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sufficient accuracy. This functionality is implemented for two operating modes: Star Tracking and Laser Tracking. During the former, the incoming light is in the visible range (between 610 nm and 660 nm), as for the latter, the laser wavelength is 1064.5 nm.

The first challenge was therefore to design an achromatic imaging subsystem, delivering high image quality in both spectral ranges: rms WFE $< \lambda/10$ in the visible and WFE $< \lambda/20$ for the laser, within a field of view of ± 30.4 mrad and an entrance pupil diameter of 2.24 mm, both after the LISA telescope magnification.

The second—and most complex—challenge was to achieve an exceptionally demanding Line of Sight (LoS) stability. Since the LISA satellites are separated by 2.5 million kilometers, they must maintain an extraordinary pointing accuracy in the order of hundreds of nano-radians. To address this, the target LoS stability of the CAS-OH—measured after telescope magnification—is below $10 \mu\text{rad}$. This requirement accounts for thermo-elastic distortions of optical elements caused by the CTE differences across the CAS-OH and the heat dissipation from the imaging detector.

Another critical design driver is minimizing spurious signal generated by CAS-OH back-reflections toward the interferometric path of the LISA Optical Bench Assembly (OBA), ensuring they do not adversely impact the scientific measurements.

To optimize the accuracy of the spot centroid measurement on the detector, the imaging subsystem must produce an aberration-free Point Spread Function (PSF) with a Full Width at Half Maximum (FWHM) of 2.4 pixels, corresponding to $24 \mu\text{m}$ at the laser wavelength. This directly affects the focal length, as the two parameters are proportional.

Finally, the CAS-OH must be precisely aligned with the exit pupil of the LISA telescope, which serves as the unit's entrance pupil.

B. Thermo-Mechanical Requirements

The LISA CAS-OH unit is designed as an integral component of the ultra-stable Optical Bench Assembly (OBA), which acts as the primary common interface for all optical elements of the LISA interferometers and the gravitational reference system (Figure 1). As one of several hosted units, the thermo-mechanical design of CAS-OH faced considerable challenges, driven by a constrained mechanical envelope, stringent mass limitations, and the demand for exceptional thermo-mechanical stability under operational conditions.

Furthermore, as a critical component for the LISA acquisition modes—encompassing both laser and star tracking—the CAS-OH must efficiently dissipate the heat generated by the high performance CIS 220 detector (developed by Teledyne), maintaining its temperature within the specified operational range. Simultaneously, it must minimize heat transfer to adjacent sensitive components to prevent any adverse impact on the performance of other thermally sensitive units within the OBA.

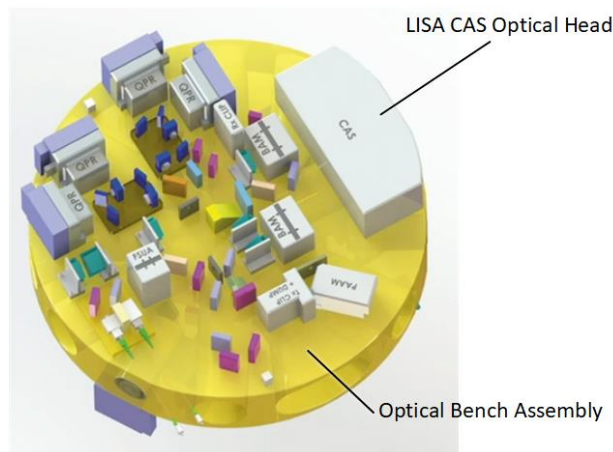


Figure 1 Overview of the ultra-stable Optical Bench Assembly with CAS Optical Head envelope
(credit: UKATC, 15th International LISA Symposium, 10th July 2024)

Despite a limited non-operative temperature range of 10°C to 40°C and a stable operational temperature maintained around 20°C in the worst cold case, and 25°C in worst hot case—achieved both radiatively and conductively within the satellite’s internal cavity—the LISA CAS-OH must fulfil multiple critical and occasionally conflicting requirements. Featuring a high-performance CIS 220 detector developed by Teledyne, the LISA CAS-OH design must ensure:

- Efficient dissipation of the heat generated by the sensor during operation, keeping the detector’s temperature below 32°C.
- Minimal thermal impact on adjacent units to prevent degradation of the overall instrument performance.

According to the requirements, heat dissipation is permitted only through radiative coupling along the out-of-plane direction (X axis, as shown in Figure 2). Radiative coupling along the in-plane directions (Y and Z axes in Figure 2) as well as conductive heat transfer through the mechanical interfaces where the CAS-OH is mounted, must be minimized. Conductive heat dissipation is inherently limited by the low thermal conductivity of the materials selected for the Optical Bench and Common Interface Pedestal (CIP) (Zerodur® and Titanium, respectively).

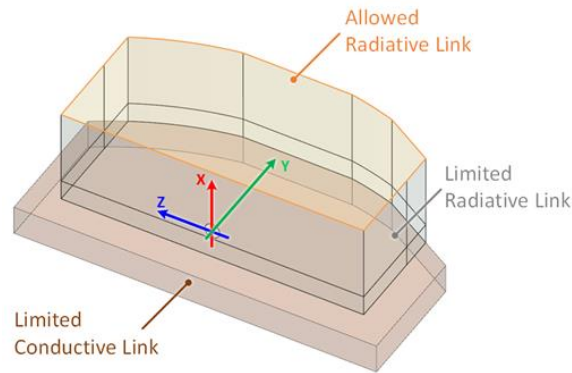


Figure 2 CAS-OH envelope, reference coordinate system and radiative and conductive links

Taking into account the above specifications, the direct consequences are:

- Heat management becomes a crucial factor for a compact unit such as the CAS-OH.
- The heat generated by the detector, combined with restricted dissipation pathways, may lead to temperature gradients within the unit, potentially compromising the optical stability of the CAS-OH during operation.

As illustrated in Figure 1, the CAS-OH is one of the largest hosted unit on the OBA. Despite its size, the unit is constrained by a strict maximum mass limit of 900 g. The designated envelope follows the curved contour of the OBA, with an overall allocated volume of 202 × 65 × 99 mm. This space must accommodate the sensitive optics, the detector, and the COH structure, all of which must be structurally robust to withstand launch loads while maintaining exceptional thermo-elastic stability throughout the operational acquisition phases.

Additionally, the volume is shared with the CIP. While the CIP simplifies the assembly and integration process of the unit onto the OBA and helps mitigate the CTE mismatch with the Zerodur® optical bench, it reduces the usable space available for the CAS-OH design by approximately one-fourth. Furthermore, the presence of surrounding equipment constrains the routing of harnesses connecting the CAS-OH to its associated electronics. Figure 3 illustrates the envelope incorporating all these constraints, highlighting the CIP volume in blue and the restricted routing area in red.

Another significant challenge influencing the CAS-OH design is the positioning of the entrance pupil. Located near the end of the envelope—at 69 mm within a total envelope dimension of 99 mm (cf. Figure 3)—its location was a key factor affecting the placement of both the optics and the detector within the available space.

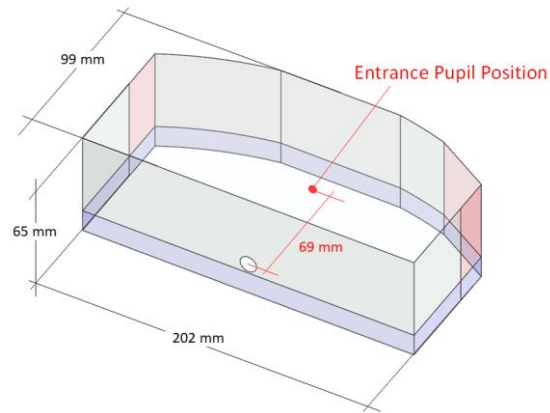


Figure 3 CAS-OH envelope dimensions and position of entrance pupil

3. DESIGN SOLUTION BY TAS-CH

C. Optical Design

At the beginning of the project, a trade-off was conducted between two optical designs. For both options, it was determined that the image plane - and consequently the detector - should be oriented parallel to the Y-Z plane (see Figure 2). This orientation was driven by the dimensions of the detector, the space required for its proximity electronics, and the position of the CAS-OH entrance pupil.

Refractive design: The first design option is based on a refractive optical design, featuring an achromatic doublet, mounted in a self-standing optical tube made of titanium, interfacing via bolted joints to the rest of the CAS-OH structure. The respective optical layout is presented in Figure 4.

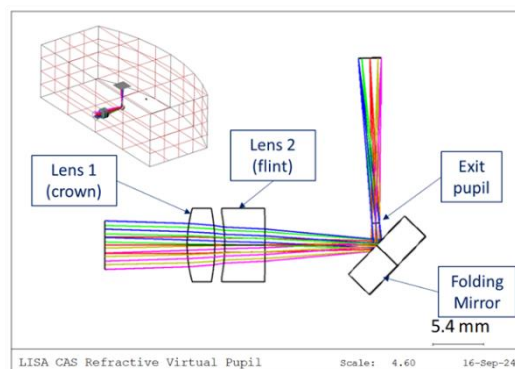


Figure 4 Optical layout of the refractive design, and its location within the assigned envelope

For maximizing the compactness of the optical layout, the doublet is placed before the entrance pupil, making it virtual, while the real exit pupil of the Telescope or Entrance Pupil of the CAS-OH unit is located right after the folding mirror.

Reflective design: The second optical layout is based on an off-axis telescope, featuring very small, aspheric mirrors from Zerodur®, designed to maximize the thermal stability during operational phases. The layout is presented in Figure 5.

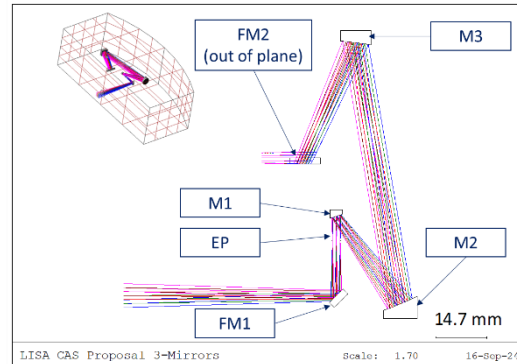


Figure 5 Optical layout of the reflective design, and its location within the assigned envelope

The trade-off criteria used to select the baseline architecture included:

- Stray light directed towards the LISA Optical Bench (spurious back-reflections)
- Image quality, assessed by rms WFE
- Line-of-sight stability
- Compactness of the optical design
- Complexity of manufacturing, alignment, and integration

The two designs underwent tolerance analysis to evaluate the as-built rms WFE, straylight analysis to assess the back-reflection and STOP analysis to compute the LoS stability under thermal loads.

Regarding image quality, the two design are comparable in the specified wavelength range, even though the reflective design is intrinsically achromatic. In collaboration with ESA, the requirement on spectral performance over the functional operating range has been refined allowing the refractive option to be acceptable.

As for the straylight generation, the reflective design performs better, however, both solutions achieve back-reflection levels more than an order of magnitude below the maximum target of 1%.

The significant differences are related to the last three criteria:

- In terms of LoS stability, the reflective design achieves smallest displacements of the optics, due to the low CTE of Zerodur®. However, due the high degree of asymmetry of the off-axis configuration and the larger number of optical elements (5), the LoS stability is more sensitive to these displacements. On the other side, the refractive design exhibits larger displacements because of its titanium structure, but the LoS is less affected, since there are less optical elements (3) involved and only one folding mirror introducing asymmetry. STOP analysis indicates that the refractive design outperforms the reflective one by nearly a factor of four in terms of LoS stability.
- Regarding compactness, the refractive solution is inherently less space-demanding, consisting of only three optical elements (two lenses plus one folding mirror). In contrast, the reflective design, comprising five optical elements (three telescope mirrors plus two folding mirrors), requires a larger volume.
- Finally, the manufacturing, alignment and integration of the refractive solution, results in a more robust solution compared to the reflective one (less demanding tolerances and geometrically simpler elements).

In conclusion, the refractive design was ultimately selected as the preferred solution due to its outstanding stability and compactness. Furthermore, it requires fewer optical elements and is easier to manufacture and align, all without compromising image quality.

The optical and thermo-mechanical designs are presented in detail in the following sections, with particular focus on how the most challenging technical requirements were successfully addressed. A 3D view of the baselined optical layout is shown in Figure 6, which is considered a significant advancement for the mission's optical system.

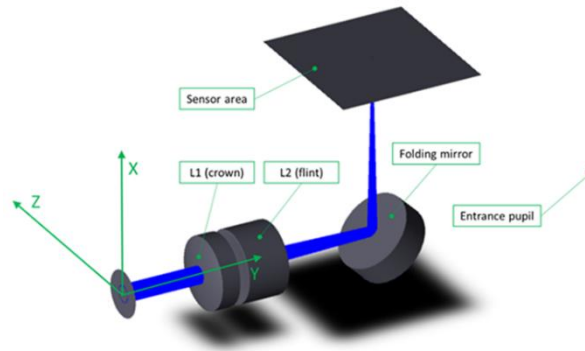


Figure 6 3D view of the baselined CAS-OH optical layout

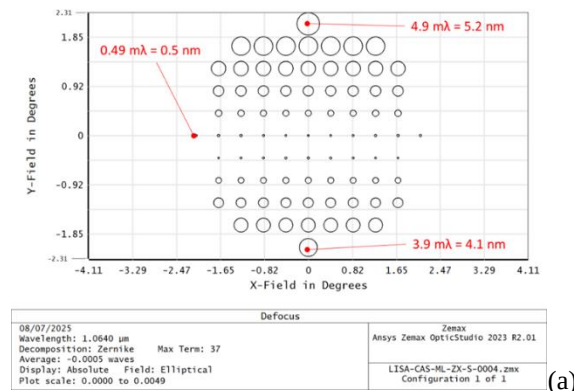
The design was optimized to minimize the rms WFE, while complying to geometric constraints such as position of detector, folding mirror and entrance pupil.

The system is quite slow, as the focal length is 49.8 mm, resulting in an f-number of 22.2, which leads to a FWHM of $24\ \mu\text{m}$ at 1064.5 nm, meeting the specified requirements.

In order to reduce the detector-induced back-reflections towards the OBA, the folding mirror deflects the incoming beam by 88 degrees to force an angle of incidence of 2 degrees on the image plane. This helped reducing the overall back-reflections by an order of magnitude with respect to the configuration where the beam was oriented orthogonally to the sensor.

The lenses and mirror substrate are made of radiation-hard glasses to ensure resistance to the Space radiation environment of the LISA mission.

The nominal rms WFE is below 8 nm for all operating wavelengths, as shown in Figure 7.



(a)

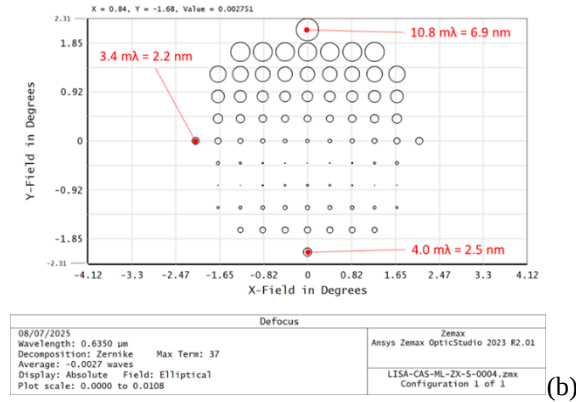


Figure 7 Rms WFE distribution over field of view, at 1064 nm (a) and 635 nm (b)

As mentioned, a Monte-Carlo tolerance analysis was performed to estimate the impact of manufacturing and positioning errors of lenses and mirror on the rms WFE.

For each randomly generated system, the maximum rms WFE across the field of view was evaluated:

- At 1064.5 nm: rms WFE = 9.1 nm - 5.5 nm / + 9.8 nm
→ always < 19 nm
- At 635 nm: ms WFE = 9.7 nm - 6.3 nm / + 11.8 nm
→ always < 22 nm

The tolerance analysis demonstrated a good image quality, reaching an rms WFE below $\lambda/20$ in the visible range and below $\lambda/50$ at the laser wavelength, meeting the specifications mentioned in section A with remarkable margin.

D.Thermo-mechanical Design

The design of the LISA CAS-OH unit was developed in order to meet the various constraints and requirements outlined in section B, as well as to accommodate the optical layout described in section C. Figure 8 shows the design of LISA CAS-OH unit as proposed for PDR, highlighting its main sub-assemblies and their respective nomenclature:

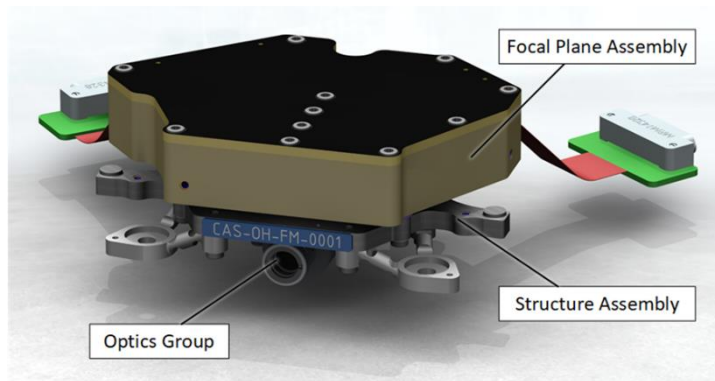


Figure 8 CAD representation of CAS-OH design with its subassemblies

Optics Group (OG): As introduced in section C, the Optics Group is the optical and opto-mechanical sub-assembly that contains all necessary optical elements—such as lenses and mirrors—to focus and fold the incoming laser beam onto the detector. It ensures the required image quality while meeting the specifications for FoV, WFE, and entrance pupil diameter

and position. Additionally, the internal surfaces of the OG are black-coated to prevent straylight.

Figure 9 depicts the Engineering Model (EM)—first model developed and manufacture by TAS-CH and Teledyne—of the Optics Group.



Figure 9 CAS-OH EM Optics Group

Focal Plane Assembly (FPA): it houses the Detector Assembly (DA) provided by Teledyne, which consists of the CIS 220 detector, its proximity electronics and the harnesses connecting the CAS-OH with the electronic unit. The FPA structure, designed by TAS-CH, offers protection against Space radiation and straylight, while delivering an efficient thermal path for dissipating the heat generated by the detector.

Structure Assembly (SA): it is the primary structural component. It includes a main plate that acts as the mechanical interface for both the FPA and the OG. The SA also has three bipods that allow the CAS-OH to be mounted quasi-isostatically onto the Common Interface Pedestal and, from there onto the Optical Bench. Additionally, the SA contains three CMM fiducials, which serve as references for alignment and integration.

The overall mechanical design has been developed to meet all envelope constraints and stay within the mass limit. Weighing just 750 g, the CAS-OH comfortably fits within the maximum mass budget of 900 g, leaving a margin of approximately 20% to accommodate potential design changes for the phase up to the Critical Design Review (CDR).

Thanks to the straightforward optical layout and the compact design of the OG assembly, the CAS-OH unit fully meets the volume constraints detailed in section B. Furthermore, the design offers:

- Increased space around the detector for placing its proximity electronics.
- The option to enlarge the FPA top cover to enhance the radiative link along the out-of-plane direction (X axis).
- Simplified routing of the Detector Assembly harnesses through designated pathways.
- Improved access and ease of handling for the FPA during integration and alignment on the SA.

Figure 10 illustrates the placement of the CAS-OH unit within the assigned volume envelope.

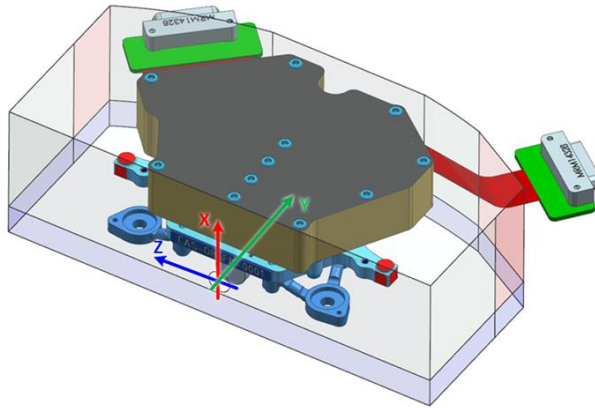


Figure 10 CAS-OH design meets the specified volume envelope

The FPA top cover is coated in black to increase the surface emissivity, thereby improving heat dissipation from the detector. As detailed in section B, this helps maintain the sensor temperature below the operational limit of 32°C.

Significant effort was devoted to optimizing the designs of the SA and OG to ensure the required demanding LoS stability of under the operative thermal conditions. With an exceptionally stringent allowable LoS stability budget of only 20 μ rad, as referenced in section A, this demanding requirement became a critical driver for the thermo-mechanical design architecture. To minimize the contribution of thermo-elastic deformations to the stability budget, the primary objective was to reduce the impact of thermal gradients caused by detector warming, as well as to address the Coefficient of Thermal Expansion (CTE) mismatch between the near-zero CTE of the Optical Bench made of Zerodur® and the higher CTE of the detector electronics. To achieve these objectives, careful material selection was the first critical step:

- Titanium was chosen for the entire SA and mechanical components of the OG, offering low thermal expansion combined with strong structural integrity. Alternative materials like Invar were excluded from consideration due to their ferromagnetic nature and the resulting limitations on their usage
- An AlSi Aluminum alloy was selected for all FPA structural parts, providing a CTE closely matched to the detector electronics while maintaining good thermal conductivity.

Additionally, the CAS-OH mechanical design was developed to maximize symmetry. Each bolted interface connecting the three main sub-assemblies—SA, OG, and FPA—is symmetrical about the Y axis (Figure 11). Three flexed bolted joints / bipods evenly spaced at 120° intervals, aligned with the on-axis beam folding point (cf. section C and Figure 11) enabled a quasi-isostatic support. This design effectively limits displacement and tilt of the sub-assemblies—especially at the FPA level—relative to the beam folding point, thereby significantly enhancing the unit's Line of Sight (LoS) stability during in-orbit operational conditions. This was demonstrated by the STOP Analysis results presented at PDR, which show a maximum LoS variation of about 10 μ rad—representing a major achievement of the COH-OH design solution.

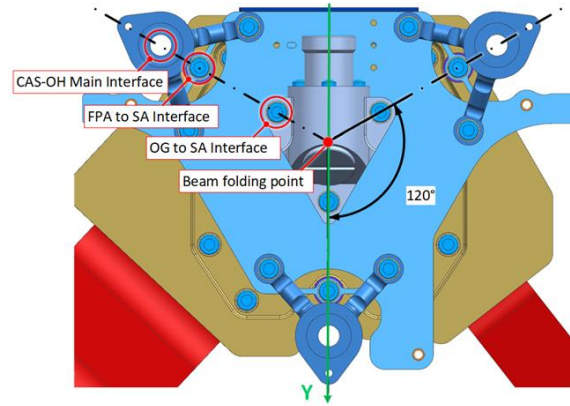


Figure 11 Symmetries in the CAS-OH mechanical design

4. INTEGRATION AND TESTING OF EM CAS-OH

The LISA CAS design has successfully passed the Preliminary Design Review (PDR) and the Engineering Model (EM) of the CAS-OH has been built and tested.

The EM was intended to be optically representative of the Flight Model (FM), with the EM Structure Assembly (SA) and Optics Group (OG) designs remaining consistent with the FM configuration presented at PDR. However, the EM Focal Plane Assembly (FPA) mechanical design was specifically adapted solely for EM testing purposes. Although it incorporates the flight sensor, the EM FPA is not representative of the final flight hardware.

Figure 12 illustrates the Manufacturing, Assembly, Integration and Test (MAIT) flow for the CAS-OH EM.

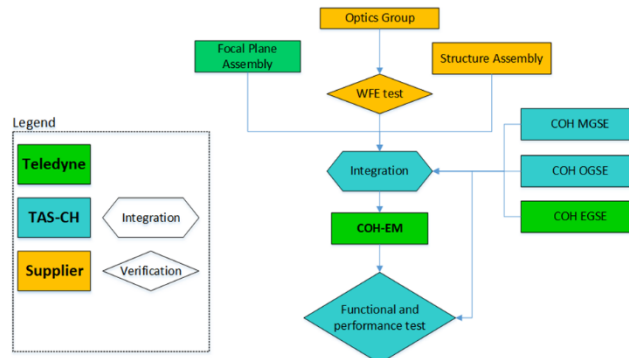


Figure 12 MAIT flow of the CAS-OH Engineering Model

For alignment purposes, the Structure Assembly was equipped with a flat reference mirror, and underwent mechanical characterization through Coordinates Measuring Machine (CMM), to derive the direction of this mirror against the mechanical interface with the Optics Group. The latter was mounted following a plug-and-play approach, with improved repeatability given by alignment pins.

The FPA was aligned in terms of de-focus adjustment and in-plane rotation, in order to make sure that the detector coordinates and the two field angle directions are decoupled below 30 mrad.

The fully assembled EM CAS-OH then underwent a series of functional and performance tests aimed at validating the unit's capabilities as defined at PDR. Figure 13 shows the EM in its test configuration.

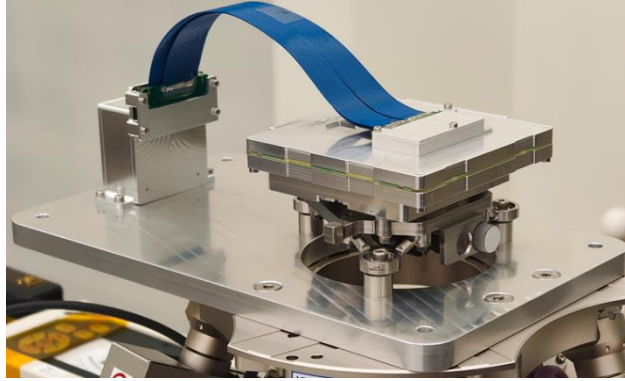


Figure 13 CAS-OH EM Hardware in test configuration

The WFE was measured using an entrance pupil diameter and field of view larger than those specified in section A, in order to provide alignment margin for the CAS-OH during the full functional and performance test outlined in the last step of the flow in Figure 12. Consequently, higher measured WFE values than those predicted by the tolerance analysis were anticipated.

The main results of the EM functional and performance tests are summarized as follows:

- A maximum measured rms WFE value of 27 nm was achieved, being well within the specified requirements.
- Successful completion of the vignetting test, evidencing stable system transmission and unchanged spot shape across variations in the field angle.
- The focused laser spot was smooth and symmetrical, with an FWHM value of 24 μm , consistent with the specification (cf. Figure 14).

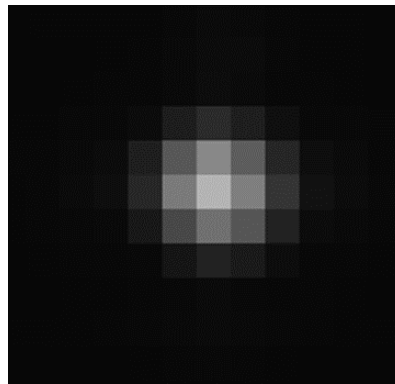


Figure 14 Captured image of the focused laser spot

- The detector rotational alignment around the optical axis (X axis, see Figure 10) was verified with a deviation of just 1 mrad—well within the 30 mrad specification—relative to the Optics Group, demonstrating the precision of the FPA-to-SA alignment process.

5. CONCLUSION

The development of the LISA CAS Optical Head represents a significant achievement in addressing the complex technical challenges associated with the LISA mission. The design successfully meets the stringent optical and thermo-mechanical

requirements, including a large Field of View (FoV) and low Wavefront Error (WFE).

The chosen refractive design offers a compact solution with better Line-of-Sight (LoS) stability and easier manufacturing and alignment compared to the reflective design.

The thermo-mechanical design of the CAS Optical Head has been carefully optimized to fit within the constrained envelope dimensions of $202 \times 65 \times 99$ mm while maintaining a mass of 750 g, well within the 900 g budget. Efficient heat management was achieved through careful material and coating selection ensuring that the detector temperature remains below 32°C while minimizing thermal impact on adjacent units. Moreover, the overall symmetric architecture of the unit assures an enhanced thermo-mechanical stability during in-orbit operative conditions, achieving an impressive LoS variation of only $10\text{ }\mu\text{rad}$, well within the stringent total budget of $20\text{ }\mu\text{rad}$.

The successful integration and testing of the Engineering Model (EM) have demonstrated the effectiveness of the optical design. The EM met all specified requirements, including a maximum measured rms Wavefront Error (WFE) of 27 nm, which is well within the specified limits. The functional and performance tests also confirmed stable system transmission, absence of vignetting, compliant PSF, and precise detector alignment.

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