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MOUNTING, METROLOGY AND VERIFICATION OF EUCLID NEAR INFRARED SPECTRO-PHOTOMETER OPTICAL ASSEMBLY NI-OA

H. Thiele[1*], A. Mottaghibonab[1], C. Gal[1], K. Gawlik[1], M. Dubowy[1],
F. Grupp[2], D. Penka[2], A. Bode[2], R. Bender[2]
[1]*OHB System AG, Manfred-Fuchs-Straße 1, 82234 Weßling, Germany.*
[2]*Max-Planck-Institute for Extraterrestrial Physics, Giessenbachstr, 85748 Garching, Germany*
**Hans.Thiele@ohb.de*

I. INTRODUCTION:

The Euclid Near Infrared Spectro-Photometer (NISP) optical system consists of a large filter and GRISM wheel, 4 aspherical lenses with a large diameter of up to 168mm and an Infrared detector array. The opto-mechanical structure, which holds and keeps these units aligned is made from SIC (see Fig. 1). The four lenses and their mounts are called Near Infrared Spectro-Photometer optical assembly (NI-OA). NI-OA is divided in 2 subunits, a lens triplet between filter wheel and detector which is named camera lens assembly (CaLA) and a single lens in front of the filter wheel, which is called corrector lens assembly (CoLA). The whole NISP instrument operates at cryogenic temperature, with the Infrared detector at 90K and the NI-OA lenses at 134K.

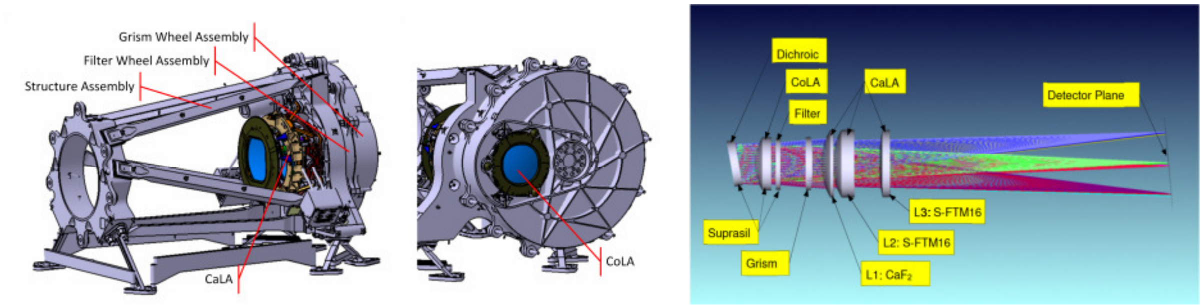


Fig. 1 Near Infrared Spectro-Photometer (NI-SP) opto-mechanical design (left) and optical layout (right)

OHB is responsible for the opto-mechanical design of these two NI-OA units. The mounting of the units is done by OHB while the alignment at room temperature is a joint task between OHB and Max-Planck-Institute for Extraterrestrial Physics (MPE). The verification of the alignment of the NI-OA units at cryogenic conditions is again under responsibility of OHB.

This paper focusses on mounting alignment metrology and verification of the alignment of NI-OA. It is structured in the following sections: Section II will briefly describe the opto-mechanical layout of NI-OA, focusing on the CaLA lens triplet and the features used for mounting and alignment of this unit. The concept to mount and align this triplet at room temperature is described in detail in section III. Section IV concentrates on the measurement concept to verify that all lenses achieve precisely the desired aligned position at cryogenic temperature. Results achieved with this concept are summarized. Section V concludes with a summary the achievements up to current state and gives a brief outlook on the next activities.

II. NEAR INFRARED SPECTRO-PHOTOMETER OPTICAL ASSEMBLY (NI-OA) OPTO-MECHANICAL DESIGN:

A. Key Design drivers

The opto-mechanical design of NI-OA is driven by some key requirements: the optical design requires different lens material for the four lenses, Suprasil, CaF2 and S-FTM16 (Fig. 1). The operational temperature of 134K and survival temperature requirement of 100K leads to an opto-mechanical design with a dedicated material for each lens mount to achieve the best possible match of the thermal expansion coefficient (CTE) between lens and mounting structure to minimize thermo-elastic stresses at operational temperature. Additionally, the deep operating temperature requires to come up with a mounting and alignment concept, which allows to mount and align the unit at room temperature with a “warm geometry”, which pre-compensates for the shrinkage and component movements during cool down and delivers a perfectly aligned system at 134K operational temperature. The optical tolerancing is also a major design driver for the stability of the opto-mechanical mount and the understanding of its thermal behavior. The lens vertices have to reach their desired position at cold temperature within a tolerance of +/-10µm laterally and +/- 15µm along the optical axis. In addition to these key drivers an extremely limited mass budget asks for extreme light-weighting of the opto-mechanical mounts of the lenses.

B. NI-OA CaLA Opto-mechanical design

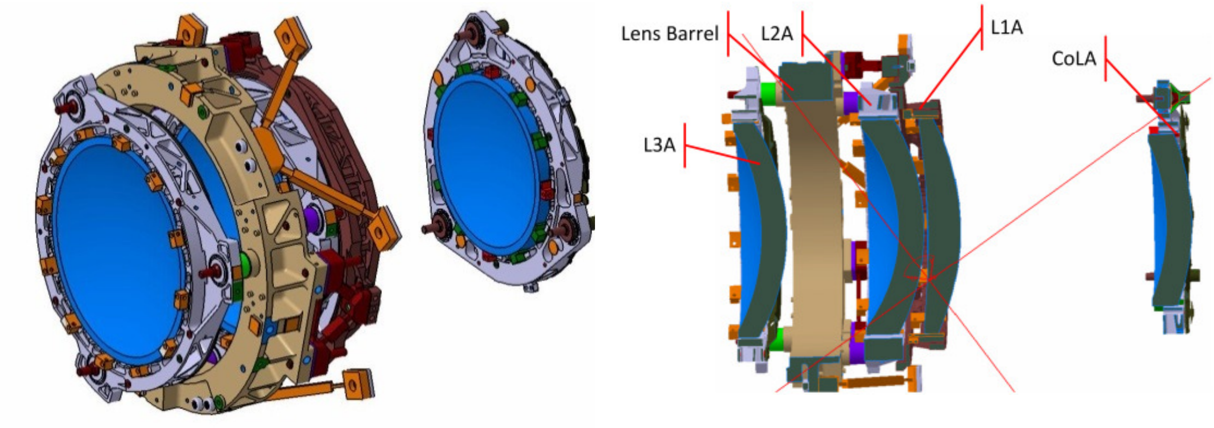


Fig. 2 3D CAD view of the Near Infrared Spectro-Photometer Optical Assembly (NI-OA) consisting of the CaLA triplet and CoLA (left), cross–section (right)

The NI-OA opto-mechanical design is shown in Fig. 2. All four lenses are mounted in their dedicated adaption ring. The CaF2 lens L1 of CaLA has a stainless steel adaption ring to match the CTE of CaF2. Both S-FTM16 lenses of CaLA, L2 and L3 are mounted in Titanium adaption rings. The separate Suprasil lens of CoLA requires an adaption ring made from INVAR M93 to minimize the CTE mismatch. The three lenses of CaLA are mounted on one central ring, the so-called lens-barrel, which is made from Titanium as well. For both Titanium adaption rings of L2 and L3 no CTE mismatch is present and they can be bolted to the lens-barrel directly. For the stainless steel adaption ring three Titanium bipods serve as interface (I/F) and decouple the CTE mismatch between adaption ring and lens-barrel.

As the CTE match between lens material and mount material is not sufficient to fully avoid severe stresses in the glass during cool down, additional flexure blades are part of each adaption ring design. Twelve flexure blades provide additional flexibility and reduce the stresses in the glass to a tolerable minimum.

To mount the individual lenses to the adaption rings an innovative gluing concept is applied. Instead of directly gluing the lens to the adaption ring flexure blades, additional metal pads are introduced between lens edge and the twelve flexure blades of the adaption rings. This has advantages with regard to the local stresses at the glue-to-glass interface. It allows to incorporate measurement features on the metal plates to monitor the lens position with optical sensors or a coordinate measurement machine (CMM) and these metal pads also allow to compensate fabrication tolerances of the lens outer diameter and the adaption ring inner diameter. By tailoring the thickness of the metal pads, the glue gap between lens and metal and metal and metal can be optimized very precisely. An extensive glue qualification campaign has been completed successfully, where all glass-to-metal and metal-to-metal glue interface combinations of NI-OA were tested under mission representative environmental conditions [1].

To be able to achieve highly reliable structural analysis for the NI-OA units, CTE measurements were performed for all glass, metal and glue materials systematically down to operational temperature. The reliability of the structural model is essential for calculating the mechanical loads on the lenses to predict their surface error distortion during cool down. Mechanical loadcases were analyzed and the resulting surface error assessed with ZEMAX. These analytical results were compared to actual surface error measurements of the lenses, which were performed with an interferometer. The comparison of the analytical and measurement results gives a high confidence in the representability of the structural model [2]. Additionally, the realistic CTE values are required to predict the warm geometry of CaLA which needs to pre-compensate the shrinkage of lenses, glue and all metal opto-mechanics.

The big bipods on the CaLA unit in Fig. 2 are used to mount the CaLA unit on the SIC panel of the NISP filter wheel. These bipods have to compensate for the CTE mismatch between SIC and Titanium and for any mechanical interface tolerances. Additionally, they have to provide sufficiently high stiffness to keep CaLA within its alignment budget while it is integrated vertically, tested horizontally and ultimately operates in orbit without gravity. Analysis and measurement on the CMM show a minor movement of the whole CaLA unit of up to 4µm between vertical and horizontal gravity loadcase.

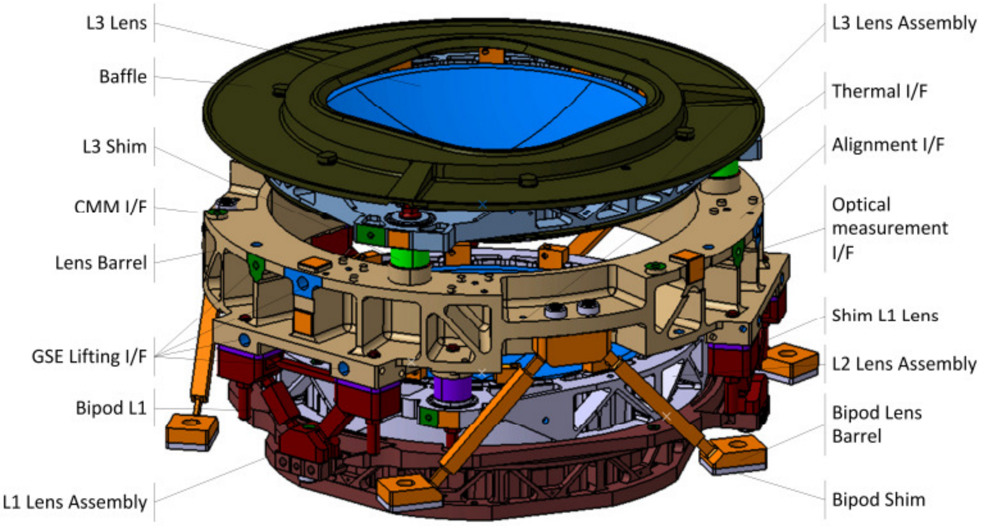


Fig. 3 CaLA opto-mechanical design

Axial positioning of the individual lenses within the CaLA unit is achieved by classical shimming, as can be seen in detail in Fig. 3. Axial shims between the adaption rings and the lens-barrel define the precise position of the lens vertices along the optical axis. As CaLA is integrated at room temperature, the axial shims also have to pre-compensate the shrinkage during cool down. Additionally these axial shims are used to compensate any tip tilt of the lenses relative to their mount. The lens gluing procedure controls the lens position quite precisely. However a minor tip/tilt of a few µm of the lens relative to the adaption ring mounting interfaces might remain. This lens tilt within its adaption ring can be precisely measured after gluing with the CMM. The lens design itself features a planar chamfer outside of the active aperture and perpendicular to its optical axis for this particular purpose. It is essential for the alignment concept to eliminate any tip/tilt of the lens, which is explained in section IV.

The axial shimming must not introduce mechanical stresses into the adaption rings, as the stress may propagate into the lens and distort its wavefront. Various concepts to minimize interface stresses have been assessed. Wedged shims could be applied to compensate for minor tip/tilt tolerance between adaption ring and lens-barrel, spherical washers could be used alternatively to adapt to these minor tip/tilt between the I/Fs. As a third alternative option, the I/F of the adaption ring can feature little flexure joints, which allow the I/F to rotate by a few µm and adapt to the I/F of the axial shim. The concept using the spherical washers was extensively studied to investigate the manufacturability, accuracy of shimming and repeatability for the desired washer material Titanium. The wedged shim option was not further considered for measurement feasibility of I/F tilts and for fabrication complexity. The I/F flexure option was analyzed structurally and bread-boarded to check manufacturability. This option finally turned out to be the most effective way to minimize I/F stresses, while µm positioning accuracy and reproducibility are maintained.

The lateral positioning of the three lenses relative to each other is not predefined by the opto-mechanical mount but is achieved during mounting and alignment. Additional alignment features can be mounted on the lens-barrel to allow relative positioning of the adaption rings with a high accuracy of a few µm.

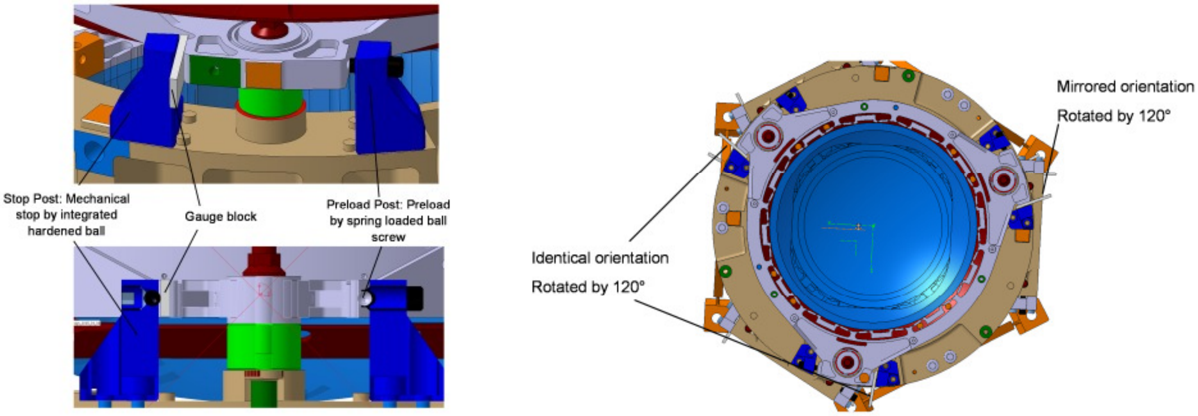


Fig. 4 Alignment features mounted on the lens-barrel for precise positioning of the lens with gauge blocks

Fig. 4 shows these alignment features for the adaption ring of L3. For L2 and L1 similar alignment features can be mounted on the lens-barrel. The principle is simple: a mechanical stop is mounted on the lens-barrel ("Stop post") and a precision gauge block is placed between this mechanical stop and the adaption ring. To achieve a constant load on the gauge block, which is necessary for good positioning reproducibility, a second "preload post" is mounted on the opposite side of the adaption ring interface, which contains a spring loaded ball screw to generate a well-defined preload. With three of these gauge blocks, oriented in 120° configuration, the position of the lens relative to the lens-barrel is precisely defined. As long as the adaption ring is not fully bolted down on the lens-barrel and still can be moved laterally, an exchange of all three gauge blocks allows a well-defined, precise movement of the lens center. Once the lens is aligned, the mounting bolts have to be tightened with full load and the adaption ring is fixed to the lens-barrel. The gauge blocks and all alignment features of the ring can be disassembled without any impact on the aligned lens position.

Positioning of the adaption ring with the help of precision gauge blocks was investigated with a dedicated alignment breadboard and showed a positional accuracy and reproducibility of one µm.

Due to mass and volume restrictions, the alignment features had to be designed so they can be mounted for alignment sequentially for each adaption ring and can be removed after successful alignment.

III. MOUNTING AND ALIGNMENT CONCEPT:

As mentioned above, the axial alignment of the lenses is achieved by shimming. The correct shim thickness is derived from CMM measurements of the adaption ring interfaces, CMM measurements of the precise position of the lens within its adaption ring and by the warm geometry of CaLA, which is calculated with the structural model and all measured material CTEs. For the lateral alignment some optical reference is needed to center the lenses relative to each other. For the Euclid NI-OA alignment a complex multi-zone computer generated hologram (CGH) was developed by MPE, which allows to center the tree lenses with µm accuracy during assembly of the unit. Fig. 5 illustrates the multi-zone CGH concept.

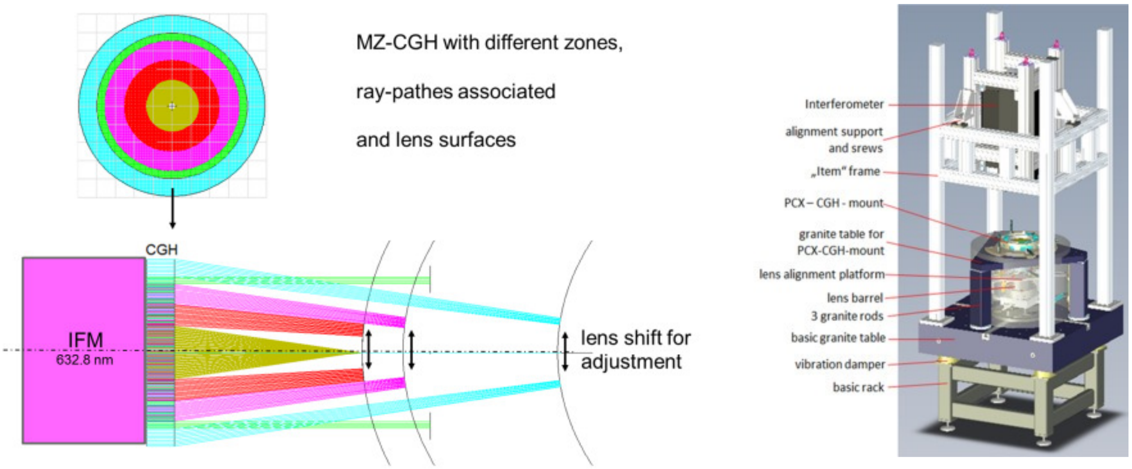


Fig. 5 Alignment concept with Multi-Zonal-CGH (left); Interferometric alignment tower (Scaled Model)

The multi-zone alignment CGH contains a number of ring zones. Each of them has a focus length which is tailored to one of the three spherical lens surfaces. An additional fourth CGH ring delivers a parallel beam, which is intended to measure a planar reference to set up the optical axis at the beginning of the mounting and alignment sequence and to be able to control the setup stability between the individual steps of the procedure. The lens radii and distances, which are used for definition of this CGH are of course the radii at room temperature and the axial distances at room temperature. The CGH therefore also contains the pre-compensation information, which is also used to define the axial shims. Interferometer, CGH and the NI-OA opto-mechanics have to be mounted in a highly stable alignment tower, as shown in Fig. 5.

As the spherical surfaces of the individual lenses are used for the interferometric measurement, the concept relies on a precise axial orientation of the lenses. They have to be precisely perpendicular to the optical axis, as the interferometric signal cannot discriminate between a small lateral shift and a small tip/ tilt of a spherical surface. Therefore the axial shimming described in the previous section has to compensate for any tip/tilt of the lenses so the interferometric signal purely detects the lateral displacement. The concept of the alignment using a multi-zone CGH has been successfully demonstrated at MPE on a scaled model. The alignment tower for the real CaLA unit is designed with a granite structure to deliver maximum mechanical stiffness and is operated in a thermally controlled ISO 5 laboratory to reduce any distortions during alignment to a minimum. The following Fig. 6 illustrates the integration and alignment sequence of CaLA:

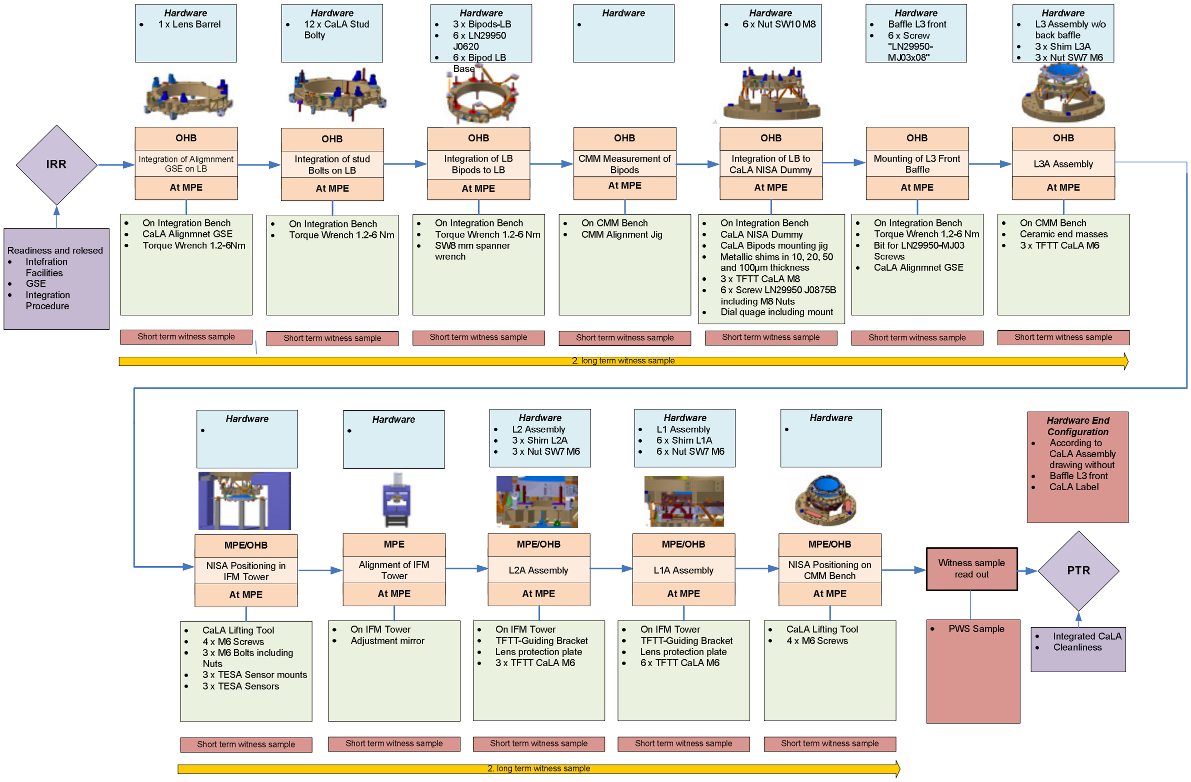


Fig. 6 CaLA integration and alignment sequence

The mounting and alignment sequence (Fig. 6) starts with attachment of CaLA bipods and alignment features to lens-barrel. This preassembly is mounted on an interface dummy. The L3 Lens assembly is then attached on the lens-barrel and mechanically centered. L3 is axially shimmed to be perfectly parallel to the lens-barrel I/F. After characterization with the CMM this assembly is integrated in the alignment tower. Interferometer and CGH now have to be aligned perpendicular to the lens-barrel mechanical axis. A plan-parallel reference mirror can be placed on the lens-barrel I/Fs. Once this is done, the optical beam of the interferometer is also perpendicular to L3. By centering the CGH/interferometer beam on the L3 lens, the optical axis is established and defines the optical axis for centering the remaining L2 and L1. As the stability of the optical axis is essential for the precision of the alignment, stability monitoring measurements are introduced. L3 is monitored with µm-resolution mechanical distance sensors to detect any sidewise movement during further integration steps. Additionally, a planar reference mirror can be placed between the interface dummy plate and the CGH/interferometer. By comparison of interferograms between each alignment step, any minor movements of the interferometer or the CGH can be detected with high sensitivity. The lens assembly for L2 can now be placed on its interface on the lens-barrel. The axial shimming between L2 and lens-barrel adjusts for any tip/tilt of L2 and positions the lens along the optical axis. Now, the little alignment features on the lens-barrel are applied. The lens is laterally positioned roughly with a generic set of gauge blocks. The interferometric measurement with the ring zone for L2 can determine the lateral offset of L2. The gauge blocks are exchanged according to the predicted alignment offset. This alignment step might have to be repeated several times, until L2 is perfectly centered on the CGH ring zone within µm accuracy. It has to be noted that during alignment of L2, the spherical surface of L3 is not accessible anymore and its position cannot be monitored optically anymore. Continuous detection of the L3 position is essential for monitoring the stability of the optical axis. Therefore, three µm-resolution mechanical sensors are attached to the interferometric tower for this purpose and allow to check if L3 and consequently the optical axis remain at their position. Once L2 assembly is fixed on the lens-barrel, the L2 alignment features have to be removed. After another stability check with the planar mirror, L1 can be integrated into the CaLA unit. In case of the L1 assembly, the L1 bipods are already attached to the adaption ring. The axial shimming consists of six planar shims, one for each bipod foot (see also Fig. 2). Similar to L2, the alignment features for L1 are installed and L1 is centered relative to the CGH with gauge blocks. After fixation of all six bipod feet, the L1 alignment features can be removed. The CaLA unit is now mounted, the lenses are positioned with their axial shims and are precisely centered relative to each other. The whole CaLA unit is now removed from the alignment tower by dedicated transport GSE (see Fig. 7 left) and is placed on the CMM to precisely measure its overall geometry. Once this room temperature geometry is documented, the CaLA unit can be placed within the cryostat to verify the correct alignment at cryogenic operational temperature. The measurement concept for this alignment verification is described in the next section.

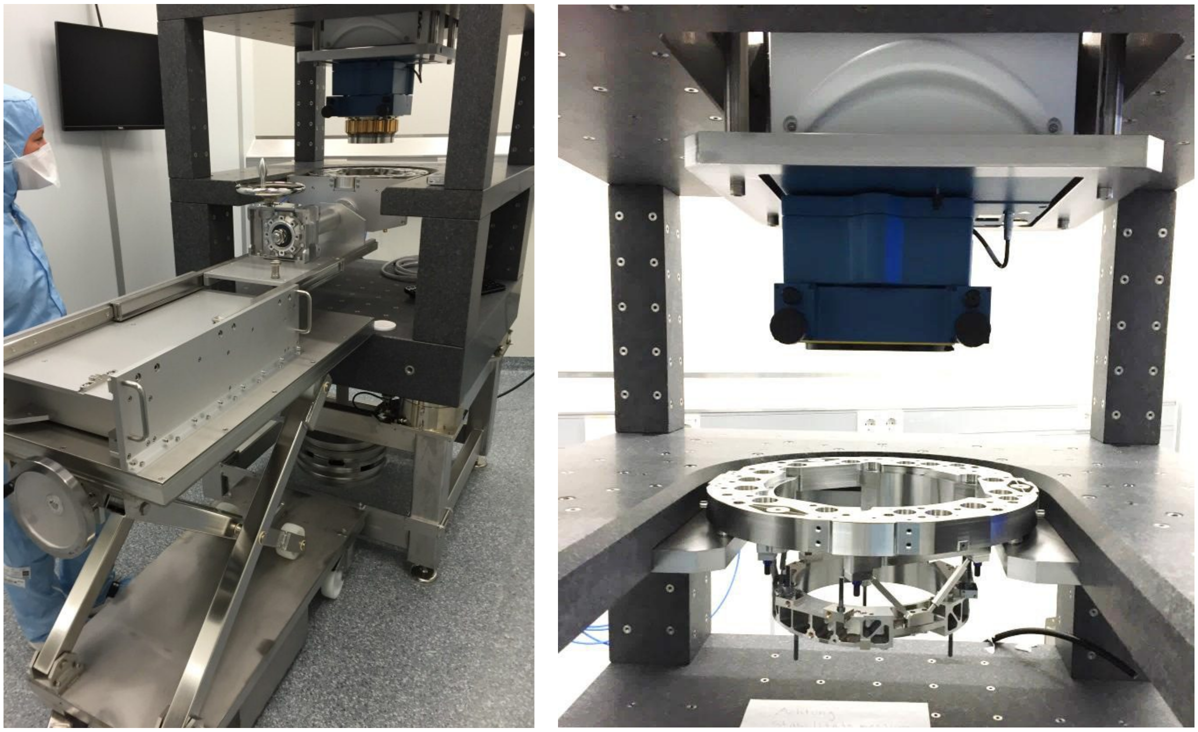


Fig. 7 Interferometer alignment tower at MPE with GSE trolley for loading and unloading of the CaLA unit (left), CaLA EQM lens-barrel and Bipods mounted on the alignment I/F dummy and placed in the alignment tower for interface fit-check (right)

IV. ALIGNMENT VERIFICATION CONCEPT:

A. *Cryogenic measurement concept*

To verify the correct alignment of the CaLA optical subsystem at the operational temperature of 134K, an innovative approach is required. A wavefront measurement through the cryostat window will not provide sufficiently accurate results as the desired data would be distorted by a cryostat window within the measurement path and allocation of alignment errors to individual lenses would be extremely challenging. Therefore, an alternative verification concept was selected, which allows to monitor precisely all positional changes of the lenses and opto-mechanics during cool down to cryogenic operational temperature. The cryogenic geometry of the system can be derived by subtraction of the cool down movements from the warm geometry. This positional measurement, which has to achieve the same accuracy as a 3D measurement with a CMM, has to take place within the cryostat at operational temperature. OHB selected a fiberoptic distance measurement sensor system, which was developed for cryogenic applications [3] and can detect movements of a flat reflective metal or glass surface in a distance range between a few cm up to more than 15cm with a sub-µm resolution.

The fiberoptic distance sensors require small, planar, polished measurement surfaces to achieve sufficient signal-to-noise ratio for their interferometric signal. For this reason, all adaption rings and the lens-barrel feature little axial and radial measurement surfaces (see Fig. 3 “optical measurement I/F” marked in orange). Each lens assembly has three radial measurement surfaces. For monitoring the axial movement of the individual lenses, the metal gluing pads between lens and adaption ring are used (compare Fig. 2. right). To allow simultaneous measurement of all three lenses, the orientation of these gluing pads for each lens assembly is slightly rotated relative to the other lenses. Thus, twelve axial sensors can monitor the tip/tilt behavior and the axial displacement of all three CaLA lenses simultaneously. To deliver a stable and precise distance measurement, these sensors have to be mounted on a highly stable sensor mount within the cryostat. The following Fig. 8 shows how this cryogenic measurement concept is realized for verification of the NI-OA alignment.

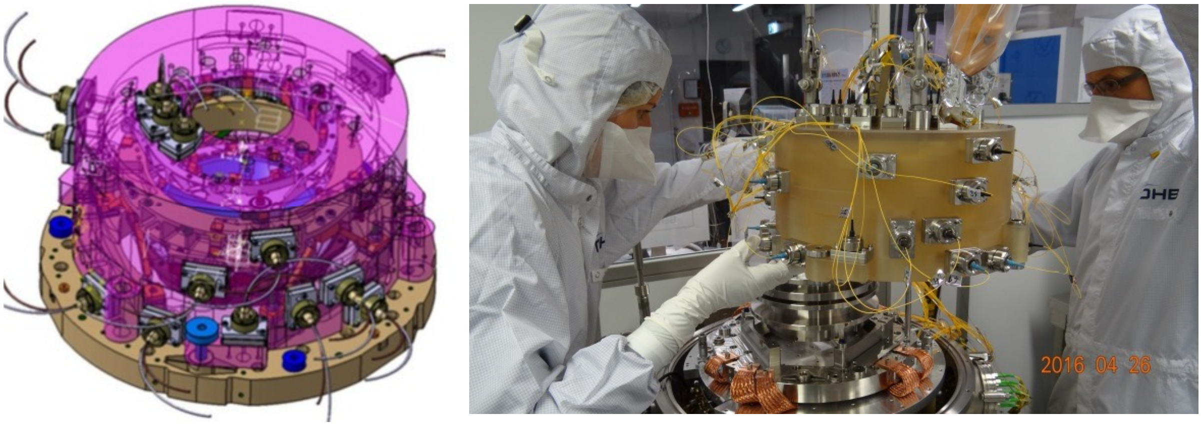


Fig. 8 Cryogenic test setup CAD view (left), actual test hardware during preparation for calibration run (right)

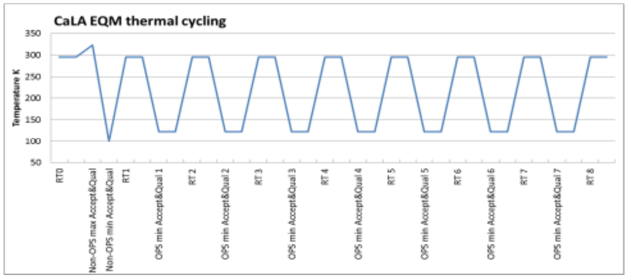
B. Cryogenic Measurement Setup

The setup to achieve these positional measurements under cryogenic conditions consists of a so-called sensor mount, which holds the individual fiber-optic sensors. Each adaption ring and the lens-barrel have a set of radial sensors. To monitor the axial movement of all lenses, twelve distance sensors are aligned axially and use the measurement surfaces of the metal glue pads. These measurement pads of the individual lenses have a slightly different rotational orientation for each lens to allow simultaneous measurement of all three lenses.

As the sensor mount has to provide maximum thermal stability during the full thermal range of the test, it is fabricated from ZERODUR. Interfaces for the fiber-optic sensors are made from INVAR to minimize stresses on the sensor mount and to minimize the thermal movement of the sensors during cool down. Nevertheless the required measurement accuracy of +/- 2µm is so high, that even the ZERODUR sensor mount with its INVAR sensor interfaces is not sufficiently stable. All movements of the sensor mount within the cryostat therefore have to be determined in a dedicated calibration run, to be able to subtract them from the actual CaLA measurements. Fig. 8 shows the sensor mount with all its fiber optic sensors attached before it is mounted on the cold plate of the cryostat. Instead of the CaLA unit, a massive CaLA dummy, made from titanium, is placed on the cryostat cold plate (see Fig. 8 right). This dummy features all measurement surfaces of the actual CaLA unit. As it is made from one material and has no mounting interfaces, shims or bipods, the shrinkage of this Titanium dummy can be precisely predicted. For the calibration test, all expected positional changes of each measurement surface can be predicted. Any additional small movements are caused by minor changes of the sensor mount geometry and are stored as test setup response function, which is later on used to correct the CaLA measurement data.

C. Verification Results for individual lens assemblies and the CaLA calibration

This whole concept was already demonstrated for each individual lens of CaLA with a dedicated smaller setup. Sensor type, ZERODUR sensor mount, data evaluation and data compensation with the calibration data of the setup was performed identically. These cryogenic tests on the individual lenses demonstrated that this concept allows to derive a lens movement of a few µm with a high reproducibility within +/- 2µm. The Lens assembly shows some settling effect during the first thermal cycle but then shows a highly reproducible behaviour for a number of full thermal cycles.



Lens to AR	Tx [µm]	Ty [µm]	Tz [µm]	Rx [arcsec]	Ry [arcsec]
RT (300K)	0 µm	-1,7 µm	0 µm	-0,2 µm	0,4 µm
OPS min (120K)	2,9 µm	-3,7 µm	-1,0 µm	-0,7 µm	1,3 µm
OPS max (142K)	2,3 µm	-2,9 µm	-0,8 µm	-0,7 µm	0,8 µm

Fig. 9 Cryogenic geometry test thermal cycling (left), results for positional change of one of the CaLA lenses relative to its adaption ring (right)

The calibration test for CaLA with a CaLA dummy, as shown in Fig. 8, achieves a reproducibility of all sensor readings during a sequence of thermal cycles below 1µm, which means that the actual CaLA measurement can be corrected for the setup response function with this accuracy.

V. CONCLUSION & OUTLOOK:

A. *Conclusion and current status*

Within the Euclid NI-OA activity the following achievements have been reached:

- Opto-mechanical design of NI-OA is completed and successfully passed CDR;
- Glue qualification is successfully completed for all material combinations of glass-to-metal and metal-to-metal gluing interfaces [1];
- CTE measurements are performed for all involved glasses, metals and glue down to 100K;
- Successful completion of vibration tests for each individual lens assembly and for both unit STMs
- Cryogenic cycling / Cryogenic geometry measurement of each individual lens assembly showing minor reproducible lens movements of up to 5µm and tip/tilt movements of a few arc-seconds;
- Positioning of a Lens assembly relative to a mounting structure was demonstrated with a dedicated alignment breadboard to reach an accuracy and reproducibility in the order of 1µm;
- MPE successfully demonstrated the Multi-zone CHG alignment concept on a scaled model;
- The STM of CaLA has been successfully mounted on the SIC Panel of NISP to test the mounting procedure and the dedicated GSE;

Recently, the EQM lenses have been glued into their adaption rings and these assemblies and the lens-barrel are characterized with the CMM. This data now allows to derive all axial shims for the CaLA EQM. The preparation of the alignment tower is under way at MPE. All GSE for integration and alignment of the CaLA unit are ready. The calibration run for the cryogenic measurements is completed and the response function of this test setup is known, so it can be used for compensation of the actual measurement of the cryogenic CaLA geometry, once the CaLA EQM alignment is completed.

B. *Outlook*

The Integration of the EQM of CaLA has started and will be under way at the time of this conference. During this activity it will become clear if the stability of the interferometric alignment tower and the alignment features of the CaLA unit allow a straightforward positioning of all lenses to the desired alignment accuracy of a few µm, or if a few iterations for each lens are required. Once the unit is integrated and aligned at room temperature, its geometry and all lens assembly positions will be fully characterized with the CMM to document the room temperature geometry. Then the cryogenic cycling with the position monitoring within the cryostat will determine if all lenses reach their defined cold position within their alignment tolerance or if the combination of all settling effects during cool down leads to lens positions which are outside of the specified tolerances. If that would be the case, CaLA has to be disassembled again. With the help of the CMM data of the aligned system and the measurement data of the cryogenic deformation, cold shims can be derived which allow to pre-compensate for any misalignment during cool down. CaLA is then reintegrated with these cold shims, just based on the mechanical alignment features and known gauge blocks and without the help of the CGH. If this cold shimming really becomes necessary or if the movement of the individual lenses is sufficiently small, as the completed tests on individual lens-assemblies indicate, will become clear within 2016. An overall optical performance test of both CaLA and CoLA in NISP configuration will be performed at MPE before these units are to be delivered to Laboratoire d'Astrophysique de Marseille (LAM) where they will be integrated in the NISP instrument.

VI. ACKNOWLEDGEMENTS

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