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HARMONI - First light spectroscopy for the ELT: Spectrograph camera lens mounts

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ABSTRACT

HARMONI is the first light visible and near-infrared (NIR) integral field spectrograph for the Extremely Large Telescope (ELT). The HARMONI spectrograph will have four near-infrared cameras and two visible, both with seven lenses of various materials and diameters ranging from 286 to 152 mm. The lens mounts design has been optimized for each lens material to compensate for thermal stresses and maintain lens alignment at the operational temperature of 130 K. We discuss their design and mounting concept, as well as assembly and verification steps. We show initial results from two prototypes and outline improvements in the mounting procedures to reach tighter lens alignments. To conclude, we present a description of our future work to measure the decentering of the lenses when cooled down and settled.

Keywords: flexure lens mount, assembly procedure, camera alignment, mounting, prototypes, ELT, cryogenic adhesive

1. INTRODUCTION

HARMONI is the first light visible and near-IR integral field spectrograph for the ELT. It covers a large spectral range from 450 nm to 2450 nm with resolving powers from $R \equiv \lambda/\Delta\lambda$ 3500 to 18000 and spatial sampling from 60 mas to 4 mas. It can operate in two Adaptive Optics modes - SCAO (including a High Contrast capability) and LTAO - or with NOAO. The project is preparing for Final Design Reviews (See Ref. 1).

The spectrograph sub-system includes four near-infrared (NIR) cameras and two visible (VIS) cameras (See Ref. 2). Our final camera designs have seven lenses of various materials and sizes for both cameras. (See figure 1). The spectrograph will operate in vacuum at 130K.

The lenses will be supported in flexure mount rings based on a design inherited from FMOS and KMOS instruments. This design demonstrated to work well for both of these projects. The KMOS instrument is currently in operation at the VLT. Its lens mounts have not reported failure since first light in November 2012.³ The spring flexure in the lens mount keeps the thermal stress resulting from a lens-to-mount coefficient of thermal expansion (CTE) to mismatch well below the optics critical values. The lens alignment is kept after cool-down and warm-up cycles, transport and survives large shock events such as earthquakes.

The alignment requirements for the HARMONI lens mount assemblies are challenging and critical to the performance of the cameras. Our alignment tolerances for each degree of freedom are described in table 1. The HARMONI lens mount design will be a modified version of the KMOS design. Improvements to the mount design are being developed through prototyping and testing.

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Figure 1. Final opto-mechanical designs of HARMONI spectrograph cameras.

DoF	DoF type	Description	Tolerance
x	Centred during mounting limited by CTE interaction	Thermal expansion coefficient mismatch decentring limitation in the lens mounts	Max. 20 μm
y			Max. 20 μm
z			$\pm 10\mu\text{m}$
Tip	Alignment DoF	Mounted lenses sub-assembly tip and tilt misalignment	10 μm run-out
Tilt			
Roll	Discrete compensator (60 deg)	Lenses clocking compensator	Compensator

Table 1. Lens mount assembly tolerance requirements.

2. DESIGN AND MOUNTING CONCEPT

2.1 Flexure mount design

The lens mount assembly design was developed by Froud, T. R. for the FMOS instrument (see Ref. 4) and improved for VLT-KMOS (see Ref. 5). Then it was implemented for the spare camera of SWIFT (see Ref. 6). Variations of this design have also been considered and tested by Allen J. (see Ref. 5). For the HARMONI cameras, we propose a modified version driven by HARMONI requirements to improve the tip-tilt alignment. The modified design will be optimised for the bond area considering the room temperature elasticity of the bonds and wedge specification for the lenses.

In the flexure mount design, the lens is held with adhesive to pads fastened to a mount ring (see figure 2 for guidance). The mount ring is made of aluminium (as the rest of the camera structure) and contracts more than the lenses themselves at their operational temperature. By employing the principle of spring action of the flexures, the thermal stress transmitted to the glass is significantly reduced. The pad material is selected to best match the lens coefficient of thermal expansion (CTE). Due to the symmetry of the flexures, the flexure mount is ideal for keeping the lenses centred. A prototype flexure mount with slotted rectangular pads achieved a maximum measured decentring of 20 microns after cool-down and settling to 130 K.⁷ The movement of the KMOS flexure mounts has not been measured but has proven to function. As further work to this manuscript, we aim to measure and confirm a similar maximum radial displacement for the HARMONI lens mounts.

The lens mount assembly (Figure 2) consists of:

- An Aluminium ring which has spring flexures equispaced radially around the inner diameter and oversized fixing holes (for radial alignment in its barrel).
- A set of threaded mount pads with the capability to fix the adhesive bond thickness. Its shape is optimised to match each lens thickness. Material CTE is closely matched to the lens material (e.g. Invar-fused silica, titanium-ZnSe).

Figure 2. Example of flexure mount design. (left) Lens mount assembly. (top right) Pad design for a lens with 10 mm edge thickness. (bottom right) The pads position can be adjusted. Our adhesive bonds consider a lens edge covered with a cotton paper layer strip and a bond thickness of 0.2 mm.

2.1.1 Mount ring

The mount ring design follows a flexure pattern that is radially symmetrical and is repeated every 60 degrees (see Figure 3). The size of the lens and its barrel defines the inner and outer diameters of the ring, respectively. The default design considers six pads to hold the lens and six fixing holes. The number of pads and their diameter can be optimised depending on the lens mass and edge thickness. The fixing holes are oversized to allow the mounts to be radially aligned in their barrels to the optical axis of the camera. The mount ring has a preferred assembly orientation which is considered when mounting the lenses. The lens optical axis is aligned to be perpendicular to the assembly face of the mount ring in the camera barrel. The mount ring design allows a 2.5 mm separation between the lens and the ring. During lens mounting this clearance allows play to correct for manufacturing wedge in the lens. It also leaves enough space to set the position of the pads to provide a 0.2 mm thick glue-line. The critical design parameters of the mount ring are the thickness of flexures and its radius of curvature, and the thickness of the mount. The flexures are designed to achieve a maximum stress on the lens lower than the lens material fracture stress. The thickness of the mount is also driven by the centre of gravity plane of its lens. Where possible, the lens centre of gravity plane is matched to the mount's edge thickness mid-plane, and offsets are avoided to minimise any torque in the flexures. The mount ring material has been selected to be 6082-T6 or C250 top plate Aluminium Alloy due to its innate flatness machinability. The expected parallelism and flatness as-manufactured tolerances are below 0.025 mm. The flexure sections of the mount ring are machined using a Wire EDM process as conventional machining processes cannot produce the 0.8 – 2.0 mm thick beam section profiles.

Figure 3. Mount ring design diagram.

2.1.2 Mount pads

The pad design is driven by the lenses edge thickness and shape, considering its chamfer. When possible, the lenses centre of gravity plane passes through the axis of the pads. Otherwise, the lens edge thickness mid-plane is chosen. From experience acquired from the FMOS and KMOS projects, the surface area that makes up the adhesive bond is circular. As shown in Figure 4, the pads have a 5-degree angle to produce an ideal bond with no hard edges. The diameter is calculated to produce a bond area that can hold alignment and distribute the weight of the lens among all pads. The pads also consider a conduit for introducing the adhesive dispenser syringe. Its thread allows adjustment of the adhesive thickness and can be set with a flat-blade screwdriver.

2.2 Mounting concept

The first step to assemble the camera modules is to align and mount the lenses to their flexure mounts. This process relies on the documentation and experience acquired by RAL Space and the University of Oxford on the projects FMOS, KMOS, SWIFT and further prototyping.

The lenses are aligned and assembled in a mount jig. The mount jig is placed on top of a rotary table and aligned to match the rotation axis of the rotary table. The mount jig has three precision setting spheres where the lens rests and a set of parallels on the sides to support the mount ring at its required height and radial position.

The mounting concept is shown in figure 5. The lens is placed on three spheres equispaced at 120 degree intervals located outside the lens effective aperture. The axis of the circumference formed by the spheres is set as the origin of the x_{sph} and y_{sph} axes. By placing the lens on the spheres, the symmetry axis of the lens can be found by clocking the rotary table and probing the lens top surface with a low-force dial gauge. The lens is incrementally displaced until it reaches alignment when the lens $x - y$ plane is parallel (within tolerances) to the $x_{sph} - y_{sph}$ plane of the spheres. When an aspherical surface is the top surface of the lens, two lens planes are

Figure 4. Mount pads design diagram.

measured at different heights, and the same procedure is followed to reach alignment. Then, the mount ring is placed on the mount jig parallels. The height of the parallels sets the mount ring edge thickness middle plane to the required location along the lens edge thickness. The position of x_{mnt} and y_{mnt} of the mount ring is adjusted to match x_{sph} and y_{sph} .

Figure 5. Lens mounting concept diagram.

3. ASSEMBLY AND VERIFICATION

The HARMONI spectrograph cameras are assembled in three main steps:

1. The seven lenses are aligned and fixed to their mount rings.
2. The mounted lenses are placed in their camera barrels and radially aligned in groups.

3. The barrels are assembled along with the camera housing.

In this manuscript, we focus on the first step, the assembly and verification steps required to mount our 42 visible and near-infrared camera lenses.

The assembly of one lens to its mount requires eight main procedures. Figure 6 displays a flow diagram of these processes.

Lens preparation: The lens and its coating is inspected following ISO 9211-4:2012(E) Annex C. The edge of the lens is cleaned to remove any trace of grease and primed with a brush. The employed primer is Dow DOWSIL 1200 OS Primer as recommended for our chosen adhesive. The cotton paper ribbon is cut out to the pad diameter and adhered to the lens edge with the cryogenic adhesive.

Mount jig preparation: All components are cleaned with an ultrasonic bath and then assembled and certified with a coordinate measuring machine (CMM). The position of the setting spheres, the height of the parallels with respect to the mount rotation reference should not defer more than 5 and 10 microns respectively. These pieces can be shimmed to correct their position.

Mount preparation: The flexure mount ring and the pads are cleaned in an ultrasonic bath, and the pads are assembled in their slots. The pads bond area is primed.

Rotary table correction: The error motion of the table limits the best achievable alignment. Thus the error motion needs to be corrected to meet the required alignment before proceeding to align the lens and mount. The error is quantified with the CMM and dial gauge and corrected accordingly with shims or with a tip-tilt platform.

Lens alignment: The lens is placed on its correct assembly orientation in the setting spheres and aligned to the rotation axis of the rotary table. The maximum allowed run out will depend on each lens. During this step it is key to constrain the alignment of the lens and maintain it until the end of the adhesive curing period.

Mount alignment: The flexure mount ring is placed on top of the mount jig parallels with great care not to touch the lens. Then it is radially aligned to the rotation axis. This step ensures the lens to be centered with respect to its flexures thus allowing them to perform as symmetric as possible during cool-down to maintain alignment.

Adhesive application: During this step the SD 340 adhesive dispenser is prepared and tested with a pressure of 100 PSI and continuous flow. The syringe is filled and centrifuged with a portion of Dow DOWSIL 6-1104CV Sealant. The bond thickness is set for each bond by using a 0.2 mm feeler gauge and adjusting with a screwdriver as shown in Fig. 4. The syringe tip is introduced in the conduit and adhesive is dispensed until it reaches the angle in the pads.

Adhesive curing: The lens assembly is left untouched on the rotary table for seven days. Further tests to determine the curing time of our bonds are planned.

The verification of the lens mounts assembly is a relatively simple process. The alignment of the lens with respect to the mount assembly surface is verified without setting spheres holding the weight of the lens. This alignment should meet our requirements.

The assembly and verification of the cameras are carried out in a clean-room environment class 7 at a controlled temperature of 18 degrees Celsius.

4. PROTOTYPES

To develop and refine the lens mount design for the HARMONI cameras, we have built two prototypes. The FMOS and KMOS lens mount assemblies did not report the final alignment per lens. The HARMONI alignment requirements shown in table 1 were a result of the tolerance analysis of the cameras. We identified that the tip and tilt alignment had a high impact on the performance of the cameras. Thus, we had to investigate what could be achieved following the assembly procedure for the previous projects.

Figure 6. Procedure flow for assembly and verification of the camera lens mounts

4.1 Flat blank with KMOS mount design

The aim of this prototype was to perform the conventional assembly procedure and identify the parameters that played a role in the tip-tilt alignment of the assembly. The blank we used for this prototype is a fused silica slab we had in our storage with no particular manufacturing tolerances. The mount ring design is KMOS like, except for a few modifications in the flexure design to ease the manufacturing in the workshop. Hidalgo, A. performed the assembly procedure based on the information collected from the previous projects. Several adhesives have been tested throughout the years, and the chosen for KMOS was Dow DOWSIL 6-1104CV Sealant, which we purchased in the UK from [Ellsworth adhesives](#). For previous assemblies problems were reported during cool-down.⁸ When the adhesive hardened, the bonds had thermal stresses around the edges of the pads beyond the lenses fracture stress resulting in damage to the lenses. One of the steps taken to mitigate this was the introduction of a cotton paper layer covering the lens edges. We have adopted this and used Arches Aquarelle hot press 190 SSM paper (used on KMOS, SWIFT spare camera and Allen J. prototypes⁶) which we bought at the local Oxford art shop. Another key element for bonding is an adhesive dispenser. We use the Semco Electropneumatic Timed Syringe Dispenser SD 340.

The procedure was carried out in the instrument assembly lab in the Beecroft building at the University of Oxford with clean-room conditions ISO class 7. The assembly process followed was a simplified version than that outlined in section 3. We measured with a CMM the blank shape, mount jig assembly and alignment, setting spheres static and dynamic position, rotary table error motion, lens and mount alignment throughout time, and the position of the spring flexures.

The mounted blank and the assembly alignment are shown in Figure 7. The achieved tip-tilt alignment for the chosen assembly orientation is 1.36 arc-minutes. Given that our requirement is 0.3 arc-minutes we investigated further how could we achieve a better alignment. The radial alignment started at 4 microns and

settled at 17 microns during curing time. The spring flexures also showed a variation in position during curing time pushing the lens towards bonds 3, 4 and 5. This movement indicated that during bonding, we had pre-loaded the spring flexures. The cylindricity of the blank is 5.6 arc-minutes which caused bonds with significant thickness variations.

For the case of a flat-flat surface, the alignment is limited by the mount jig. The CMM measurements gave an angle between the plane of the setting sphere and plane of the mount jig parallels of 1.5 arc-minutes. The heights of the parallels and the setting spheres had variations of up to 69 microns, causing this angle. The set-up was not optimal, and despite that, a good alignment was achieved.

Figure 7. Flat blank with KMOS mount design prototype. (left) The mounted blank on top of the rotary table. (right) Angle between the mount's top surface and the blank's top surface measured with the CMM. The measurement day refers to the number of days since bonding. First number is for bonds 1,3 and 5. Second number is for bonds 2, 4, and 5.

4.2 HARMONI *mock* lens and mount pre-design

Allen J.⁶ rebuilt the Oxford SWIFT spare camera and described the procedure for mounting lenses with curvature and diameters < 120 mm. HARMONI camera lenses diameters range from 286 to 152 mm. The objective of this prototype was to mount a HARMONI like lens with the thinnest acceptable edge thickness.

The *mock* lens used has a 205 mm diameter, a flat surface and a convex surface with a radius of 151.33 mm, and weights about 2 kilograms. The lens material is HK9. This lens was manufactured with no particular tolerances. We only requested that it had a lens edge thickness of 10 mm. We designed a flexure mount for this lens which is a variation of the design now used for the flat blank with KMOS mount design prototype.

The assembled lens, along with its achieved alignment, is shown in figure 8. For this prototype, the achieved tip-tilt alignment was 1.05 arc-min. Similarly to the previous prototype, we followed the assembly and verification steps described in section 3 with the additional CMM measurements. During this assembly iteration, we corrected the height of the parallels and setting spheres with shims to have variations lower than 10 microns. These steps improved the achieved alignment but still did not meet our requirement. We identified that the rotary table rotation axis had an error motion of 0.45 arc-minutes with respect to the mount jig parallels plane. Additionally, the CMM flatness measurements of the probed surfaces with the dial gauge were not satisfactory for the alignment. The plano surface of the lens has a flatness of 64 microns and the mount top surface 154 microns. Flatness and cylindricity of the probed surfaces for alignment play a significant role.

After the curing period of the adhesive, on measurement day 13\10 the alignment was 0.76 arc-minutes. That day we removed the setting spheres, and the bond carried the weight of the lens. The tip-tilt angle between the mount reference surface and the top lens surface increased by 0.3 arc-minutes. We suspect that this is due to the bonds being somewhat elastic at room temperature.

Figure 8. HARMONI *mock* lens and mount pre-design prototype. (left) The mounted blank on top of the rotary table and CMM bench. (right) Angle between the mount's top surface and the flat lens top surface measured with the CMM. The measurement day refers to the number of days since bonding. First number is for bonds 1,3 and 5. Second number is for bonds 2, 4, and 5.

5. CONCLUSIONS AND FUTURE WORK

Allen J. and Barnsley R. described bond failures when the lens alignment moved as the bonds carried the weight of its lens, and the lens showed a change in position larger than its tolerance. This change was measured on both of our prototypes. The first prototype had a larger surface area than the second, and the change was lower. Thus, further work is needed to refine the mechanical design for the HARMONI lenses. The lens bond area and thickness needs to be optimized for each lens, considering its mass and edge thickness. We have also planned to characterize the cryogenic mechanical properties of the adhesive by doing a shear test in the engineering science facilities at the University of Oxford.

Flatness, cylindricity and roundness specifications need to be tightened for the surfaces that are probed to define alignment through the assembly process. The use of a low force dial gauge is optimal for this set-up. We will design a mount jig for the rotary table at RAL Space and correct its error motion.

The prototypes presented in this manuscript are well documented and have provided useful information to improve the lens mount design. The assembly and verification process has also been refined. We identified several key parameters to achieve the alignment of the lens to its mount during assembly. We aim to have a matured and reliable process put in place for when the HARMONI cameras are assembled. We will design a new mount for a second HARMONI *mock* lens prototype.

In early 2021 we will cold test at 130K the mounted prototypes. We aim to measure the position (x and y) of the lens with respect to the mount after cool down and settling and validate our decentration lens tolerances. We will also measure the lens change in tip and tilt orientation after cool down and settling. Furthermore, we will test the bond survivability throughout a HARMONI's accelerated lifetime cryogenic cycling.

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REFERENCES

- [1] Thatte, N. and collaboration, H., “HARMONI - first light spectroscopy for the ELT: instrument final design and quantitative performance predictions,” International Society for Optics and Photonics, SPIE (2020).
- [2] Rodrigues, M., Capone, J., Earle, A., Foster, T., Hidalgo, A., Lewis, I., Lynn, J., O’Brien, K., Tosh, I., George, E. M., Accardo, M., Alvarez, D., Conzelmann, R., Hopgood, J., Clarke, F., Schnetler, H., Tecza, M., and Thatte, N., “The HARMONI/ELT spectrographs,” in [*Ground-based and Airborne Instrumentation for Astronomy VII*], Evans, C. J., Simard, L., and Takami, H., eds., **10702**, 2991 – 3000, International Society for Optics and Photonics, SPIE (2018).
- [3] Observatory, E. S., “KMOS News, Timeline of instrument status.” Website announcements, September 13th, 2020 <https://www.eso.org/sci/facilities/paranal/instruments/kmos/news.html>. (Accessed: 10 December 2020).
- [4] Froud, T. R., Tosh, I. A. J., Edeson, R. L., and Dalton, G. B., “Cryogenic mounts for large fused silica lenses,” in [*Optomechanical Technologies for Astronomy*], Atad-Etchedgui, E., Antebi, J., and Lemke, D., eds., **6273**, 781 – 789, International Society for Optics and Photonics, SPIE (2006).
- [5] Masters, R. J., Lewis, I. J., Tosh, I. A. J., Tecza, M., Lynn, J., Watkins, R. E. J., Clack, A., Davies, R. L., Thatte, N. A., Tacon, M., Makin, R., Temple, J., and Pearce, A., “KMOS: assembly, integration and testing of three 0.8-2.5 micron spectrographs,” in [*Ground-based and Airborne Instrumentation for Astronomy III*], McLean, I. S., Ramsay, S. K., and Takami, H., eds., **7735**, 1888 – 1896, International Society for Optics and Photonics, SPIE (2010).
- [6] Allen, J., *Instrumentation for HARMONI and the mass ratios of ring galaxy systems*, PhD thesis, University of Oxford, <https://ora.ox.ac.uk/objects/uuid:3df69b43-eb71-4931-b3cf-722c2612f422> (2017).
- [7] Allen, J. R., O’Brien, K., Lynn, J. D., Thatte, N. A., Tosh, I. A. J., and Tacon, M., “Characterizing the performance of cryogenic lens mounts for the HARMONI spectrograph,” in [*Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation II*], Navarro, R. and Burge, J. H., eds., **9912**, 1452 – 1462, International Society for Optics and Photonics, SPIE (2016).
- [8] Tosh, I., “Private communication.” RALspace (2017-2020).