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## DEVELOPMENT AND VERIFICATION OF HIGH PRECISION CRYOGENIC LENS HOLDERS

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### I. INTRODUCTION:

#### A. Mission Objectives

The Near-Infrared Spectrometer and Photometer (NISP) is one of the key instruments on-board the Euclid satellite, one of the major mission of ESA's 2015 Cosmic Vision program. The instrument is located at the payload of the Euclid satellite, and it is initially planned to be operated at ~135 K, except the detectors that are cooled to about 90 K. The NISP instrument will perform spectroscopic observations and photometric imaging in 3 near-infrared bands (Y, J, H) covering a wavelength range from 0.92  $\mu\text{m}$  – 2.0  $\mu\text{m}$  over a field of view (FoV) of ~0.5 deg<sup>2</sup>.

The Euclid mission is optimized for two primary cosmological probes: Weak Lensing (WL) and Baryonic Acoustic Oscillations (BAO) [1]. The two operating modes of the NISP instrument, photometry and spectroscopy, are designed for the WL and BAO probes respectively. The photometry mode of the NISP instrument is a crucial part of the weak lensing science probe. This mode will be used to supplement the visible shape measurements with multiband, near-infrared photometry of all the imaged galaxies. This data will be used for photometric estimations of galaxy redshifts. With the large survey area (>20,000 deg<sup>2</sup>) and its multiple near-infrared bands, the photometry mode of the NISP instrument will also yield a highly valuable dataset for legacy science.

BAOs are wiggle patterns imprinted in the clustering of galaxies, which provide a standard ruler to measure dark energy and the expansion in the universe. BAO requires a high near-infrared spectroscopic capability to measure accurately galaxies redshifts at  $z > 1$  and the ability to survey the entire extra-galactic sky. This kind of surveys will also allow measurements of galaxy clusters and redshift space distortions that will provide additional measurements of the cosmic geometry and structure growth.

A central design driver for Euclid is the ability to provide tight control of systematic effects in space-based conditions. Together, these information will be able to constraint the dark energy parameters and test accurately the cosmological model. The spectroscopic redshift survey will give census of more than 108 H-alpha emission line galaxies over most of the sky in the redshift range of  $z = 0.5..2..$

#### B. NISP Instrument

The objective of the current phase of the EUCLID program is to establish the technical definition of the NISP instrument at system level and the high precision lens holder design at sub-system level that complies with its technical requirements specification. The success of recent activities has major impact on the advancements of the EUCLID project, as well as, technological development achievements are meaningful for future programs employing large lens mounts with high positioning accuracy.

Fig. 1 illustrates the NISP instrument, which consists of the optical bench, the detector mounting system (for 16 H2RG detectors), filter- and grism wheel mechanisms as well as the optical system, which is subdivided into the Corrector Lens Assembly (CoLA) and the Camera Lens Assembly (CaLA).

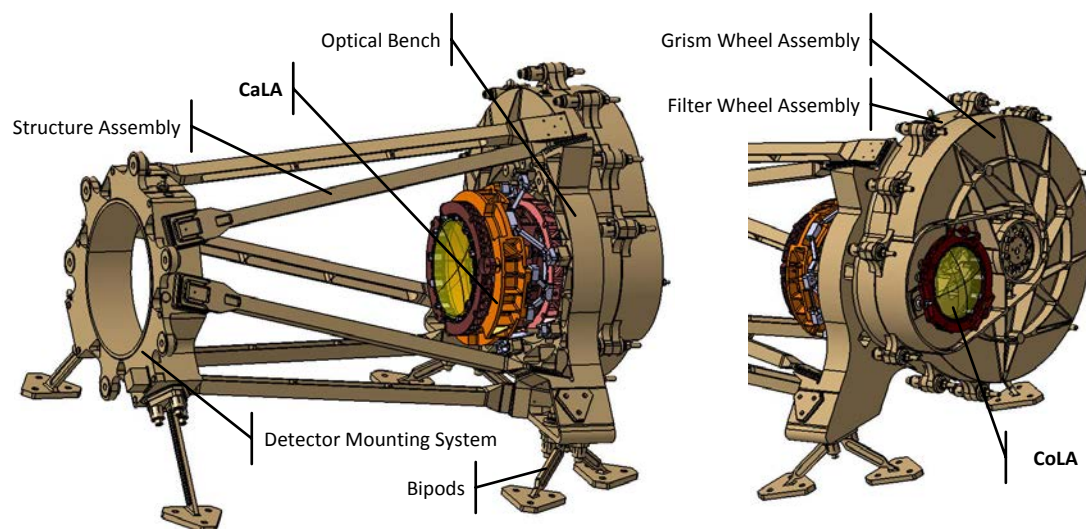


Fig. 1 NISP instrument design

The CaLA design accommodates three aspherical lenses (L1: CaF<sub>2</sub>; L2 & L3: S-FTM16), which are mounted by using adaption rings (AR) that are fixed on a robust and stiff lens barrel structure, as illustrated in Fig. 2. The slightly smaller CoLA lens is mounted onto the Grism and Filter wheel structure made of SiC using a three-foot mount and adequate inserts.

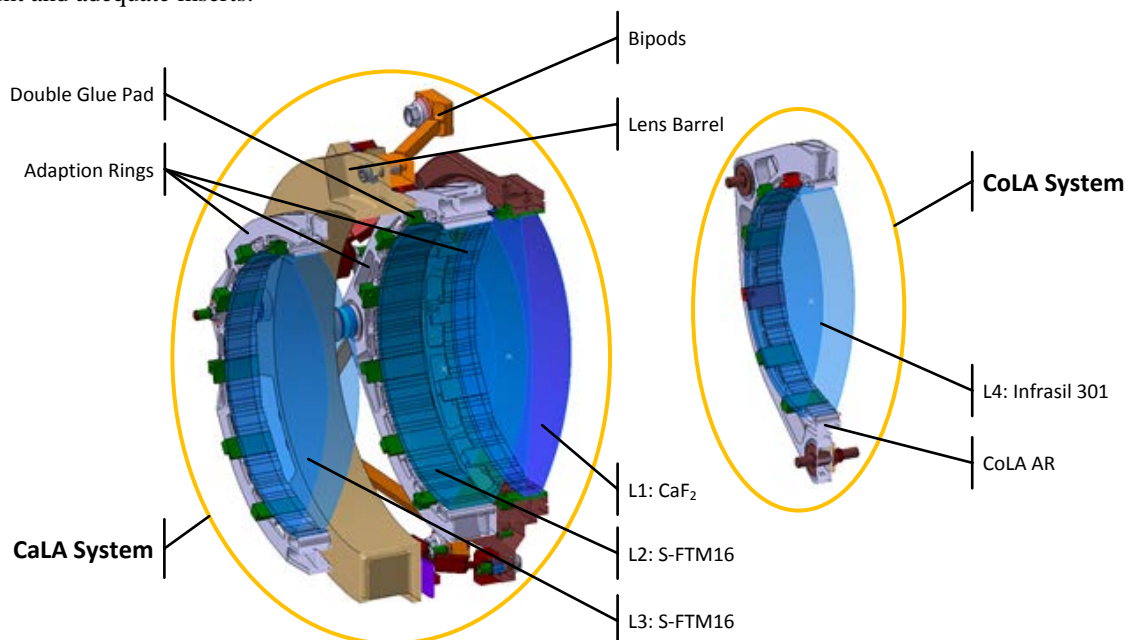
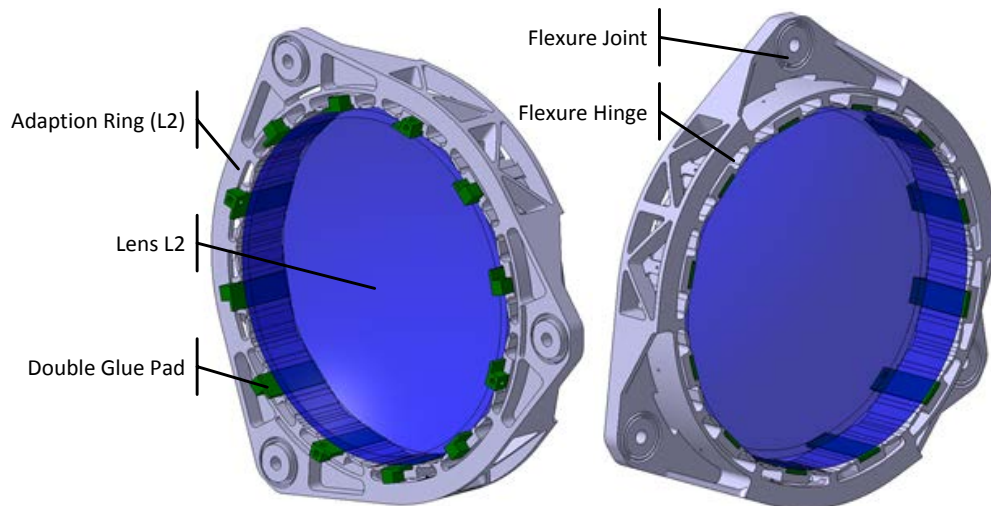


Fig. 2 CoLA and CaLA designs

The accommodation of the lenses with the needed position accuracy and operation temperature has been assessed as critical due to the positioning requirement, the large lens dimension of up to 168 mm, and the cryogenic conditions. In the context of the EUCLID project, a representative lens holder has been developed and successfully tested at OHB.

### C. Adaption Ring Design

During the analytical activities several concepts have been investigated considering material selection, manufacturing processes, operating conditions, low lens deformation, assembly procedure, etc. and selected down for candidate concept and verification tests. Each lens is glued in an adaption ring via double glue pads, which provides the necessary elasticity caused by different CTEs of the lens, glue, and ring materials at cryogenic temperatures. Furthermore, it allows high position accuracy of the lenses relative to the lens barrel and the optical axis if environmental loads are present.



**Fig. 3** Adaption Ring design of L2

Also the production, assembly, integration and test operations and maintenance of the lens holder are important technical aspects for the lens mounting concept. The results of the analytical calculations led to the AR design illustrated in Fig. 3, where the AR of the L2 lens is presented as an example. The lens is supported by complex flexure hinges that are attached to the lens by applying glue pads and space qualified epoxy bond [2]. The bonding pad diameter for each spring shall have the same dimension and thickness, otherwise, asymmetric deformation of the lens is introduced, and hence, the accurate position is not guaranteed. The AR material has similar CTE as the lens material to avoid significant stress in the lens material. Also the interface to the lens barrel is realized by means of flexure joints that allow both the high position accuracy of lens mounting and the low lens deformation introduced by CTE mismatch of the support structure.

## II. REQUIREMENTS AND DESIGN DRIVERS

The combination of technical requirements such as large lens diameter (and mass), high position accuracy, cryogenic conditions and sensitive glass and crystal materials Infrasil, S-FTM16, and  $\text{CaF}_2$  makes the design absolutely challenging. A dedicated development program has been successfully finished to design and develop the first prototype of the adaption ring and to demonstrate the functional performance at representative operational conditions. Main design drivers of the NISP instrument are

- >200 Hz eigenfrequency
- Design limit loads (20g in plane, 15g out of plane)
- Aspherical lenses
- High position accuracy (alignment + operation) requirements ( $< \pm 10 \mu\text{m}$ ) in combination with large lens diameters
- Low wavefront distortion introduced by the lens supporting structure
- Operation in cryogenic conditions ( $\sim 135 \text{ K}$  operational,  $110 \text{ K}$  survival)
- Lens material  $\text{CaF}_2$
- Mixture of different lens materials with deviating CTEs
- Survival of >10 temperature cycles
- Large diameters of lenses up to 170 mm
- High mechanical loads

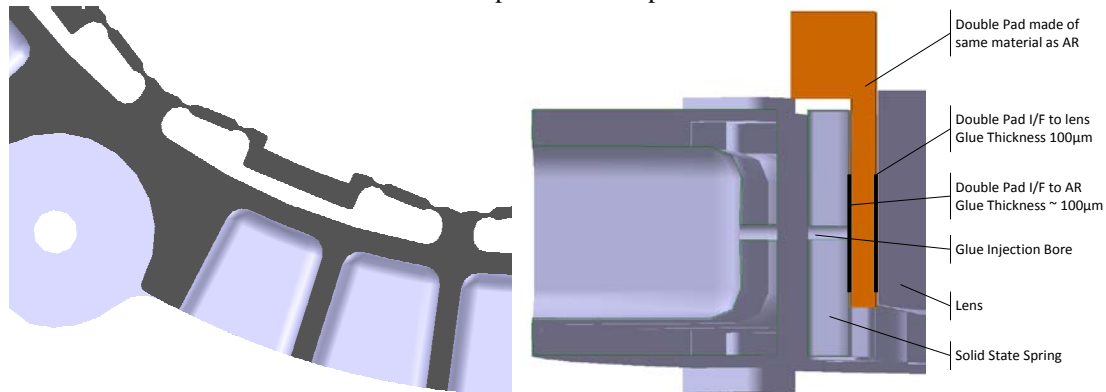
The combination of all these drivers has impact on the design feasibility. Applying of aspherical lenses has the benefit of the reduction of optical elements and thus the increased optical transmission. An additional effect is mass and envelope savings. These benefits are however related to complex lens manufacturing and increased position requirements, both for alignment as well as for stability.

## III. DESIGN & DEVELOPMENT OF NISP OPTOMECHANICAL ASSEMBLY

The 4 lenses of NISP are divided into 3x lenses for the CaLA and 1x lens for the CoLA [2]. Each lens is glue mounted to the so called double glue pads and to flexure hinges, which is part of the adaption ring. The adaption ring shall provide protection against vibration loads at ambient temperature, and high positioning and stability accuracy. Furthermore, the design shall maintain quasi load free mounting of the lens under operational

conditions, which is essential to avoid refractive index and polarization variations. To reduce thermo-mechanical loads on the lens, the CTE of the adaption ring is adapted to that of the lens. The glue between lens, double glue pad and solid state spring has to withstand high tension loads during vibration. At the operational temperature the deviating CTE between glue and lens/adaption ring introduces shear loads into the glue interface, which are critical, in particular for the fragile  $\text{CaF}_2$  lens material. For the case of NISP the shear loads are controlled with the glue pad dimension, the glue thickness, and double glue pad design.

The lens of an AR are mounted by using 12x double glue pads that are bonded on one side to the lens, on the other side to the AR itself using the same glue type. The glue pad diameters are the same for each flexure hinge with an accuracy  $<0.1$  mm, which is essential for high precision lens mounting. Otherwise, after cooling down asymmetric deformation of the corresponding lens would be introduced, and hence, the accurate position and form of the lens could not be guaranteed. Also the high precision manufacturing process of the springs by means of wire eroding is of critical importance, since its thickness shows up with the third power in the spring force, which introduces additional lens movement at the operational temperature.



**Fig. 4** Flexure hinge and glue pad design

Baseline for AR material selection is the similarity of the CTE of both lens and AR to minimize any stress in the lens material. The remaining force at OPS temperature is further reduced by the springs and so the lens deformation is kept as low as possible. Benefit of the design is that the assembled AR is mechanically very rigid and withstands the vibration loads at RT. The AR interface to the lens barrel is realized by means of 3x bipods for the case of L1 lens and 3x flexure joints for the rest of the lenses. This interface solution allows both the high position accuracy of lens mounting and a low lens deformation introduced by CTE mismatch of the support structure.

The lens barrel unit – assembled with the 3x ARs of the CaLA lenses – is mounted to the SiC structure of structural assembly by using 3x bipods. This design is necessary to compensate interface mismatch between the two systems, while the overall precision of the instrument is maintained even at cryogenic temperatures. The fixation of the bipods to the SiC structure is provided by using special inserts that have large enough surfaces and provide enough mechanical strength to supply the load conditions and offer the required position stability of the mounted lens. Any residual position changes due to the different alignment (ambient) and operational ( $\sim 135$  K) temperatures as well as manufacturing errors of the AR systems have to be compensated by shimming at CaLA an CoLA system level. The baseline shimming concept employs either polished spherical washers for the 3 fixing interfaces of the adaption rings or flexure joints. The final selection process is still an ongoing activity.



**Fig. 5** Spherical washer design

For fixation of the bolts at the interfaces a special hydraulic tool has been developed. Regular bolt connections apply relative large torque during fixation, which has the consequence of large structural deformations and hence, significant lens position change furthermore lens deformation. To avoid such deformation, a torsion free tensioning tool is developed and applied. The concept of hydraulic pulling of the screw is selected as baseline for screw tightening, and also the required space for the adequate GSE tool is foreseen in the overall instrument mechanical design.

#### IV. LENS INTEGRATION AND GLUING TOOL

The assembled adaption ring can be shimmed during the system assembly procedure; however, the lens shall be aligned relative to the AR as accurately as possible ( $<100\ \mu\text{m}$ ) in the course of the gluing procedure. The main purpose of the lens integration into the AR is the uniform glue gap and good initial orientation (centring, parallelism of reference surfaces, etc.) of the glued pieces. The adjustment and gluing of the lens relative to the AR is performed in two separate steps and with two different integration tools, the so called Double Pad Gluing System (including glue dosing station) and Lens Mounting Tool.

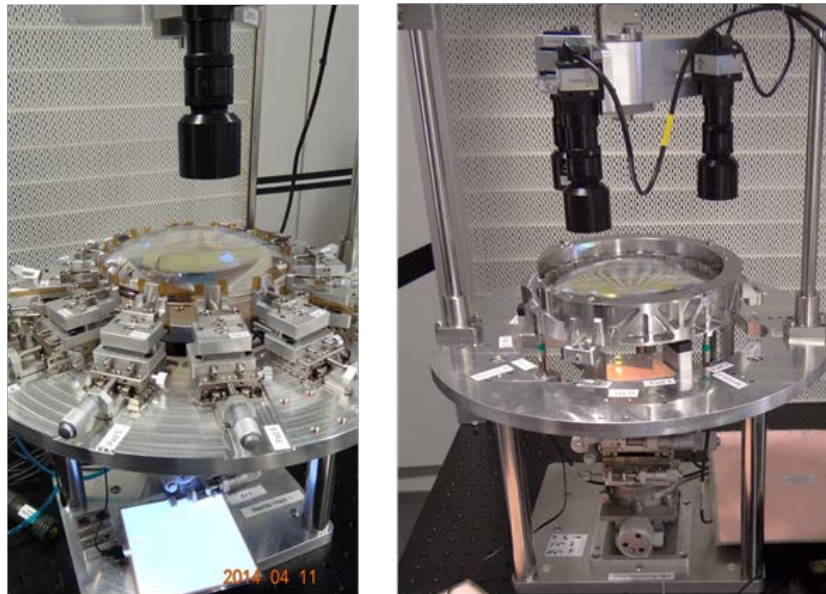


Fig. 6 Double Pad Gluing System (left); Lens Mounting Tool (right)

The Double Pad Gluing System allows the gluing of double pads on the lens with appropriate glue gap and glue pad diameter. The Double Pad Gluing System is equipped with a hexapod system and three radially placed high-precision mechanical distance sensors ( $<1\ \mu\text{m}$  accuracy), which makes possible to move the lens in the right position (lens centering and correct height) and fixate it without any stress applied to the lens. The appropriate gap between the double pads and lens is maintained by inserting plastic shims in the vicinity of the glue. After dosing the required glue volume into the glue injection holes the double pad is pressed with defined force until the glue is finally cured. The glue gap dimension and glue pad diameter are monitored by using a digital camera, and self-written software routine. Finally, the quality of the gluing procedure is inspected by laser light and the introduced stress in the glass is measured by a polarimeter.

In the second step of the lens integration procedure the Lens Mounting Tool is employed. The lens including the double pads is lifted up to the accurate position and its relative place to the adaption ring is continuously monitored by using high precision inductive distance sensors. The equidistant glue gap and glue diameter is essential to reduce asymmetric stress in the lens material, especially if the lens is cooled down to the operational temperature. Finally, the lens position and gluing gaps are adjusted then the gluing of double pads to adaption ring is performed. The required glue diameter will be reached by simultaneous monitoring the injection area by digital cameras. After gluing process the glue is cured at ambient temperature according to the glue data sheet. Relative to the adaption ring reference plane this technology allows 25 arcsec tip/tilt and  $50\ \mu\text{m}$  in-plane integration accuracy. The sequence of the integration procedure is illustrated in Fig. 7.

During the whole gluing procedure any vibration or shock of the Lens Mounting Tool shall be avoided, otherwise the position precision and symmetry of the assembly is not preserved.

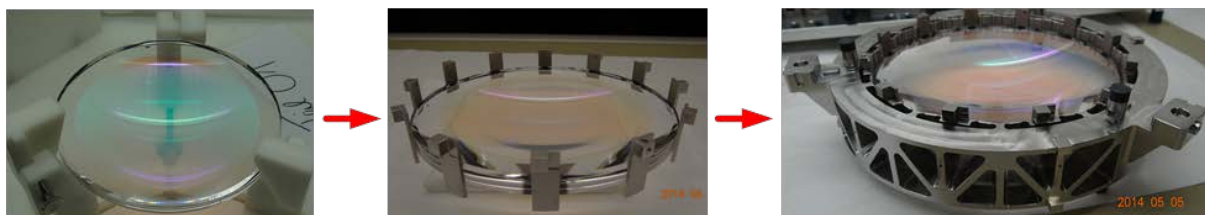


Fig. 7 Lens integration sequence

V. ANALYTICAL PERFORMANCE VERIFICATION

Detailed structural and thermal analyses have been carried out with the NISP opto-mechanical assembly (NI-OA). In the course of the analysis various environmental loads are considered at system level, such as glue shrinkage effects, I/F tolerances, screw tightening, thermal gradient over the lens surface, cooling down from ambient to operation temperature, gravity, and gravity release. All these loads change the lens optical behaviours and produce position changes and thermo-elastic deformations of the lenses assembled in CaLA and CoLA. In the context of the investigation the surface front error of all NI-OA lenses as well as the RMS WFE at the NI-OA focal plane is assessed in the Zemax model of the optical system, and results are compared with the nominal instrument performance.

A. Assessment Process Description

The steps of the performance assessment are visualized in Fig. 8. The procedure is relative complex since the assessed data are processed with different CAD tools (Femap, Nastran, Matlab, Zemax) having different input and output data format.

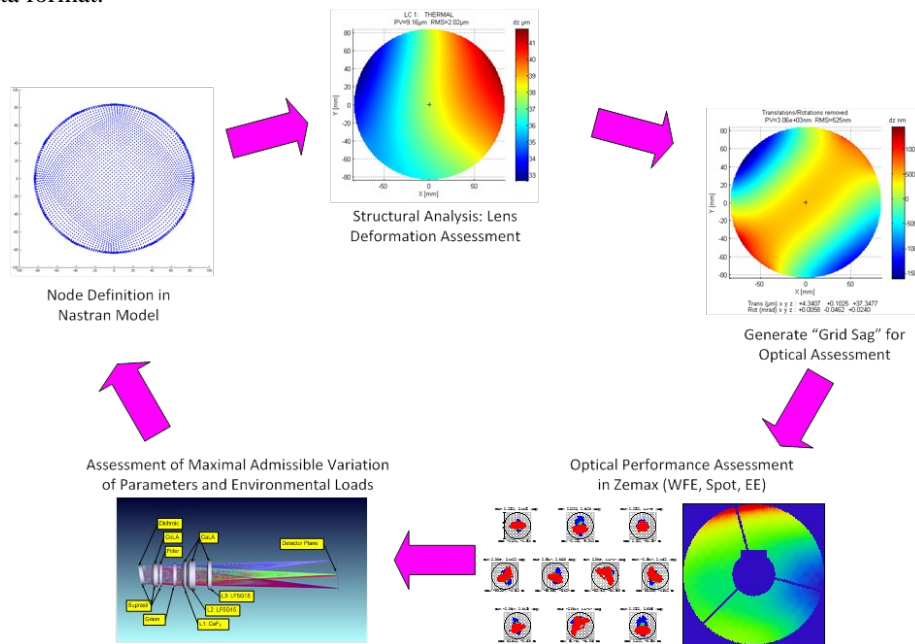


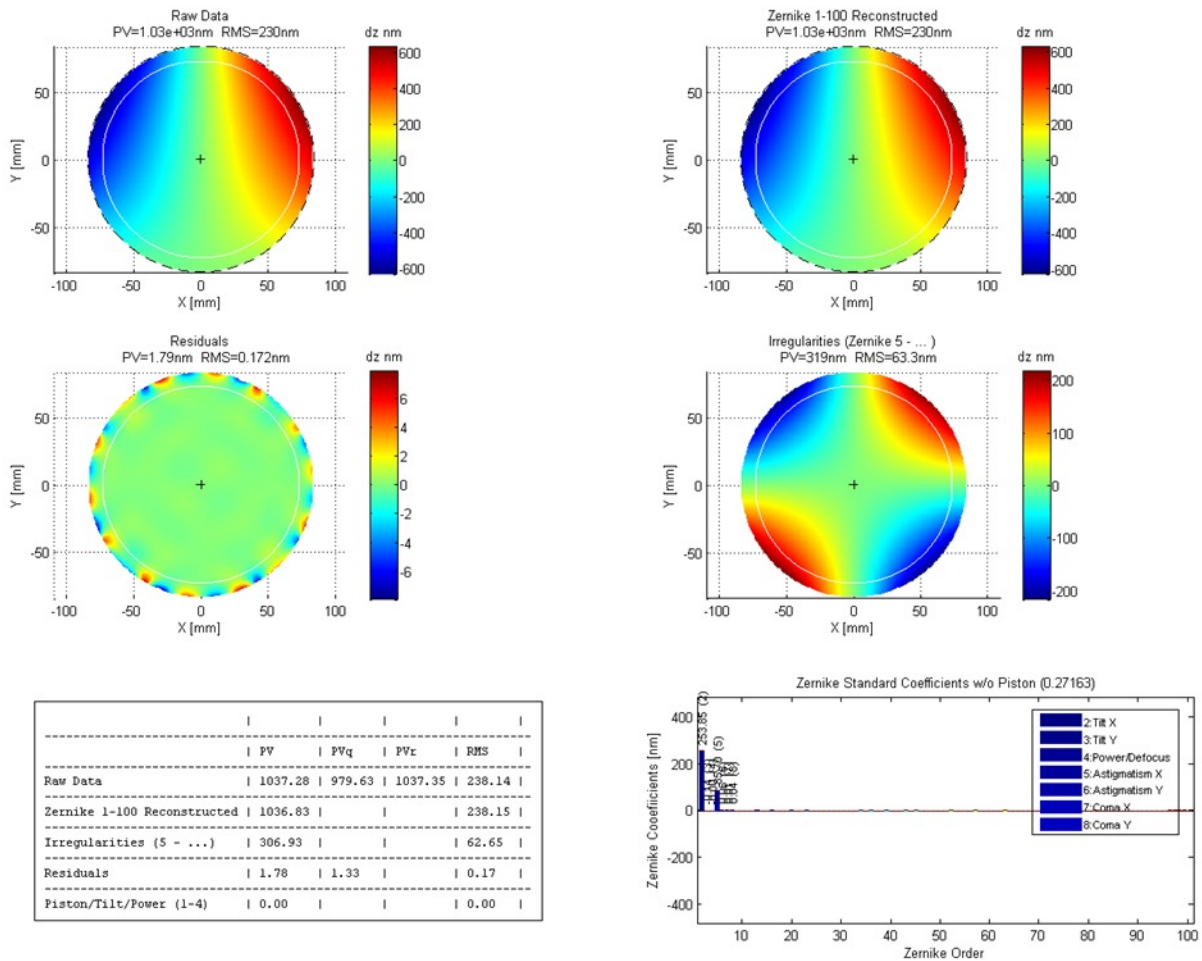
Fig. 8 Performance verification process

At first, the lens form from the optical model is provided for structural modelling using e.g. step model or analytical definition of the surfaces. Then in the structural model the mapping of the lenses and all mechanical mounts and the relevant components of fixing are performed at system and sub-system levels. These resulting nodes describe the structural behaviour of the system at the presence of environmental loads.

For further optical performance analysis the numerical data of Nastran (structure analysis software tool) that describe lens deformation and position change have to be exported using in-built program routines. The numerical data of the deformed lens surfaces have to go through on additional data processing prior to the optical performance assessment. With the mathematical tool Matlab the nodes that are used in the structural model are fitted with Zernike-polynomials. The coefficients of the Zernike-polynomials are then used in Zemax for optical modelling of lens deformations and displacements. A typical deformation of the CaLA L1 concave lens surface is depicted in Fig. 9, which is generated by the Matlab tool. For the assessment the following environmental loads are involved:

- Lens deformation due to glue shrinkage during curing,
- I/F tolerances (set of different interface tolerances),
- Thermal loads including gradient over the lens surface, and
- Gravity load in lens axial-, and radial directions.

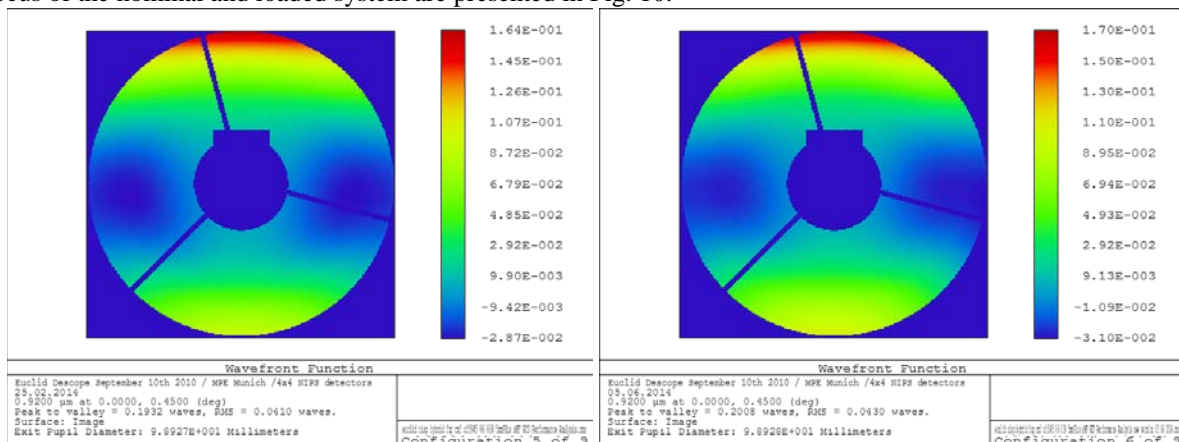
It is well seen that the initial lens surface deformation of 1 µm peak-to-valley or 230 nm RMS (top left) is fairly good reconstructed by the Zernike polynomials (top right). The residual fit error is at the range of 1.8 nm that rather negligible to the overall deformation introduced by the environmental loads; however, the effect of the 12 glue pads are clearly recognizable.



**Fig. 9** Deformation of the L1 lens in presence of environmental load (lens units in mm, deformation in nm). Raw data of the lens deformation (top left), Zernike fit of the reconstructed deformation (top right), Residual terms of the Zernike fit (middle left), irregularity terms of the Zernike fit (middle right), fit statistics (bottom left), distribution of fitted Zernike coefficients (bottom right)

**B. Assessment Results**

Each lens surface is assessed one by one and the Zernike fit results are imported to the Zemax optical model of the instrument. After implementation the numerical data the optical system is optimized in terms of detector position and tilt angle, which is according to the alignment procedure. The corresponding WFE maps at the focus of the nominal and loaded system are presented in Fig. 10.



**Fig. 10** WFE map at 920 nm for one relevant field angle for the nominal (left) and loaded NIOA system (right)

At system level the RMS wavefront deformation contribution of the environmental loads can be evaluated from the nominal performance of the NI-OA system by considering the quadratic sum rule of WFE calculation:



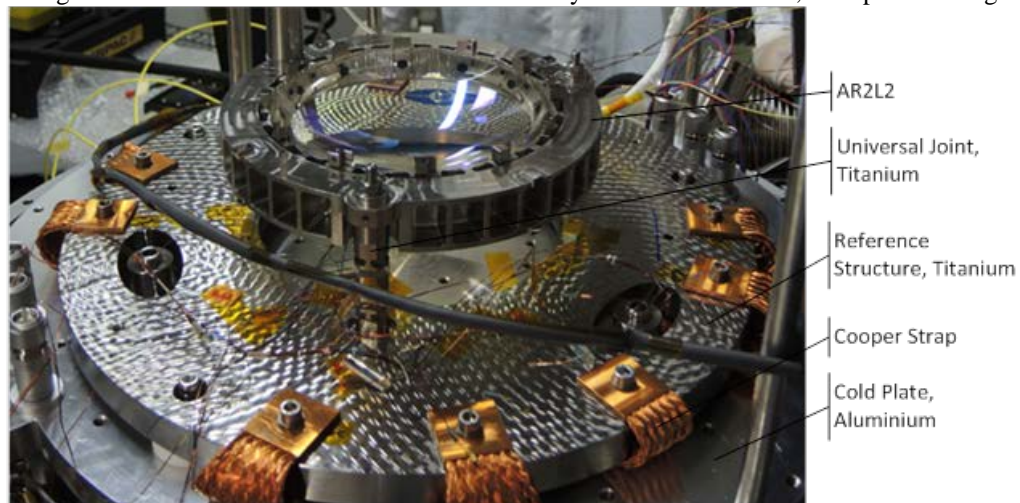
$$\Delta WFE_{\text{Loaded System}} = \sqrt{WFE_{\text{Nominal}}^2 - WFE_{\text{Deformed}}^2}$$

For one relevant field angle the WFE deformation introduced by the environmental loads is calculated to be 12 nm, which is at acceptable small level compared to the nominal 38 nm RMS WFE. Based on the detailed assessment investigation it can be concluded that gravity effects have marginal impact on the WFE performance. However, main contributor is the interface tolerance, as well as thermo-mechanically induced lens deformations. The resulting WFE distortion is approximately 40 nm at the NISP system level, which does not significantly affect the imaging quality of the instrument.

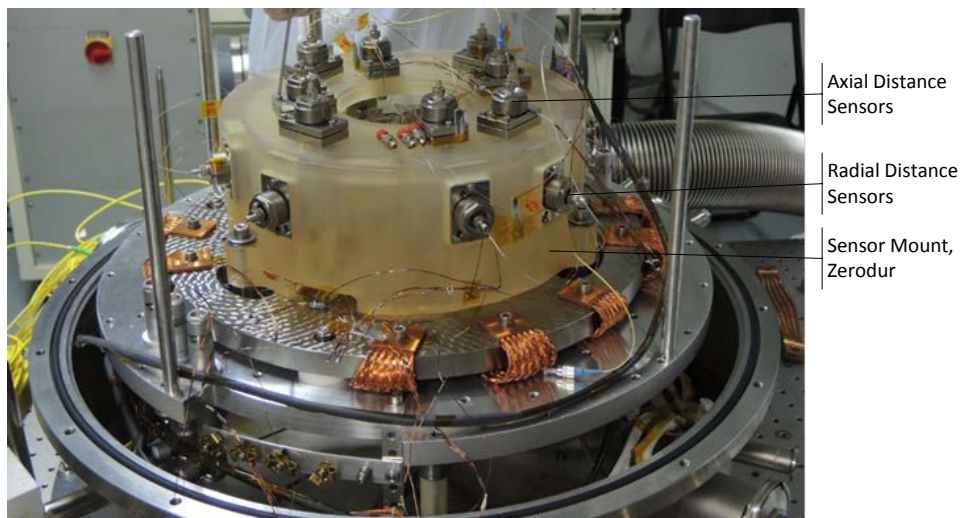
## VI. FUNCTIONAL TESTS

### A. Test Setup description

Complex functional tests have been carried out during the test campaign performed with CaLA L2 lens made of S-FTM16. The lens assembly successfully survived the vibration-, thermal cycling-, bake-out-, and cryogenic tests. This section of the paper concentrates only on the cryogenic test results. Main goal of the test is to demonstrate the position stability of the lens to the adaption ring at the operational temperature of 135 K. Several calibration measurements have been performed with the distance sensors (product of Attocube) in order to be able to calculate the lens movement in radial and axial directions, similarly as presented in [3]. The test setup involves the following components: reference structure (titanium, function is the decoupling of adaption ring from cryostat cold plate made of Al), 3x universal joints (titanium), CaLA L2 assembly (titanium, S-FTM16), and sensor mount (Zerodur). Copper straps provide appropriate thermal connection between cryostat cold plate and adaption ring. 21 thermal sensors record the temperature measured at different positions of the setup, as seen in Fig. 11. The movement of the lens are measured by 18 distance sensors, as depicted in Fig. 12.



**Fig. 11** Cryogenic test setup of CaLA L2 lens



**Fig. 12** Sensor mount with distance sensors

B. Results of the measurement

After one settling cycle three temperature plateaus ambient (300 K),  $OPS_{min}$  (120 K) and  $OPS_{max}$  (142 K) are reached and stabilized. The translation and tip/ tilt movements of the lens are derived from the calibration data and from the measured distances, as illustrated in Fig. 13.

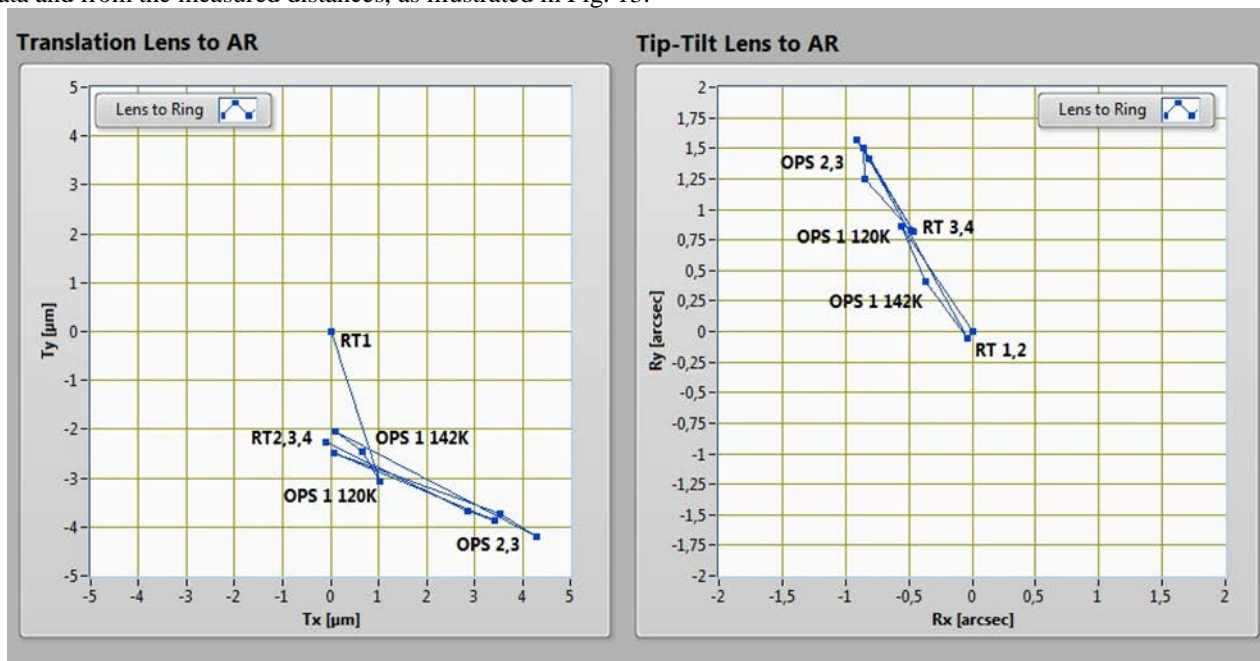


Fig. 13 CaLA L2 assembly: relative translation between lens and adaption ring (left), relative tip-tilt between lens and adaption ring (right)

The lens shows repeatable displacement behaviour in the order of  $<4 \mu\text{m}$  at cryogenic temperatures down to 120 K. Also the tip/tilt values are  $<1.5 \text{ arcsec}$ , which proves the excellent design, manufacturing, and assembly procedure of the system. All these values are well within the requirements of  $\pm 10 \mu\text{m}$  for displacements in any directions and  $\pm 10 \text{ arcsec}$  for angular movements. The small position change however is due to manufacturing accuracies e.g. the solid state springs that results in small variation of the spring constant or variation of the glue gap and glue pad diameter, which might cause some asymmetry in the lens assembly during cooling down and hence lens movements relative to the adaption ring.

VII. ACKNOWLEDGEMENTS

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