

Development of the HARMONI spectrograph for ESO's Extremely Large Telescope



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For all the girls who dream of becoming scientists,
for the women who already are,
and for everyone in the HARMONI collaboration who is making the
instrument come true.

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HARMONI is the integral field spectrograph (IFS) for the European Southern Observatory's Extremely Large Telescope (ELT). This versatile instrument assisted by adaptive optics will deliver diffraction-limited spectroscopic capabilities across the near-infrared wavelength range, taking full advantage of the ELT's combination of exceptional spatial resolution and vast collecting area to enable groundbreaking scientific research. HARMONI is a unique ground-based astronomical instrument due to its size and the fact that it will be the first IFS to operate on an ELT. Some of HARMONI's technology was already implemented in previous astronomical instruments, but at a smaller scale, lower level of integration complexity, and never for this type of telescope. Consequently, multiple development challenges must be addressed for its successful realization. This thesis addresses two development challenges: implementing a lens mount for HARMONI's spectrograph cameras and evaluating the potential for dielectric mirror coatings to enhance instrument throughput. This thesis proposes a flexure lens mount for HARMONI's spectrograph cameras and demonstrates how it can be implemented to meet the cameras' alignment requirements. The thesis meticulously presents the assembly process and validation of the radial alignment of two lens mount engineering models in a HARMONI-simulated operational environment. Secondly, this thesis demonstrates that dielectric mirrors are a feasible technology for the HARMONI instrument by establishing that broad-spectrum coatings can be designed and manufactured, and by validating four coating types for HARMONI's lifetime and operational conditions. Additionally, the thesis provides transmission estimates, highlighting the substantial throughput improvements achieved by applying dielectric mirror coatings to eligible surfaces.

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Chapter 1

Introduction

1.1 A new era for ground-based telescopes

Astronomers have been highly successful at devising instruments to observe the universe with increasing detail and at ever greater distances. The devices they used reflected the technologies available at the time, and significant astronomical discoveries were brought by technological innovation.

Back in 2008, Ian McLean argued that we have reached a point where we have designed optical instruments that have transmission factors and efficiencies that are virtually impossible to improve due to fundamental effects associated with the refractive and reflective properties of the materials and the quantum efficiency of the detector itself [27]. Once the quantum limits of sensitivity in detectors and instruments have been reached, the only way to gain significant factors in efficiency is to construct even larger ground-based telescopes and to develop methods for counteracting the image-blurring effects of turbulence in the Earth's atmosphere.

He was one of many to have reached this conclusion. The major 8m class telescopes (e.g. Keck/VLT) came online in the mid-late 1990s. Once they were operational, the community naturally turned to the next generation, which is the 30m class telescopes. Astronomical communities around the world organised and proposed the construction of these even larger ground-based telescopes, and in the early 2000s, several projects were funded to start feasibility studies.

At the time of writing, in 2023, the era of extremely large telescopes is under way. Telescopes are considered to be "extremely large" when their primary mirrors are wider

than 30 meters. There are currently three ELT projects in the world, two of which are under construction: ESO's Extremely Large Telescope (ELT)¹[32], the Giant Magellan Telescope (GMT)[55], and the Thirty Meter Telescope (TMT) which is currently on hold [35].

Along with the approval and funding of new telescopes also come proposals for new instruments. Collaborations of astronomers come together to decide how to best use and exploit the telescopes, and a compromise is made based on the following considerations. What is the best possible science that can be achieved with technology that can be developed and validated in a reasonable amount of time, while matching the secured resources and funding? Then, even larger collaborations of astronomers, scientists and engineers embark on a 20+ year project to design, develop and commission the proposed instruments[9]².

1.2 ESO's Extremely Large Telescope

ESO's Extremely Large Telescope, or ELT for short, is a ground-based telescope that will have a 39-metre primary mirror and will be the largest visible and mid-infrared light telescope in the world for the foreseeable future [34]. The European Southern Observatory (ESO) is leading the project.

The ELT will use adaptive optics to correct atmosphere turbulence to achieve diffraction-limited observations[30]. Its diffraction-limited spatial resolution in the near-infrared (1-2.5 microns) will be 10-14 milliarcseconds; a factor of five better than any existing near-infrared telescopes.[10]. Its large aperture will allow observing targets with a level of detail nearly four times more than 8-m class ground-based telescopes and will collect 16 times more light[31].

At the time of writing, the ELT dome structure has started to take shape at the top of the Cerro Armazones in the Atacama desert, with the aim to start scientific observations in 2028[14].

¹At the time of writing, ESO's ELT is the only telescope that is fully funded.

²This is the case for example for the HARMONI instrument, which I introduce in Section 1.3.

1.3 First light spectroscopy for the ELT with HARMONI

HARMONI³ is the first-light visible and near-infrared integral field spectrograph for the ELT. HARMONI is conceived as a 'general purpose' instrument, and its top-level requirements have been defined to enable studies of a whole range of astronomical targets, from our own solar system right up to the most distant (very earliest) galaxies in the Universe.

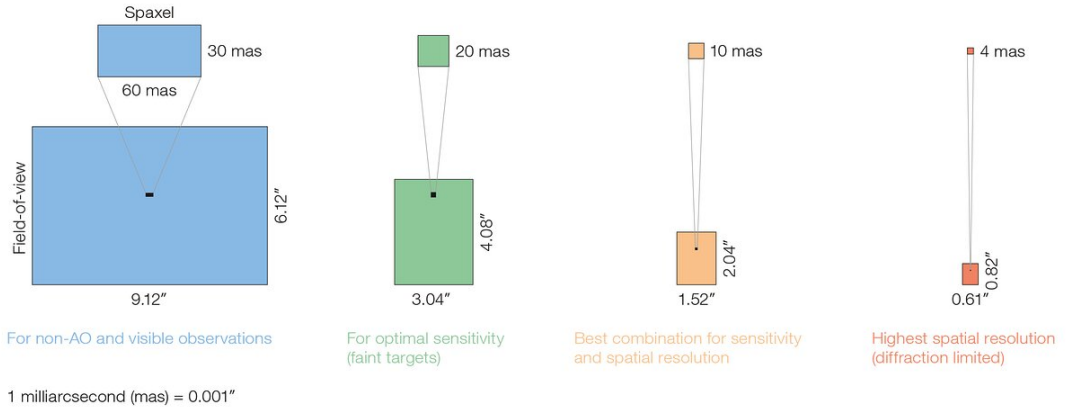


Figure 1.1: HARMONI spatial pixel scales. [Credit: HARMONI collaboration]

For these scientific cases, HARMONI has been designed as an adaptable instrument to provide four spaxel⁴ scales of 60×30 , 20×20 , 10×10 and 4×4 mas with fields of view on the sky of $9.1 \times 6.1''$, $3.0 \times 4.1''$, $1.5 \times 2.0''$ and $0.6 \times 0.8''$ respectively. Eleven spectral resolution settings of $\sim 3,500$, $7,500$, and $18,000$ in the NIR and $\sim 3,500$ in the VIS bands are available in all spatial scales⁵. The wavelength range of HARMONI is divided between visible and near-infrared, covering from 0.47 to $0.82 \mu\text{m}$ and from 0.80 to $2.45 \mu\text{m}$ respectively [17][8]. Figure 1.1 illustrates HARMONI's various spatial pixel scales and corresponding fields of view. Moreover, HARMONI has been designed to

³HARMONI is an acronym for High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph. In this thesis, I use the term HARMONI to refer to the instrument.

⁴Spaxels are spatial pixels. The image slicers in HARMONI provide spectra over a single contiguous field measuring 204×152 spaxels in size.

⁵HARMONI provides 11 grating settings. Due to differences in detector technologies, 10 (between 0.8 and $2.5 \mu\text{m}$) are fed to a near-infrared (HgCdTe) detector, and 1 (0.5 to $0.8 \mu\text{m}$) is fed to a visible (CCD) detector).

include adaptive optics capabilities, and it can operate in four different modes: NoAO (seeing-limited), LTAO (laser tomography adaptive optics), SCAO (single-conjugate adaptive optics) and HCAO (High Contrast Adaptive Optics)⁶.

1.3.1 Instrument anatomy

Figure 1.2 shows a HARMONI instrument render. Some of HARMONI’s main systems are shown in the figure—the Laser Guide Star Sensors (LGSS) register high order wavefront errors with laser guide stars for LTAO operation. The Natural Guide Star Sensors (NGSS) measure wavefront errors including positions and focus. The calibration and relay system (CARS) is also shown; this system includes the calibration module, the instrument static structure (ISS) and the focal plane relay subsystem (FPRS), which relays the scientific light to the integral field spectrograph. The Integral Field Spectrograph (IFS) contains the core scientific opto-mechanics inside a single cryostat at $\sim 130\text{K}$, shown in orange in Figure 1.2 and red in Figure 1.3.

Figure 1.3 shows a cutout of the cryostat where the pre-optics subsystem (IPO) provides spatial pixel scale choice. Then the integral field unit (IFU) splits and slices the field into four output slits, each feeding one of four spectrograph subsystems (ISP). The spectrographs collimate, disperse, and focus the light onto detectors, providing a choice of spectral ranges and resolving powers. Each spectrograph subsystem includes a near-infrared (NIR) camera and a visible (VIS) camera⁷[50]. The NIR detectors are further cooled to $\sim 40\text{K}$ [8]. HARMONI is over 8 meters high, and weighs in total 39 tonnes. The IFS cryostat is 3.5m in diameter. The spectrographs weigh nearly 500kg each, and even the camera barrels (the focus of Chapters 2 and 3) are 800 mm long and weigh over 50 kg.

1.3.2 Challenges

HARMONI is a very large endeavour split across multiple institutes and numerous scientists and engineers. In this thesis, I focus on two development aspects of the instrument design, which are vital to enabling the very best science performance of

⁶Specifically for looking for faint companions (planets) next to bright stars.

⁷The baseline funding only provides VIS cameras in two of the four spectrographs.

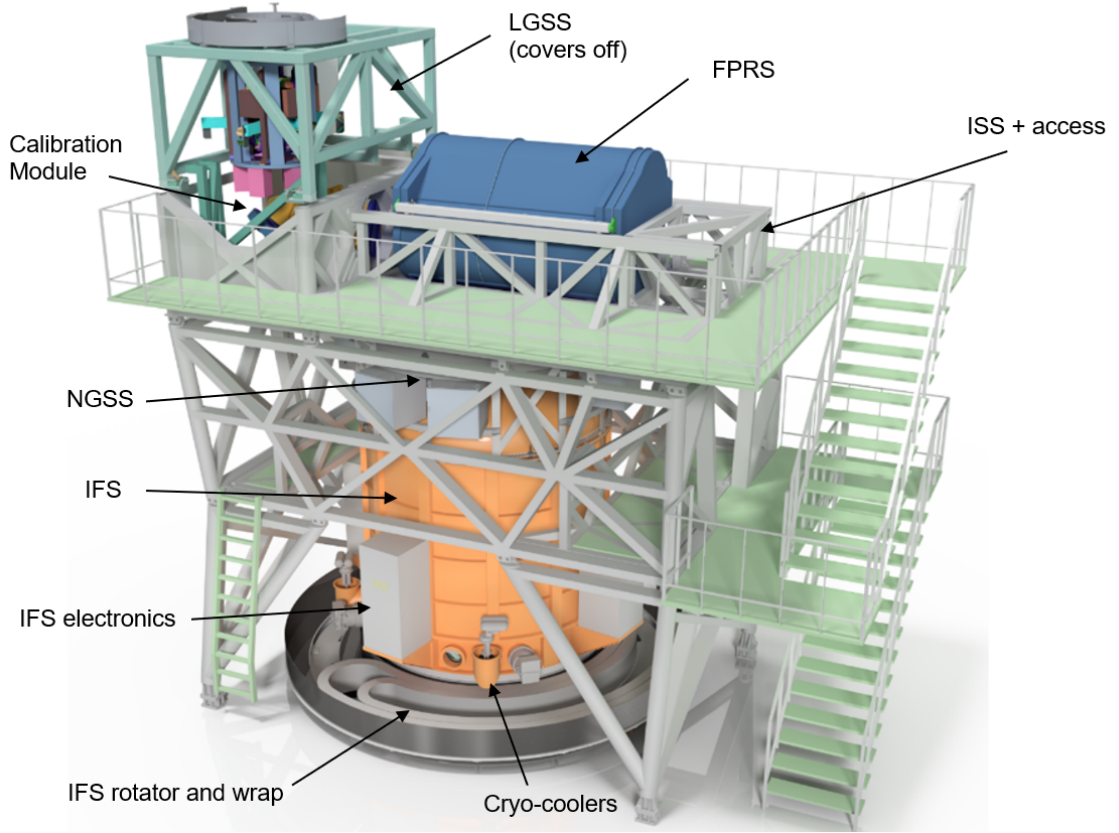


Figure 1.2: HARMONI render highlighting some key features. Acronyms in the figure correspond to the following expressions. LGSS: Laser Guide Star Sensors, NGSS: Natural Guide Star Sensors, ISS: Instrument Static Structure, IFS: Integral Field Spectrograph, FPRS: Focal Plane Relay Subsystem. [Credit: HARMONI collaboration]

the overall instrument; 1) the accurate and repeatable alignment of camera lenses to achieve maximum image quality and spectral resolution, and 2) prototype dielectric mirror coatings which, if feasible, offer a dramatic (up-to 50%) gain in instrument sensitivity.

1.3.2.1 Lens mounts

The four spectrographs for HARMONI, which will be delivered by Oxford, each have two cameras to focus the dispersed light onto the detectors. These cameras each consist of up-to seven lenses, which must all be held in alignment to within 20-30 microns to achieve optimal performance. The spectrograph camera lenses are supported in flexure mount rings based on a design inherited from FMOS and KMOS instruments. Figure

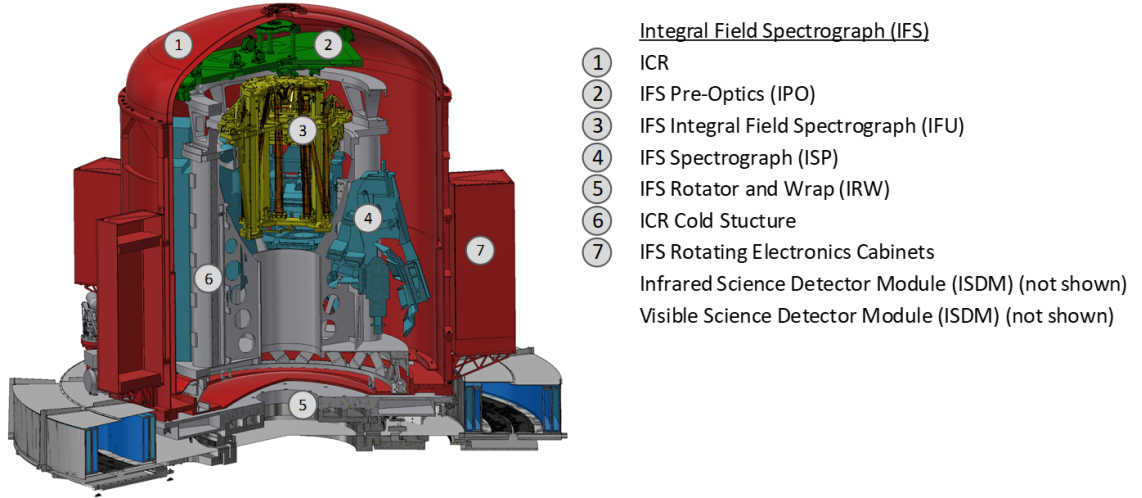


Figure 1.3: Integral Field Spectrograph System render. [Credit: HARMONI collaboration]

1.4 shows a spectrograph section view with two concept cameras assembled for visible and near-infrared wavelengths respectively. Figure 2.49 shows a render of both cameras. A major concern for all cryogenic instruments is maintaining optical alignment when the instrument is cooled down. The spring flexure in the lens mount (see Figure 2.10) keeps the thermal stress resulting from a lens-to-mount coefficient of thermal expansion (CTE) to mismatch well below the optics critical values. In principle, with this lens mount design, lens alignment is kept after cool-down and warm-up cycles, and the mounted lenses can be transported to the Atacama desert. Plus, they can survive significant shock events such as earthquakes. This design was demonstrated to work well for KMOS and FMOS, but for HARMONI, more complex and tighter alignment requirements are needed. These alignment requirements are challenging and critical to the performance of the cameras. In Chapters 2 and 3, I tackle some of these challenges, covering the design, the assembly and the verification.

1.3.2.2 Throughput of reflective surfaces

The purpose of the HARMONI instrument is to guide, organise, disperse and detect photons that have travelled across the universe to learn more about what produced them. Considering how precious these photons are, we must minimise the number that

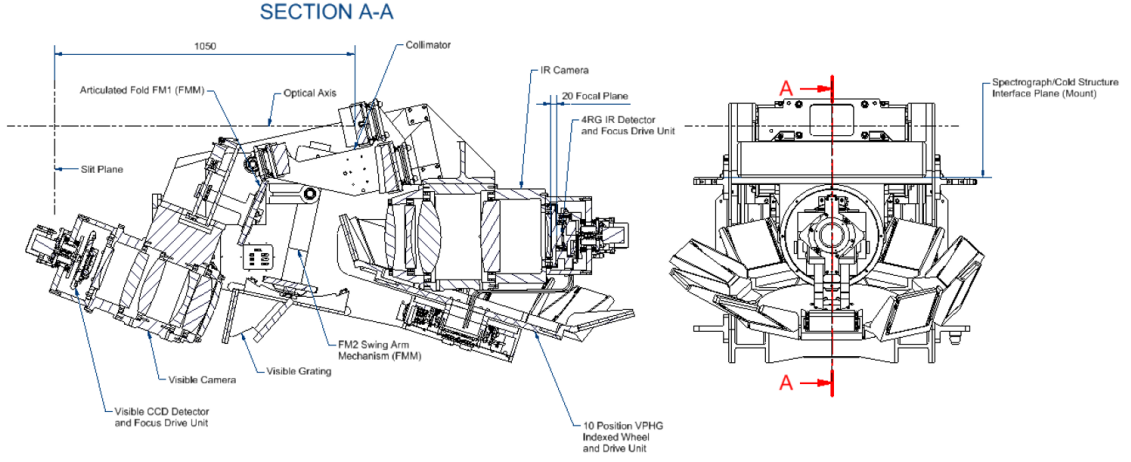


Figure 1.4: Spectrograph section view. [Credit: HARMONI collaboration]

are lost, scattered or absorbed as they travel through the telescope and the instrument. For this purpose and because reflections from a wavefront error point of view are achromatic, the optical design of HARMONI almost entirely relies on reflective surfaces for the optical elements participating in scientific detections.

Depending on the adaptive optics mode, the scale, the path at the IFU and the selected spectral resolution, there can be up to 27 reflections between the instrument entrance and the science detectors. Therefore, the reflective coating applied to these surfaces plays a central role in the achieved throughput of the instrument; even a slight loss or gain impacts the potential scientific output. The baseline design for HARMONI uses well-proven metallic coatings, which reflect typically 98.5% of incident light. Dielectric coatings in contrast are capable of reflecting upwards of 99.8% of incident light. The gain over 27 surfaces can be dramatic (c.f. 66% vs 95% total transmission). The challenge with dielectric coatings is to make them work over such a large wavelength range as HARMONI, and prove their suitability in cryogenic conditions. In Chapter 4, I explore the feasibility of broadband dielectric coatings with high reflectivity.

1.4 Development

The approach to development followed for the development of HARMONI aligns with systems engineering principles. To situate the work in this thesis, I present a Vee

diagram and propose the application technology readiness levels to understand my contribution.

1.4.1 Vee diagram

A traditional Vee diagram can capture the ideology of instrument development by systems. It lays out the decomposition and the integration of the instrument architecture. The Vee model describes the development lifecycle of a system from its conception to its operation[60]. In the case of Figure 1.5, the diagram starts with the definition of the instrument architecture and ends with the science commissioning, following the development lifecycle of a ground-based astronomical instrument.

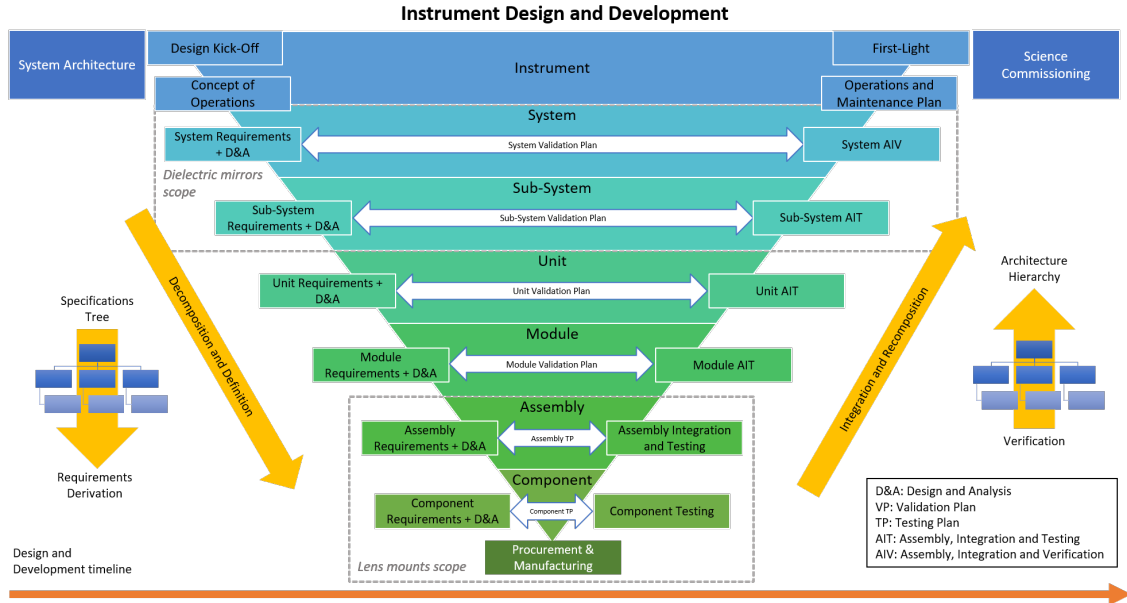


Figure 1.5: Example of a Vee diagram presenting instrument design and development.

Figure 1.5 puts my work into context, illustrating its scope and its objectives. The dashed grey boxes help representing this graphically. Chapters 2 and 3 aim to develop and validate parts at an assembly and component level where the system is the integral field spectrograph, the subsystem is the spectrograph, the modules are the visible and infrared cameras and the assemblies are the lens mounts. Chapter 4 explores the feasibility of dielectric mirrors for the reflective surfaces in the science path, while also giving an outlook on the increase in throughput. Chapter 4 covers two systems: the

calibration and relay system and the integral field spectrograph. The transmission estimates are given per subsystem and at the instrument level.

The approach presented in Figure 1.5 is an idealised version of what was actually followed for HARMONI. The actual approach has not been quite as sequential as presented in the figure. The development of the instrument follows ESO’s project management procedures and is guided by a design review process and its stage gates.

1.4.2 Technology Readiness Level

Technology readiness levels measure technological maturity, and is usually employed when developing a new system. Technology readiness assessments provide an insight into the maturity of a technology at a given time. The readiness levels describe degrees of development and estimate how mature a design is, how well integrated and how ready to operate a particular technology is based on its level of verification and validation.

This notion of maturity was formalised by the US National Aeronautics and Space Administration (NASA)[23] and later modified for use by the Department of Defense (DoD), the Air Force Research Laboratory (AFRL), and the US Department of Energy (DoE), as well as a growing number of non-governmental organizations[43].

I apply Technology Readiness Levels (TRLs) in this work to break down the steps of development and to serve as a measure of my contributions. In Figure 1.6, I propose an adjusted Technology Readiness Level definition for ground-based astronomical instruments. The proposed definition focuses on the first seven TRLs as these are within the scope of this thesis. The TRL definition from NASA includes nine levels in total. Level 8 relates to system qualification through test and demonstration, and level 9 to system proven through successful mission operations[23]. HARMONI is a pioneering ground-based astronomical instrument as it will be the first integral field spectrograph to operate on an extremely large telescope. HARMONI combines seemingly mature technologies demonstrated in other astronomical instruments with similar environments and levels of individual integration, thus pursuing a natural technological progression. These instruments include MUSE, KMOS, SINFONI, FLAMES and VIMOS at the Very Large Telescope, FMOS at the Subaru Telescope, SWIFT at

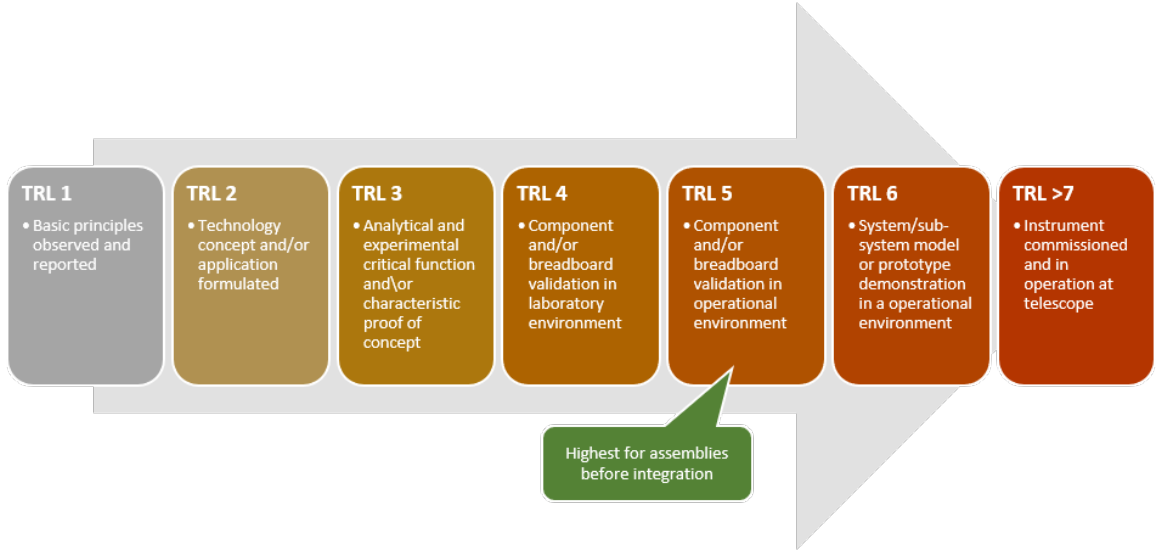


Figure 1.6: Technology Readiness Level definition from NASA [29] adjusted for ground-based astronomical instruments.

the Hale Telescope, MEGARA at the Gran Telescopio Canarias and WEAVE at the William Herschel Telescope⁸.

Through the development of the technologies discussed in this thesis, I realised that the technological maturation of HARMONI faced several challenges. Technical challenges were due to the added intricacy of an ELT instrument incorporating multiple adaptive optics systems in addition to a complex integral field spectrograph system. Further challenges came from loss of knowledge due to a lack (or loss) of documentation, a decade of tight budgets, and stretched staff. Performing technology assessments became a critical basis for my DPhil work, shedding light on my starting point and on the progress that I made.

1.5 Thesis aims and scope

The research aims of this thesis are:

1. Demonstrate that the flexure lens mount assembly can be implemented for the HARMONI spectrograph cameras.

⁸This list is not extensive but it does mention the instruments with relevant contributions.

2. Validate the flexure lens mount design in a HARMONI-simulated operational environment.
3. Demonstrate that dielectric mirrors are a feasible technology for the HARMONI instrument.

1.6 Thesis organization

This thesis comprises five chapters. Chapter 1 is the introduction to the thesis. Chapter 2 (Lens mounts) and Chapter 3 (Lens mounts cold testing) are complementary to each other and should be read one after the other. These two chapters address the first two aims of the thesis. Chapter 4 (Dielectric mirrors) can be read as a standalone piece of research. It addresses the third thesis aim. Lastly, Chapter 5 contains the conclusions of the thesis.

The purpose of developing and validating technology for the HARMONI instrument joins these chapters into a narrative; what brings coherence is a systems engineering approach (as illustrated in Figure 1.5). Chapters 2 and 3 take the lens mount assembly as their system of interest interfacing to the spectrograph camera of the HARMONI integral field spectrograph system (IFS). Chapter 4 takes the HARMONI instrument as its system of interest and focuses on the optical surfaces in the science path across multiple subsystems.

1.7 Ownership

The lens mounts concept with flexures has been implemented in multiple projects for various applications. The particular design used for this research was conceived by Tim Freud and the opto-mechanical team that developed the FMOS instrument at RALSpace in the early 2000s. The design was further developed by Jim Lynn in collaboration with RALSpace and implemented for the KMOS instrument around 2010. James Kariuki, as lead mechanical engineer, the HARMONI spectrograph team (which I was part of throughout my DPhil) and the RALSpace team have worked on the design for the HARMONI spectrograph cameras. Within the HARMONI project, my

role extended to providing essential guidelines for lens mount design, solidifying camera manufacturing tolerances, lens manufacturing and alignment tolerances, advising on appropriate optical materials selection, devising assembly procedures, conceptualising integration methods, and developing comprehensive testing protocols. I designed all the necessary components to execute the work in this thesis. I supported the commissioning of the clean room laboratory once it was handed over to our research group following its construction, and then I equipped and maintained it. The Oxford physics mechanical workshop performed the mechanical manufacturing and procurement of materials. The work presented in Chapter 4 originated from a collaboration instigated by my supervisor, Fraser Clarke, and drew upon the transmission model established during the preliminary design review of HARMONI as a foundational starting point. Beyond this, I fully own the work presented in this thesis as part of my DPhil project supervised by Fraser Clarke and John Capone⁹.

⁹John Capone was my thesis co-supervisor until his departure from Oxford, in March 2021.

Chapter 2

Lens mounts

2.1 Introduction

As telescopes grow in size, driven by scientific goals of detecting fainter and fainter light, they also become more demanding technologically. Methods and technology that had been successfully implemented for previous telescope instruments cannot be simply re-implemented, as they face ever more demanding requirements¹. This is the case for HARMONI's flexure lens mounts. This technology has been successfully implemented in two previous instruments at the VLT²: FMOS and KMOS. The latter is still in operation.

The previous design guidelines of FMOS and KMOS, along with their manufacturing tolerances, alignment procedures and the associated verification methods, need to be re-developed and improved to meet HARMONI's requirements, which, in practical terms, translate to tighter tolerances.

Moreover, a challenge lies within the astronomical instrumentation community when developing a new instrument as the time between instruments is so long (typically a decade or longer) that specific techniques and tools may no longer be available for future instruments, and the organisational knowledge of how to do things needs to be relearned each time. There is also the fact that the level of product and quality

¹In this case, perhaps it is worth noting that the 'more demanding requirements' are that the physical size of the instruments and the optics tend to scale up with the telescope, whilst the tolerances tend to stay the same (or even be pushed harder, as there is a societal drive for each generation of instruments needs to be 'better' than the previous).

²Very Large Telescope.

assurance required tends to increase with the size of the projects, which demands a more quantified understanding of the techniques than was required before.

In November 2017, I joined HARMONI as a DPhil student and inherited the challenge of developing a lens mount assembly and its early AIT³ concept for the HARMONI spectrograph cameras.

The first step was to collect the background information needed to build up my research. I then had to analyse it to understand the current maturity status and to decide what actions and judgements were needed to develop the assembly for the HARMONI cameras. After analysing the available background information, I made a technology readiness assessment. I quickly realised that there needed to be more clarity about the maturity of previously implemented lens mount assemblies.

2.1.1 Research aims

My research aims for this chapter were to :

- Understand the factors at play to achieve the desired performance of the lens mount assembly in operational conditions
- Understand the alignment parameters of the lens mount assembly and how they interface with the camera alignment.
- Develop the lens mount assembly technology and increase its maturity.
- Mount a prototype lens mount assembly and identify the procedure steps for assembly and alignment.
- Provide feedback to the D&A and AIT teams on improvements and work needed to implement the lens mount technology for HARMONI.
- Address historical/inherited issues and propose a development pathway.

³Assembly, integration and testing.

2.1.2 Chapter structure

My objective with this chapter is to show what I did for this thesis project but also to serve as building block in the development of the lens mounts technology for HARMONI. The work on the lens mounts is written in two chapters, the present chapter focused on the design and warm assembly and Chapter 3 focused on cryogenic verification of the lens mounts. Additionally, I have written detailed procedures and shared the *how-to* knowledge with the team at Oxford and RALspace.

In section 2.2, I summarize the available information on the lens mount technology. From the design conception, I go through its evolution, passing through two instruments and prototyping efforts. In Section 2.3, I show the design parameters and guidelines of the components that make up the lens mount assembly. I introduce the mount jig design and the mounting concept for several cases of lenses. In Section 2.5, I explain how I assembled two lens mount assemblies. I present a developed assembly procedure inspired by the one carried out for FMOS and KMOS and provide measurements of the achievable alignment tolerances. In Section 2.6, I present two methods for carrying out the alignment verification of the assembly at room temperature and show the resulting measurements from two lens mount assemblies. I identify the mechanical parameters that play a role in the alignment and point out the limitations of the current setup. In Section 2.8, I briefly introduce the concept plan to integrate the lens mount assembly in the camera module. I propose a definition for the alignment interface between the assembly degrees of freedom, their barrel and the camera housing. In Section 2.9 I discuss the limitations of the warm alignment and the current alignment tolerance budget. I set out guidelines for a new mount jig. I discuss the assembly imperfections which have consequences on the assembly performance. In Section 2.9.1, I summarise the work and knowledge learned. I outline the limitations of my results and give recommendations to develop the D&A⁴ and AIT of the lens mount assembly. I discuss future work needed to implement this technology for HARMONI.

⁴Design and Analysis.

2.2 Background

This section focuses on how the lens mount flexure design came to be and how it has evolved throughout several instrument implementations and prototypes. It analyses what had been done before, what worked and what did not. This section is vital because HARMONI has adopted a lens mount design based on previous successful designs. However, a big part of the background knowledge had not been written down or was stored in the form of technical reports, Excel sheets, photos on private computers or in the minds of people who are no longer available. It was very challenging to put this section together and to get access to the information needed to write it. This is my best effort to compile what I was able to learn.

2.2.1 Design conception

The flexure lens mount assembly was designed by Tim Froud in 2003 for the FMOS instrument at CLRC Rutherford Appleton Laboratory⁵ (see Ref.[15]). The camera in FMOS has six lenses, all made of fused silica. The camera operated between 200 K and 77 K. The flexure was initially made of stainless steel, and it was one piece that included the lens bonding pads. Figure 2.1 on the left shows a mounted FMOS lens in the initial design. The pads were rectangular and followed the curvature of the lens edge to ensure a uniform bond thickness. The team at the time calculated the thermal stress of the bonds depending on their bond thickness following the method proposed in [7].

Their selected thickness was 0.2 mm for best performance in shear stress. The adhesive that was initially used was Corning 93500 2-part silicone RTV. In July 2005, the FMOS camera was assembled and cooled down for verification. Lenses 3, 4, 5 and 6 broke during the cooldown around the adhesive bonds. Figure 2.1 on the right shows a zoom-in of a bond failure. An investigation was launched to determine the causes of the bond failure, which triggered an evolution of the design.

⁵The CLRC Rutherford Appleton Laboratory is now known as RALSpace.

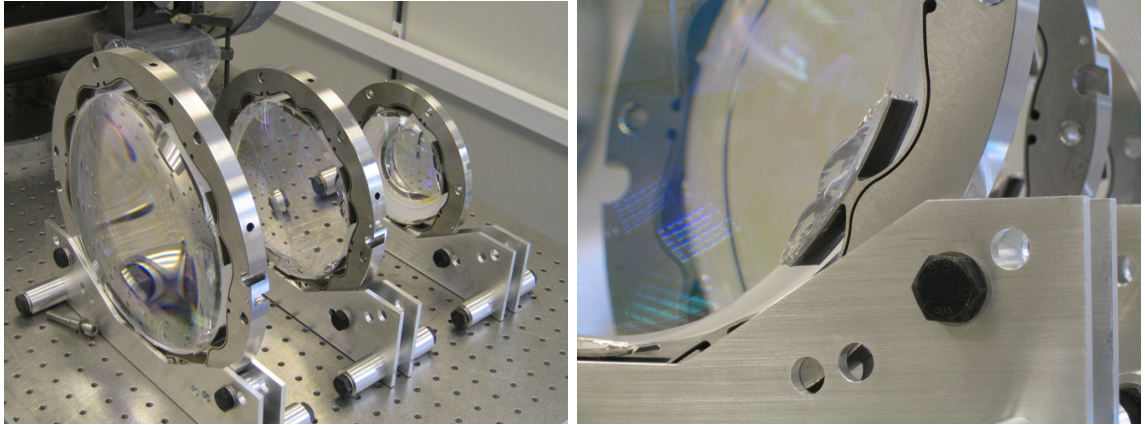


Figure 2.1: (left) FMOS lens mount assemblies after being dismantled due to bond failure. (right) Detail of a bond failure. The cause of this failure was not the bond but rather a failure of the lens due to excessive thermo-mechanical stress. Image credit: RALSpace.

2.2.2 Design evolution

After damaging 4 out of 6 lenses in FMOS, the design evolved through several periods. First, with the effort towards delivering FMOS, then with its implementation for KMOS, then with prototyping experiments and the assembly of the SWIFT spare camera. The primary concern for successfully delivering FMOS was reducing the shear stress transmitted by the flexure and pad combined with the adhesive stiffness. Finite element analysis simulations were carried out to test variations of the design with its pad and bond that could reduce the stress. The best-performing design by a significant amount was the stainless steel ring with a relieved cylindrical Invar bond pad [59]. These simulations were carried out with assumptions for the mechanical properties of the adhesive at cold temperatures. Thus, further action was required to ensure the safety of the lenses[58]. A cold test was carried out to study the interaction of the pad, bond and lens without the flexure. It was found that the adhesive damaged polished and ground surfaces in a lens. This discovery triggered an effort to test more adhesives and carry out an adhesive selection (see Section 2.2.3). Dow Corning 6-1104 was the only adhesive that did not present *bond failure*⁶ for polished surfaces but did ground

⁶The term bond failure has been widely used to describe any problem related to the interface between the adhesive-pad-lens.

surfaces[46]. A layer of cotton paper was introduced to mitigate the risk of bond failure at the interface between adhesive and lens[22]. FMOS lens five was tested with all these changes: round Invar pad, Dow Corning 6-1104 adhesive, and a strip of cotton paper covering the edge of the lens. The cryogenic tests were successful in that the lens survived, and Figure 2.2 shows the newly adopted design for FMOS.

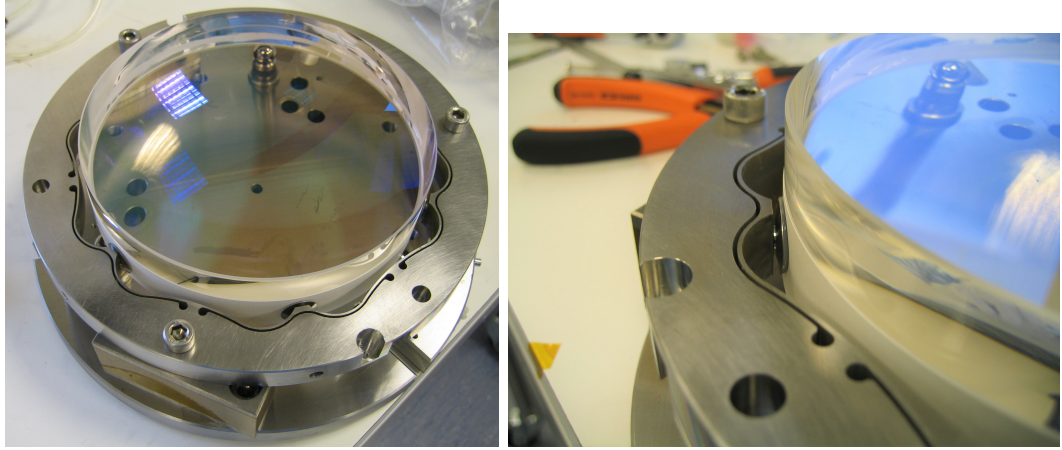


Figure 2.2: Modified FMOS lens assembly 5. Image credit: RALSpace.

In 2009 the design with the improvements was adopted for the KMOS camera as shown in Figure 2.3. The material of the lens mount ring changed to aluminium and the

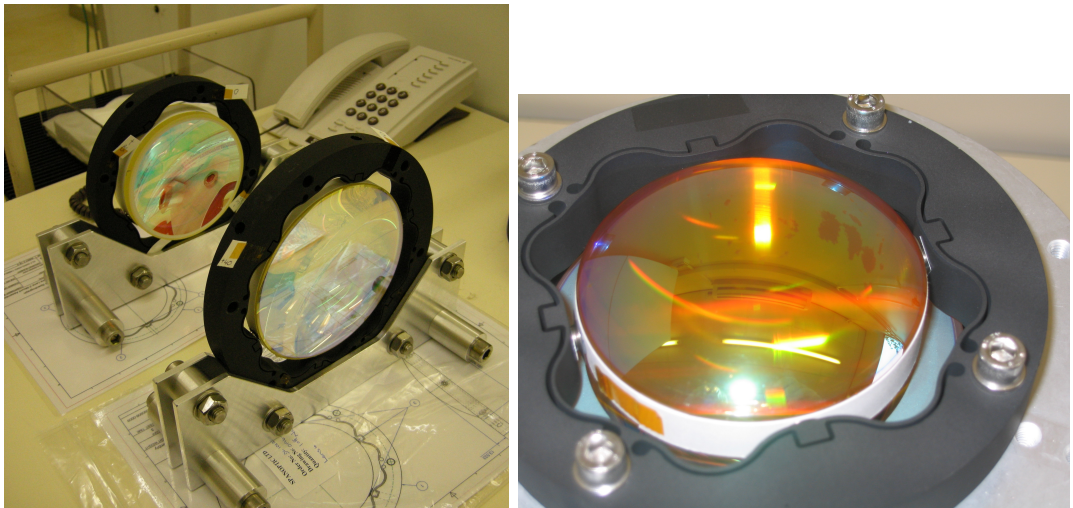


Figure 2.3: (left) Two mounted KMOS lenses. (right) A Zinc Selenide lens mounted with titanium pads. Image credit: RALspace.

material of the pads was changed to match the CTE of the material of its lens. Invar

was chosen for fused silica, titanium for zinc selenide (see Figure 2.3), beryllium copper for calcium fluoride. There were no bond failures or damages to the lenses registered with the combination of lens CTE matched circular pads, cotton paper adhered to the lens edges and adhesive Dow Corning 6-1104. Additionally, the mechanical design was slightly changed to reduce the thermal stress induced on the lenses [47]. Between FMOS and KMOS, this technique has now been used to successfully mount 20 cryogenic lenses with no known failures.

2.2.3 Adhesives

Since the conception of FMOS in July 2022, there have been 14 adhesives tested for the flexure lens mounts at RAL and UOX⁷. These are listed in Table 2.1 along with a summary of their properties and notes on their performance. Most of these adhesives were tested at RAL after the FMOS lenses were damaged during cooldown as part of the action to resolve bonding failure[58]. The best performing adhesive was Dow Corning 6-1104[46], which was adopted for the FMOS and KMOS instruments[15, 24]⁸. The rest of the adhesives in Table 2.1 were tested by Jamie Allen (JA) for his prototyping efforts[1]. He carried out an adhesive selection because the adhesive Dow Corning 6-1104 was and is difficult to supply to the UK. Jamie Allen demonstrated that the adhesive CV 1142 worked for his lens mount prototypes[2], but when applied to the SWIFT spare camera, the bonds did not perform well for alignment[4].

Adhesive	CTE 25°C [10 ⁻⁶ /°C]	GTT [K]	Outgassing	Notes
DC 93500	300	189	TML = 0.30%, RML = 0.28%, CVCN = 0.03%	Initially adopted for FMOS, used when lens fractured around bonds
DC 6-1104	387	156	TML = 0.18%, RML = 0.14%, CVCN = 0.03%	Warm and cold tested by RAL and selected as best, used in FMOS and KMOS

⁷University of Oxford.

⁸It is worth noting that Dow Corning 6-1104 is a silicone based adhesive, which can lead to restrictions on its use in certain classes of clean room. It is, however, space-rated in terms of out-gassing.

EP21TDC-2	70 to 90	min OT 4	Meets NASA low outgassing	Passed warm test and cold tested at RAL; showed bond failures
EP37-3FLFAO	108 to 117	min OT 4	Meets NASA low outgassing	Passed warm test and cold tested at RAL; showed bond failures
3M 2216	45 at -100°C	391	TML = 1.42%, RML = 0.75%, CVCML = 0.01%	Passed warm test and cold tested at RAL; showed bond failures
Stycast 2850FT	29	313	TML = 0.38%, RML = 0.24%, CVCML = 0.01%	Passed warm test and cold tested at RAL; showed bond failures
HYSOL EA-9394	55.6 at 40°C	NF	NF	Passed warm test and cold tested at RAL; showed bond failures
EP30DP	153 to 171	4 to 394 STR	NF	Warm tested at RAL, determined too runny
EP37-3FLF	108 to 117	4 to 394 STR	Meets NASA low outgassing	Warm tested at RAL, determined too runny
EPOTEK 301-2	61 ↓T _g	≥353	TML = 0.89 CVCML = 0.01	Warm tested at RAL, determined too runny
Eccobond 286	36	218 to 378 STR	NF	Passed warm test and cold tested by JA; showed bond failures
Lord 3135	57	NF	NF	Passed warm test and cold tested by JA; showed bond failures
CV 1142	90 ↓T _g , 320 ↑T _g	ST ~158	TML = 0.41%, RML = 0.31%, CVCML = 0.01%	Warm and cold tested and selected by JA, applied in SWIFT spare camera and lens mount prototypes

Table 2.1: List of adhesives that have been tested for selection by RAL and UOX. Further details and the datasheet references can be found in [19]. (CTE: Thermal Expansion Coefficient, GTT: Glass Transition Temperature, OT: operational temperature, STR: service temperature range, ST: stiffening temperature, NF: not found)

For this work, I chose the adhesive Dow Corning 6-1104 and found a supplier with a three-month shipping date. I put forward this adhesive for the HARMONI camera lens mounts. I chose it because it has more instances of successful application than other adhesives, including for various optical materials and for size ranges relevant to

the HARMONI camera lenses. Furthermore, it was the one for which I could access the most documentation about its handling.

2.2.4 Prototyping

After the FMOS and KMOS projects, Jamie Allen carried out an effort to review and try new lens mount designs as part of this DPhil thesis work. Along with James Lynn, he proposed an aluminium mounting ring with slots to place interchangeable pads. He used the adhesive CV 1142 and adopted the cotton paper layer and Invar as pad material. The insertable pads had a spring flexure integrated. He tested three types of pads by mounting them with a fused silica blank. He tested the pad types: double beam spring with a curved long bond surface, double beam spring with a flat short bond surface and z-spring with a curved short bond surface. He found that the best performing design was the combination of the slotted mounting ring with grooved double-beam pads. He cold tested the radial alignment of this design and measured an $18\mu\text{m}$ displacement[1].

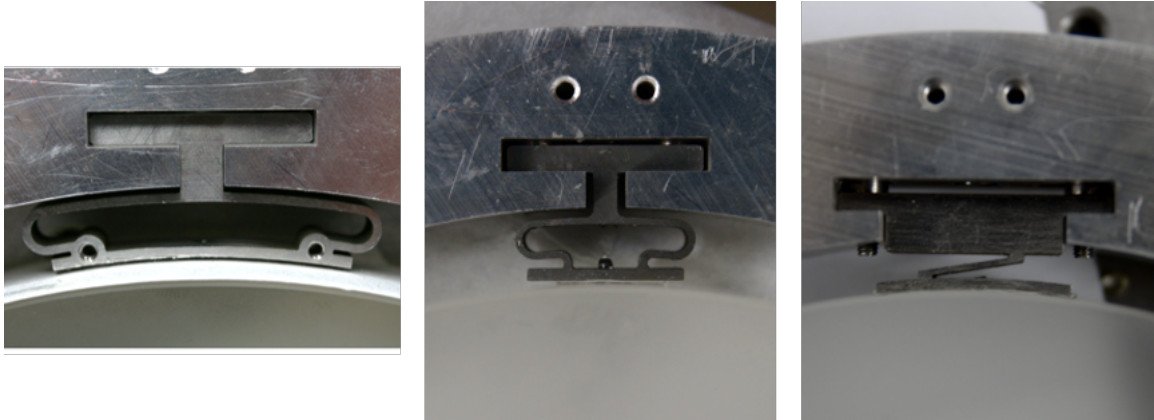


Figure 2.4: T-slotted aluminium mount ring with interchangeable spring pads. (left) double beam spring with a curved long bond surface (centre) double beam spring with a flat short bond surface (right) z-spring with a curved short bond surface. Image credit: Jamie Allen.

John Capone tested the alignment during transport of Jamie Allen’s successful prototype: the slotted mount ring combined with six double beam springs with a flat short bond surface. John placed the lens mount assembly prototype on a shake-table and accelerated the prototype using a transport power spectrum specified by ESO. He

measured a maximum 10-arcsecond change in the tip/tilt of the lens relative to the mount prototype at room temperature[6]. Figure 2.5 shows the measuring setup.

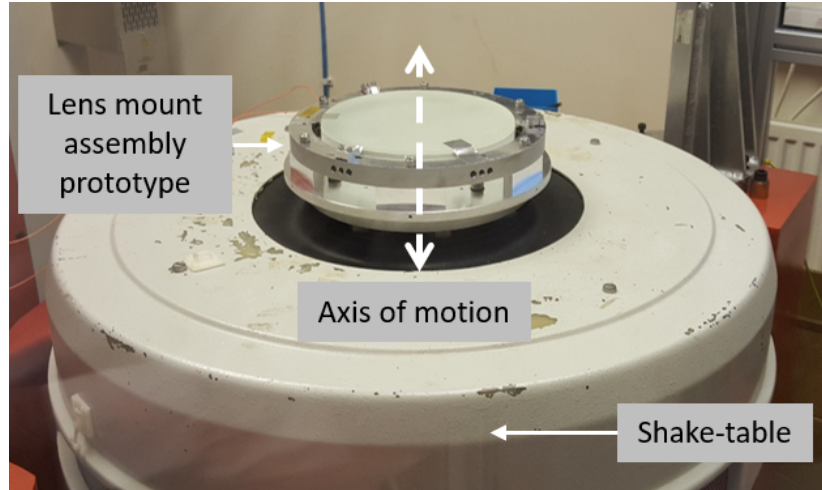


Figure 2.5: Test setup to measure the alignment during transport of a lens mount assembly prototype. Credit: John Capone.

2.2.5 Mounting jigs

A mounting jig has always aided the mounting of lenses in RAL and UOX. Two types have been designed.

Figure 2.6 shows the FMOS and KMOS mount jig design. The principle is to place the lens on top of three setting spheres mounted on a rotary table. The lens is rotated and probed to align it to the rotation axis of the rotary table. Then, the mount is placed on top of a set of parallels. It is rotated and probed to align it to the rotation axis of the rotary table. The alignment to the lens and the mount are fixed, and the lens is bonded to its mount. This mounting jig principle was used for all the lenses in FMOS and KMOS. Three parallels were manufactured for each lens type and placed at specific positions according to the lens size. [22]

Jim Lynn and Jamie Allen developed a new type of lens mounting jig for remounting the lenses of the SWIFT spare camera. Figure 2.7 shows their mounting jig. The mounting jig design had three setting spheres where the lens rested, but it would not be moved once positioned. Instead, the mount was placed on a three-point kinematic platform on differential adjusters to allow the mount to move in the axial direction

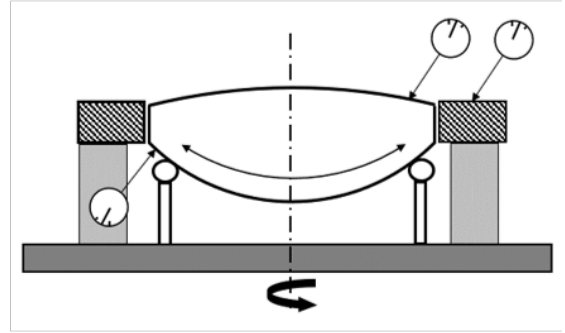
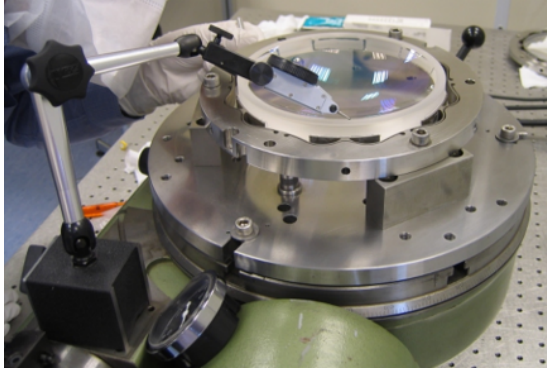


Figure 2.6: Mount jig design (left) and alignment diagram (right) used in FMOS and KMOS at RALspace. Image credit: RALSpace.

and to adjust the tip and tilt relative to the lens^[1]. They proposed this new type of mounting jig to minimise lens movement while resting on the setting spheres. They also changed the alignment measurement; instead of using a rotary table and a dial gauge to probe the surfaces, all measurements were carried out with a CMM.

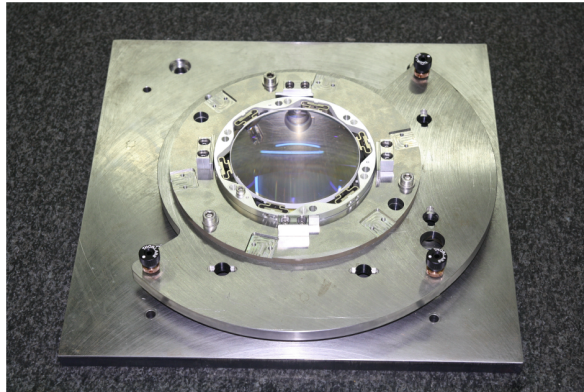


Figure 2.7: Mounting used for remounting the optics of the spare SWIFT camera. Image credit: Jamie Allen.

2.2.6 Technology readiness level assessment

Achieved technology readiness levels for previous successful instruments and later prototyping efforts had been lost due to a lack of documentation and proper information transfer⁹.

The challenge was not going to lie solely in re-developing the lens mount assembly to comply with the tighter alignment requirements of HARMONI, but also in rebuilding

⁹In order to bridge this gap, I have dedicated a section in this chapter to the background.

the foundations of the lens mount assembly. In Figure 2.8, I show my TRL assessment of key aspects of the lens mount assembly for the design developed for FMOS and KMOS and in Figure 2.9 for the design developed by Jamie Allen. For both, I present the assumed state, as well as the actual state in which it was handed over to me when I started my DPhil. Below, I summarise the reasons for my assessment.

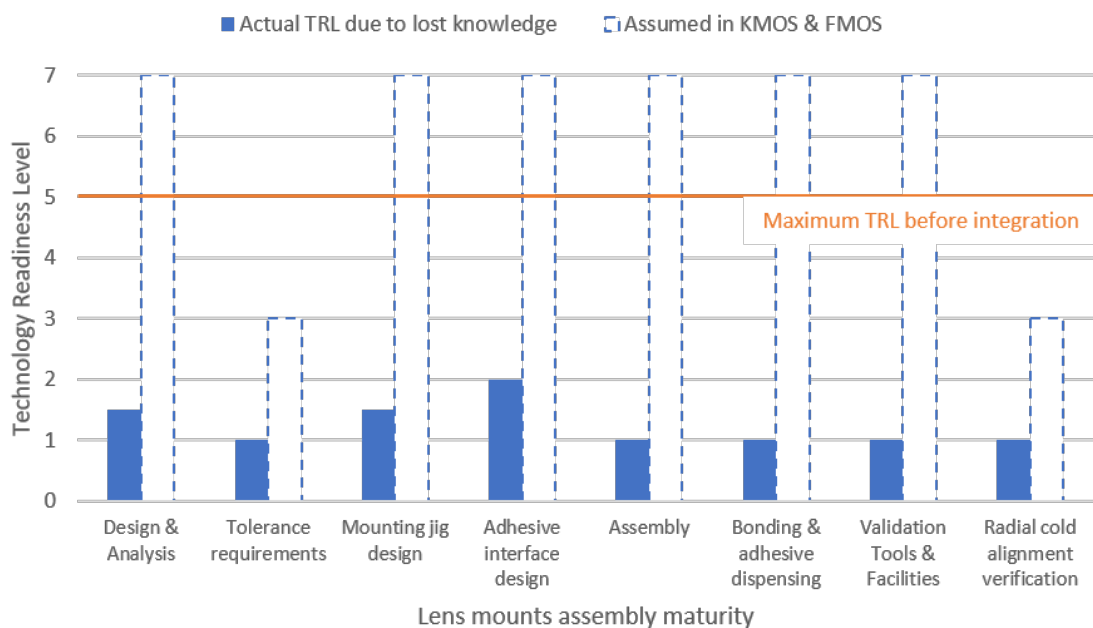


Figure 2.8: Lens mounts assembly maturity status based on the FMOS and KMOS instruments at the start of my DPhil.

Design and analysis: The lead mechanical engineer, Jim Lynn, who worked in KMOS and who designed the prototypes for Allen designed a similar mount for HARMONI. Tragically, after a period of illness, Jim Lynn passed away in August 2019. The design principles and analyses of both designs had neither been fully documented nor the new engineers were familiar with it. Hence we were effectively put back to a conceptual stage.

Tolerances requirements: The operational alignment tolerances for the HARMONI near-infrared camera design at PDR¹⁰ stage were $40\mu\text{m}$ for the axial and radial positions and were derived from an educated guess. A sensitivity or tolerance

¹⁰Preliminary Design Review.

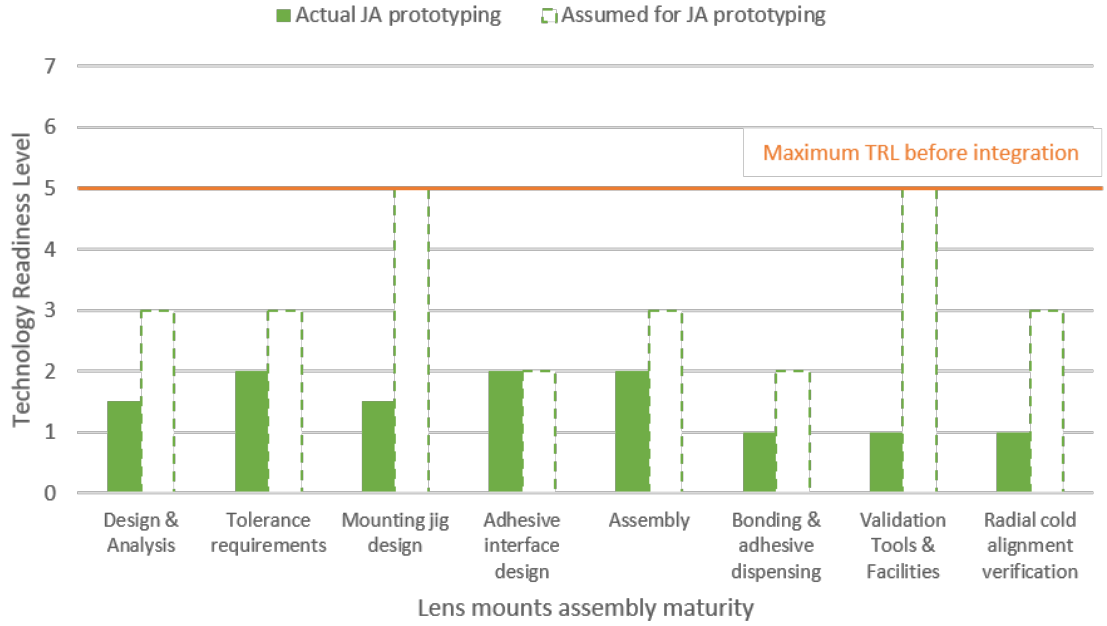


Figure 2.9: Lens mounts assembly maturity status based on the prototyping efforts of J. Allen (slotted mount ring with double beam spring pads) at the start of my DPhil.

analysis and a mechanical tolerance stacking for the camera design had not been adequately flowed down to the assembly level. The slotted mount ring with double beam spring pads was measured for radial alignment at operational temperatures. The measurements somewhat fulfilled the radial alignment requirement but were not repeatable. The FMOS and KMOS cameras had no available measurements of achieved performance on individual KMOS and FMOS lenses. Design data and the fact that the cameras worked when assembled suggest they got at least close to their requirements of $\sim 40 \mu m$ centring and ~ 40 arcminutes for tip-tilt.

Mounting jig: For both cases (FMOS and KMOS), previously used mount jigs were not available, and neither were any of their parts. A new rotary table was to be used. Similarly to the lens mount, its design principles had not been documented and were at a concept stage.

Bonding and adhesive dispensing: For the FMOS/KMOS design, we knew the recipe to ensure functionality (rounded pads with angles around the edges, cotton

paper, dispensed Dow Corning 6-1104 adhesive with a 0.2 mm thick layer, cure seven days) but this had never been practised since the delivery of KMOS in 2012. Additionally, the adhesive interface had no mechanical data we could model or simulate. The adhesive was believed not to be available, we did not have the necessary equipment, the technician that performed the procedure was leaving RAL, and the procedure had not been documented. For the slotted mount ring with double beam spring pads (during Allen’s assembly of the SWIFT spare camera) it was believed that the adhesive bonds had failed and proof of concept had not been quite reached. Allen’s bonding procedure had not been implemented well, and his equipment could not be used. The procedure needed further understanding and had not been well documented.

Assembly: The procedures for assembling the lens mounts had not been documented beyond conceptual level, nor had the achieved alignment tolerances been reported for any lens mount design. There was a need to redevelop these procedures, find out the range of alignment tolerances produced and refine the process to make it reliable and repeatable.

Validation tools and facilities: HARMONI had new requirements on cleanliness and dust particles, which meant that its components would need to be assembled in a cleanroom environment standard ISO 7. The equipment for adhesive dispensing needed to be identified and purchased. The cold testing facilities used for Allen’s tests also needed to be re-commissioned. When I arrived, the cleanroom was yet to be available, and none of the procedures described above had been performed in an environment like this.

Cold alignment: The FMOS/KMOS flexure design was operational and successfully implemented in two instruments, but the alignment of the individual elements had not be specifically measured at operating (cryogenic) temperatures. The slotted mount ring with double beam spring pads had been measured but showed a non-repeatable displacement. The method that Allen developed to perform this alignment measurement had not been fully documented. A level was lost because these measurements were not made available and could not be reproduced.

2.2.7 Design choice

It was a difficult choice. I presented the status for both to the team, and we decided to pursue the development of the FMOS/KMOS flexure design along with its adhesive as there had been more instances of it working and maturing would be faster with fewer changes made to the design and having the target objective of validating its performance at operational temperatures. The first step would be to document its design, measure its alignment at room temperature and finally find its alignment at operational temperatures. The idea was to build on learnings from RAL and the University of Oxford for both designs[20].

2.3 Design

The lens is held with adhesive to lens CTE matched pads fastened to an aluminium mounting ring, with spring flexures in the ring allowing for differential thermal contraction. Due to the symmetry of the flexures, this type of mount is ideal for keeping the lenses centred.

The lens mount assembly (Figure 2.10) consists of:

- an aluminium ring with wired-eroded 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 set the adhesive bond thickness. Its shape is optimised to match each lens edge thickness. Its material is chosen to closely matched to the lens material CTE (e.g. Invar-fused silica, titanium-ZnSe);
- two types of adhesive bonds. A bond for adhering the lens edge to the cotton paper layer. And a bond for each pad adhering the pad to the cotton paper layer. The latter bond has a central thickness of 0.2 mm;
- a cotton paper layer to cover the lens edge, having with an average thickness of ~ 0.26 mm;
- the assembly corresponding lens.

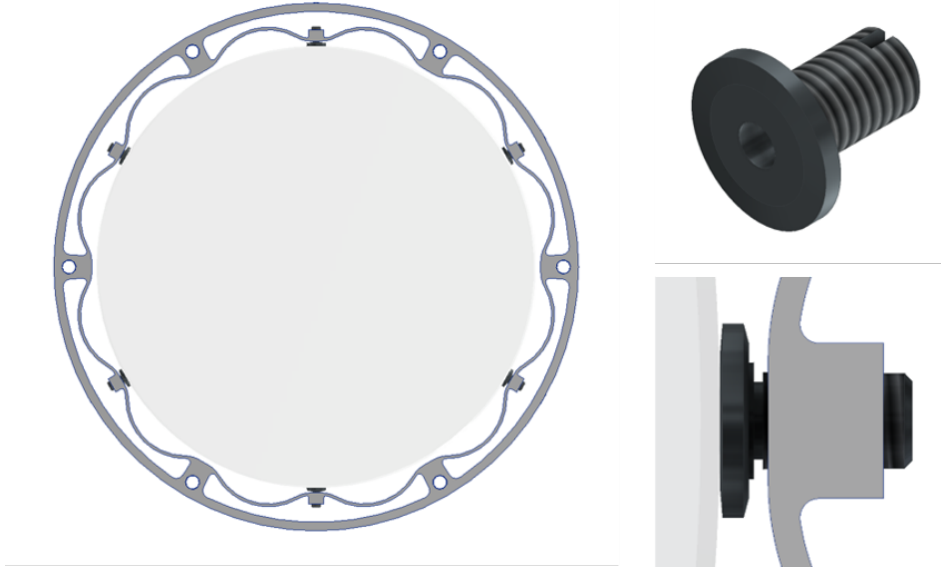


Figure 2.10: Example of flexure mount design. (left) Lens mount assembly. (top right) Pad design for a lens with 10 mm edge thickness. (bottom right) The pads position can be adjusted via a threaded shaft. Our adhesive bonds consider a lens edge covered with a cotton paper layer strip and a bond thickness of 0.2 mm.

2.3.1 Mount ring

The mount ring design follows a flexure pattern that is radially symmetrical and is repeated every 60 degrees (see Figure 2.11). The mount ring is sized to match the relevant barrel and lens dimensions. For example, for lens 3, the diameter of the ring is larger than usual to fit its barrel position. The fixing holes are oversized to allow the mounts to be radially aligned with respect to the optical axis. The optical axis is perpendicular to the assembly face of the mount rings. Thus they have preferred assembly orientations which will be considered when mounting the lenses. The mount ring design allows a 2.5 mm separation between the lens and the ring, which allows play to correct for manufacturing wedge in the lens. It also leaves space to set the position of the pads to provide a 0.2 - 0.5 mm 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. When possible the lens centre of gravity plane is matched to the mount's edge thickness mid-plane, offsets are avoided to minimise any

torque in the flexures. The mount ring material has been selected to be 6082T6 or C250 top plate Aluminium Alloy due to its innate flatness and machinability. The expected parallelism and flatness as-manufactured tolerances are 0.025 mm. The flexure sections of the mount ring are machined using a Wire EDM process as conventional machining processes cannot produce the beam section (0.8 – 2.0 mm) profiles. The mechanical concentricity between the lens outer diameter and the pitch circle diameter of the M6 mounting holes is achieved by adjusting the threaded the pads in the manner of a four jaw chuck.

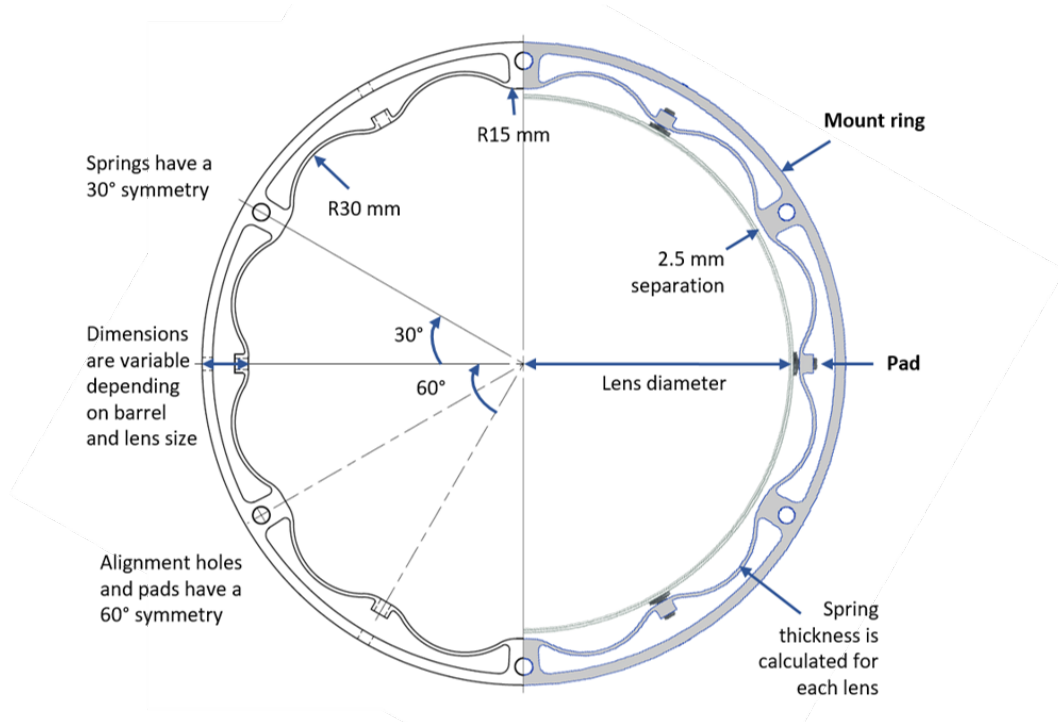


Figure 2.11: Mount ring design diagram.

2.3.1.1 Flexure spring

The flexure spring provides compliance that minimizes the thermal stress transmitted to the lens due to a contraction mismatch between the aluminium mount ring and its lens. The principle to design the flexures assumes that the pad and the bonds play a smaller role in the contraction mismatch because the pad material is chosen to closely match the lens CTE and the bonds are very small in comparison to the rest of the other

parameters. In Figure 2.12 a diagram for the lens mount assembly flexure contraction is shown.

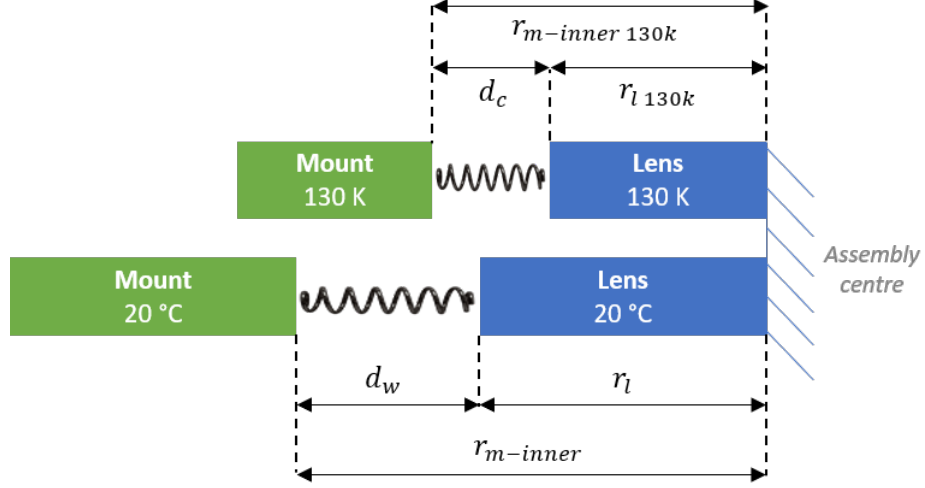


Figure 2.12: Flexure contraction diagram

The parameters involved in the spring flexure design are:

$$d_w = r_{m-inner} - r_l \quad (2.1)$$

As shown in Figure 2.12, d_w is the distance between the inner side of the mount ring and the lens at room temperature. $r_{m-inner}$ is the radius of the inner side of the mount ring and r_l is the radius of the lens at room temperature.

$$d_c = r_{m-inner_{130K}} - r_{l_{130K}} \quad (2.2)$$

As shown in Figure 2.12, d_c is the distance between the inner side of the mount ring and the lens at 130 K. $r_{m-inner_{130K}}$ is the radius of the inner side of the mount ring and $r_{l_{130K}}$ is the radius of the lens at 130 K.

The change in size due to thermal contraction of the lens Δr_l can be calculated as:

$$\Delta r_l = r_{l_{130K}} - r_l = \alpha_l r_l \Delta T \quad (2.3)$$

where α_l is the lens linear thermal expansion coefficient and ΔT is the change in temperature from room temperature to 130 K.

The change in size for the mount $\Delta r_{m-inner}$ is similarly calculated as :

$$\Delta r_{m-inner} = r_{m-inner_{130K}} - r_{m-inner} = \alpha_{Al} r_{m-inner} \Delta T \quad (2.4)$$

where α_{Al} is the mount linear thermal expansion coefficient.

The change in distance between the mount and the ring from room temperature to 130 K is Δd and can be expressed as:

$$\begin{aligned} \Delta d &= d_c - d_w \\ &= \Delta r_{m-inner} - \Delta r_l. \end{aligned} \quad (2.5)$$

The spring flexure force F follows Hooke's law:

$$F = -k\Delta d, \quad (2.6)$$

where k is the spring constant of the flexure. Each lens mount is designed according to the lens that it holds, thus there is a k for each assembly. k can be estimated by simulating an assembly and changed by varying the mount edge thickness, the flexure thickness or its symmetry¹¹.

The spring flexure should be stiff enough to hold the alignment of the assembly at room temperature and during the operational phase, but should not transmit a force large enough to significantly deform the lens or to even damage it. Each lens material and lens shape should be considered when estimating this force.

2.3.2 Pads

The pad design is driven by the lenses' edge thickness and shape, while also considering its chamfer. When possible, the lenses' centre of gravity plane pass through the axis of the pads. Otherwise, the lens edge thickness mid-plane is chosen. Like the FMOS and KMOS projects the adhesive bond is circular. As shown in Figure 2.13, the pads have a 5-degree chamfer to produce an ideal bond with no hard edges. The diameter is calculated to produce a bond area that can hold alignment and support the distributed weight of the lens among all pads. The pads also include a conduit for introducing the adhesive dispenser syringe tip. The shaft of the pad is threaded to allow adjustment of the adhesive thickness and can be set with a flat-blade screwdriver.

¹¹The details of the calculation are performed by the mechanical engineers.

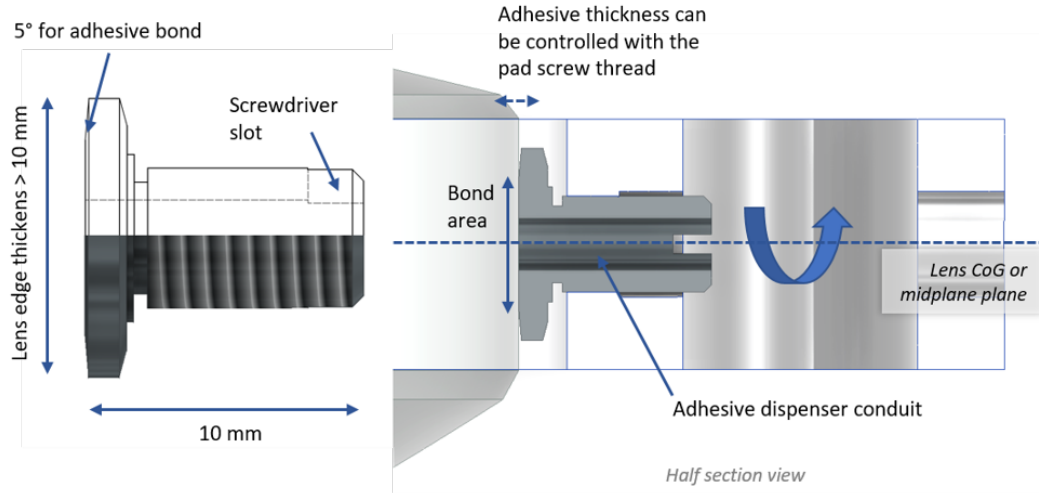


Figure 2.13: Mount pads design diagram.

2.3.3 Bonds

In the lens mount assembly, there are two adhesive bond types. See Figure 2.14. The first is the bond that adheres the lens to the cotton paper layer. This bond aims to fix the cotton paper layer to the edge of the lens, and its thickness is not controlled. A thin layer of adhesive is applied to the paper and spread with a wooden rod while removing the excess adhesive. Then the paper layer is carefully adhered to the lens edge. The second bond is the bond that adheres the pad to the cotton paper layer. This bond is repeated for each pad, aiming to hold the lens at several points. The central thickness of the bond is set at 0.2 mm. See Figure 2.14 top right. The adhesive is applied with a dispenser through the conduit in the middle of the pad. The bond thickness is not uniform because it fills the gap between the flat pad and the curved lens edge, and corrects small alignment errors such as lens edge parallelism.

2.4 Alignment concept

2.4.1 Definitions

The first step when developing alignment is to define the degrees of freedom of the component to align. Then defining what alignment is with respect to the degrees of freedom for these components. This alignment definition is at a concept stage thus

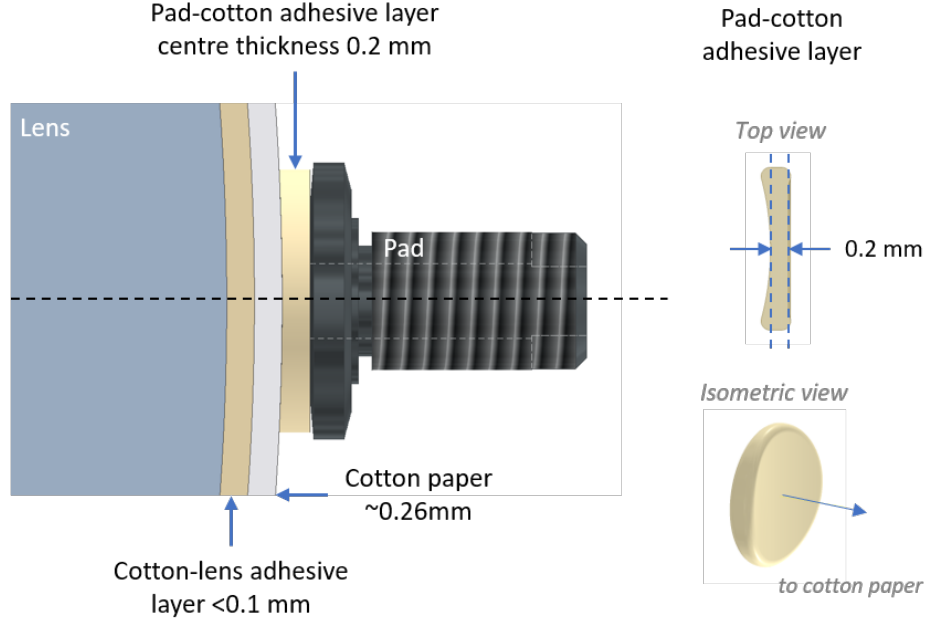


Figure 2.14: Lens mounts assembly bonds diagram.

provides the building block for alignment development for the spectrograph cameras. The limitations of the alignment include the current alignment concept set-up that is described in this section.

2.4.1.1 Radial alignment

The lens x_l - y_l plane is defined as the plane orthogonal to the direction of light propagation coinciding with the lens axis of symmetry, its origin is the lens optical axis. See Figure 2.15 on the right, where the front of the side corresponds to the plane of light incidence. The x_l and y_l lens axes are not constrained by a particular orientation unless needed due to a manufacturing imperfection, otherwise it is assumed that a lens is rotationally symmetrical.

The mount x_m - y_m plane is defined as the plane orthogonal to a best fit cylinder encompassing the outer edge of the mount. See Figure 2.15 on the left, where the front of the mount is chosen as the reference surface. The x_m and y_m axes are not constrained by a particular orientation unless needed due to a manufacturing imperfection, otherwise it is assumed that the mount is rotationally symmetric every 60° .

Δx_l , Δy_l , Δx_m and Δy_m are the uncertainties in finding the origin of the x-y plane experimentally.

Radial alignment is achieved when $x_l \pm \Delta x_l \approx x_m \pm \Delta x_m$ and $y_l \pm \Delta y_l \approx y_m \pm \Delta y_m$ ¹². During assembly at room temperature the radial alignment of a lens mount assembly can be limited by:

- the roundness or cylindricity of the lens and/or of the mount;
- the lens surface's wedge;
- the rotational radial error of the rotary table;
- the uncertainty of the measuring device.

Depending on these limitations, the radial alignment could look different than initially intended. If the lens' cylindricity error is extreme and/or if one of its surfaces is severely wedged, the apparent centre of the lens will not *look centred* in the mount to achieve the best possible radial alignment.

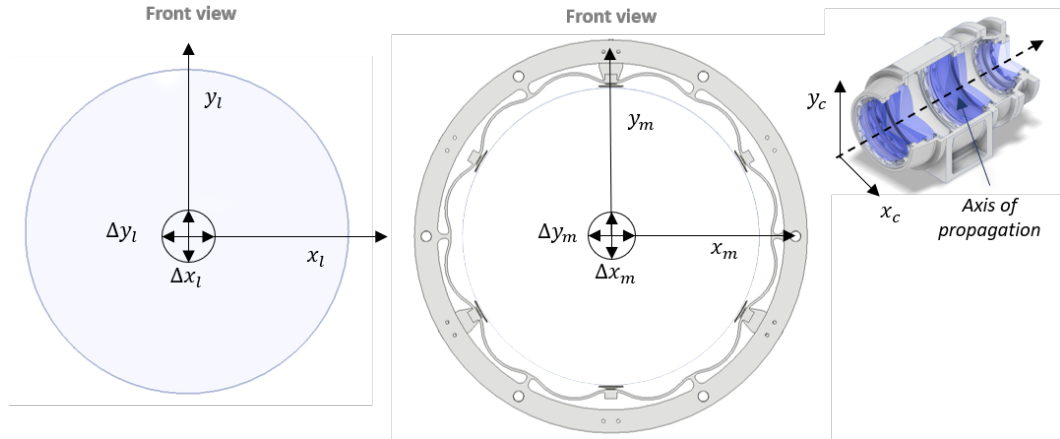


Figure 2.15: Definition of the x and y axes for lens and mount.

¹²In other words, radial alignment is achieved when (x_l, y_l) is co-incident with (x_m, y_m) within the tolerances.

2.4.1.2 Air gap

The air gap refers to the space between lenses in an optical design. For the lens mount assembly, it refers to the position of the lens and mount along the direction of propagation. For the lens, the z_l axis coincides with the axis of symmetry or the optical axis of the lens. The origin is determined at the middle of the lens edge thickness and it is perpendicular to the lens $x - y$ plane. See Figure 2.16 on the left. For the mount the z_m axis goes along the cylindrical axis of a best fit cylinder. Its origin is found at the middle plane between both of its top and bottom surfaces. See Figure 2.16 on the right. Δz_l and Δz_m are the uncertainties in the origin position of the z axis for the lens and the mount respectively.

Alignment is defined when $z_l \pm \Delta z_l \approx z_m \pm \Delta z_m$. Placing the lens at the correct position is key to position the lens centre of gravity at its design position for its mount. During assembly at room temperature the air gap alignment of a lens mounts assembly can be limited by:

- the lens thickness not being within tolerance;
- the height of the mount jig parallels not being within tolerance;
- the height of the mount jig setting spheres not being within tolerance.

2.4.1.3 Tip and tilt

Given that the lens and the mount are rotationally symmetric, the tip and tilt can be seen as a combined 3D angle. The 3D angle, α_{l3D} is defined by the angle between the direction of light propagation of the camera and the axis of symmetry of the lens. For lenses with spherical surfaces, the axis of symmetry of the lens is the optical axis of the lens. See Figure 2.17 on the left. Similarly to the lens, the 3D angle for the mount, α_{m3D} is defined by the angle between the direction of light propagation of the camera and the axis of symmetry of the mount. See Figure 2.17 on the right.

Tip and tilt alignment is achieved when $\alpha_{l3D} \approx \alpha_{m3D}$ or when the mount $x - y$ plane is close to-orthogonal to the axis of symmetry of the lens. $\Delta\alpha_{l3D}$ and $\Delta\alpha_{m3D}$ describe the uncertainty in the knowledge of where the lens and mount framework of

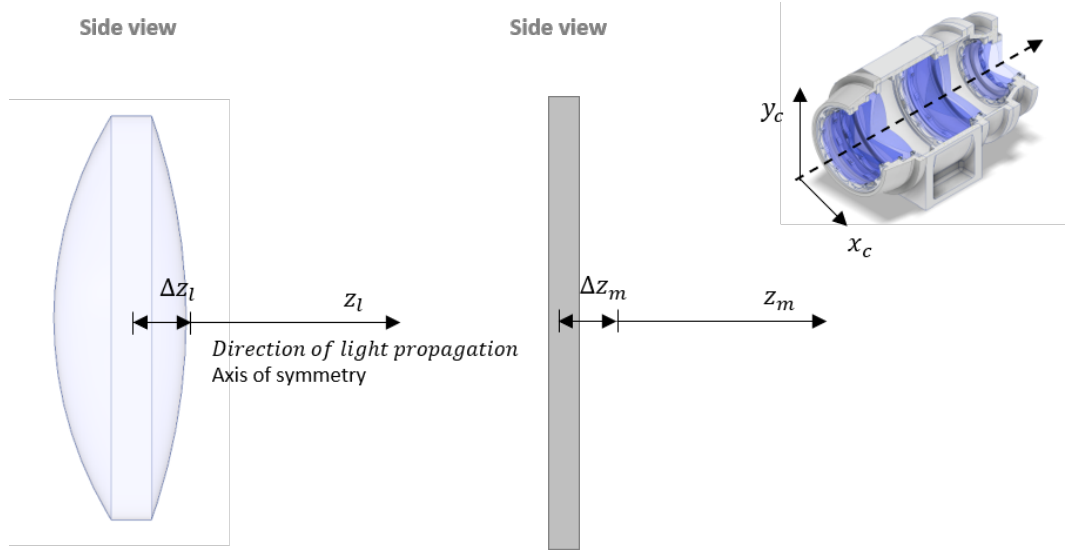


Figure 2.16: Degrees of freedom definition z for lens and mount.

reference is. For the lens mounts assembly it is key to control the tip and tilt alignment up to its tolerance at this stage because correcting or compensating the error at later stages of the camera assembly leads to significant complications. During assembly at room temperature the tip and tilt alignment of a lens mount assembly can be limited by:

- the parallelism between the mount assembly surfaces;
- the flatness of the mount reference surface;
- the height difference between the mount jig parallels;
- the height difference between the mount jig setting spheres;
- the parallelism between the mount jig base plate surfaces;
- the rotational error of the rotary table;
- how well it is experimentally possible to find the axis of symmetry of the lens.

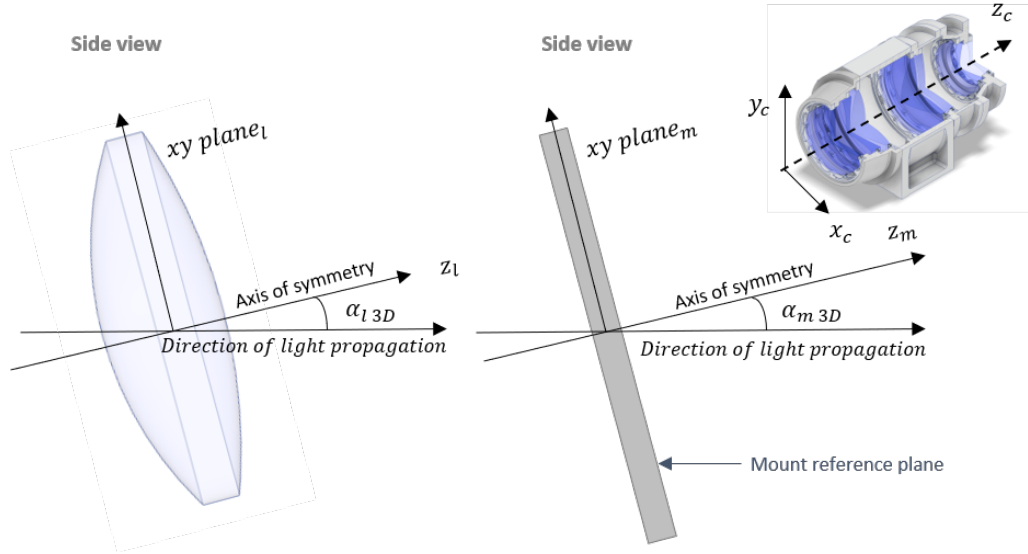


Figure 2.17: Degrees of freedom definition *tip* and *tilt* as α_{3D} for lens and mount.

2.4.1.4 Roll

The roll of the lens and mount is defined as the orientation of its $x-y$ plane. See Figure 2.18. Alignment in this degree of freedom is not defined as it is a compensator. The lens can be rotated around its axis of symmetry if needed. The mount can be rotated around the axis of the best fit cylinder if needed. When mounting, the lens mount assembly can be rotated every 60 degrees when assembled to its barrel to compensate for any misalignment or imperfection.

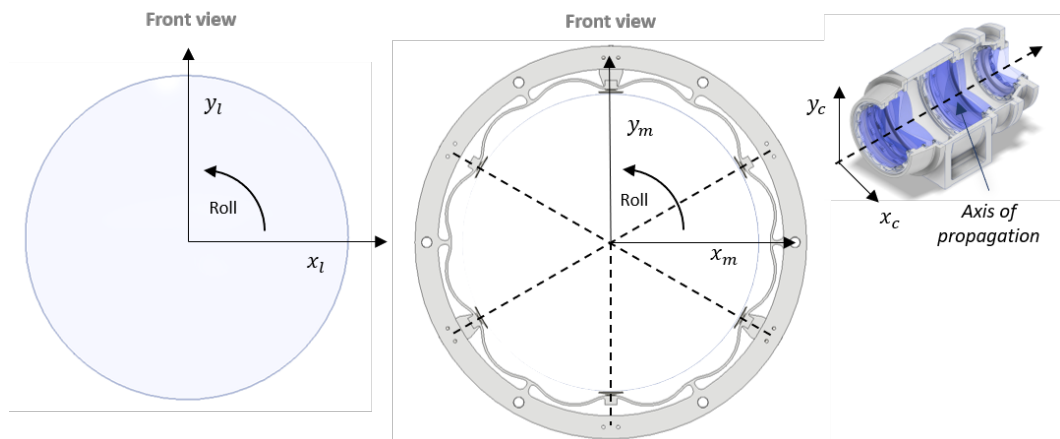


Figure 2.18: Degrees of freedom definition *roll* for lens and mount.

2.4.2 Mounting concept

The mounting concept describes the process of how a lens is aligned and mounted. This process relies on the documentation and experience acquired by RAL Space and the University of Oxford on the projects FMOS, KMOS, SWIFT as well as further prototyping.

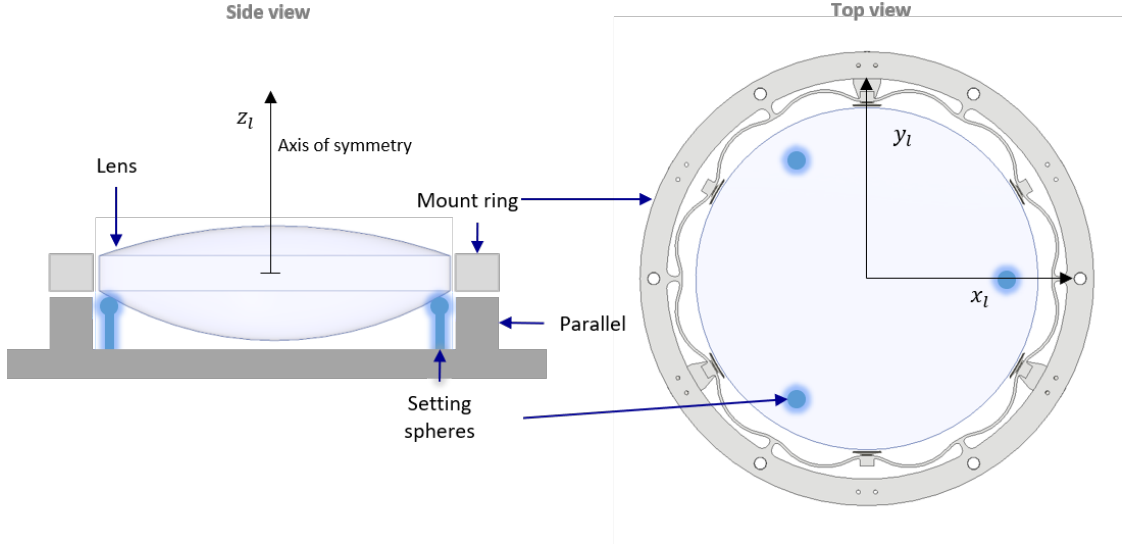


Figure 2.19: Lens mounting setup concept.

Figure 2.19 shows the lens mount assembly placed on its mounting jig which in turn is placed on a rotary table. The idea is to use the rotational axis of the rotary table is to find the axis of symmetry of the lens while holding it safely, then to place the mount and find its cylindrical axis, to constrain the positions of the lens and of the mount, and finally to apply adhesive to fix the alignment. 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 setting spheres and parallels are custom made for each lens, based on the known first-order parameters of the lens (e.g. RoC, diameter, centre-thickness, etc.).

The logic to define alignment throughout the mounting goes as follows (see figures 2.20 and 2.21 for guidance):

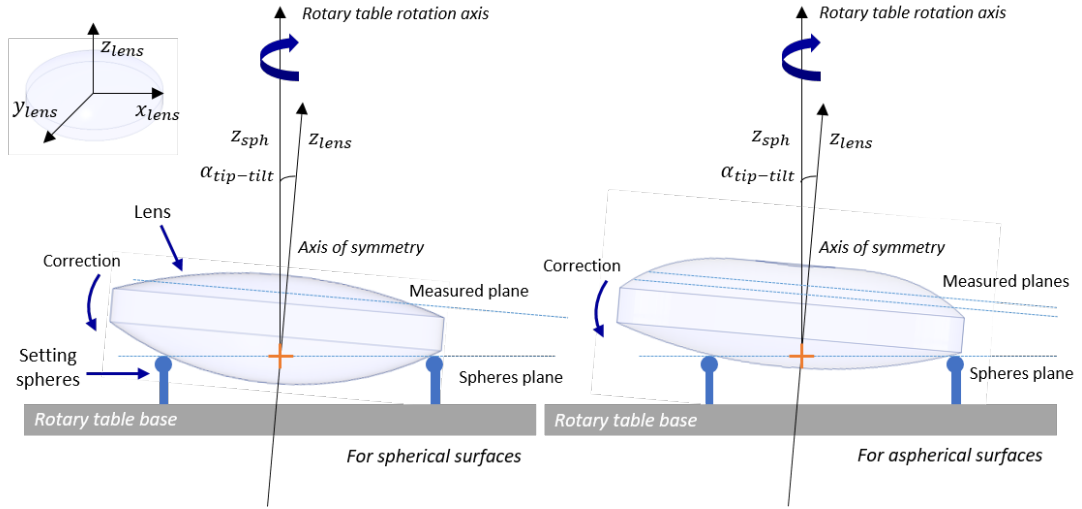


Figure 2.20: Lens mounting concept diagram.

- the mount jig is placed and aligned with the rotational axis of the rotary table and the axis of the circumference formed by the spheres is set as the origin of the x_{sph} and y_{sph} axes.
- the lens is placed on three spheres equispaced at 120 degree intervals located outside the lens effective aperture.
- 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.
- 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} .
- The lens is then adhered to the mount and the components keep their alignment in place.

When an aspherical surface is the top surface of the lens, two lens planes are measured at different heights, and the same procedure is followed to reach alignment.

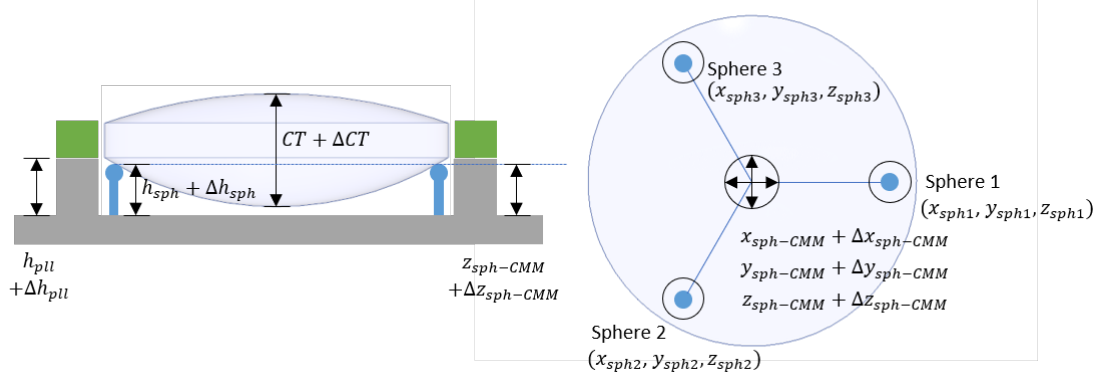


Figure 2.21: Mount jig mechanical tolerances.

2.4.3 Mount jig

Following the mounting concept laid out in Section 2.4.2, the components of a mount jig are: a base, parallels and three setting spheres. See Figure 2.22 for guidance. The number of parallels can vary, depending on the size of its mounting assembly. The material chosen for the mount jig base and parallels is the same as the mount material, aluminium C250 plate. It is chosen due to its properties as it is practically stress free, thus retaining its flatness and dimensional tolerances after machining and even thermal cycling.

After researching, designing and understanding the mounting concept, I set out to design a mount jig to assemble two sample lenses with their associated mounts (in Section 2.5.1 I introduce these assemblies and discuss them in detail). In principle, each lens mount assembly has its own, unique mounting jig design. For HARMONI, for example, the infrared cameras will have up to 7 different lenses¹³, each of which will be requiring a specific mount jig. For my thesis project, I set out to design a mounting jig that could be compatible with both of my sample lenses and their mounts with minimal changes. The base I designed included two options for positioning setting spheres at different heights as shown in Figure 2.23. The proposed mount designs for

¹³Since completing my DPhil work, the camera's design has been changed, but the mounting principle remains the same.

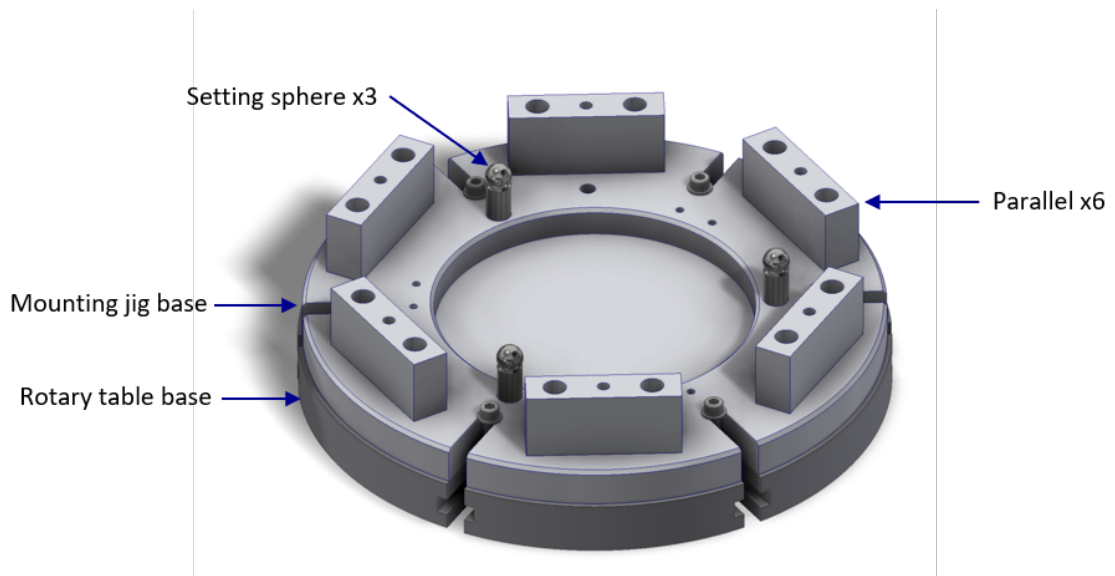


Figure 2.22: Mounting jig design inspired by FMOS and KMOS alignment methods.

my sample lenses were symmetrical every 60° degrees, thus I designed the jig to include six parallels. Manufacturing tolerances play a big role in the final alignment that a mount jig can allow. I spoke with the mechanical workshop at the Physics department of the University of Oxford and chose tolerances that had been used before for this type of application. The tolerances were tight but allowed for efficient manufacturing.

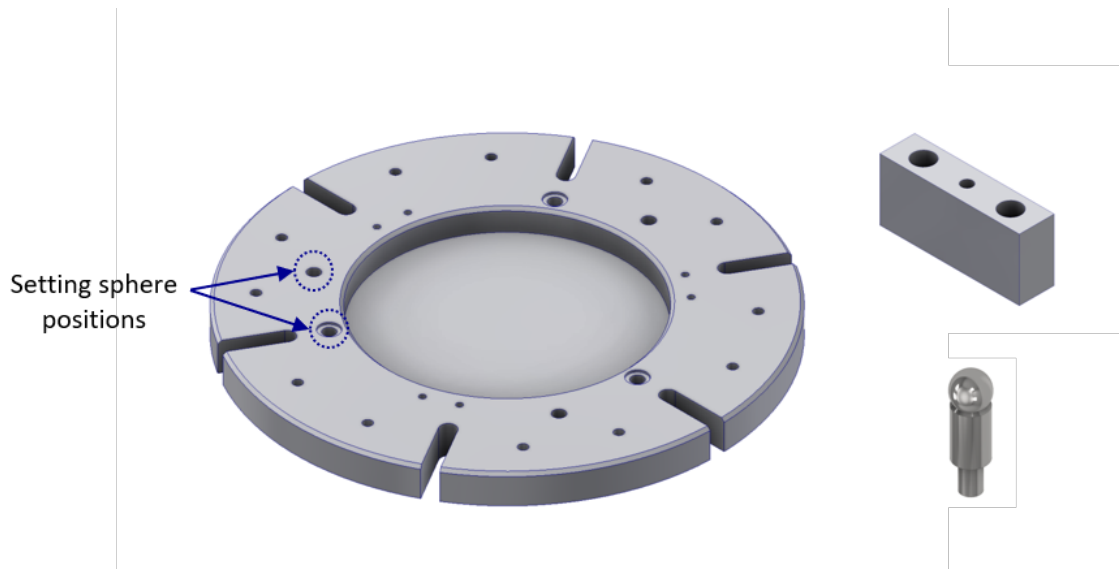


Figure 2.23: Mounting jig components. This particular base plate design has two setting sphere positions to mount two types of lens.

2.4.3.1 Base

The base of the mounting jig is an extruded circle that matches or is compatible with the rotating plate of the rotary table. It is the base for the mounting jig alignment and sets the foundations for alignment. Its design requirements are:

- the plate must be parallel and flat within a tolerance that allows for the alignment requirements of the lens mount assembly;
- allow a safe space gap between lens vertex and base plate;
- place holes to fix setting spheres with a tight fit and allow for shimming if necessary. These holes must also provide the setting spheres with the corresponding design height;
- place slots to fix the base to the rotary table plate;
- place holes to fix the parallels;
- add visual guides for placing lens centred;
- put a continuous surface parallel to the rotational axis for probing the position during alignment;
- minimize sharp edges to reduce the risk of damaging elements during assembly.

2.4.3.2 Parallels

The parallels are extruded rectangles with a compatible height to match both lenses. The main design requirements are their height, their parallelism and their flatness. These must be compatible with the alignment requirements of the mounting jig. Also, the design should allow for shimming of the parallel to make its height match that of other parallels. Ideally they should be machined together to match in height. The manufacturing tolerances I chose for this version of the parallels are shown in [Figure 2.24](#). Additionally, the parallels follow the same general tolerance requirements as the base for surface roughness, linear and angular tolerance.

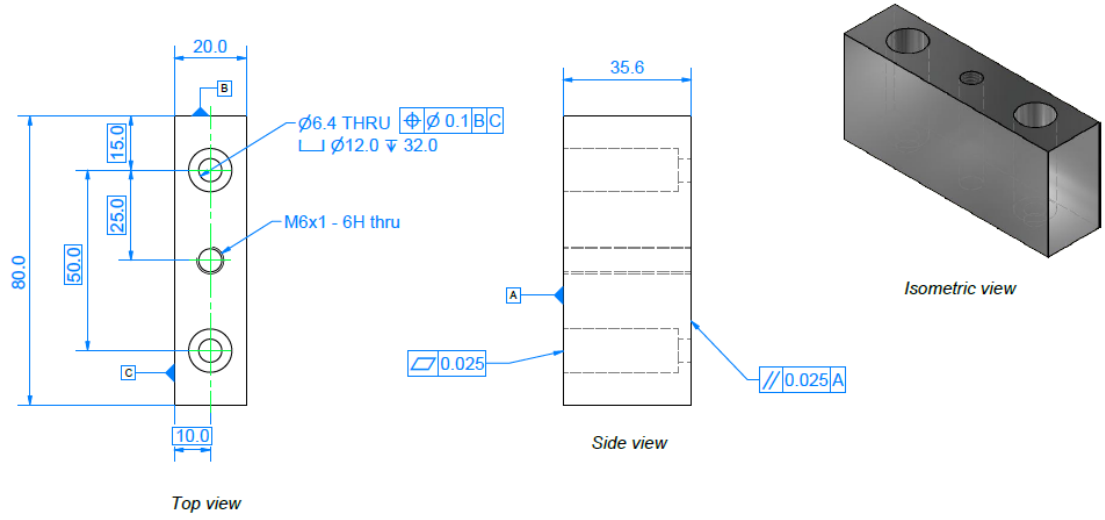


Figure 2.24: Manufacturing drawing extract of the parallels.

2.4.3.3 Setting spheres

The setting spheres¹⁴ are made out of hardened steel and have a plain body with metric dimensions¹⁵. The tolerance in the sphere's diameter is $+0/-0.005$ mm and on its pin ± 0.0025 mm. I selected them with a sphere diameter of 14 mm to reduce surface damage after performing tests with various diameters.

2.4.4 Tolerances

Alignment is never perfect but is deemed acceptable when it meets its design requirement. The tolerances shown below in Table 2.2 are only applicable to the lens mount assembly and are meant to verify the quality of the assembly at room temperature.

DoF	Description	Tolerance limit
x	Lens decentring within mount ring	$\pm 5 \mu\text{m}$
y		
z	Lens decentring within mount ring	$\pm 10 \mu\text{m}$
Tip	Angle between lens optical axis and mount reference surface	$\tan^{-1}(\frac{20 \mu\text{m}}{\phi_l})$
Tilt		
Roll	Assembly clocking	60° Compensator

Table 2.2: Tolerance limits for lens mount assembly for room temperature verification.

¹⁴In the industry they are used as tooling ball reference pins.

¹⁵For future reference, the setting spheres were purchased from WDS components code WDS 3502.

The tolerances are estimations from what is mechanically achievable combining manufacturing tolerances and the available measuring devices. In Section 2.9 I perform an evaluation of these tolerances against the calculated requirements from the tolerance analysis of the camera optical design.

The radial alignment tolerance in x and y is proposed as a maximum value for Δx_l , Δx_m , Δy_l and Δy_m . The alignment tolerance along the direction of propagation z is proposed as a maximum value for Δz_l and Δz_m . The tip and tilt alignment defines a maximum value for α_{l3D} and α_{m3D} .

As the mount assembly alignment is dependent on the mount jig references, it is important to understand where these references are and if the mount jig meets a minimum requirement for the lens mount assembly to stay within its tolerances. On Figure 2.21, I show on the left the mechanical tolerances that play a role in terms of airgap and tip-tilt, and on the right I show the ones that play a role in radial alignment:

- h_{pll} is the average height of the mount jig parallels and Δh_{pll} is the deviation in height of the parallels;
- h_{sph} is the average height of the setting spheres and Δh_{sph} is the deviation in height of the setting spheres;
- CT is the centre thickness of the lens and ΔCT its manufacturing error;
- $z_{sph-CMM}$ is the z axis origin position of the mount jig reference framework and $\Delta z_{sph-CMM}$ is the uncertainty of this position;
- x_{sph-i} , y_{sph-i} and z_{sph-i} define the position of the setting sphere i ;
- x_{sph} and y_{sph} are the x and y axis origin positions of the mount jig reference framework. $\Delta x_{sph-CMM}$ and $\Delta y_{sph-CMM}$ are the uncertainties of these positions.

Note that the mount jig reference framework is a geometrical construction defined by the positions of the setting spheres which I measured with a Coordinate Measuring Machine (CMM). Furthermore, the positions of the setting spheres with respect to its base need to be verified at the manufacturing acceptance.

Thus alignment for a lens mount assembly referenced to its mount jig is:

$$\begin{aligned}
&\text{RT rotation axis} \parallel z_{sph-CMM} \Rightarrow \text{RT } z\text{-axis rotation error} \leq \Delta z_{sph-CMM} \\
&x_{sph-CMM} \parallel x_l \Rightarrow \Delta x_{sph-CMM} \leq \Delta x_l \\
&y_{sph-CMM} \parallel y_l \Rightarrow \Delta y_{sph-CMM} \leq \Delta y_l \\
&x_{sph-CMM} \parallel x_m \Rightarrow \Delta x_{sph-CMM} \leq \Delta x_m \\
&y_{sph-CMM} \parallel y_m \Rightarrow \Delta y_{sph-CMM} \leq \Delta y_m
\end{aligned} \tag{2.7}$$

The alignment of z_l and z_m is set by the set-up. Before mounting, h_{pll} and h_{sph} should match the design height for the lens mount assembly.

2.5 Assembly

The assembly of one lens to its mount requires eight main procedures. Figure 2.25 displays a flow diagram of these processes. In this section, I describe the assembly procedures I developed inspired by samples of KMOS lens mount assemblies and Allen's prototyping efforts. I performed the assembly on two lens mount models. The main objectives were:

- measure alignment at room temperature;
- analyse tolerance stack up throughout the assembly including equipment, mount jig, mount and lens;
- develop and document the assembly¹⁶.

2.5.1 Engineering models

I planned the assembly and testing of two engineering models to demonstrate updated design concepts, the assembly procedure I developed, and later to test their performance in operational conditions. Each model had its objectives to demonstrate. Figure 2.26 shows both models assembled, and in the sections below, I list the objectives for prototyping these models.

¹⁶Since the conception of the flexure mounts and throughout its history, the procedure had never been documented.

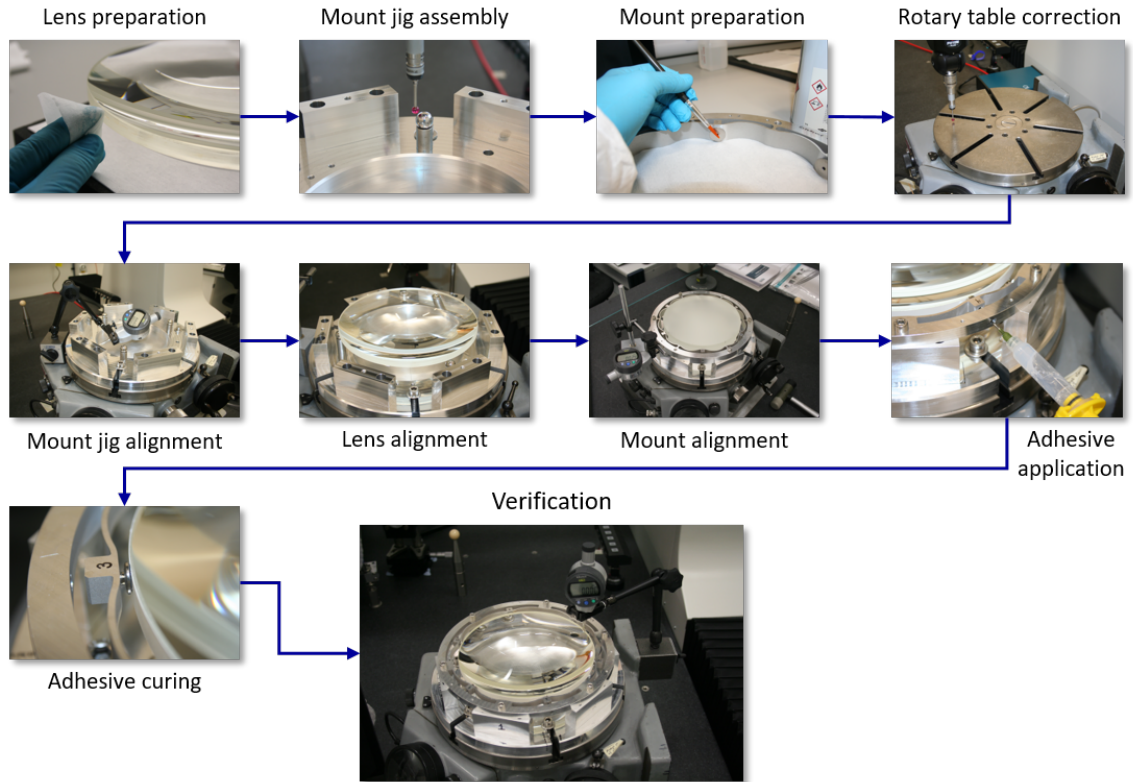


Figure 2.25: Lens mount assembly procedures.

2.5.1.1 KMOS design with a fused silica blank

The objectives for prototyping the KMOS design with a fused silica blank model were:

- re-create a model similar to the slotted mount ring with double beam spring pads developed by Allen, but with the FMOS/KMOS flexures (for performance comparison);
- develop and practice the assembly procedure with the least complicated setup (flat-flat lens surface);
- test the most extreme example of thermal stress due to material combination (fused silica with aluminium);
- demonstrate adhesive bond success at room temperature and in operational conditions;
- demonstrate an updated flexure mount design concept in operational conditions.

Table 2.3 lists key technical details of this model.

Specification	Blank	Mount	Pads
Material	Fused silica	Aluminium C250 Plate	Invar
Size	Ø200mm Thickness 30 mm	Ø265mm Thickness 20 mm	Ø17mm $\angle 2.5^\circ$
Tolerances	Parallelism 0.10 mm Flatness 0.025 mm	Parallelism 0.025 mm Flatness 0.025 mm	$\pm 0.5\text{mm}$

Table 2.3: Engineering model 1: KMOS design with fused silica blank details. Blank tolerances measured with the coordinate measuring machine. Mount and pad tolerances are specified as in their manufacturing drawing. Whilst previous projects had shown that the concept was achievable, there was little or no documentation or experience left on how the details of *how* to achieve it.

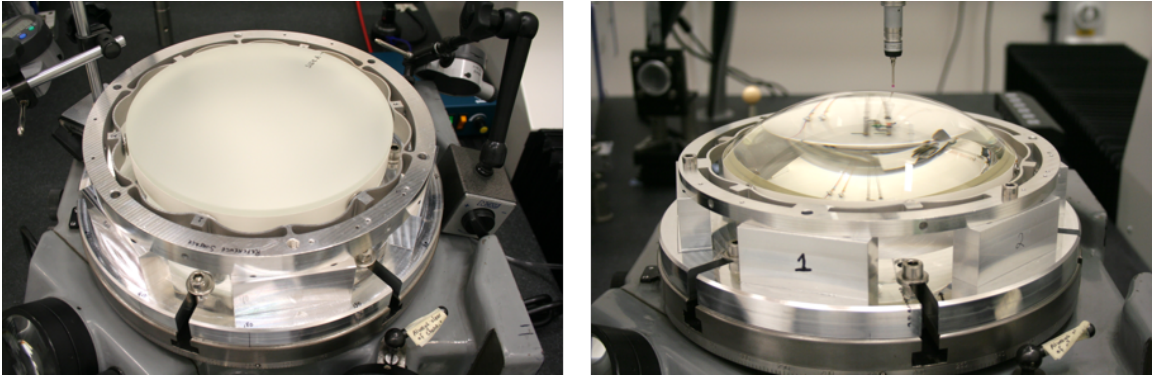


Figure 2.26: Engineering models. (left) KMOS design with fused silica blank. (right) Pre-HARMONI design with an HK9 lens.

2.5.1.2 Pre-HARMONI design with an HK9 lens

The objectives for prototyping the Pre-HARMONI design with an HK9 lens model were:

- demonstrate an updated flexure mount design concept based on HARMONI-like lens size ranges and a centre of gravity outside the lens edge in operational conditions;
- develop and practice the assembly procedure with a flat-convex lens of similar size as HARMONI camera lenses and with the edge thickness set to the minimum allowed;

- test the performance of the updated flexure mount design with a challenging lens shape at operational temperatures.

Table 2.4 lists key technical details of this model.

Specification	Lens	Mount	Pads
Material	HK9	Aluminium C250 Plate	Invar
Size	$\varnothing 205\text{mm}$ Thickness 50.37 mm RoC 300 mm Plano-Convex	$\varnothing 265\text{mm}$ Thickness 10 mm	$\varnothing 10\text{mm}$ $\angle 5^\circ$
Tolerances	Not measured	Parallelism 0.025 mm Flatness 0.025 mm	$\pm 0.5\text{mm}$

Table 2.4: Engineering model 2: Pre-HARMONI design with HK6 lens details.

2.5.2 Assembly approach

There was much uncertainty around assembling when I started. A reliable and repeatable procedure to mount lenses, barrels and cameras had to be developed to determine what tolerances could be achieved and this information then had to be used to optimise a camera design. In other words, a camera had to be designed so that it could be built with our facilities while meeting its image quality requirements.

I focused on the first step: mounting lenses. I started with a list of steps that J. Lynn had written, and I then developed a concept procedure in 3D with CAD models. I developed the definitions of alignment for the shapes of lenses considered in the design of the cameras. The clean room for instrument assembly had just been handed over after construction to our research group, and the CMM had just been purchased. I led the commissioning of the clean room along with its equipment and trained to operate the CMM.

I then prepared the assembly setup, rehearsed the procedure without adhesive, practised the steps, and refined them, including programming measuring routines in the CMM. First, I assembled the KMOS design with a fused silica blank model and verified its alignment. Then I assembled the Pre-HARMONI design with an HK9 lens.

The procedures I detail in the sections below are based on assembling and rehearsing the procedure several times.

2.5.3 Dispensing adhesive

Adhesive dispensing was the topic with the most uncertainty in the assembly procedure. I had never dispensed adhesive before. I had no solid ground from where to start in Oxford because it was thought that during J. Allen’s prototyping bonds had failed¹⁷. Unfortunately my DPhil only just overlapped with the RALSpace technician who assembled the FMOS and KMOS cameras before his retirement. I therefore could only have a brief discussion on adhesive dispensing techniques with him. Therefore, I taught myself how to do it. I borrowed a large lens from the undergraduate optical laboratory¹⁸ and designed a test to learn how to use all functionalities of the adhesive dispenser. Figure 2.27 shows the adhesive samples I dispensed on the lens. I dispensed adhesive on the lens surface and varied pressure, dispensing time, primer application and use of cotton paper.

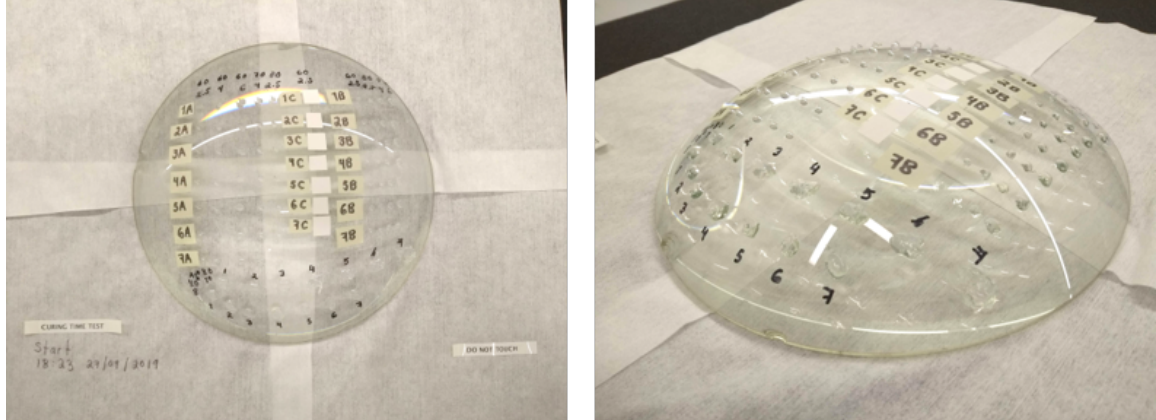


Figure 2.27: Adhesive dispensing testing sample.

This exercise taught me that:

- the adhesive dispenser works well, and it is possible to combine pressure with dispensing times to dispense a repeatable amount of adhesive;

¹⁷Moreover, Jamie did not use an adhesive dispenser but rather a manual dispensing pistol, which really limited repeatability and quality control.

¹⁸I wanted to use a lens to learn to dispense on optical surfaces.

- for this type of adhesive¹⁹, the best supply pressure is 100 psi;
- as specified from the datasheet: the adhesive dries when in contact with air. It dries from the outside to the inside. Curing time depends on the amount of applied adhesive and the surface area in contact with air, and it is not just a standard of seven days. The smallest amounts of adhesive cured within a day, and the largest within five to seven days;
- the adhesive changes opacity throughout curing. When cured, it is clear. Figure 2.28 on the left shows an uncured opaque adhesive sample;
- during this test, I saw no difference on primed and not primed surfaces²⁰;
- the adhesive adhered well to the paper and could be removed and cleaned;
- the adhesive can be cleaned from a polished optical surface at any stage of curing with great care and isopropyl alcohol;
- the best way to clean adhesive is isopropyl alcohol. It is best not to use water;
- the cured adhesive is very elastic and malleable, Figure 2.28 on the right shows how elastic a sample of adhesive can be;
- it is important to remove bubbles in the dispensing syringe, or the bubbles will splash when coming out.

2.5.4 Assembly steps

In the following sections, I describe the steps I finalized after assembling both lenses into their mounts. This section can serve as a starting point to assemble the lenses for the HARMONI cameras. The steps in this section are written for future guidance, and describe the best practice I developed.

¹⁹The adhesive I refer throughout the assembly section is Dow Corning 6-1104.

²⁰This test was observational, I did not measure mechanical properties.

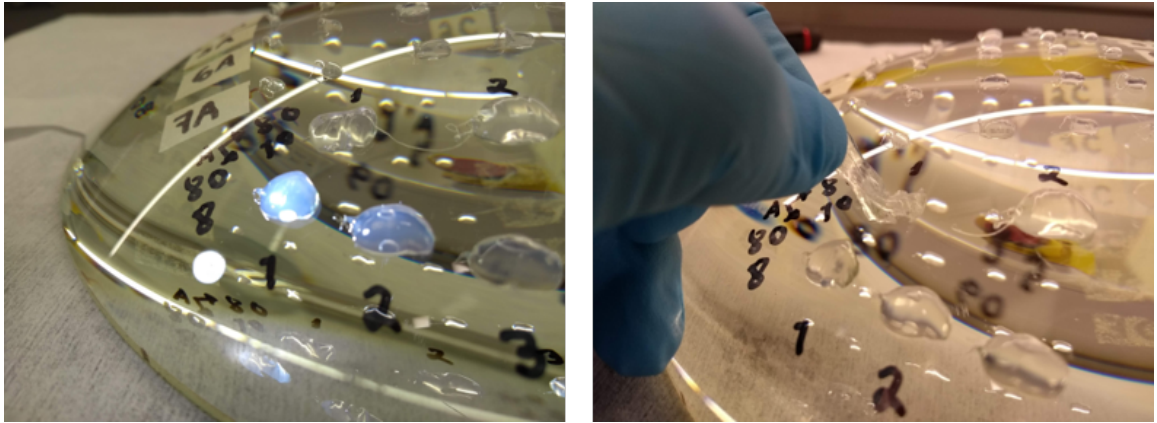


Figure 2.28: (left) The adhesive when curing changes opacity until it becomes clear after it is fully cured. (Right) Cured samples of adhesive are malleable and are elastic.

2.5.4.1 Lens preparation

The lens preparation gets the lens ready to be mounted into the lens mount. This involves inspecting the blank, cleaning the edge, and adhering a strip of paper to that edge. The paper strip can be measured and cut beforehand, but all other steps must take place in cleanroom conditions; partly to aid good bonding, but also to minimise the risk of contamination of the optical surfaces. This process takes approximately 3.5 hours per lens and can be performed by one person.

The required materials and equipment needed for this step are cotton paper (Arches Aquarelle Hot Press 190 SSM), knife, cutting board, ruler, adhesive (Dow DOWSIL 6-1104CV), Dow DOWSIL 1200 OS Primer decanted into a small container, brush, wood stick, Kapton tape, cleaning wipes, distilled water, isopropanol, acetone, a thick foam covered with a non-scratch wipe to place the lens on top and of course the lens.

The procedure steps go as follows (see Figure 2.29 for reference):

1. Measure or read from the manufacturing drawing the pads' and lens diameter. Cut the cotton paper strip length to fit the lens diameter size plus 4-5 mm to allow a slight overlap, and with a thickness of at least the pad's diameter and, if allowed by the lens edge thickness, 2 or 3 mm wider.
2. Prepare the setup with the necessary materials and equipment to adhere the paper strip to the lens. Carefully place the lens on top of the thick foam piece

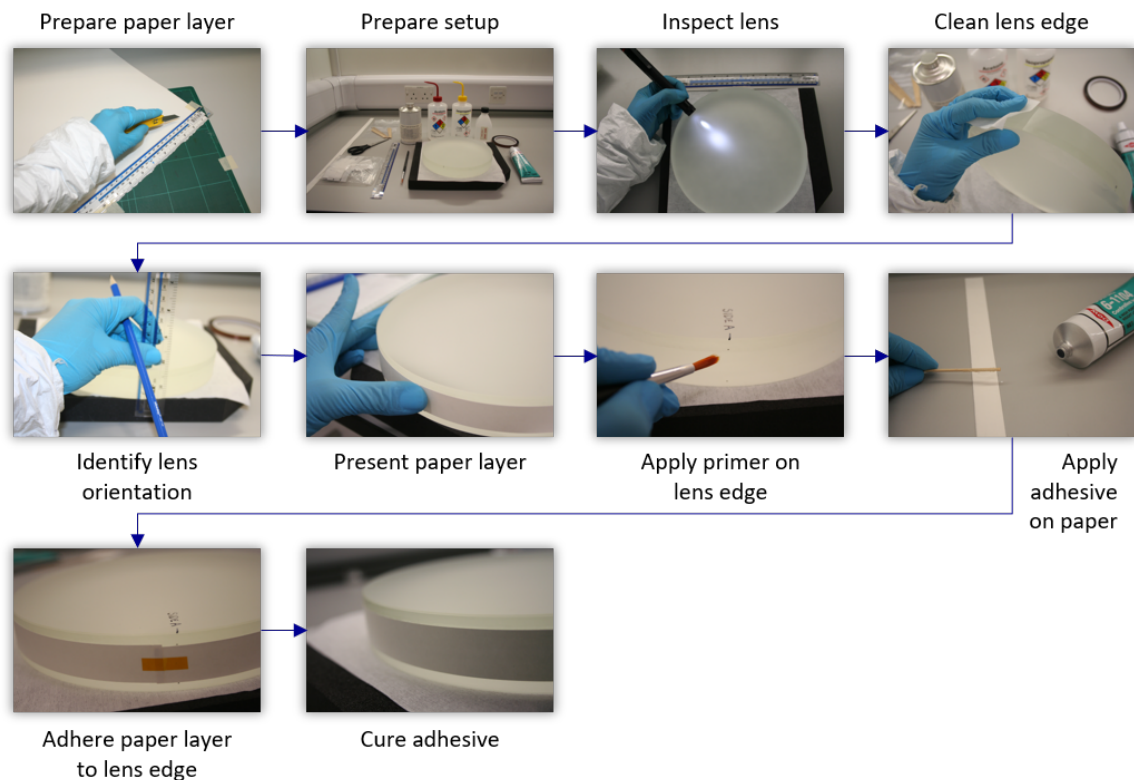


Figure 2.29: Lens preparation steps.

covered in a clean non-scratch tissue.

3. Inspect the lens and coating following ISO 9211-4:2012(E) Annex C. Record the current state of the lens surface, including any surface imperfections.
4. Clean lens edge if necessary. Removing any grease traces is most important to a successful bond. Use distilled water and a swab to remove stains, then use wipes with isopropanol and acetone. Take great care in not touching or damaging the lens's effective aperture.
5. Identify the lens assembly orientation and place the paper layer on the lens edge without adhesive. Practice this movement and consider how to handle the paper layer as if it had adhesive on one side without unintendedly spreading it on the lens's surface. If necessary, use a pencil to mark the position of the strip on the lens edge. It should match the pad's assembly position.

6. Using a brush, apply primer to the edge of the lens and let it dry for a few minutes. Take extra precautions to avoid painting anywhere else other than the lens edge when applying primer. Such a solvent might degrade the coating or stain the lens surfaces.
7. Apply a thin adhesive layer to one side of the cotton paper strip²¹. Apply enough adhesive to cover the cotton paper strip and no more to avoid side spillages.
8. With slow movements and care, adhere the strip to the lens edge in its position. Use your fingers to press the strip all around the lens edge perimeter. Secure the strip ends with Kapton tape²².
9. Let the adhesive dry overnight.
10. Review that the cotton paper strip had adhered well to the lens edge.

2.5.4.2 Mount jig preparation

The assembly steps here are specified for the mounting jig I designed. If HARMONI uses a different mounting jig for the final lenses, slightly different steps would of course apply, but the general principles should be the same. Ideally, the mount jig parts must be manufactured within tolerance and the assembly verified for the lens mount alignment to be successful. I mounted the first lens mount model without verifying the mount jig assembly tolerances. When I analysed the lens mount model's final alignment, I realised that the parallels and spheres had varying heights that limited the model's best achievable final alignment. The steps I document here are what I did for the second lens mount model. This process takes approximately 0.75 hours per mount jig and can be performed by one person.

The required materials and equipment needed for this step are sandpaper (fine or extra fine grit), water, wipes, mount jig parts (including screws), tools for assembly (i.e. Allen keys), precision dial gauge and base, rubber mallet, calibrated rotary table,

²¹I applied a small portion of adhesive to one side of the paper strip and used a toothpick to spread it.

²²Tip: prepare in advance a strip of Kapton and have it in hand.

isopropanol, acetone, coordinate measuring machine (CMM) with a standard probe, cutting board, knife, shim sheet (0.0005 inches thick), ruler and marker.

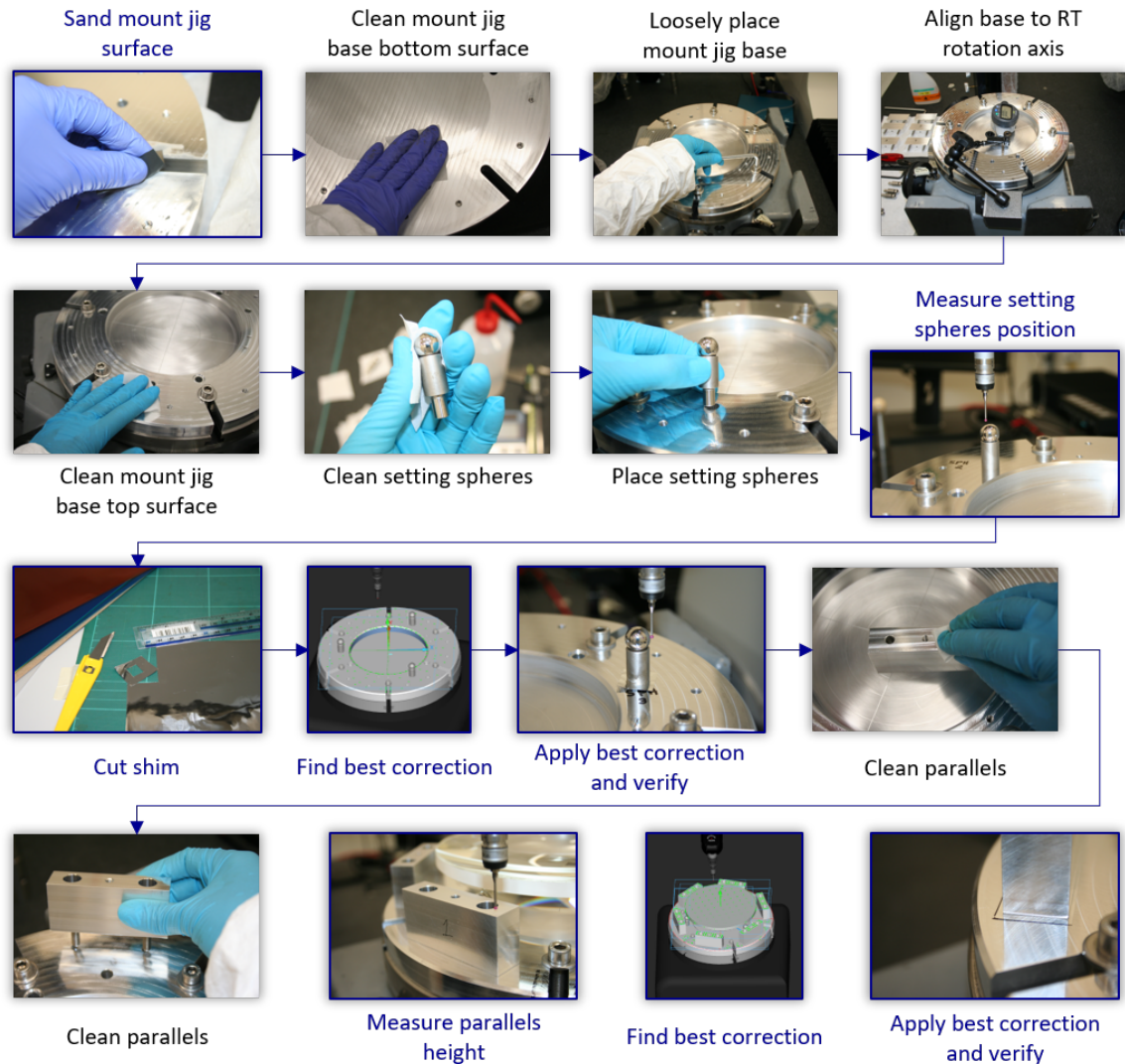


Figure 2.30: Mount jig preparation assembly steps.

The procedure steps go as follows (see Figure 2.30 for reference):

1. Sand the mount jig base and parallels²³. The idea is to smooth the assembly surfaces and deburr the parts thoroughly. Rinse with distilled water and pat dry all parts.
2. Clean the mount jig base bottom surface with isopropanol and acetone.

²³Not inside of the cleanroom.

3. Place the mount jig base on the rotary table top plate and screw it loosely in its position. Tap the mount jig base with a rubber mallet.
4. Align the mount jig base to the rotary table rotation axis by probing the base with the dial gauge. Progressively screw the base in position.
5. Clean the mount jig top surface and the setting spheres with isopropanol and acetone.
6. Place the setting spheres in their assembly position and tap them with the rubber mallet²⁴.
7. Measure the spheres' centre position with the CMM relative to the mount jig base. Verify that the radial location of the spheres meets the tolerance specified in its manufacturing drawing.
8. From the CMM measurements, determine the shims needed to set a common height on all the spheres. The maximum height deviation should be below 10 μm ²⁵.
9. Cut the shim sheet to fit the setting spheres' height correction.
10. Place the shims and re-assemble the setting spheres. Verify with the CMM the correction in height variation.
11. Wipe the parallels with isopropanol and acetone.
12. Assemble the parallels, pat them with the rubber mallet and fix their position.
13. Similarly to the setting spheres, measure the height and radial position of the parallels. Verify that these measurements meet the manufacturing drawing specifications.

²⁴To ensure they are fully seated in their holes.

²⁵The height deviation tolerance depends on the lens alignment tolerance and its shape, 10 μm applies for a 200 mm lens diameter with an alignment tolerance of 0.3 arcminutes.

14. Find the best height correction with shims. The maximum height deviation should be below $9\text{ }\mu\text{m}$ ²⁶.
15. Cut the shim sheet to fit the parallels' height correction.
16. Place the shims and re-assemble the parallels. Verify the correction in height variation with the CMM.

The quality of the mount jig's alignment to the rotary table's rotational axis is critical to achieving the best possible lens alignment. I would further improve this procedure by cleaning the mount jig plate, parallels, setting spheres, and screws with an ultrasonic bath.

2.5.4.3 Rotary table preparation and characterization

As described in Section 2.2.5, RAL assembled and aligned the FMOS and KMOS cameras. RAL did not produce any reports to document the achieved alignment at the time. As the HARMONI cameras are considered to be more challenging than the KMOS or FMOS cameras (a large field of view), it was vital to know at least the order of magnitude of the alignment that could be achieved using the same method to continue the development progression. A key element for this procedure is a rotary table. Jim Lynn located a decommissioned rotary table from the physics workshop at UOX, and I used this rotary table to mount my two lens mount assembly models. This is the procedure I did²⁷ in order to characterize the rotary table and use it. The procedure is not standard, and it should be adapted according to available equipment and rotary table. This process took me about a day to perform and several days of planning and discussions.

The required materials and equipment needed for this step are a coordinate measuring machine (CMM) with a standard probe, sandpaper (fine or extra fine grit), white spirit, water, isopropanol, acetone, and wipes.

The procedure steps go as follows (see Figure 2.31 for reference):

²⁶When computing the tolerance stack up, the height variation of the parallels and the spheres add up, reaching the lens alignment tolerance budget of a 200 mm lens diameter with an alignment tolerance of 0.3 arcminutes.

²⁷I learned quite a lot about metrology by trying out several procedure ideas, performing them and analysing my measurements. I chose to show this one because it is the one that makes the most sense.

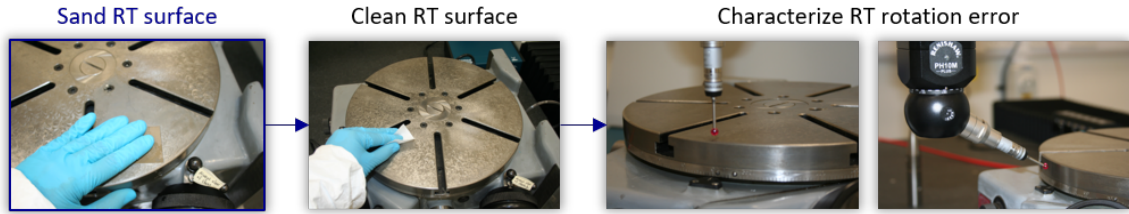


Figure 2.31: Rotary table preparation steps.

1. Clean the rotary table top plate with white spirit and sandpaper²⁸.
2. Wipe the rotary table top plate with isopropanol and then with acetone.
3. Characterize the rotary table rotation error by measuring the axial error motion (radial, tip-tilt and Z-axis) every 30 degrees with the CMM.

Figure 2.32 shows the rotary table run out or rotation error expressed as a 3D vector for a rotation position every 30 degrees. The largest rotation error is 12.2 arcseconds at 90 and 270 degrees.

2.5.4.4 Mount preparation

The mount preparation can be performed in advance of the lens mount assembly. The setup for this procedure is simply a clean working surface, and it takes approximately 0.5 hours per mount and can be performed by one person.

The required materials and equipment for this step are a flexure mount ring, pads, water, isopropanol, acetone, wipes, sandpaper (fine or extra fine grit), Dow DOWSIL™ 1200 OS Primer (a small portion in a container) and a brush.

The procedure steps go as follows (see Figure 2.33 for reference):

1. Deburr and clean the flexure mount and pads with wet sandpaper, isopropanol, and acetone²⁹.
2. Assemble the pads into the flexure mount ring and fully screw them inwards.

²⁸Note that this procedure was performed in the cleanroom due to extenuating circumstances (COVID-19 pandemic). Future procedures must not occur inside of the cleanroom as it risks contaminating it.

²⁹This step can be improved by reviewing the deburring after manufacturing and cleaning the parts with an ultrasonic bath.

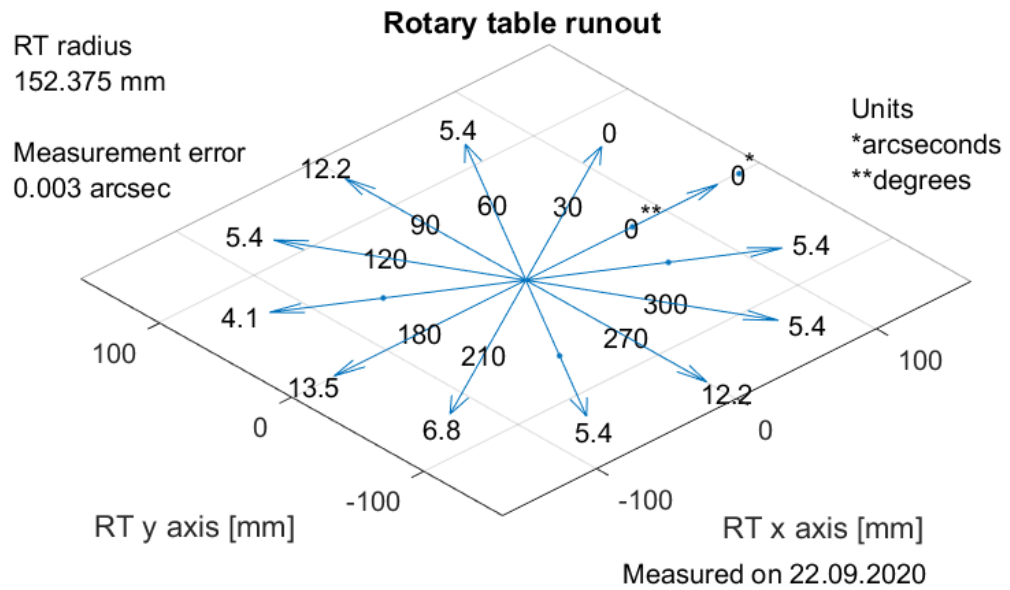


Figure 2.32: Rotary table rotational error.

3. With a brush, paint the pads' bond surface with Dow DOWSIL 1200 OS Primer and let them dry for a few minutes³⁰.
4. Place the mount in a clean and safe place until needed.

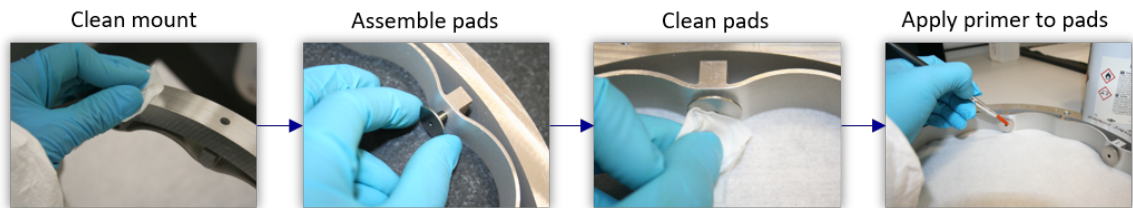


Figure 2.33: Mount assembly preparation steps.

2.5.4.5 Lens alignment

This step starts from the prepared lens (Section 2.5.4.1) and it occurs on the aligned mount jig on top of the rotary table. This process takes approximately 1.0 hours per

³⁰Note that the primer should be applied close to the time of bonding.

lens³¹ and can be performed by one person comfortable handling large optics³².

The required materials and equipment needed for this step are a low-force precision dial gauge (with magnetic stand), light rubber mallet, assembled and aligned mount jig, prepared lens (with cotton layer bonded), and coordinate measuring machine (CMM) with a light force probe³³.

The procedure steps go as follows (see Figure 2.34 for reference):

1. Identify the correct assembly orientation of the lens and prepare the mount jig assembly area. Clear the moving path from where the lens is placed to where the mount jig is located. Ideally, it should be as short as possible. Clear the working surface of unnecessary equipment.
2. Using both hands, hold the lens by the edge and lift it³⁴. Visualize the centre of the rotation axis in the mount jig and aim for it when placing the lens in the setting spheres.
3. Carefully place the lens in its correct assembly orientation on top of the setting spheres³⁵.
4. Place a low-force dial gauge perpendicular to the lens edge (outside the cotton paper layer).
5. Measure the radial alignment without correcting by rotating the mount jig. Analyse the lens position and correct the alignment by lightly knocking the lens with the mallet.
6. Place a low-force dial gauge perpendicular to the top lens surface outside the lens' effective aperture.

³¹It can take much less, but it is better to plan plenty of time as this step requires the assembly person to be fully focused and calm.

³²As a kind reminder when handling optics it is of utmost importance to wear tight gloves and facemask.

³³Note that the CMM is only used for confirmation of the alignment during this testing and is not needed for the procedure.

³⁴I recommend practising this move on a mock lens.

³⁵The position of the mount jig spheres must be designed in accordance with the lens manufacturing drawing, and the lens ideally must have at least 5 mm of clearance outside its effective aperture.

7. Measure the alignment without correcting by rotating the mount jig. Analyse the lens position and correct the alignment by lightly knocking the lens with the mallet³⁶.
8. Carefully remove the dial gauge from the lens top surface.

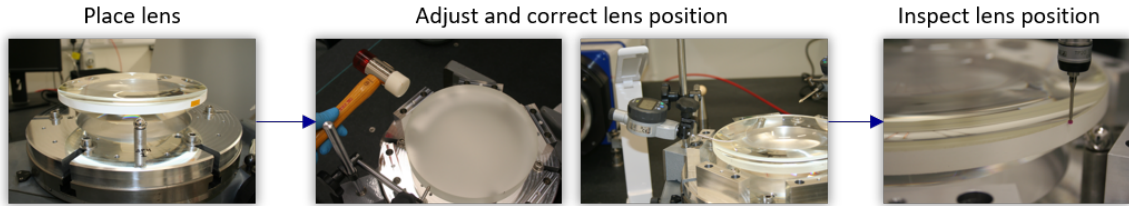


Figure 2.34: Lens alignment assembly steps.

I placed the rotary table on the CMM measuring surface of the UOX cleanroom to align the lens mount assembly models. This allowed me to record the lens alignment by measuring it with the CMM. I did not use the CMM to align, as my objective was to quantify the alignment by recreating the procedure used by RAL to assemble the lens mounts for the FMOS and KMOS instruments.

For this particular setup, this step would benefit from adding a feature to the mount jig that would allow the lens alignment to be locked.

2.5.4.6 Mount alignment

During this step, the flexure mount ring is radially aligned to the rotational axis of the rotary table. The setup is the same as the previous step, and the mount preparation must have been carried out. This process takes approximately 0.5 hours per mount and can be performed by one person comfortable assembling large optics.

The required materials and equipment for this step are a flexure mount ring, aligned lens and mount jig, assembly screws, assembly tooling, lightweight rubber mallet, precision dial gauge with a magnetic stand and coordinate measuring machine (CMM) with a standard probe.

The procedure steps go as follows (see Figure 2.35 for reference):

³⁶The alignment required for each lens varies depending on its tolerance and dimensions. Alignment for a 200 mm diameter lens with a 0.3 arcminute tolerance for this particular setup is achieved when the tip/tilt variation is below $10\mu\text{m}$.

1. Identify the correct assembly orientation of the flexure mount ring and ensure it is the matching mount for the aligned lens. Ensure that the pads are fully screwed out, leaving the maximum centre space.
2. Using both hands, hold the mount by the edge and lift it. Visualize the lens and its centre and aim for it when placing the mount on the mount jig parallels.
3. Carefully place the mount in its correct assembly orientation on top of the mount jig, resting on the parallels. Take extra precautions not to touch any lens surface while performing this operation.
4. Loosely screw the mount screws in the parallels. Place a dial gauge on the side edge reference and measure the alignment.
5. Correct the radial alignment by lightly knocking the mount with the mallet³⁷. When the mount alignment is achieved, screw the mount screws gradually and symmetrically³⁸.

As with the lens, I recorded the flexure mount ring alignment by measuring it with the CMM (see Section 2.6).

2.5.4.7 Adhesive application

This step requires two setups. The first setup is to prepare the adhesive dispenser, and the second is to apply the adhesive and bond the mount ring to its lens. This process takes approximately 3.0 hours per mount and can be almost entirely performed by one person, with another person performing a check before adhesive application.

The required materials and equipment for this step are a 0.2 mm feeler gauge set, pads' screwdriver, low force dial gauge and magnetic stand, mount and lens aligned,

³⁷Note that the tip-tilt alignment of the mount cannot be corrected with this mount jig setup.

³⁸Radial alignment of the mount to the rotary table's rotational axis ensures that the lens's optical axis is centred with respect to the mount. This is not key to achieving barrel or overall camera alignment, as it is possible to correct radial alignment when assembling the lens mount into its barrel, considering the current mechanical design. However, this alignment is vital for ensuring an isotropic thermal behaviour for the flexures and the lens. The alignment is limited by the radial rotation error to the table, which is 12.2 arcseconds for the table I used

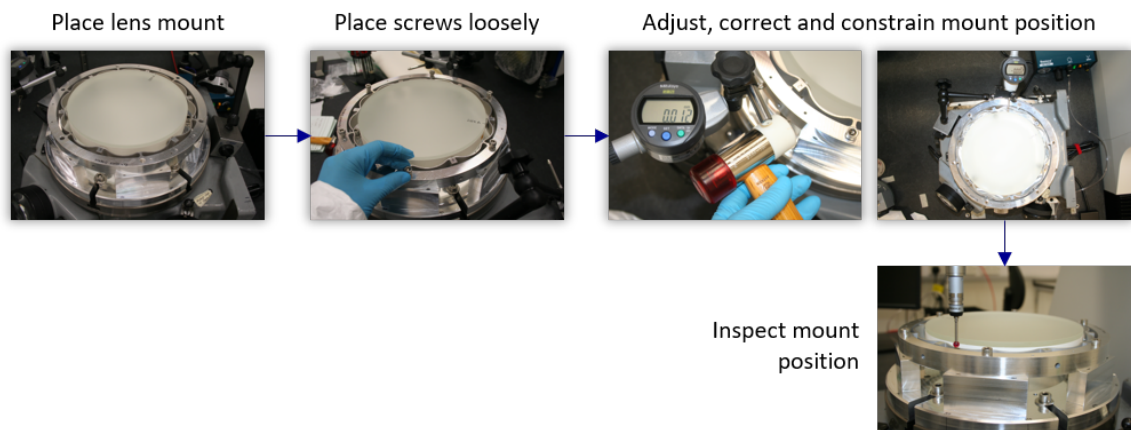


Figure 2.35: Mount alignment assembly steps.

Dow DOWSIL 6-1104CV Sealant, SD 340 automatic dispenser kit with a 5 cc syringe and 1.5" 14 gauge dispensing tip, cord, wipes and isopropanol.

The procedure steps go as follows (see Figure 2.36 for reference):

1. Before assembly familiarise with the flexure mount ring. Inspect the flexure strength of the mount ring³⁹, then during assembly rehearsal, try screwing the pads to compress a mount flexure and identify the force needed to deform or load the flexure. Find out the screwing position of the pad that constrains the lens without loading the flexure while avoiding losing lens alignment⁴⁰.
2. Clean the 0.2 mm feeler gauge set with isopropanol.
3. Constrain the position of the lens by screwing three opposing pads without loading the mount flexures. Use a feeler gauge to represent the space occupied by the adhesive bond.
4. Now, prepare the adhesive dispensing. Assemble and configure the SD 340 automatic dispenser as instructed in the datasheet. Set the pressure to 100 PSI with a continuous adhesive flow. Test the dispenser by pressing the pedal. Air should flow continuously through the syringe with a pressure of 100 PSI. Disconnect the syringe and clean it with isopropanol.

³⁹Try compressing it with your fingers without going beyond its elastic stress.

⁴⁰This is an essential step because each mount ring will have a different flexure force as they are designed for each lens.

5. Open the Dow DOWSIL 6-1104CV Sealant and screw in a large tip. Introduce the tip into the syringe and dispense adhesive into the syringe, roughly two centimetres. Put a 1.5" 14 gauge dispensing tip in the syringe. Close the Dow DOWSIL 6-1104CV Sealant and return it to an airtight container.
6. Inspect the syringe and centrifuge it to distribute the adhesive correctly and eliminate bubbles⁴¹.
7. Assemble the syringe into the dispenser, dispense a small amount of adhesive in a wipe, and write down the date and time⁴². Use this adhesive sample as a rough reference for the curing progress. In a few hours, the adhesive should be dry to the touch. In 24 hours, the surface area in contact with the atmosphere should be dry. The inner volume will take a few days to cure fully.
8. Adhesive application is now ready. First, enumerate the bonds⁴³. Bonds 1, 3 and 5 can be the ones that currently constrain the lens alignment.
9. For bond 2 set the bond thickness to 0.2 mm with a 0.20 feeler gauge, then test the bond thickness with 0.15 and 0.25 feeler gauges and adjust if required. Introduce the tip of the syringe into the bond conduit. Look through the gap between the lens and the pad. Centre the tip in the conduit. Press the dispenser pedal and dispense the adhesive until it reaches the angle in the pads. The adhesive layer should uniformly spread across the pad. Carefully take out the tip through the conduit and clean it with a wipe and some isopropanol.
10. Inspect the bond and check that it looks correct (no overflowing adhesive and well distributed).
11. Repeat the last two steps for bonds 4 and 6.

⁴¹I tied the syringe to a 30 cm cord, held the other end and made the syringe rotate for a few seconds.

⁴²The purpose is to have a sample which can tell you when the main adhesive is cured and you can safely move the lens.

⁴³You can use a permanent marker to write a number next to the bonds in the mount.

12. Place a low-force dial gauge normal to the top lens surface. Make sure it is outside of the clear aperture. Review the lens alignment and correct it if needed with the mallet.
13. Clean the leftover adhesive in the syringe with isopropanol. (Do not use water or acetone.) Dispose of the used tip.
14. After one day, release feeler gauges standing in for bonds 1, 3 and 5 and repeat the procedure for each bond from steps 9 to 13.

For the lens mount assembly models, for verification, I recorded the lens alignment with respect to its mount with the CMM before this procedure, after bonding pads 2, 4, and 6, then after bonding pads 1, 3, and 5. More details are found in Section 2.6.

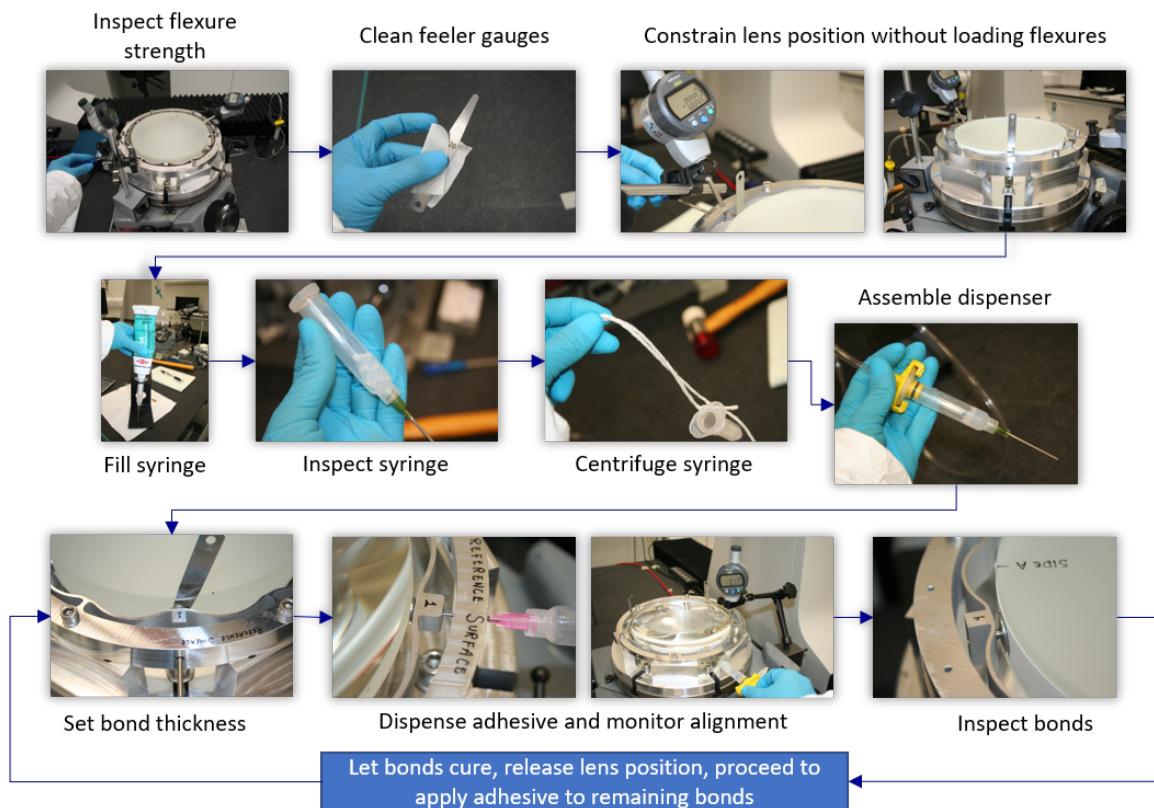


Figure 2.36: Adhesive application assembly steps.

2.5.4.8 Adhesive curing

Adhesive curing is the last process step in assembling a lens mount. After bonding the lens to its mount, this final process is about letting the adhesive cure while maintaining alignment. This process takes approximately seven days per lens mount assembly⁴⁴ but only requires 10-15 minutes per day and can be performed by one person.

The required materials and equipment for this step are an aligned and just bonded lens mount assembly in its mount jig.

The procedure I performed for this was quite simple: leave the lens assembly untouched on top of the rotary table for seven days.

I additionally measured the radial and the tip-tilt alignment for alignment verification purposes which I discuss in Section 2.6.

2.6 Alignment verification

When you set out to develop technology and have to meet requirements, there is a verification step to ensure that you have met these requirements. In this case, there were no specific requirements setting direction for alignment at room temperature. Instead, I needed to find out what was technically possible using the methods that had been developed. This was then feedback this to the project to have a better understanding when setting top level requirements what is feasible at component level. In this section I explain the methods I developed to *verify* or rather to measure the alignment of two examples of lens mount assemblies. I also show the results of my measurements.

2.6.1 Methodology

I developed two methodologies to confirm the alignment of the lens assemblies with the vision of setting out a verification methodology for the lens mounts assemblies for HARMONI. The plan for HARMONI was considered that RALspace would mount the

⁴⁴Seven days is a subjective number. It is the number indicated in the datasheet for a complete adhesive cure, but as mentioned before, curing depends on the volume and surface area exposed to ambient air. Bond prototypes must be tested to measure their mechanical properties throughout curing to determine the curing time for the type of bonds in the HARMONI camera lens mounts.

lenses in their facilities, thus I got informed of what facilities were available to them, and refined and verified the existing method based on a rotary table and dial gauge accordingly. Then I developed a second method using a CMM machine to double check my measurements. This second method was important because, for HARMONI only the method with the rotary table method will be carried out. One of my research goals is to develop a reliable and repeatable assembly and verification methodology of lens mounts assemblies at room temperature, and the CMM allows an independent validation of the performance of the rotatory table method.

2.6.1.1 Rotary table and dial gauge

This method followed the logic of what had been done at RALSpace for the KMOS and FMOS instruments.

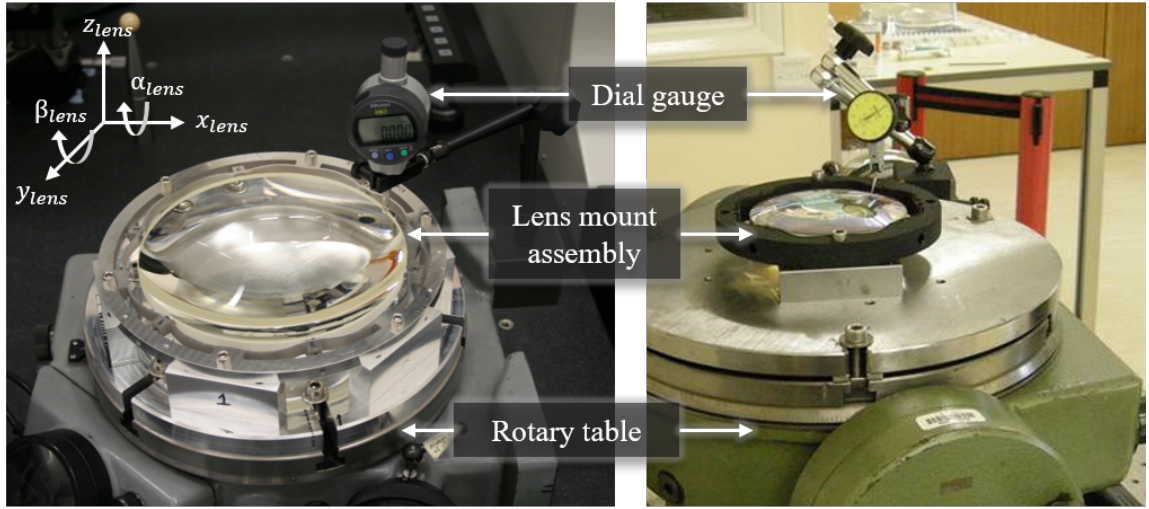
2.6.1.1.1 Concept

The rotary table and dial gauge method follow the principles of run-out alignment. The misalignment is measured with a probe that is perpendicular to the measurement axis. This method aligns with the alignment method described in Section 2.4.2 and it is possible to measure radial and tip-tilt misalignment. The airgap cannot be measured.

Additionally, I measured the loading of the flexure springs while setting the bond thickness and also when dispensing adhesive. I did this by placing a probe at the back of the counterpart of the pad that I was working on. This allowed me to maintain alignment during these steps, as well as to avoid loading the spring in a certain direction.

2.6.1.1.2 Setup

Figure 2.37 shows on the left the setup I prepared in the Oxford instrument assembly lab. On the right I show the setup that was used to mount the lenses of the KMOS camera at RALSpace. The main components of the setup are a dial gauge and its magnetic mount, the lens mount assembly to measure and a rotary table. Given that the lenses must remain clean and free of dust for optimal performance, the assembly and verification of the cameras were carried out in a clean-room environment class 7 at a controlled temperature of 18 degrees Celsius.



HARMONI “mock” lens in the Beecroft lab at OUX

KMOS lens at RAL

Figure 2.37: Test setup for lens mount alignment verification

2.6.1.1.3 Procedure

At this stage I evaluated the alignment that I had performed during assembly. For each lens:

- place the mount jig (without setting spheres) on a well-tuned rotary table;
- align the mount jig with respect to the rotation axis of the rotary table (max runout $\pm 4\mu m$) and constrain position;
- place the lens mount assembly on the mount jig;
- align the lens mount assembly with respect to the rotation axis of the rotary table (max runout $\pm 4\mu m$) and constrain position. If the runout exceeds $\pm 4\mu m$ then record the best runout;
- measure and record the runout of the tip-tilt axis at the mount assembly’s top surface (three rotations minimum);
- measure and record the runout of the tip-tilt axis at the top lens surface, outside its clear aperture (three rotations minimum).

Only if the aspheric lens surface is the test surface: additional runout measurements of top lens should be performed at different heights ensuring all measurements are outside the lens' clear aperture.

2.6.1.2 Coordinate measuring machine

Performing measurements with a coordinate measuring machine (CMM) is an excellent way of structuring metrology and repeating the same procedure in the exact order for each lens mount assembly. I found this method of verification superior due to its versatility, possibility to automate, increased precision and measurement history log. With this method it is possible to measure radial alignment, axial alignment and air gap. Unfortunately there is no CMM available in cleanroom conditions at the RALspace facilities, thus I only used this method to validate the dial gauge and rotary table method.

2.6.1.2.1 Concept

The lens mount assembly is placed in the CMM measuring bench area and a framework of reference is selected. For radial alignment I measured a few points in the lens circumference and the mount circumference, and constructed a circle for each set of points. Then I was able to calculate the radial alignment by comparing the centres of the constructed circles for the lens and for the mount. This produces a measurement in the x and y axes. To measure tip-tilt alignment, I measured a set of points on the top surface of the mount and of the lens, and created a plane of reference. Then I calculated a 3D angle of their normals. This produces a direct tip-tilt measurement. This method is well controlled and can be programmed into the CMM (see Figure 2.39). It is therefore repeatable in the exact same order possible, and it can be easily adjusted to different lens mount assemblies.

2.6.1.2.2 Setup

Figure 2.38 shows the setup for measuring lens mount assemblies in cleanroom conditions at the instrument assembly lab at the University of Oxford. This method does

not require a rotary table or a dial gauge. The lens mount assembly just needs to be placed within an adequate range of measurement in the CMM bench area.



Figure 2.38: Coordinate measuring machine setup for measuring lens mount assemblies in cleanroom conditions at the instrument assembly lab in the University of Oxford. (Interferometer not used for this test.)

2.6.1.2.3 Procedure

1. Measure the rotary table framework of reference⁴⁵.
2. Place the mount jig on the rotary table and measure its framework of reference. Verify that the height of the setting spheres and of the parallels has been optimized.
3. Perform the assembly of the lens onto its mount, and measure the alignment at the following steps:
 - (a) before applying adhesive;

⁴⁵This step would not be required if the rotary table was not being used as a base.

- (b) after applying adhesive to bonds 1, 3 and 5;
- (c) after day 1 of curing the bonds 1, 3 and 5;
- (d) after applying adhesive to bonds 2, 4 and 6;
- (e) then every 2nd day during the curing process;
- (f) after removing the setting spheres from the mount jig.

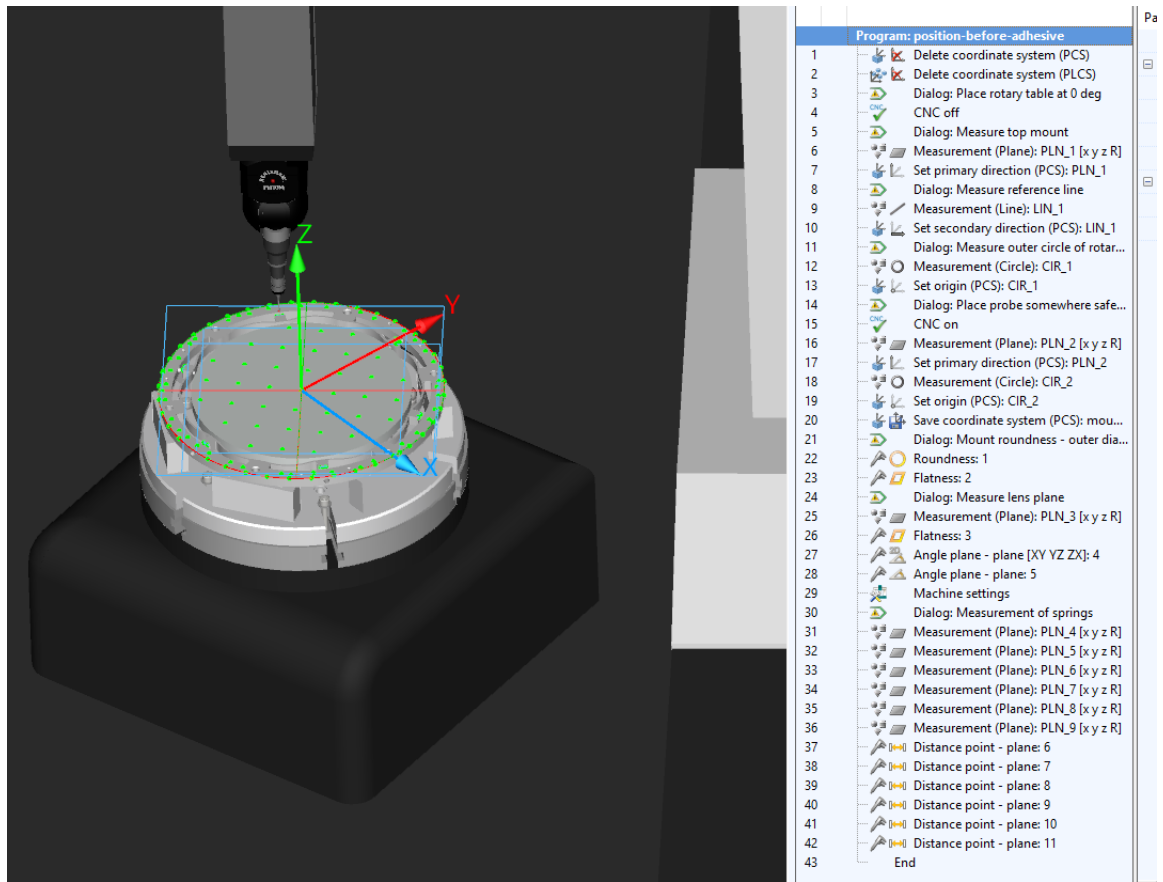


Figure 2.39: Screen shot of the CMM measuring program. This Figure shows the lens mount assembly sample with a fused silica flat blank before applying the adhesive.

2.6.2 Alignment results and analysis (tip-tilt)

In this section, I report the achieved tip-tilt alignment for both lens mount assemblies.

2.6.2.1 KMOS design with a fused silica blank model

I started alignment verification for the KMOS design with the fused silica blank model at the beginning of adhesive curing (see Section 2.5.4.8) and followed the procedure described in Section 2.6.1.2.3. Figure 2.40 shows the tip-tilt alignment throughout curing of the KMOS design. The model with a fused silica blank model is shown on the left and the Pre-HARMONI design with an HK9 lens model is shown on the right. Additionally, on day 10, after measuring the alignment without the setting spheres, I flipped the model and measured the alignment on the other side out of curiosity.

The alignment remained stable throughout curing, varying less than 0.01 arcminutes from day 0 to day 8 (see Figure 2.40). When I removed the setting spheres on day 10, the alignment changed from 1.44 to 1.36 arcminutes, improving 0.08 arcminutes. For the KMOS design with a fused silica blank model, the target tolerance I proposed in Section 2.4.4 of $\leq \tan^{-1} \frac{20\mu m}{\phi_t}$ would have a corresponding tolerance of 0.34 arcminutes, which was not achieved. To understand why the alignment turned out to be 1.36 arcminutes, I identified the alignment contributors and tallied the measurements I did with the CMM throughout the assembly procedure. Table 2.5 shows this tally. The top part of the table refers to the KMOS design with a fused silica blank model. Given the shape of the blank's flat-flat surfaces, the rotary table's rotational error and the dial gauge uncertainty do not play a role in the alignment of this model (see Table 2.5).

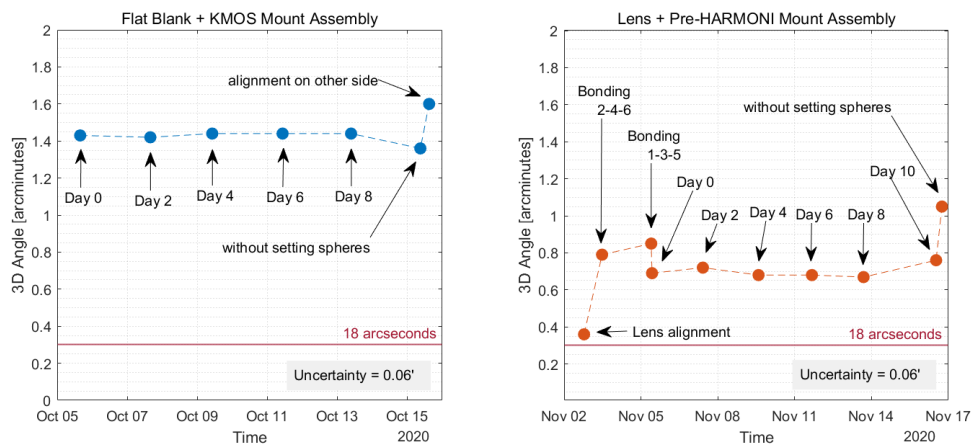


Figure 2.40: Tip-tilt alignment measurements for both models. The 18 arcsecond line denotes the target alignment that resulted from the optical design tolerance analysis.

During the alignment of this first model, I did not correct the height variation between parallels and spheres and only measured this afterwards. As shown in Table 2.5, the height variation was uncontrolled and contributed to a tip-tilt of 13.2 arcseconds. After seeing this variation in the parallels and the spheres is when I looked up the thinnest shims I could find and bought a *Plastic Shim Pack*[61] and updated my mount jig procedure to include a maximum variation of $10\mu\text{m}$ after correction (see Section 2.5.4.2). Then there was the parallelism. It turned out that the parallelism I measured with the CMM for the flexure ring was $146.6\mu\text{m}$, exceeding the 0.025 mm manufacturing tolerance indicated on its drawing. No parallelism tolerance was assigned for the blank⁴⁶.

Upon calculating the measurements for both mount alignment and blank alignment, I discovered that a satisfactory alignment could be achieved if the difference between these two alignments fell within the alignment tolerance range⁴⁷.

	<i>Flexure ring (KMOS design)</i>		<i>Fused silica blank (Flat-Flat)</i>	
	Height error [μm]	Tip-Tilt [arcsec]	Height error [μm]	Tip-Tilt [arcsec]
ΔHeight (parallels/spheres)	16.4	13.3	26.0	26.5
Parallelism	146.6	114.0	5.5	5.7
Flatness	14.5	11.3	22.5	23.2
	Alignment [arcsec]	138.6	Alignment [arcsec]	55.4
			Alignment* [arcmin]	1.4

Table 2.5: Measurements of contributors of tip-tilt alignment for the KMOS design with a fused silica blank model. This table shows the stack alignment. The yellow cells indicate actual measurements and the calculated values are shown in green cells. *The alignment performance is the difference between the two alignment totals. Note that the goal alignment is 0.34 minutes or 18 arcseconds as indicated in Figure 2.40.

2.6.2.2 Pre-HARMONI design with an HK9 lens model

In Figure 2.40 on the right, I show the outcome of the alignment of this model.

Before bonding, I achieved a lens alignment of 0.36 arcminutes, and after bonding 0.69 arcminutes. See Figure 2.40 for reference. The alignment remained stable around 0.70 arcminutes through curing with a standard deviation of 0.03 arcminutes. After

⁴⁶Because I used a blank I found in the laboratory with unknown origin.

⁴⁷For example, if the fused silica blank would have been less parallel, I could have achieved a better alignment.

removing the setting spheres, the alignment changed from 0.76 to 1.05 arcminutes, increasing by 0.29 arcminutes. The target tolerance of 0.34 arcminutes (18 arcseconds)⁴⁸ was not met. Similarly to the last model, I tallied the alignment contributors from the measurements I performed throughout assembly and verification to understand why 1.05 arcminutes was the achieved alignment. In the bottom panel of Table 2.6 I show the results of this tally. In this case, using the rotary table was necessary to perform the alignment of the lens thus, rotational error, dial gauge uncertainty and human error are considered. The rotational error I considered is the one I reported in Section 2.5.4.3.

	<i>Flexure ring (Pre-HARMONI design)</i>		<i>HK9 Lens (Flat-Convex)</i>	
	Height error [μm]	Tip-Tilt [arcsec]	Height error [μm]	Tip-Tilt [arcsec]
Rotational error	NA	NA	9.0	12.2
Δ Height (parallels/spheres)	5.0	4.1	3.0	3.3
Parallelism	14.0	10.9	NA	NA
Flatness	181.0	140.8	65.0	65.3
Dial gauge uncertainty	NA	NA	7.0	14.4
Ability to align	NA	NA	10.0	20.6
	Alignment [arcsec]	155.72	Alignment [arcsec]	115.9
			Alignment* [arcmin]	0.7

Table 2.6: Measurements of contributors of tip-tilt alignment for the pre-HARMONI design with an HK9 lens model. This table shows the stack alignment. The blue cells represent estimated values, while the yellow cells indicate actual measurements. The calculated values are shown in green cells and the cells with no format display values from drawings or calibration certificates. NA is used when a value is not applicable. *The alignment performance is the difference between the two alignment totals. Note that the goal alignment is 0.34 minutes or 18 arcseconds as indicated in Figure 2.40.

In Figure 2.41, I report the height variation before and after correction for the setting spheres and the parallels. I measured the flexure ring’s flatness and the lens, revealing an unexpected value. The flexure ring was bent, which made me recollect what had happened⁴⁹. The dial gauge uncertainty is based on the calibration certificate of the dial gauge with an error of $\pm 3 + \pm 1 \mu\text{m}$ (shown in Table 2.6 as dial gauge uncertainty). For this model, the lens mount alignment cannot be exactly explained in Table 2.6. I estimated two values, the parallelism of the flexure ring⁵⁰ and my ability to align (the

⁴⁸The target tolerance for this model is very similar to the last model as the diameter of the lens is only 5 mm larger.

⁴⁹After the models’ flexure rings had been manufactured, I gave them to the electronics workshop to fit its circuit board for cryostat testing (I will discuss this next chapter), the technician drilled holes while holding the flexure rings with a clamp.

⁵⁰I did not realise I had skipped the parallelism measurement of the flexure ring until after un-mounting and reviewing the measurements.

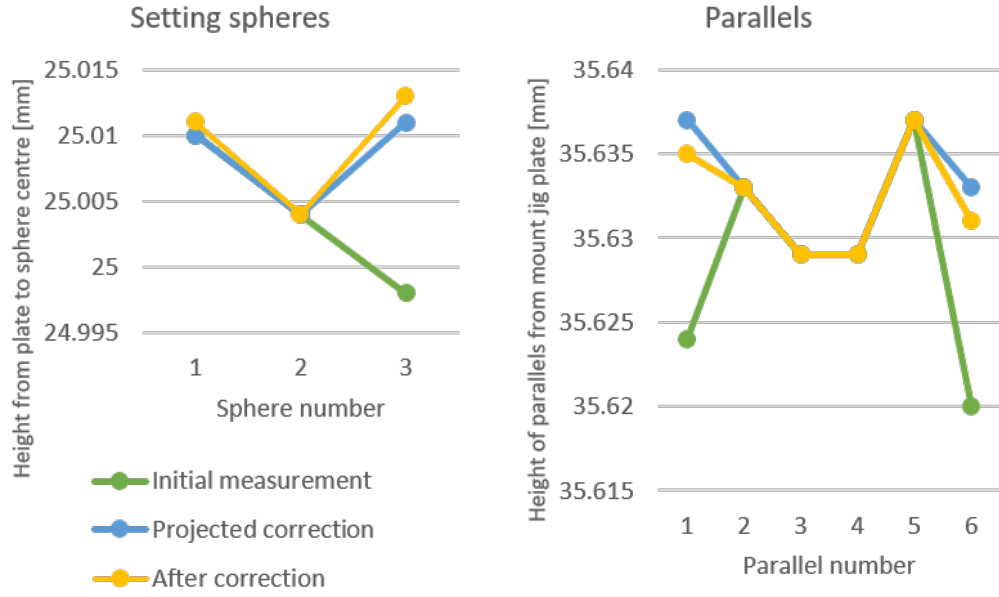


Figure 2.41: Height measurements of parallels and setting spheres used for height correction. I shimmed sphere 3 and parallels 1 and 6.

human error). The measurements and estimates give a good idea of how the alignment was achieved. Additionally, for this model, the change in alignment after removing the setting spheres is also due to the silicon adhesive being flexible at room temperature after curing⁵¹.

2.6.3 Alignment results and analysis (centring)

In this section, I present the results from the radial alignment measurements for the lens mount assembly models.

2.6.3.1 KMOS design with a fused silica blank model

Figure 2.42 shows the radial alignment of the KMOS design with a fused silica blank engineering model. The blue circles in the Figure denote the best and worst runout I measured on the lens with the dial gauge without moving it and simply rotating the plate of the rotary table during the lens alignment procedure. The variation between

⁵¹Note that the edge of the HK9 lens is 10 mm and the corresponding pad has been designed to match this lens edge. The bonds surface area of the KMOS design with a fused silica blank model is about ~ 2.8 times more as the pad is 17 mm in diameter, therefore more stable.

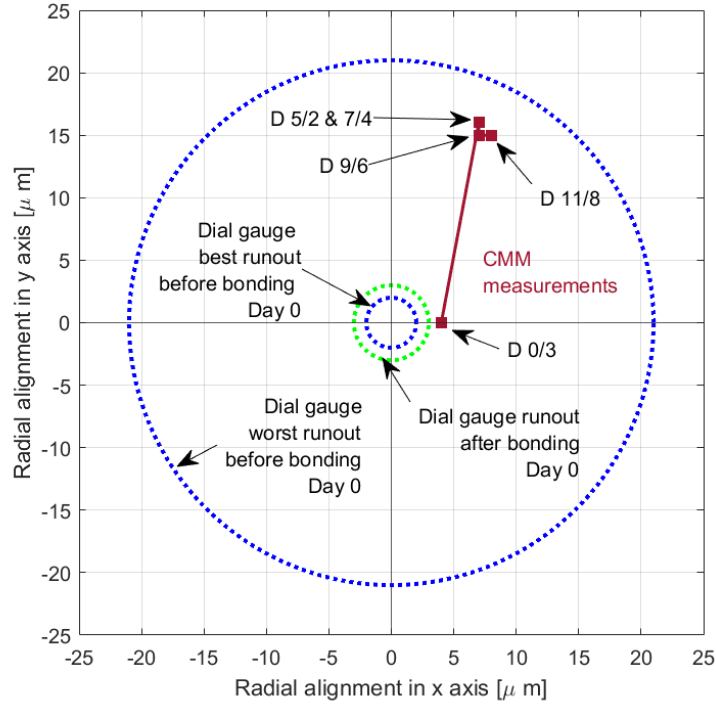


Figure 2.42: Radial alignment measurements with dial gauge and CMM for the KMOS design with a fused silica blank model. Day 0 indicated by the blue and green circles corresponds to bonds 1, 3 and 5. CMM measurements start at day 0 of bonds 2, 4 and 6, DX/X indicates the curing day with the first number denoting the curing day for bonds 1, 3 and 5 and the second for bonds 2, 4 and 6. Day 0 of bonds 1, 3 and 5 marks the reference position for the displacements.

worst and best is $19\ \mu m$, denoting the *radial* rotational error of the rotary table. The green circle corresponds to the runout I measured after applying adhesive to the first set of bonds (for this model, 1, 3 and 5). In red, I show the radial alignment CMM measurements of the model through curing (lens with respect to mount ring) starting after applying adhesive to the second round of bonds (2, 4, and 6). It is possible to see that the lens moved in a particular direction throughout curing. The achieved alignment during lens alignment was $4\ \mu m$ and at the end of curing $17\ \mu m$. The alignment is above the proposed tolerances in Table 2.2 of $\pm 5\ \mu m$. In addition to the radial alignment measurements performed on the lens and mount, I tracked the position of the bonded flexures throughout curing. In Figure 2.43 shows the displacements of each of the six flexures; it is possible to see that the behaviour seen in Figure 2.42

is consistent with the movement of the flexures. Flexures 1, 2 and 6 see a negative movement and flexures 3, 4 and 5 see a positive movement indicating that the lens favoured a direction in movement (see small diagram on the bottom left corner in Figure 2.43).

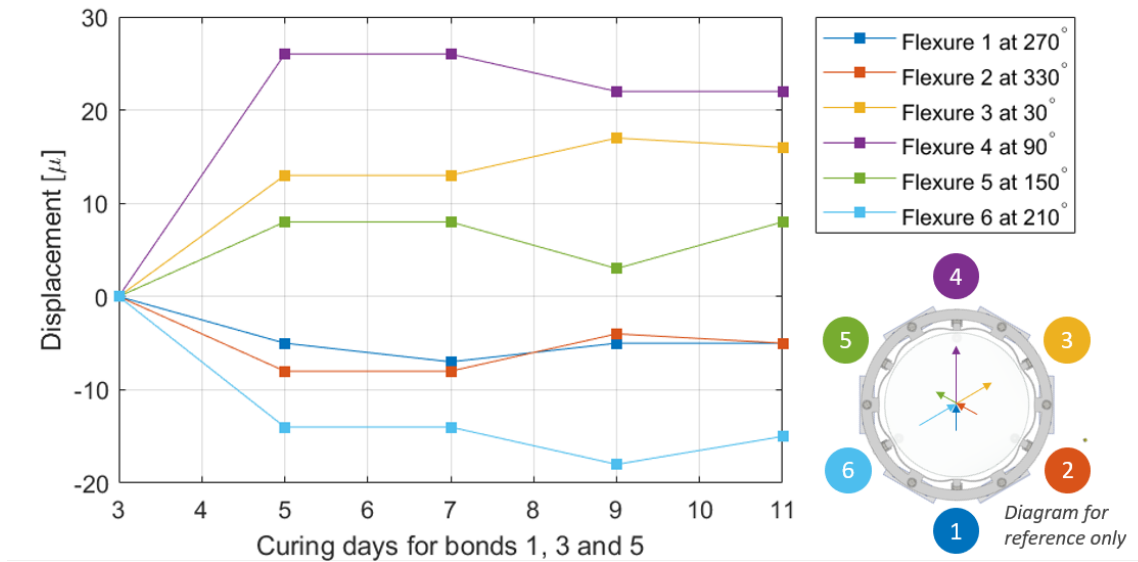


Figure 2.43: Flexure displacement through curing for the KMOS design with a fused silica blank model.

2.6.3.2 Pre-HARMONI design with an HK9 lens model

I aligned the pre-HARMONI design with an HK9 lens model using a dial gauge, similarly to the other model. As shown in Figure 2.42 the radial error motion of the rotary table could vary up to 21 μm . For this model, I achieved an alignment within the rotary table rotational error of 19 μm (above the proposed achievable tolerances in Table 2.2), and then I proceeded to align the flat plane of the lens to the mount ring reference surface following the procedure listed in Section 2.5.4.5. For this model, I did not measure radial alignment with the CMM because the 10 mm thick lens edge was fully covered in cotton paper, and due to the need to manually manoeuvre in a reduced space with the probe⁵². I did track the position of the flexures throughout curing; see

⁵²At the time, I thought that given that I had aligned a lens that did not have any manufacturing tolerances the alignment that mattered for verification was tip-tilt. Additionally, I had performed radial alignment of the lens on the edge covered in paper, which meant I did not have a not very

Figure 2.44. In this case, the radial alignment did not move in any particular direction⁵³, it hovered throughout curing, and when I removed the setting spheres, it went back to the day 0 position within $\pm 5\mu m$.

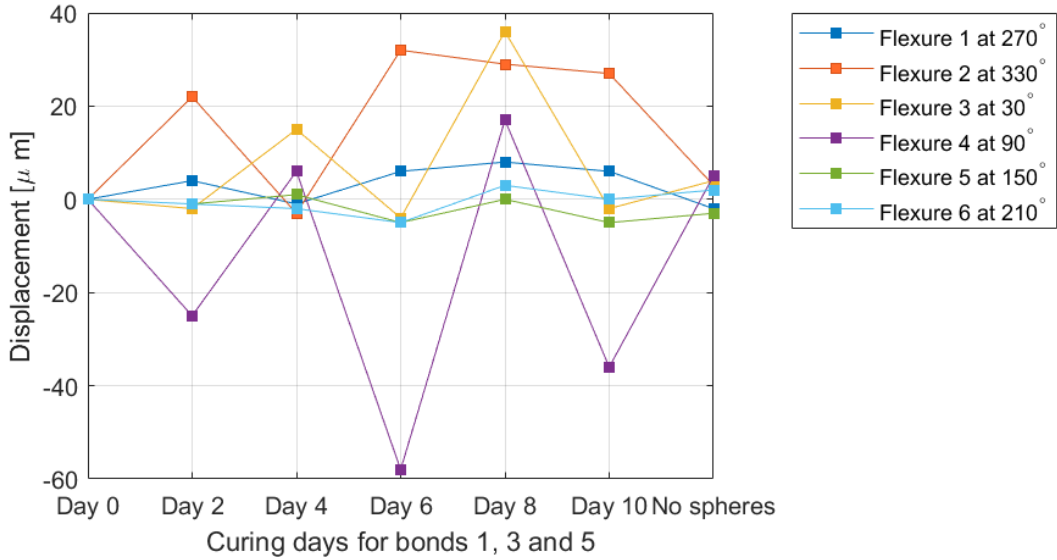


Figure 2.44: Flexure displacement through curing for the Pre-HARMONI design with an HK9 lens model.

2.7 Bonding outcome

One of the objectives of carrying out the work for this chapter was to develop in-house knowledge to adhere lenses to their flexure mounts reliably and to be able to reproduce good results. In this section, I would like to document the bonds I achieved for both engineering models. In Section 2.5.4.7, I narrated the best-to-my-knowledge outcome procedure I learned during and after producing the bonds for both models, meaning that I made slightly different approaches for the bonding until I reached a desired outcome. I first performed a mock bond by bonding a metal bar to one of the pads in the flexure ring of the flat blank model. Figure 2.45 shows the bonding process and inspection.

round surface to align on. In the end, I only kept the knowledge that the radial alignment was below $21\mu m$ in step number 5 from the procedure in Section 2.5.4.5.

⁵³As this lens surface was convex and resting on three setting spheres.

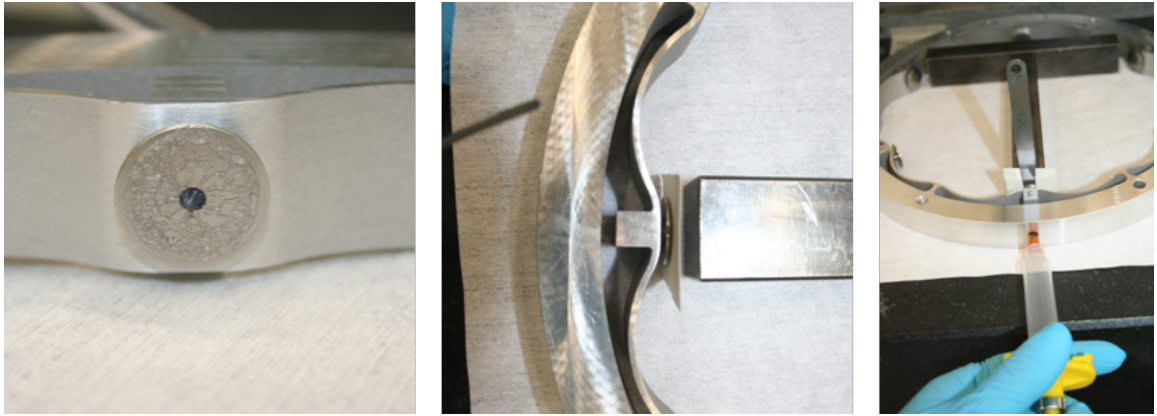


Figure 2.45: Mock bonding and its inspection.

This first mock-up bonding aimed to understand how much adhesive would be needed and whether the glue would uniformly distribute across the bond. After dispensing the adhesive, I unbonded the pad and the paper with the metal bar and saw that the adhesive was well spread. I cleaned up the adhesive and repeated the procedure. Then, I proceeded to follow the assembly procedure for the KMOS design with a fused silica blank model. On October 2nd 2020, I applied adhesive to bonds 1, 3 and 5. For these first three bonds, I placed a dial gauge on the opposite flexure to indicate if I was losing alignment while applying adhesive. I supplied adhesive in a continuous flow for 10.5 seconds 20 to 25 times, with a pressure of 100 psi using a 14 gauge tip 1.5 inches long, while monitoring the dial gauge and keeping the flexure movement caused by the pressure below $5\ \mu m$. After performing this, I learned that it was more important to monitor the adhesive distribution and to ensure I did not press the needle tip against the lens than trying to ensure that the dispensed adhesive was repeatable. The maximum time I could set up in the dispenser (10.5 seconds) was less than the time needed for the bonds to fill with the required amount of adhesive; since I did not have thicker tips, I decided for the following bonds to apply sealant continuously and to control the dispenser with the pedal. I did this for the subsequent three bonds of the KMOS design with a fused silica blank model on October 5th, 2020 and the six bonds of the pre-HARMONI design with an HK9 lens model where I first applied adhesive to bonds 2, 4, and 6 on November 3rd and the rest on November 5th 2020. In figures [2.46](#) and [2.47](#), I show pictures of each of the bonds for both models.

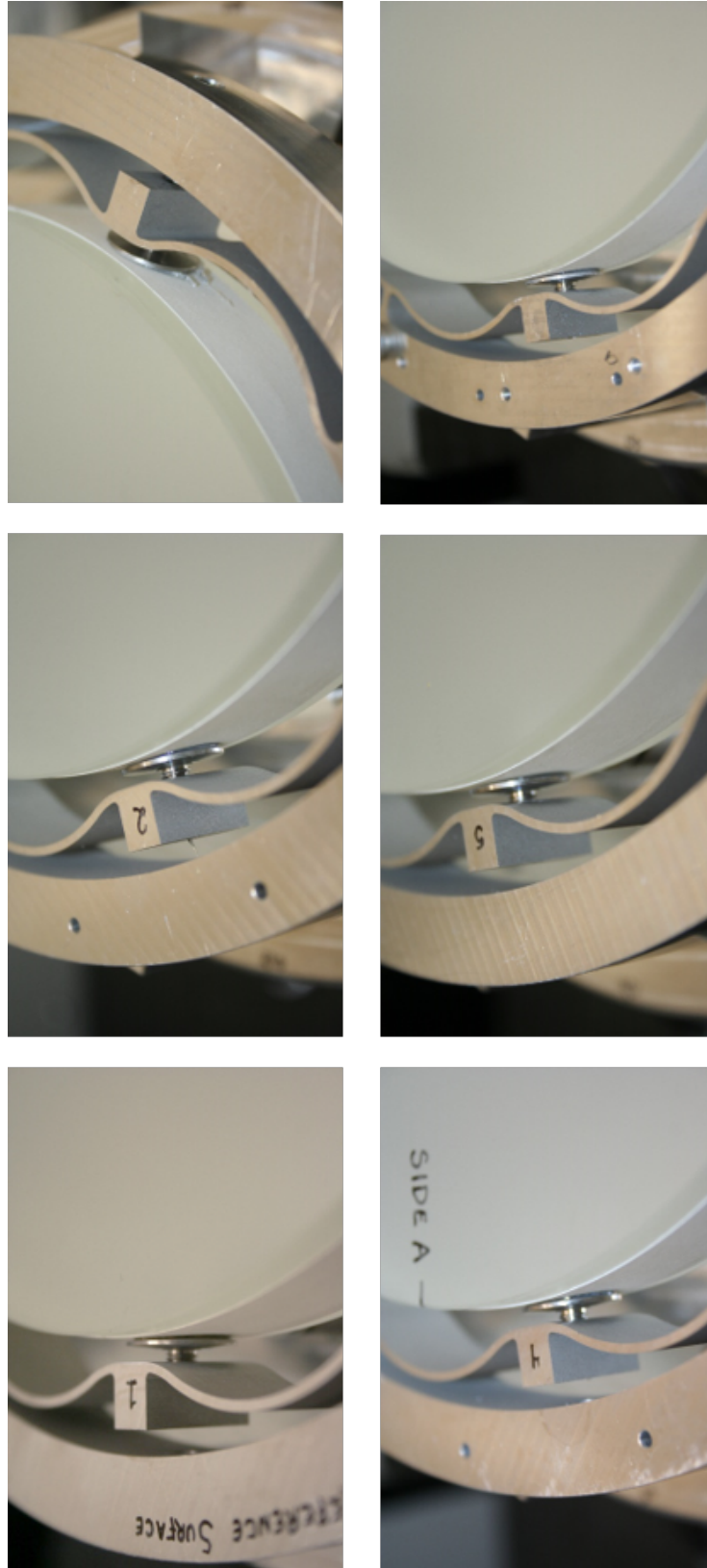


Figure 2.46: Cured bonds of the KMOS design with a fused silica blank model.

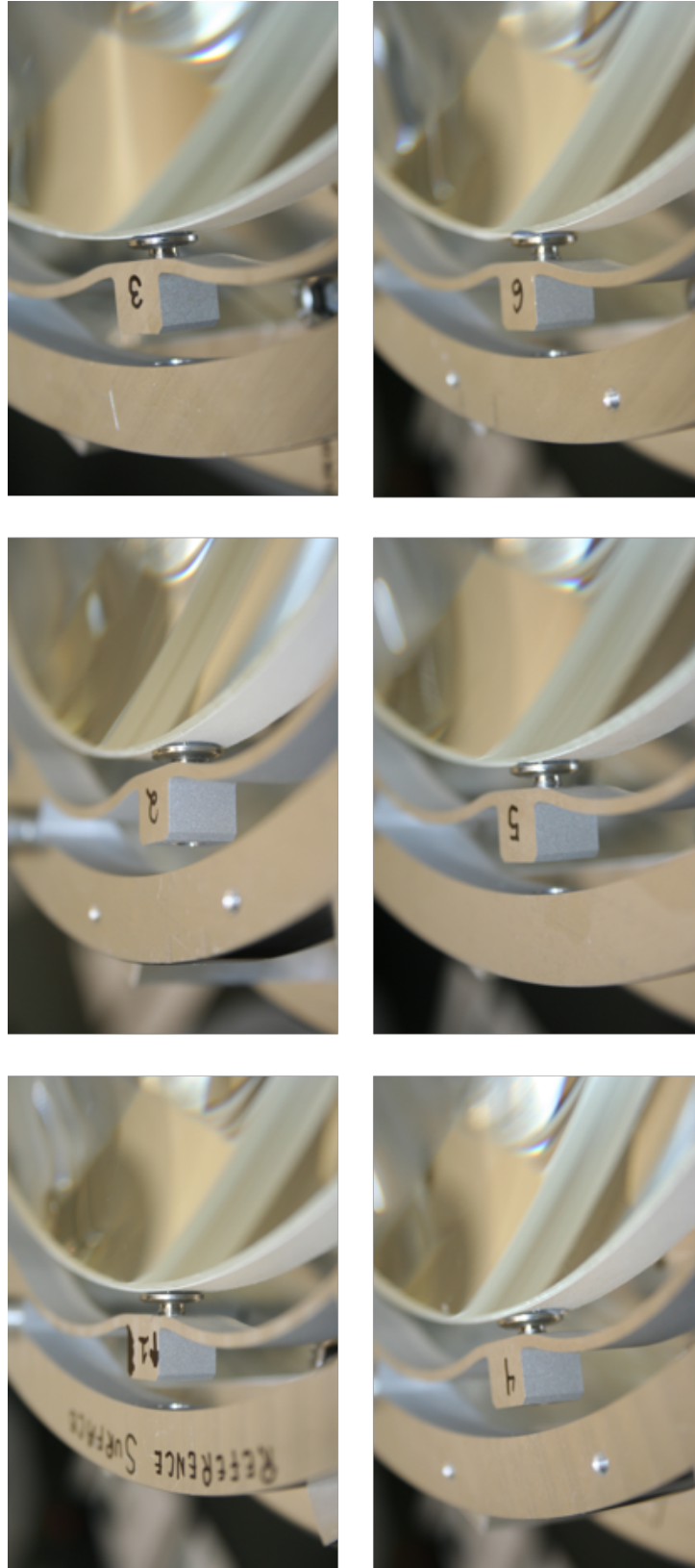


Figure 2.47: Cured bonds of the pre-HARMONI design with an HK9 lens model.

Through this bonding process, I learned that it is crucial to visualise and understand the bonds (see Section 2.3.3). Regardless of the care and time you take to ensure that the *central* thickness is 0.2 mm, bonds will be irregular and serve as compensators for manufacturing tolerances and imperfections of the lens and mount; this can be acceptable if this compensation is not *extreme*. Below, I list the imperfections I observed that the bonds were compensating for.

- Lens edge is not parallel and/or flat (for example, it has a pyramidal shape).
- Pad bonding surface is not parallel and/or flat.
- Pad assembly hole is not parallel to the flexure ring alignment reference surface.
- Pad assembly hole axis does not intersect the centre axis of the flexure ring.

In the KMOS design with a fused silica blank model, it is possible to see how the lens edge and the pad bonding surface were not entirely parallel (see Figure 2.46) and the bonds vary in thickness, showing a slight triangle shape. This type of imperfection is more evident in the pre-HARMONI design with an HK9 lens model (see Figure 2.47). In bond four, it was not possible to distribute the adhesive uniformly across the bonding surface, and it spilled towards one side rather than filling the missing area. Then in bond six, the lens and the pad surfaces seem parallel, but the heights do not match as the pad is slightly higher than the edge of the lens, which allowed the adhesive to spill towards the lens top surface. In contrast, bonds one and two look perfect.

Additional to the mechanical imperfections, I also learned about mishaps that could happen while dispensing adhesive.

When I applied adhesive to bond three of the KMOS design with a fused silica blank model, a bubble was trapped in the adhesive while dispensing, causing a small explosion (see Figure 2.46, top rightmost image). This mishap did not affect the bond, as I could apply enough adhesive, and the dial gauge did not indicate a movement beyond 0.005 mm. This mishap can be easily prevented by centrifuging the syringe well before dispensing the adhesive, monitoring the adhesive flow in the syringe, and stopping dispensing when a bubble is observed.

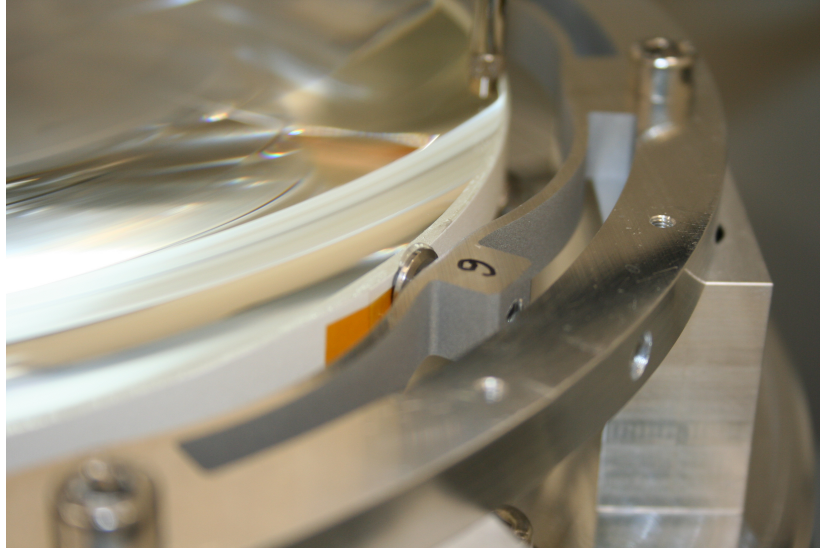


Figure 2.48: Pad six of the pre-HARMONI design with an HK9 lens model was bonded on the Kapton tape.

Then, after I applied adhesive to bond 6 of the pre-HARMONI design with an HK9 lens model, I realised that I had applied glue on the Kapton tape that was securing the cotton layer strip ends (see Figure 2.48). I had inspected the model before and after alignment, but I did not look from two different perspectives (compare Figure 2.47 bottom rightmost with Figure 2.48). I do not know if this could be a problem, but it could be a root cause of failure as it changes the bond mechanics with respect to the other bonds; it is best to avoid it. To prevent this, I suggested in Section 2.5.4.7 to perform the final check before the adhesive application with two people⁵⁴.

2.8 Integration

When the lens mounts are assembled, they are integrated into the camera barrels. This section provides a conceptual overview of the integration process of the lens mount assembly into the camera, intending to provide foresight of how the lens mounts achieved alignment during assembly is referenced to its lens group and then to the camera's optical axis⁵⁵. The cameras are assembled in three main steps:

⁵⁴A procedure protocol could also be implemented.

⁵⁵During my work on the lens mount assembly, I contemplated integration at a conceptual level. RALSpace, as part of its work package, delves deeper into the particulars, considering the constraints and capabilities of its facilities and tooling.

1. The seven lenses are aligned and fixed to their flexure mount rings.
2. The mounted lenses are placed in their camera barrels and radially aligned in groups (as described in Section 2.5).
3. The barrels are assembled into the camera housing.

2.8.1 Camera integration aspects

There are several questions when considering the lens mount assembly within the overall design of the camera. How will the assembly be mechanically mounted? How will the alignment be referenced to the overall camera optical axis? How many lenses does the camera have, and are there lens groups? What are the materials of the lenses and what is their shape? The lens material plays a significant role in the flexure design, given its coefficient of thermal expansion, and the shape of the lens determines the location of the centre of gravity, which defines the plane where the pads should intersect. The shape also defines how the lens will be mounted and how the alignment should be approached.

Several iterations of the near-infrared and visible camera design were developed throughout this project. The common guidelines have been:

- five to seven lenses combining four to five different types of materials;
- lens diameters ranging from 100 to 400 mm;
- mounting groups of lenses in barrels (defined by the optical design);
- convex and concave surfaces.

Figure 2.49 presents an example of an iteration of a near-infrared camera and a visible camera with seven lenses; this design was used as a baseline for this thesis at the time of writing.

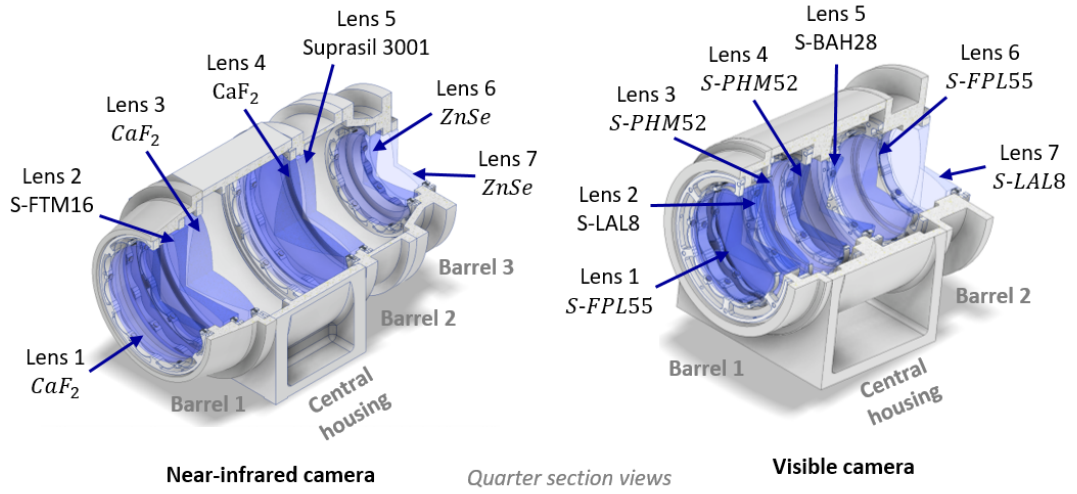


Figure 2.49: HARMONI spectrograph camera design until May 26th, 2023.

2.8.2 Concept alignment and assembly

In Section 2.4.1, I defined the alignment of the lens mount assembly and in Section 2.4.2, I defined how to achieve this alignment during mounting. The next step is to reference the lens mount alignment to the barrel and to the camera alignment in order to fully understand the alignment.

Figure 2.50 shows a three-lens barrel integration concept. The reference surface of the lens mount assembly should be placed facing the direction of light propagation when assembled in its position in the barrel (if possible)⁵⁶. When the lens mount assembly is placed on the barrel, the barrel assembly surface becomes the lens mount reference to the camera's optical axis for tip-tilt and air gap. This alignment could be adjusted with shims. The radial alignment origin is referenced to the barrel's central axis intersection of the lens mount assembly surface plane and can be adjusted by moving the lens mount within this plane with millimetric screws. The lens group alignment for a barrel then gets referenced to the housing assembly surface and the barrel's central axis. Thus, when designing a barrel, the assembly surfaces for lens mounts should be orthogonal to the barrel's central axis (which is the camera's axis of light propagation) and be well toleranced to ensure the correct air gap between lenses.

⁵⁶This is because alignment measurements will likely be attached to this surface, and tracing the alignment of the camera will be easier if this convention is kept.

The barrel integration example in Figure 2.50 illustrates a conceptual procedure for assembling three lenses with a rotary table and a dial gauge similar to the lens mount assembly. Through this thought process, the lens mount tip-tilt alignment becomes evident to avoid tip-tilt re-alignment with shims in the barrel and remove the need to probe the lens surface again. Additionally, the air gap must be well tolerated to simplify the barrel assembly procedure and avoid using shims for corrections. I contributed to a more detailed conceptual procedure for barrel alignment, which can be found in [53].

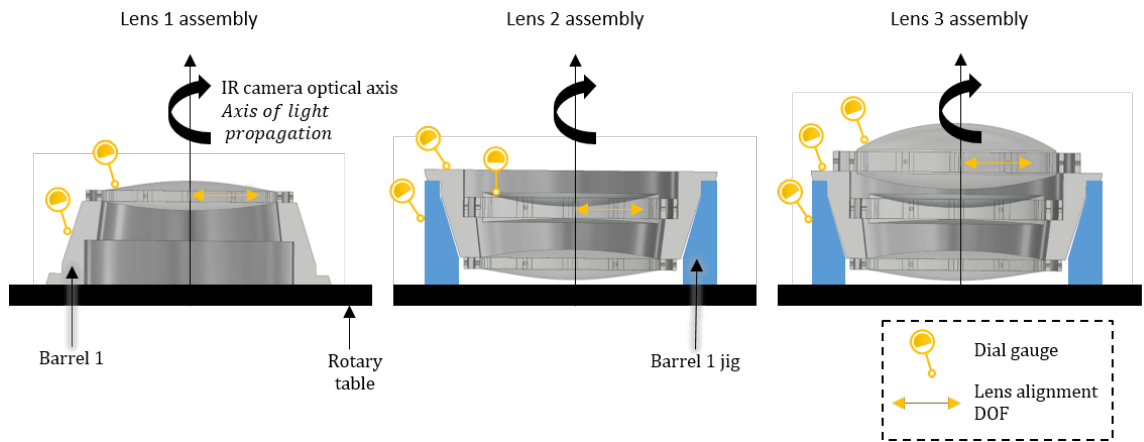


Figure 2.50: Barrel integration concept.

Figure 2.51 shows two camera integration concepts with two or three barrels and a central housing. The barrels' central axes must intersect and be parallel to one another to achieve a camera alignment. Thus, the interface surfaces between the barrels and housing are central and must be well specified and tolerated. The airgap and tip-tilt alignment could be corrected with shims and the radial alignment of the lens groups could be corrected by moving barrels within the housing interface surface. The housing is attached to the spectrograph support structure carrying the camera alignment to the overall spectrograph alignment.

The example camera integration concepts shown in Figure 2.51 illustrate a conceptual assembly procedure using a rotary table and a dial gauge similar to the lens mount assembly. This initial approach considered that a CMM would not be available for this procedure or an optical alignment device throughout the procedure, similar to what

was done for the FMOS and KMOS cameras. Through this thought process, it becomes clear that barrel tip-tilt alignment should not be considered within the assembly design as a compensator, first to potentially avoid probing a lens surface again (if the alignment is mechanically measured) and second to reduce the risks while handling the overall camera assembly. A step-by-step conceptual procedure can be found in [53].

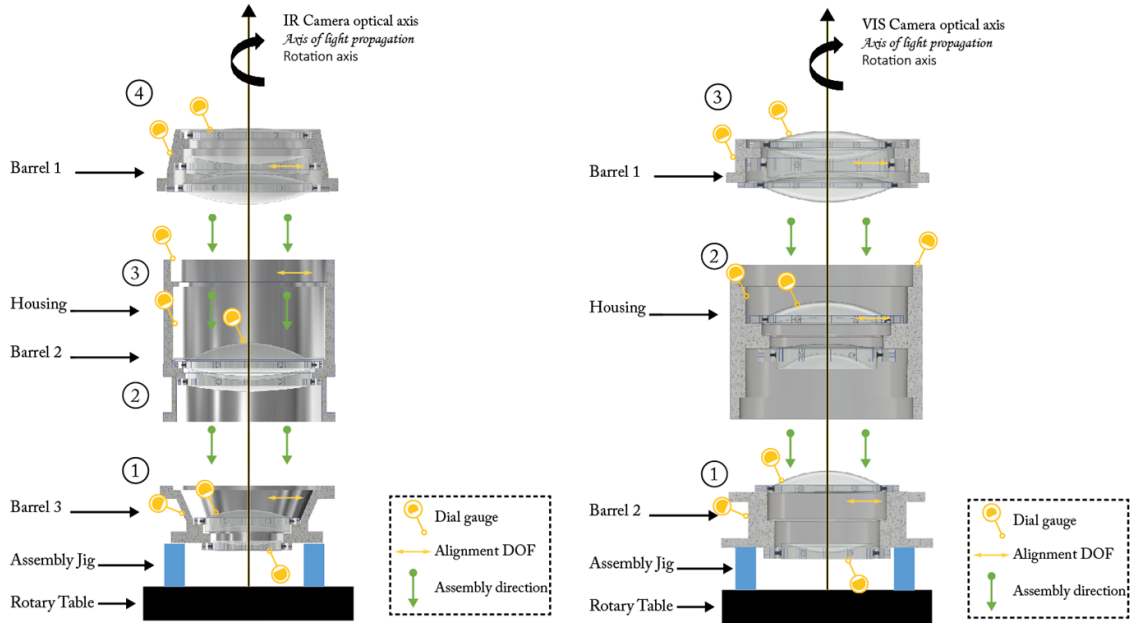


Figure 2.51: NIR and VIS camera integration concept (image edited by RAL).

2.9 Discussion and conclusions

In this last section, I summarise my findings and the work presented in this chapter. I look back at the research aims of this project and discuss how I realised them. I examine what I learned, analyse key topics such as tolerance evaluation and present my conclusions.

2.9.1 Chapter summary

In the introduction of this chapter (Section 2.1), I presented the challenge of developing lens mounts for the HARMONI spectrograph cameras. The task was to develop flexure mount rings to hold the camera lenses in a vacuum at 130K based on a *proven* design

with extensive documentation gaps and no helpful verification record. The cameras were designed in parallel during this time, indicating tighter alignment tolerances which required re-development of the *proven* design and a more rigorous approach.

The research aims proposed in Section 2.1.1 were addressed as follows.

- *Understand the factors at play to achieve the desired performance of the lens mount assembly in operational conditions.*

I split this aim into two parts. The first part is to understand the factors influencing performance at room temperature, which I address in this chapter. From building a background for the design, writing down design guidelines, defining alignment, narrating an assembly procedure based on two models, analysing the alignment of these models and finally proposing a concept integration into the cameras. The second part of this aim is to understand the factors influencing performance at 130 K; I dedicated Chapter 3 to this topic.

- *Develop the lens mount assembly technology and increase its maturity.*

Development is achieved through traceable evidence and ensuring the reproducibility and repeatability of results for further development. This chapter provides traceable evidence of my contributions to mature the lens mount assembly and increase its TRL in critical aspects. In Section 2.9.4, I present a re-evaluation of the TRL after having performed my work.

- *Understand the alignment parameters of the lens mount assembly and how they interface with the camera alignment.*

In the alignment and integration sections (2.4, 2.6 and 2.8), I defined the lens mount assembly degrees of freedom, built up alignment through mounting, identified the contributors to misalignment and referenced the alignment at a conceptual stage to the camera.

- *Mount a prototype lens mount assembly and identify the procedure steps for assembly and alignment.*

I developed a mounting process (Section 2.4.2), designed a mount jig (Section 2.4.3) and assembled and aligned two lens mount assembly models. In Section 2.5, I narrate the procedure steps that I fine-tuned while performing this exercise.

- *Provide feedback to the D&A and AIT teams on improvements and work needed to implement the lens mount technology for HARMONI.*

I provided feedback to the D&A and AIT teams throughout by DPhil in weekly meetings and took the time to share my findings with everyone working on the lens mount development. The impact of my feedback on the lens mount development can be seen in the subsequent activities after my departure. Additionally, in Section 2.9.2, I present a summarised list of lessons learned through the work presented in this chapter and in Section 2.9.4, I present my ideas for future work.

- *Address historical/inherited issues and propose a development pathway.*

The background section (2.2) resulted from a two-year-long strenuous journey of finding and putting pieces of information back together. Straightening up and writing the story was central to this chapter's work. I chose to further develop the KMOS flexure design based on the evidence I gathered (see Section 2.2.7). From this point onwards, I proposed a development pathway and saw it through. Bonds and adhesive dispensing were critical inherited issues I addressed in this work. I listed all adhesives considered throughout the entire history of the flexure mount rings in Section 2.2.3 along with its selection criteria, I defined bond design in Section 2.3.3, I captured my dispensing exercise in Section 2.5.3, I narrate the adhesive application and curing procedures I used in sections 2.5.4.7 and 2.5.4.8; and lastly I documented the bonding outcome of the two lens mount assembly models I assembled in Section 2.7.

2.9.2 Lessons learned

Completing the work in this chapter has produced valuable knowledge for developing flexure lens mounts. In this section, I discuss vital lessons I learned.

- What J. Allen and R. Barnsley described as bond failures when the bond did not detach but changed size affecting the position of the lens is not a bond failure. It only means that bonds are elastic at room temperature because the adhesive is elastic. The adhesive becomes stiff at the cameras' operational temperature.
- The elasticity of the bonds in the lens mount assembly must be considered when designing the flexure mount for a lens. It should be part of the tolerance stacking. Ideally, the lens bond area and thickness should be optimised for each lens, considering its mass and edge thickness.
- Further characterisation of the mechanical properties of the adhesive at room and operational temperature is needed to achieve a customised design for each lens.
- For the HARMONI cameras, the lens mount assemblies must not be cured, handled or placed vertically as in the KMOS camera (see Figure 2.3). The alignment that was verified according to Section 2.6 is lost due to the elasticity of the bonds.
- A low force, high precision dial gauge must be used for lens alignment.
- The mounting jig developed for the SWIFT spare camera should be developed as it removes alignment constraints in the DOFs⁵⁷ of the lens (see Figure 2.7) and not just because it protects the lens surface.
- C250 Aluminium as a choice of material is fundamental for alignment tolerances. The special casting and heat treatment techniques make the plate extremely stress-free. It retains its flatness and dimensional tolerances after machining and repeated heating and cooling.

⁵⁷Degrees of Freedom.

- Bonds have variable thicknesses across the bonding area. It will only have 0.2 mm thickness on a small region, and throughout the rest of the bond, it will follow the bond shape and compensate for manufacturing imperfections.
- Lens tip and tilt alignment should be constrained at this stage of camera alignment to ease the assembly steps at the barrel and camera levels.
- Alignment tolerances must be stacked up and verified throughout the assembly.
- Realistic stacked-up alignment tolerances must be considered during the cameras' optical design.
- Only use isopropanol to clean uncured adhesive. Do not use water to clean it.
- Inspect all bonds from various perspectives before constraining the flexure ring position during assembly to avoid bonding over Kapton tape (see Figure 2.48).
- The height correction for the mount jig parallels and setting spheres should be done together. The height variation should be kept under 10 μm .
- A flexure in the KMOS design with a fused silica blank model was pre-loaded during the adhesive application, which caused the lens to travel in a certain direction by 13 μm . This was not the case for the pre-HARMONI design with an HK9 lens model.
- A measurement protocol is strongly recommended to make sure measurements are recorded during verification. Planning measurements in advance does improve the quality of the data recorded.
- Keeping a research log is useful for later interpretation and understanding.
- After manufacturing, parts must be verified and safeguarded to avoid damage. Later limitations of alignment like this can be easily eliminated.
- The fused silica blank and the HK9 lens I used for the models were not manufactured up to the quality standards expected for the HARMONI camera lenses.

- A rotary table with a well-characterized error motion is central to achieving alignment. It is worth investing in a good rotary table or maintaining and understanding the ones we already have.
- Flatness, parallelism, cylindricity, and roundness specifications must be indicated, considering surfaces referencing alignment throughout the assembly process.

2.9.3 Implications and practical applications

There is further development needed to realise the HARMONI cameras. Regarding the lens mounts, by re-designing the mount jig to accommodate more DOFs and validating the alignment with a HARMONI lens with the current alignment tolerances, the lens mount assembly will reach TRL 5 and be ready for integration.

For the HARMONI project, assembling and curing the lens mount assemblies in series might not be feasible regarding the AIT timeline as it would require about ten calendar days per lens (with everything prepared). This can be solved by developing a way to lock alignment in a *curing jig* where alignment can later be verified.

The cameras' work package was handed over to RALSpace in March 2021.

This research will have a significant impact on the HARMONI instrument and future astronomical instruments. Understanding and improving flexure mounts for astronomical instrumentation produces higher-quality data and decreases the development cost and timeline of future instruments.

2.9.4 Evaluation and future work

In this last section, I would like to present a re-evaluation of the technology readiness levels presented in the introduction of this chapter for the FMOS and KMOS flexure lens mount. Figure 2.52 shows this reassessment. The lens mount assembly progressed from a technology concept not yet formulated for a HARMONI lens (TRL 1.5) to a model tested in a laboratory environment requiring more work to validate the alignment requirements (TRL >3 but not quite 4). The mount jig design progressed as well from a technology concept not yet formulated for a HARMONI lens (TRL 1.5) but did not quite reach a higher maturity because it needs to be re-designed to allow the

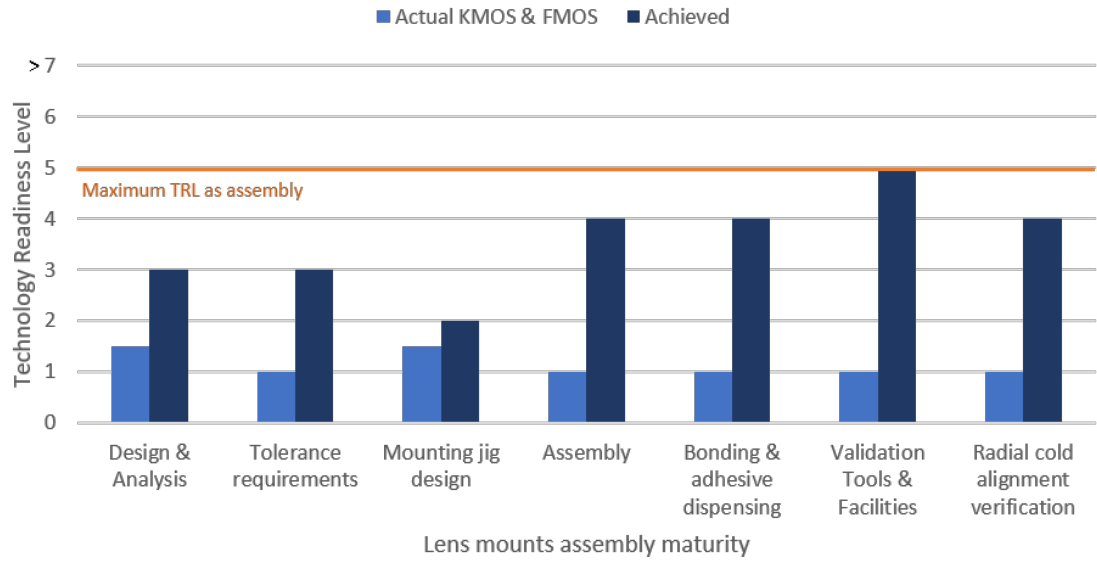


Figure 2.52: Improved technology readiness for the FMOS and KMOS flexure lens mount.

assembly to reach tighter tolerances (TRL >2 but not quite 3). Through this work, the spectrograph team acquired assembly and bonding knowledge and facilities for validating the lens mount assemblies. I started by observing basic principles (TRL 1) to validating the assembly, bonding and adhesive dispensing in a laboratory environment and even at operational temperatures (TRL >4 but not quite 5). Moreover, to reach TRL 5 in this aspect, it will be necessary to prove that the lens mount assembly can reach and maintain alignment considering the leeway produced by the elastic bonds at room temperature. Lastly, I have dedicated a Chapter (3) to discussing radial cold alignment verification; I started by formulating the radial cold alignment concept based on basic principles observed to testing the lens mount assembly models in operational conditions.

Chapter 3

Lens mounts cold tests

3.1 Introduction

Near-infrared astronomical instruments (especially those working beyond 1.6 μm) operate at cryogenic temperatures to minimize thermal background from the instrument itself. For instruments such as HARMONI, temperatures below 140K are typical, with detectors operating down to 40K. Without this cooling, the instrument would be blinded by its own thermal radiation[56].

HARMONI covers the optical and near-infrared domains, which will share the same optical path up to the collimator before the dispersing element (see Sections 1.3.1 and 4.2.1). Thus the HARMONI integral field spectrograph (from pre-optics to detector) is enclosed in a large cryostat with an overall operating temperature of 130 K and additional cooling for each detector, ensuring negligible thermal radiation up to the largest wavelength of interest, 2.45 μm .

The cameras in HARMONI must operate in vacuum at 130K, thus be designed for these operational conditions and have their performance validated accordingly.

The purpose of this chapter is to further the development of the FMOS/KMOS flexure mount design for use in the HARMONI spectrograph cameras.

In Chapter 2, I focused on understanding the lens mount design considerations and alignment through assembly at room temperature; in this chapter, I focus on how the produced lens mount models behave at their operational temperatures.

3.1.1 Background

In Section 2.2, I summarised the information available on flexure lens mounts from the FMOS and KMOS instruments, along with prototyping activities at the University of Oxford with a perspective on design and room temperature alignment. This section provides background on the specific cold testing activities that contributed to developing the flexure mount ring.

The FMOS camera was assembled and mechanically aligned at room temperature. Then, the camera was installed on a cryogenic vessel for verification; see Figure 3.1 on the left. The mechanical operation of the camera was demonstrated in vacuum, and the focus mechanism was shown to be functioning correctly at 293K. Cooldown started, and thermal equilibrium was achieved after four days. The camera was inspected through the window, and it was possible to see that several lenses were damaged; see Figures 3.1 and 2.1 on the right[58]. The camera was not validated, and the design evolved as mentioned in Section 2.2.2.

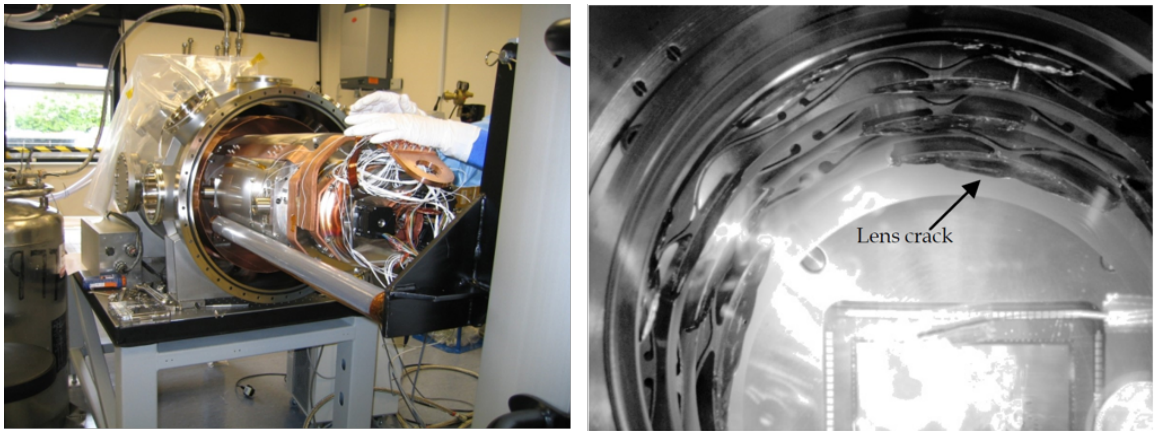


Figure 3.1: (left) FMOS camera was installed in a cryogenic vessel to validate performance during thermal cooldown and equilibrium. (right) View through the cryogenic vessel window after reaching thermal equilibrium. [Credit: RALspace/FMOS consortium]

The flexure design was improved to reduce thermal stress at the bonds, and it was implemented on camera lens 5 of the FMOS instrument. The improved design was validated for cold operation; see Figure 3.2. The rest of the lens mounts were assembled with the improved design, and the FMOS instrument operated at the Subaru telescope

between 2008 and 2016. Key elements of the flexure design were lifetime validated in operational conditions with the FMOS instrument, such as the adhesive, the bond composition¹ and the circular pad design.

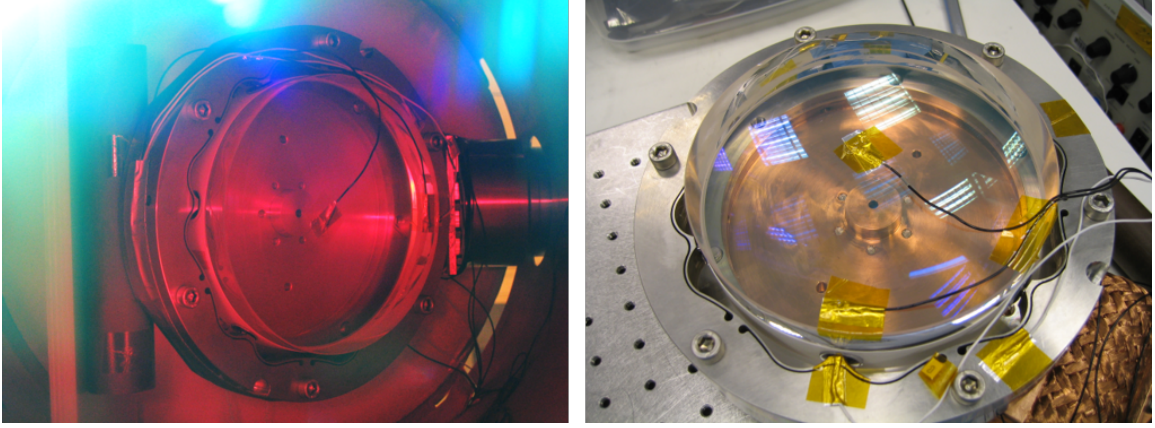


Figure 3.2: (left) FMOS camera lens 5 cold test validation after improvement. (right) Inspection after cooldown, the lens did not show cracking. [Image credit: RALspace/K-MOS consortium]

The KMOS camera included these improvements and was successfully implemented; see Section 2.2.2. In the KMOS instrument, further bond compositions were lifetime validated in operational conditions, aluminium was validated and included as a preferred choice of material.

The image quality of the KMOS camera was measured at room temperature as shown in Figure 3.3, and cold temperature validation was carried out for the spectrograph[24]². No cold validation was explicitly developed for the flexure mount design, and it remained uncharacterised at its design operational temperature. The camera did achieve its cold performance requirements, therefore the system as a whole was validated, but the individual elements were not investigated.

J. Allen performed the first radial alignment measurements of a flexure mount. Figure 3.4 shows the setup Allen used. He mounted a fused silica blank on an aluminium mounting ring with slots and interchangeable pads (see Section 2.2.4). The

¹Invar + adhesive primer + 0.2 mm of adhesive + cotton paper + a thin line of adhesive + adhesive primer + steel.

²Furthermore, three small lens mount assembly models were cooled down each with a different bond composition. The combination of a blank of zinc selenide with titanium pads, a blank of calcium fluoride and beryllium copper pads, and a blank of fused silica with Invar pads were tested.

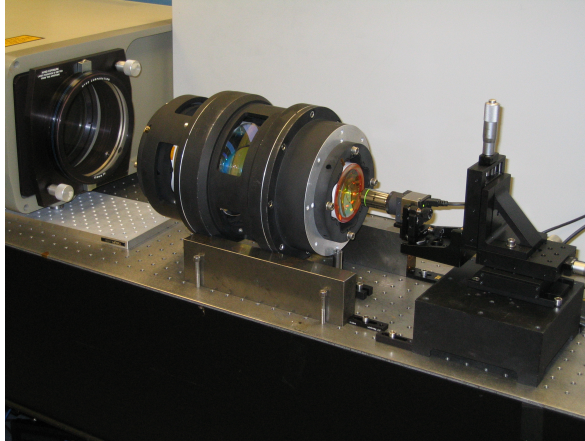


Figure 3.3: The image quality of the KMOS camera was measured at room temperature in July 2010. [Image credit: RALspace/KMOS consortium]

best-performing pads he tested were the double beam spring with flat short bond surface pads. The mount ring prototype with flat double beam spring pads was cycled at least 11 times (room temperature to 130 K to room temperature), showing a repeatable displacement magnitude of $18 \pm 3 \mu\text{m}$ at 130 K despite re-assembly and re-alignment but unpredictable direction of movement per instance[1]. Allen’s results combined measurements from several cycles and did not mention whether thermal equilibrium had been reached at 130K³. The FMOS/KMOS model remained uncharacterised. In April 2018,



Figure 3.4: Jamie Allen’s setup for measuring radial alignment of flexure mounts.

I held a brainstorming session with the spectrograph team and presented the status and background of the flexure mount knowledge[18]. The session’s conclusion was to

³Furthermore, calibration and measurements analysis were only superficially mentioned.

pursue the development and validation of the FMOS/KMOS flexure mount ring design (see Section 2.2.7).

3.1.2 Research aims

The research aims for this chapter build on the findings of Chapter 2. They are as follows.

- Confirm the survivability of the engineering models assembled in Chapter 2 at operational conditions.
- Re-develop a measuring method to record radial misalignment of flexure mounts that considers time, and present results in a reproducible manner.
- Measure the change in radial alignment between room temperature and HARMONI operational conditions for the engineering models assembled in Chapter 2.
- Validate the cold alignment performance for the HARMONI lens mounts, and see if the $20\mu m$ target assumed for the FMOS/KMOS flexure mount is realistic.

3.1.3 Chapter structure

This chapter is structured as follows: in Section 3.2, I describe the cold test I performed with details of the setup and how the measurements were acquired. In Section 3.3, I show the cold test runs that I performed along with their cooldown and warm-up cycles. In Section 3.4, I demonstrate how the measurements were calibrated and list the contributors to displacement that I considered. In Section 3.5, I show the results of how the radial alignment changed from room temperature to HARMONI operational temperatures. In Section 3.6, I conclude by presenting my findings of the cold testing of the lens mount models.

3.2 Test description

I re-developed a test setup to measure radial decentring for the lens mount models I assembled. I used the test cryostat and the camera jig that J. Allen utilised for his measurements. However, I designed a new cryostat lid with only one window at the centre, changed the target and position, replaced the camera with a CCD, attached a spider to the lens mount models and placed speckle patterns as targets in the lens and the spider centre. Figures 3.5 and 3.6 show the concept test setup. Furthermore, I implemented new connections to accommodate more temperature sensors and to allow for remote monitoring of temperature, pressure and target imaging. In this section, I show how I recommissioned the cryostat and set up the lens mount models for testing.

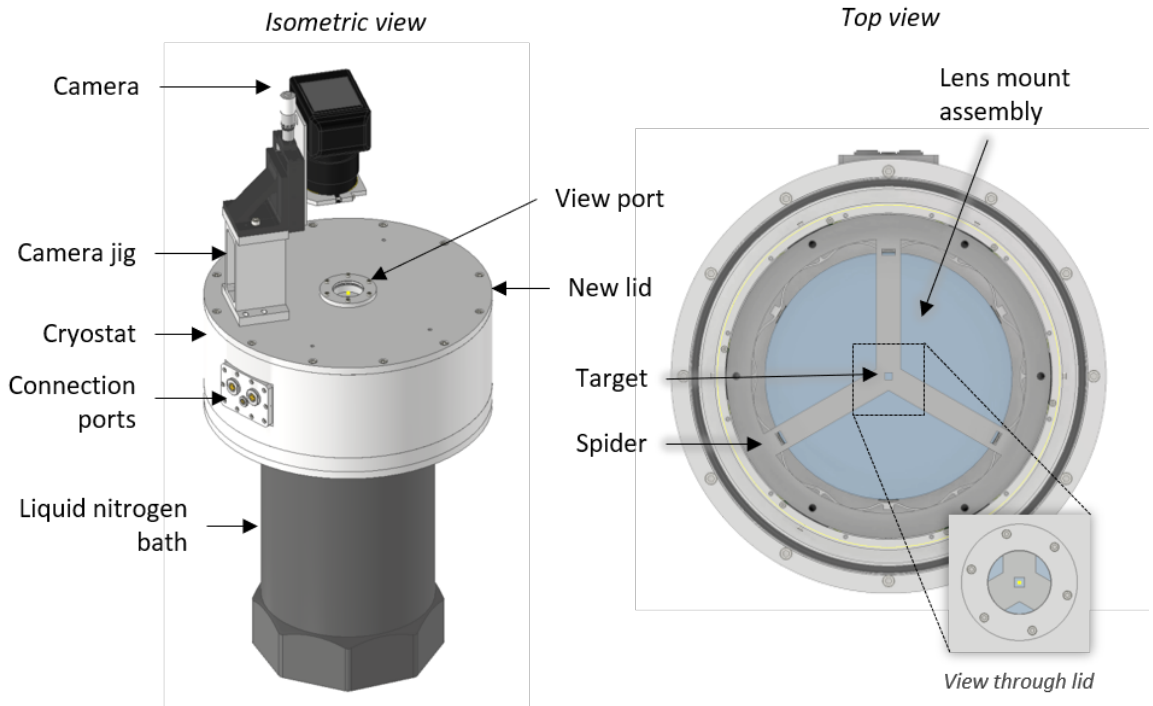


Figure 3.5: Concept test setup for measuring radial decentring of lens mount assembly models.

The new test concept shown in Figures 3.5 and 3.6 allows for direct measurement of radial misalignment from the lens centre and the mount geometrical centre. Additionally, with the inclusion of remote monitoring and camera automation, the only

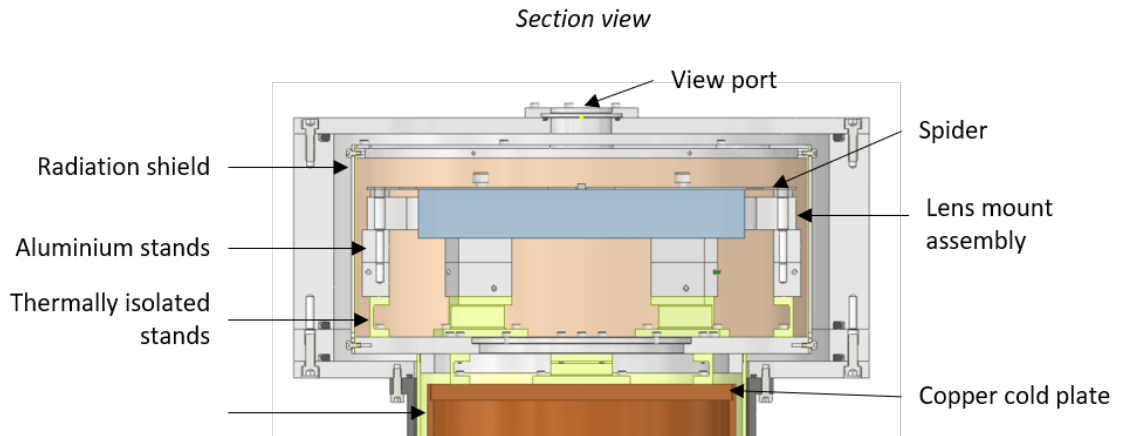


Figure 3.6: Cryostat concept test setup for measuring radial decentring of lens mount assembly models.

requirement for cycling was to refill liquid nitrogen. The new setup allowed for undisturbed data acquisition per cycle, thus enabling analysis of measurements per cycle and preservation of records of cycle durations.

3.2.1 Cryostat

The cryostat I used for testing had been used for other tests since J. Allen used it. I could not use the current connections and lids we had available as I could not mount the CCD and macro lens on top. The connection port was incompatible with having a lens mount model installed inside, or the electrical connections were in unusable conditions with numerous false contacts. I prepared cold testing by disassembling the cryostat inner chamber with all connections and cleaning all parts before reassembling. I maintained all the vacuum connections, applied grease to the O-rings and fixed a broken window from a viewport. I designed new connections with ports and circuits, and Rik Elliot from Central Electronics at the University of Oxford installed them (schematics are referenced in appendix G.2). I also modified the radiation shield cover to include a central viewport and designed a new lid. I co-supervised a master's student project with Dr. Myriam Rodrigues, and we implemented and installed a remote monitoring system for the cryostat. Before starting tests, I pumped and baked out the cryostat for a week.

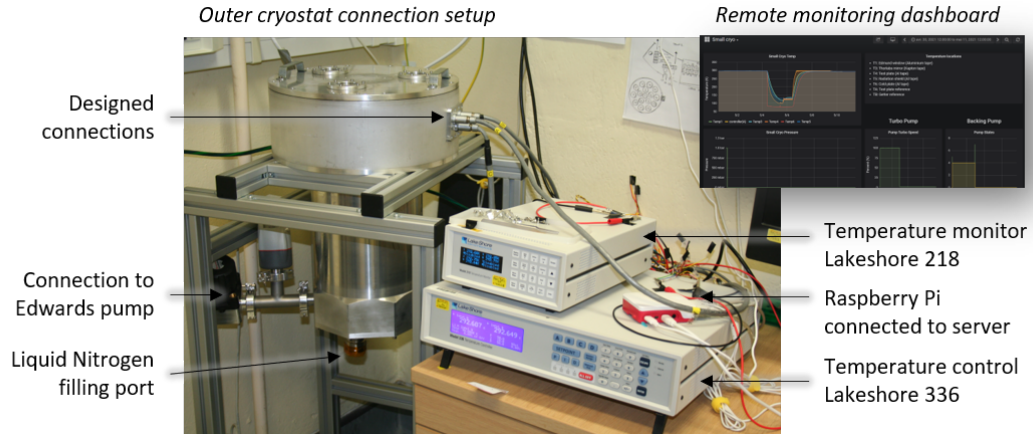


Figure 3.7: Commissioned cryostat with new connections and remote monitoring integrated for temperature and pressure.

Figure 3.7 shows the external connections of the temperature control and monitoring circuits. The temperature control circuit that were connected to a Lakeshore 336 included six heaters in parallel placed in the aluminium stands, a temperature sensor placed in the mounting ring and another in the getter for temperature control⁴. The temperature monitoring circuit that were connected to a Lakeshore 218 included six temperature sensors for monitoring the cold plate, radiation shield, lens centre, lens edge, spider and mount ring. Figure 3.8 shows the internal connections of the cryostat. I attached the PT100 sensors with aluminium tape to that the sensors were thermally linked to the area I wanted to measure.

The pressure of the cryostat was measured with a gauge and connected to an Edwards pump. The Lakeshore devices 218 and 336 and the pump were connected to a raspberry-pi which uploaded its measurements to a server, and we monitored the measurements through a Grafana dashboard.

3.2.2 Camera setup

I took images of the target throughout the cycling with an astronomy camera and a macro lens mounted on the cryostat lid. Figure 3.9 shows the imaging setup for the cryostat, and the lab setup that I had for controlling it. Additionally, during cycling, I placed a lamp next to the cryostat lid and covered the cryostat with two large white

⁴All temperature sensors I used were PT100.

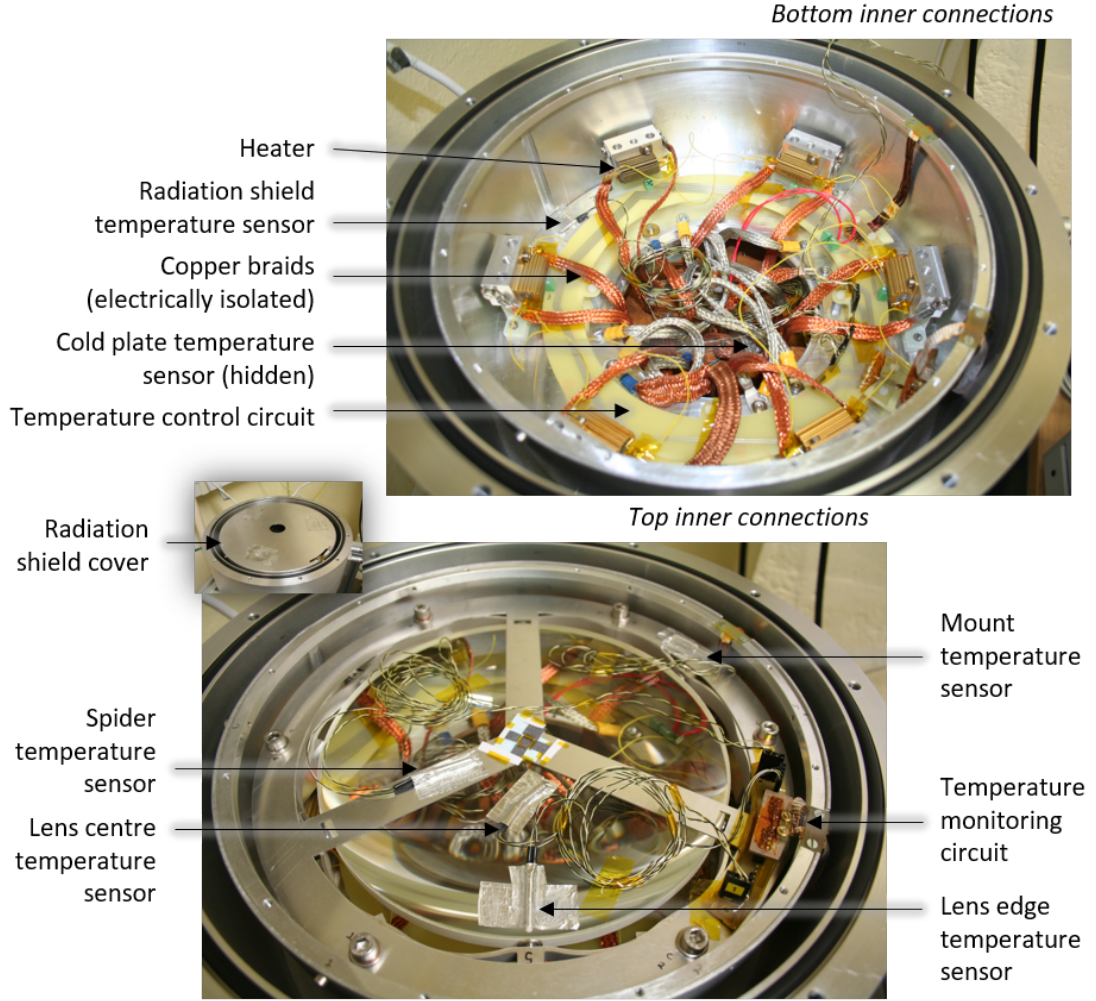


Figure 3.8: Commissioned cryostat inner connections.

cardboard panels; this ensured uniform target lighting throughout the day, which was vital for ensuring measurement quality. I adapted the camera jig that J. Allen used for this setup with a linear micrometer for focal adjustments.

3.2.2.1 Target

I used the technique of digital image correlation (DIC), a widely used method in experimental mechanics for full-field measurement of displacements and strains^[44]. The target I selected for this purpose was a random speckle pattern printed on paper⁵. Since my test aimed not to measure strains or material deformations but movement or displacement through time and temperature, I printed a speckled pattern on paper

⁵The paper changes minimally in size and shape while in a vacuum and at 130 K temperature.

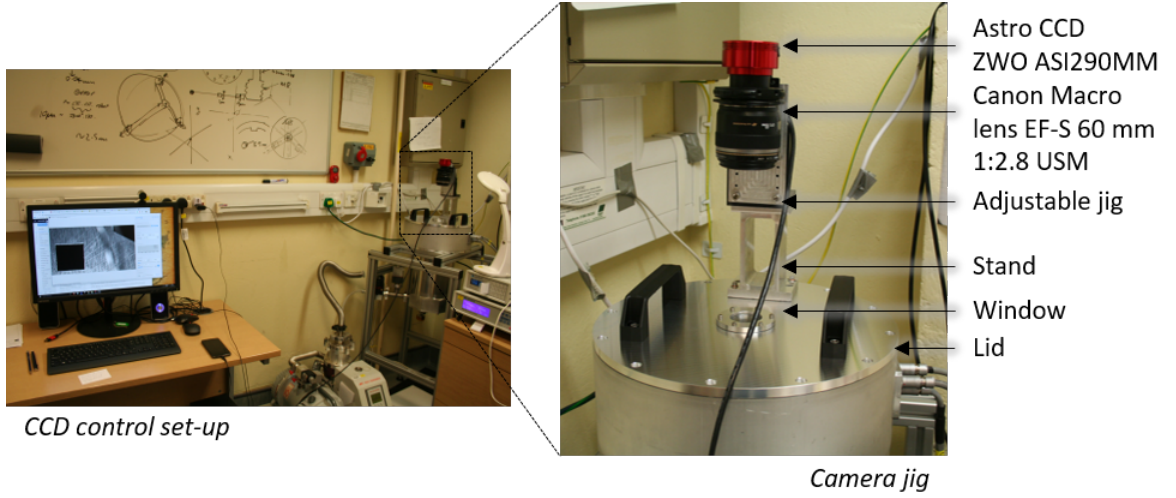


Figure 3.9: Astronomy camera control setup and camera jig.

and adhered it strategically to the spider and lens centre. I selected the pattern with speckles with an average size of 3–7 pixels in the acquired image as proposed in [48].

Figure 3.10 show how I set up the speckled pattern for the KMOS design with a fused silica blank model and the pre-HARMONI design with an HK9 lens model. I also placed a piece of millimetric paper in the camera’s field of view to measure the image scale during room temperature thermal equilibrium in between cycling.

The lens and mount speckle patterns had a height difference of one millimetre for the pre-HARMONI design with an HK9 lens model and about three for the KMOS design with a fused silica blank model. In both cases, the patterns were in the camera’s focus range at the start of each cycle at room temperature⁶.

3.3 Cold testing

This section summarizes the cold testing steps and the test runs I performed, including improvements made to the test setup to ensure high-quality measurements.

⁶This small detail became the primary source of image noise in my measurements as the height difference increased at colder temperatures varying focus and having different image blurriness. If this type of measurement is repeated, I suggest ensuring that the lens and the mount target have a minor height difference and thermal contraction of the models and cryostat interior is considered.

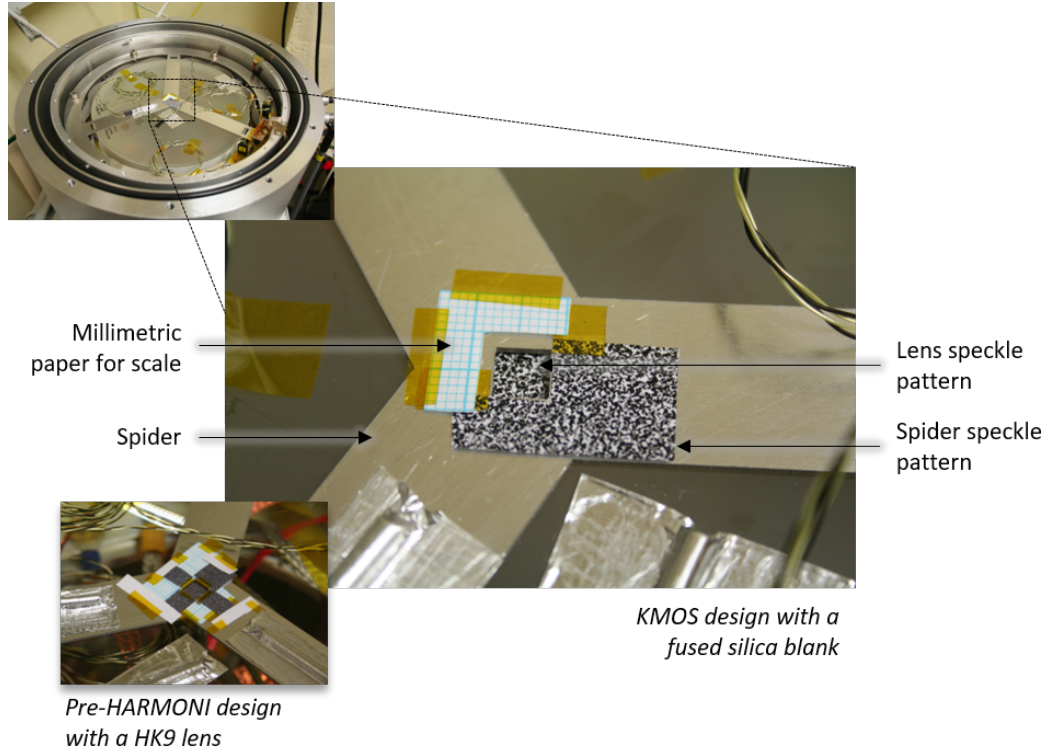


Figure 3.10: The analysed target was a speckle pattern adhered to the lens or blank centre and the spider. The tape was placed strategically for the spider speckle pattern to move and contract with the edges of the spider window.

3.3.1 Setup evolution

I initially replicated J. Allen’s setup for measuring radial decentring of lens mounts through three windows in the cryostat but did not analyse the data using the same technique as my references were different⁷. I tried several targets from contrasting shapes adhered to the mount ring and the blank (observe targets in Figure 3.11 top left) to several sizes and types of speckle patterns attached to aluminium fingers. I performed four cycles with the KMOS design with a fused silica blank model and recorded radial measurements, improving their quality every cycle. However, I realised that the combination of the changes in distance measured for each window was trickier than I anticipated, and it was required to reference the changes in distance to one another in position, time and temperature. The measurements per window occurred at different points in time, as the camera could only capture one window at a time.

⁷I did not add prism mounts, I instead trialled various types of targets.

Additionally, through cool down and warm up, the measurements per window occurred at different temperatures as they happened at different times; thus, corrections and interpolations in data were required to combine them at a given temperature. The target illumination was different per window through various times of the day, adding additional uncertainties. Furthermore, unscrewing and screwing the camera jig to the cryostat lid was required to point it to every window for recording measurements, disturbing the setup every 30 minutes through cycling. Due to COVID restrictions in place at the time, this option was not practical. After several discussions and design work I changed the setup to the one described in [3.2](#).

Figure [3.11](#) shows an image and three plots. The image on the top left shows how two types of targets were set up, one with contrasting figures and another with two types of speckle patterns. The plot on the top right shows the total displacement recorded per window during cycle three. The bottom left plot shows the radial movement of the fused silica blank with respect to its mount ring; it is possible to discern hysteresis describing the lens mount behaviour during cooldown and warmup. The calculated radial displacement in 2D is shown on the bottom right plot. However, as mentioned above, it is important to note that there are significant systematic uncertainties in these results.

3.3.2 Cycles

This section describes the required steps to perform a *cycle*.

3.3.2.1 Preparation

I cleaned the cryostat lid and the sealing surface of the cryostat, and reviewed wiring and vacuum connections. Then, I pumped for at least 48 hours after setting up a lens mount model as described in [3.2](#), as well as after opening the cryostat for inspections.

3.3.2.2 Cycle steps

Room temperature equilibrium: Before recording a measurement of the *initial* position of the lens mount, the room temperature must be controlled so as not

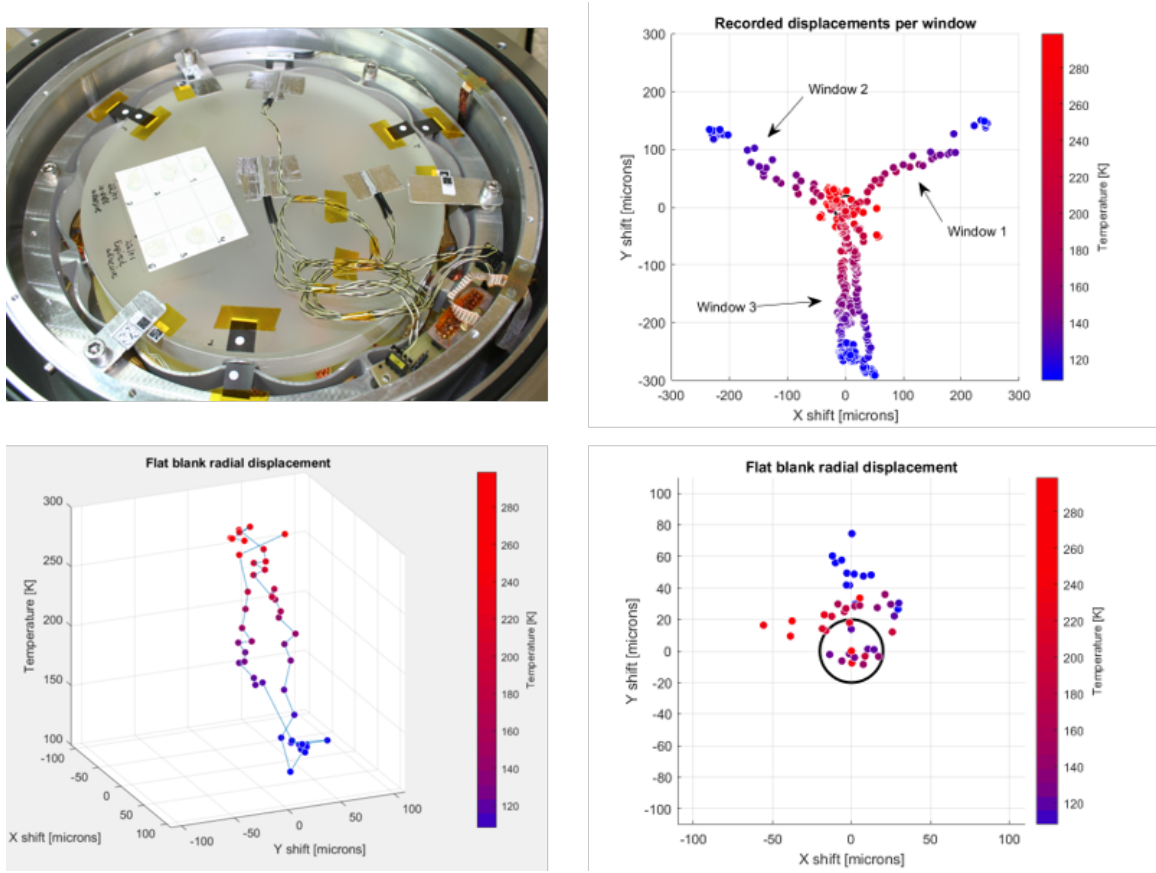


Figure 3.11: The cold testing setup evolved as I learned more and more about how to interpret the radial displacement of the KMOS design with a fused silica blank model. The plots show the results from cycle 3.

to vary by more than 3K per 12 hours⁸. I set the room temperature around 298 K in order to set up and test the temperature control before a cycle. This also ensured stability throughout the day and through cycles, as the laboratory had large windows with no thermal isolation⁹. I set the camera focus and recorded position and scale measurements with the camera every two hours during this stage.

⁸This period could overlap with the pumping time of the preparation step.

⁹During the first cycles I performed, I did not do this, and I only pumped and set the reference position of the lens with respect to its mount before cooldown. Then when I warmed up and completed the cycle, I noticed that I could not compare the initial and final position of the lens with respect to its mount because the room temperature conditions were different. At the end of a cycle, if the cryostat still has some liquid nitrogen on its dewar, it will continue to cool down if the temperature is not controlled. Even if liquid nitrogen has been exhausted, it will cool down due to inertia and temperature control is needed to reach and maintain room temperature for a while.

Cool down: During this step, I filled the liquid nitrogen reservoir of the cryostat and proceeded to cool down the lens mount model. I pumped until achieving a high vacuum.

When exposing optics to temperature changes, it is vital to do it gradually to prevent shattering or cracking. I initially set the temperature control with a maximum variation of 2K per minute for the fused silica blank and 9K per hour for the HK9 lens. By running several cycles, I realised that the lens mount models were quite a large mass to cool down for the cryostat setup. I added additional links between the cold plate, the radiation shield and the aluminium stands. Even with the additional links, I concluded that the KMOS design with a fused silica blank model would cool down passively at a slow enough rate. The cooldown duration varied per cycle depending on the temperature control and the number of thermal links. The most time-efficient cooldown I achieved for the KMOS design with a fused silica blank model was 15 hours (see Figure 3.13). The cooldown duration for the pre-HARMONI design with an HK9 lens model took 20 hours (see Figure 3.14). I recorded measurements every 10 minutes.

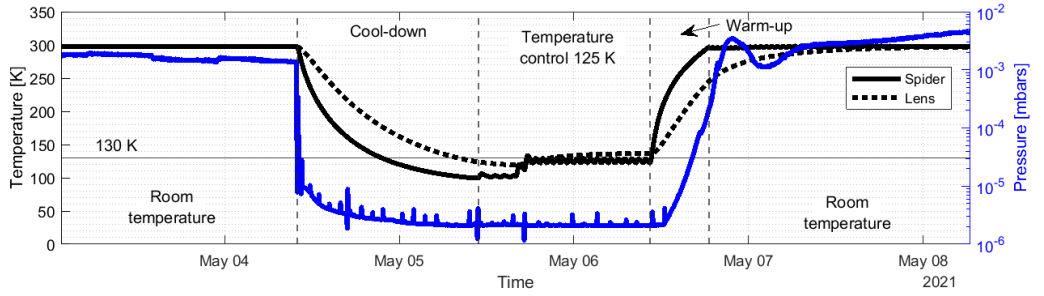


Figure 3.12: Temperature and pressure through the cycle 5.

Cold temperature equilibrium: The HARMONI instrument is expected to operate at 130K and remain at this temperature for most of its lifetime, only warming up for maintenance. Therefore, an equilibrium at cold temperatures must be achieved to characterise the flexure mount in operational conditions. I set up the temperature control to stabilise at 120 K in the mount ring¹⁰ with a purely

¹⁰Moreover, I monitored the temperature of the lens at the edge and in one edge to ensure a thermal equilibrium at 130 K in the overall assembly.

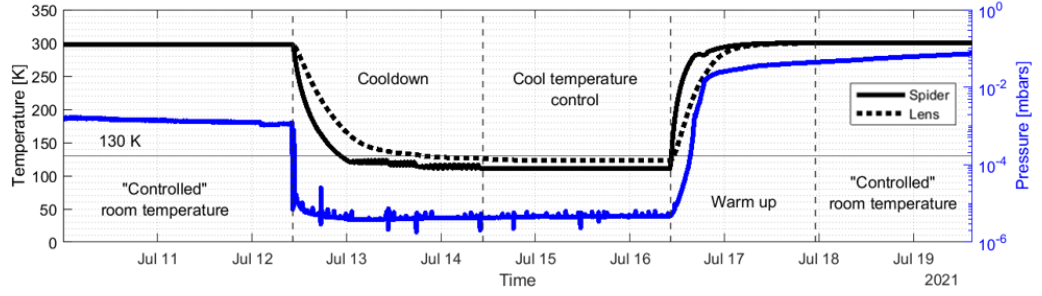


Figure 3.13: Temperature and pressure through the cycle 6.

proportional control¹¹ for a minimum of 24 hours. For this step, I recorded measurements every 10 to 30 minutes.

Warmup: Similarly to the cooldown, I set up initial rules to limit the temperature change: 2K per minute for the fused silica blank and 9K per hour for the HK9 lens. In this case, these rules remained for both models with proportional control. The warmup duration varied depending on the liquid nitrogen content of the cryostat dewar, although it was usually faster than the cooldown. I recorded measurements every 10 minutes.

Room temperature equilibrium: After performing several measurements with the three-window setup and analysing the data, I realised how important this step is to compare the lens position before and after cooling¹². I repeated the same step done at the start of the cycle, but this time for 24 hours in order to compare both lens mount positions. I let at least a couple of hours in between cycles before starting a new cycle.

Figures 3.12, 3.13 and 3.14 show cycles 5 and 6 of the KMOS design with a fused silica blank model and cycle 7 with the pre-HARMONI design with an HK9 lens model.

Section G.1 describes in detail the procedure followed to perform a cycle.

¹¹I tried several PID control configurations and had the best response with only P control. Figure 3.12 shows a PID control that did not stabilise; subsequent cycles were only P.

¹²Does it return to its initial position? Does it change position, by how much?

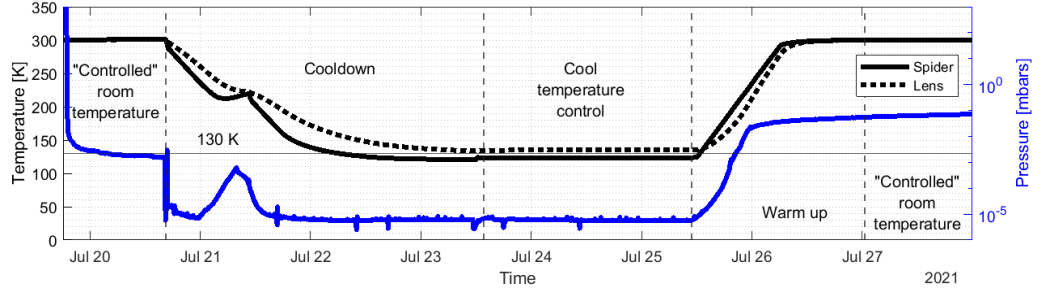


Figure 3.14: Temperature and pressure through the cycle 7.

3.3.3 Measured parameters

Throughout cycling, I took pictures of the speckle patterns in the camera's field of view. To calculate radial decentring, I selected two regions in the images, one from the lens pattern and another from the spider pattern. Using these regions, I tracked the lens and spider movement throughout cycling. The initial reference position was equivalent to the average position of the lens and spider during the controlled room temperature stage of the cycle. Furthermore, for every image, I recorded a time and a temperature¹³. Figure 3.15 shows the camera's field of view and the selected regions for cycle 5 (the KMOS design with a fused silica blank model).

3.3.4 Test runs

In Table 3.1, I summarise the cycles I conducted during cold testing. I started the first cycle on February 22nd, 2021 and completed it on February 27th, 2021. The pattern of reference for this first cycle was a white circle on a black background, one on the lens and another on the mount ring. I developed two algorithms to analyse the results: one that found the centre of each circle and tracked its position through the cycle, and another that calculated shifts with cross-correlation. During this first cycle, I realised that I needed to control the room temperature at the start and end of a cycle. The results from cycles 1 to 4 were deemed unusable as the systematic uncertainties attached to the combination of the measurements per window were too large due to the setup itself. I performed cycle two on March 8th-18th, 2021, cycle three on March

¹³Temperature and pressure were measured for cycle eight, but the data access was lost when the IT department put the server offline. The server recovery was ongoing at the time of writing.

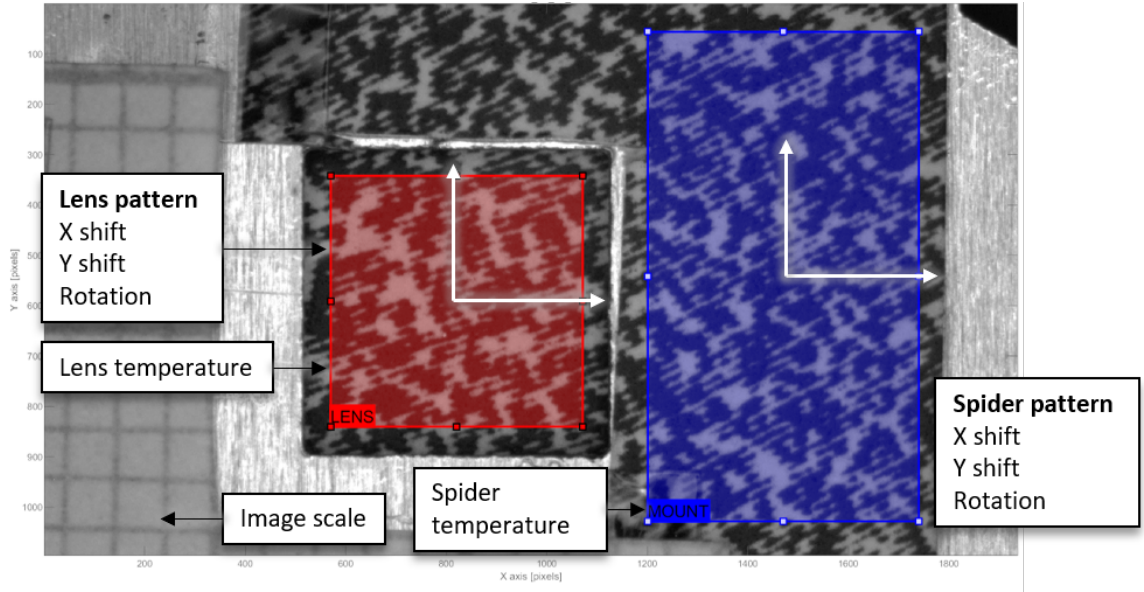


Figure 3.15: Measured parameters through cycling. Recorded shifts were calculated with respect to a stable room temperature position.

18th-23th and cycle four on April 27th-29th. Cycle four was interrupted as it was then that the decision was made to upgrade the cryostat setup.

Cycle	Model	Setup	Pattern	Camera	Results
1	KMOS design + FS blank	Three-window	Contrasting circles	Cannon	Not reported
2	KMOS design + FS blank	Three-window	Contrasting circles	Cannon	Not reported
3	KMOS design + FS blank	Three-window	Speckle pattern	Cannon	See Figure 3.11
4	KMOS design + FS blank	Three-window	Speckle pattern	Cannon	Not reported
5	KMOS design + FS blank	Spider	Speckle pattern	Astro CCD	See Section 3.5
6	KMOS design + FS blank	Spider	Speckle pattern	Astro CCD	See Section 3.5
7	Pre-HARMONI design + HK9 lens	Spider	Speckle pattern	Astro CCD	See Section 3.5
8	Pre-HARMONI design + HK9 lens	Spider	Speckle pattern	Astro CCD	See Section 3.5

Table 3.1: List of cycles conducted. Throughout this chapter, I reference the cycle number when discussing each cycle.

Cycles five, six, seven and eight ran smoothly, as shown in Figures 3.12, 3.13 and 3.14. Cycle eight was conducted on September 20th-27th, 2021. In Section 3.4, I detail how I analysed the data collected for these cycles and in Section 3.5, I report their results.

3.4 Measurements analysis

In this section, I detail the analysis I performed step by step to infer the radial decentring during testing based on the measured parameters.

3.4.1 Hypothesis

1. The setup inside the cryostat will thermally contract and expand differently from the camera setup through cycling. Thus the captured image will appear to *drift* through cycling compared to initial conditions. The apparent drift occurs because the temperatures inside the cryostat will decrease, and the camera setup will remain at an uncontrolled room temperature.
2. The spider speckle pattern will move towards the volumetric centre of the spider (because it is fixed to the mount ring) as temperatures cool due to thermal contraction. The frame of reference of this movement is the edge of the spider window, where the speckle pattern is adhered and the centre of the selected region during analysis. The dimensions of the spider window are 6.2x6.6 mm. Orientation is required to calculate the spider's contraction through cycling.
3. The lens will move within its mount and decentre from its initial position. The lens can decentre radially and rotate with respect to the mount.
4. There will be a change of focus due to axial contraction through cycling. The change will be apparent overall in the image due to cooling in the interior of the cryostat. Furthermore, a different change in focus will be apparent for the spider and the lens, as each has a different coefficient of thermal expansion.

3.4.2 Calibration

The first step of the analysis was to verify that the movement I could detect through image analysis was correct. I measured 50 and 10 μm steps using the camera setup mounted on the cryostat lid. This section details the method I followed and reports my results.

3.4.2.1 Set up

Figure 3.16 on the left shows the camera setup. I placed the cryostat lid on two plastic stands ensuring that its vacuum surface would not be damaged. Under the lid in the rough position of the spider and lens, I placed a linear stage with a micrometer attached. I adhered two speckle patterns on the edges of the linear stage, one following the movement and another to be stationary and serve as a reference. Figure 3.16 on the right shows the camera's field of view. I measured 50 and 10 μm steps at a vertical, horizontal and 45° orientation.

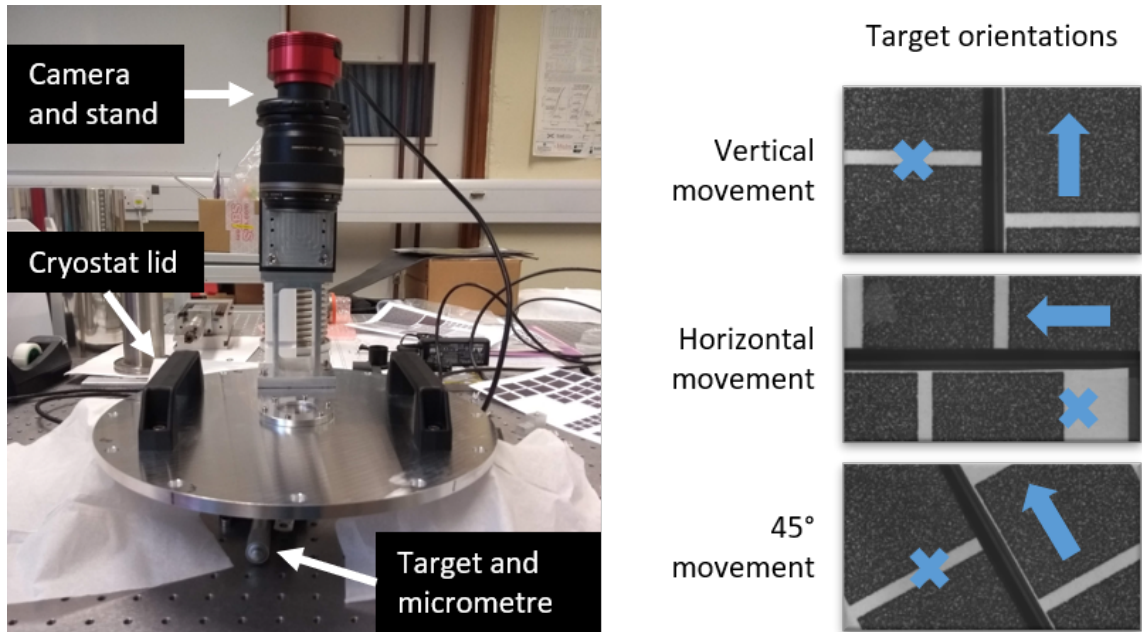


Figure 3.16: (left) Micrometer step measurements setup. (right) Target orientations. Arrows correspond to the target movement with respect to a fixed target.

3.4.2.2 Calibration scale

For each orientation, I placed a ruler on the camera's field of view and took an image. Figure 3.17 shows the images I recorded. I used Adobe Illustrator to measure the number of pixels for each ruler mark and calculated an image scale of $10.83 \pm 0.05 \mu\text{m}/\text{pix}$ for horizontal and vertical movement and $10.84 \pm 0.05 \mu\text{m}/\text{pix}$ 45° movement.

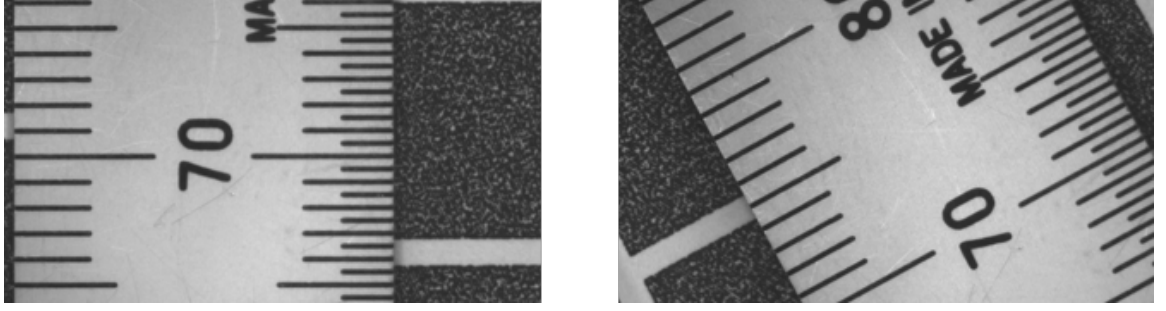


Figure 3.17: (left) Horizontal and vertical movement scale measurement. (right) 45° movement scale measurement.

3.4.2.3 Image registration

I used the feature-based image registration algorithm from the image processing toolbox in MATLAB to find the micrometre displacements. Figure 3.18 shows how I performed image registration.

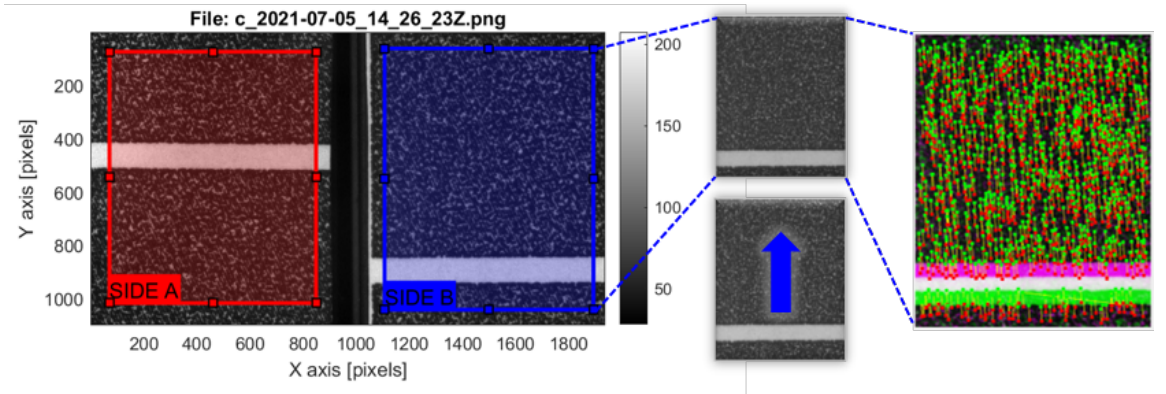


Figure 3.18: Example of a vertical movement detected by feature-based image registration. The 'non-moving' pattern (side A) is a fixed reference, and is used to take out any global movements of the whole set-up.

The distance the micrometer moved is the displacement registered in the pattern attached to the moving edge of the linear stage minus the displacement registered in the non-moving pattern, and it is calculated as follows:

$$\Delta d = s(\Delta d_B - \Delta d_A) \quad (3.1)$$

where Δd is the distance the micrometer moved in microns, Δd_B is the distance that the moving target moved by in pixels, Δd_A is the distance the fixed target moved by

in pixels¹⁴, and s is the scale of the image in μm per pixel.

3.4.2.4 Micrometer measurements

I performed ten $50\mu\text{m}$ steps in the vertical orientation followed by another ten $10\mu\text{m}$ steps. Then I recorded the scale and repeated the same procedure for the horizontal and 45° orientation. While operating the micrometer, I noticed that the micrometer was not calibrated and had slippage; nevertheless, I continued and was careful when moving the handle. Figure 3.19 shows the results for the micrometer displacement in the three orientations. On the plot on the left, it is possible to observe that the steps were close to $50\mu\text{m}$ and on the right to $10\mu\text{m}$. Table 3.2 lists the average steps per orientation and its standard deviation¹⁵.

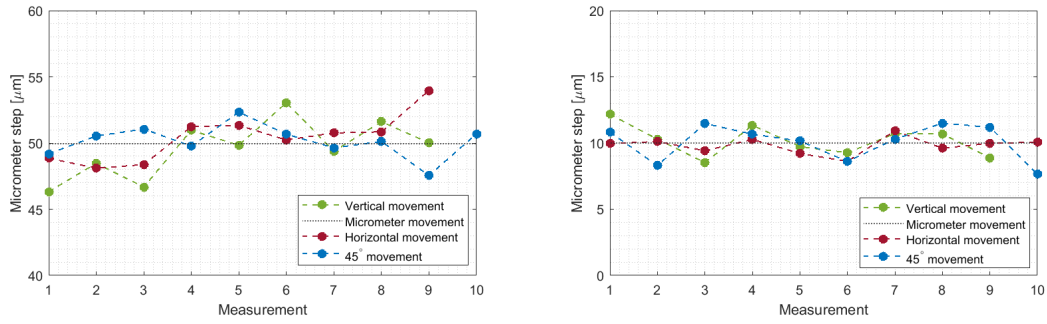


Figure 3.19: (left) $50\mu\text{m}$ steps for the three orientations. (right) $10\mu\text{m}$ steps for the three orientations.

Step	Horizontal movement	Vertical movement	45° movement
$50\mu\text{m}$	$49.59 \pm 2.12\mu\text{m}$	$50.41 \pm 1.82\mu\text{m}$	$50.15 \pm 1.27\mu\text{m}$
$10\mu\text{m}$	$10.18 \pm 1.19\mu\text{m}$	$9.82 \pm 0.64\mu\text{m}$	$10.06 \pm 1.39\mu\text{m}$

Table 3.2: Results from the measured micrometer steps with image registration per orientation.

These results prove that the image registration method I used during cycling can be used to infer displacements accurately¹⁶. The measurements show a residual of a

¹⁴Note that for this setup no movement is expected for Δd_A as there is no significant temperature change throughout this calibration step nonetheless I express Δd on relative movement terms.

¹⁵The uncertainty shown in the table does not consider the scale uncertainty.

¹⁶Regardless of how well I moved the micrometer on incremental steps and how much the micrometer screw slipped, as these values were not the objective of this calibration exercise.

few microns, and this includes uncertainty and error in the physical movement of the micrometer. The sensing error on the image registration method can be considered a $< \pm 1\mu m$, and therefore a negligible contributor to the overall sensitivity.

3.4.3 Image scale

Following the results in Section 3.4.2.2, I processed the room temperature images per cycle on DS9 and ImageJ. Figure 3.20 shows the scale measurements of cycle eight. I rotated the image and fit a grid on the millimetric paper; then, I averaged the measured grid sizes. This new method allowed for a 0.001 pixels measurement precision.

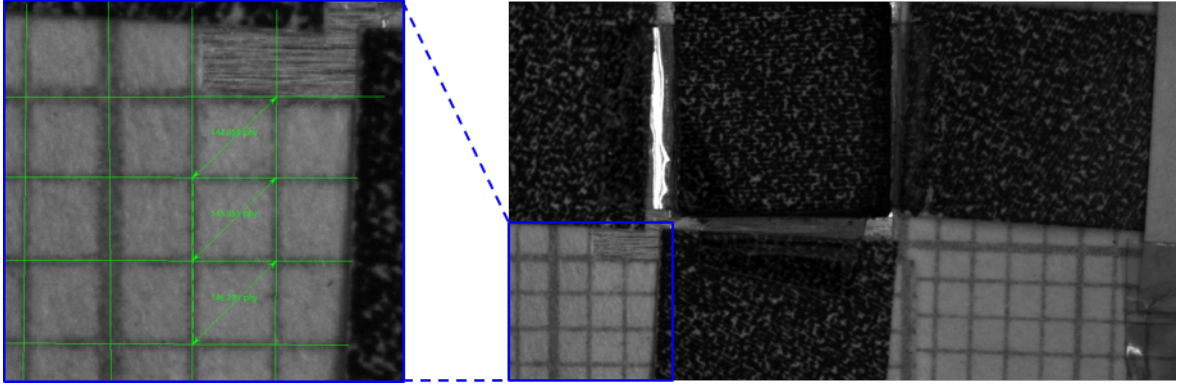


Figure 3.20: Example of scale measurement (cycle 8 target).

Table 3.3 lists the calculated scales with standard deviation in $\mu m/pix$ per cycle. The scale was recorded at room temperature equilibrium, described in Section 3.3.2.2.

Cycle	5	6	7	8
Scale [$\mu m/pix$]	10.134 ± 0.067	10.109 ± 0.297	9.761 ± 0.138	9.769 ± 0.101

Table 3.3: Image scale per cycle. I improved the target from cycles 5 to 6 to incorporate more speckle patterns in the spider, thus the slight change in the scale. In cycles 7 and 8, I did not change the target.

3.4.4 Drift

Following the experiment hypothesis mentioned in Section 3.4.1, the setup inside the cryostat thermally contracted and expanded differently from the camera setup through cycling. The apparent drift was calculated using image processing techniques similar

to the micrometer measurements in Section 3.4.2.3. Figure 3.21 shows the lens drift parameters.

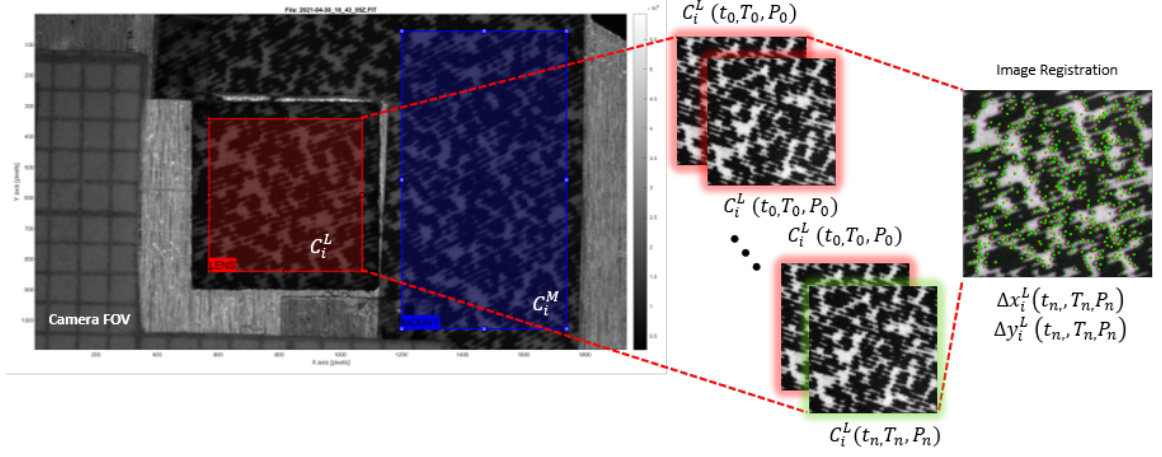


Figure 3.21: Definition of lens and mount drift (δ) through cycling where i is the cycle number, l corresponds to the lens or blank movement, M corresponds to the mount/spider movement, C is a camera FOV measurement at a specific point in time (t_j), temperature(T_j) and pressure(P_j), t_0 is the initial cycle time, T_0 is the initial cycle temperature, P_0 is the initial cycle pressure and n is the total number of camera FOV measurements in the cycle. The camera FOV shown in this figure corresponds to cycle 5.

An image combination¹⁷ taken during the room temperature equilibrium period at the start or end of the cycle was selected as the reference C_i . Then an image combination taken during cold temperature equilibrium (C_{130K}) is computed and used to determine the image registration configuration for the cycle, thus ensuring good feature extraction for all camera FOV measurements, C . The image registration between C_i and C_{130K} is the most significant displacement and de-focus throughout the cycle.

Drift has a value for the detected shift in x and y and can be expressed as:

$$\delta_i^L(t_j, T_j, P_j) = \begin{pmatrix} \Delta x_i^L(t_j, T_j, P_j) \\ \Delta y_i^L(t_j, T_j, P_j) \end{pmatrix} = ImReg [C_i^L(t_j, T_j, P_j), C_i^L(t_0, T_0, P_0)] \quad (3.2)$$

$$\delta_i^M(t_j, T_j, P_j) = \begin{pmatrix} \Delta x_i^M(t_j, T_j, P_j) \\ \Delta y_i^M(t_j, T_j, P_j) \end{pmatrix} = ImReg [C_i^M(t_j, T_j, P_j), C_i^M(t_0, T_0, P_0)] \quad (3.3)$$

¹⁷I combined multiple images to get a higher signal to noise ratio image.

where δ_i^L is the drift of the lens at the given time t_j , temperature T_j and pressure P_j and δ_i^M is the drift of the mount. Δx_i^L and Δx_i^M are the shifts of the lens and mount in the x axis of the corresponding image C_i^L or C_i^M . Δy_i^L and Δy_i^M are the shifts in the y axis.

Figure 3.22 shows the captured apparent movement of the lens and mount for cycle 5. The FS blank and mount drift in similar directions and magnitudes. As expected, the cold lens mount assembly is moving relative to the camera on the outside of the cryostat. The measured drifts for cycles 6, 7 and 8 show as similar behaviour; for these cycles, I placed additional patterns on the spider and selected three regions for feature extraction.

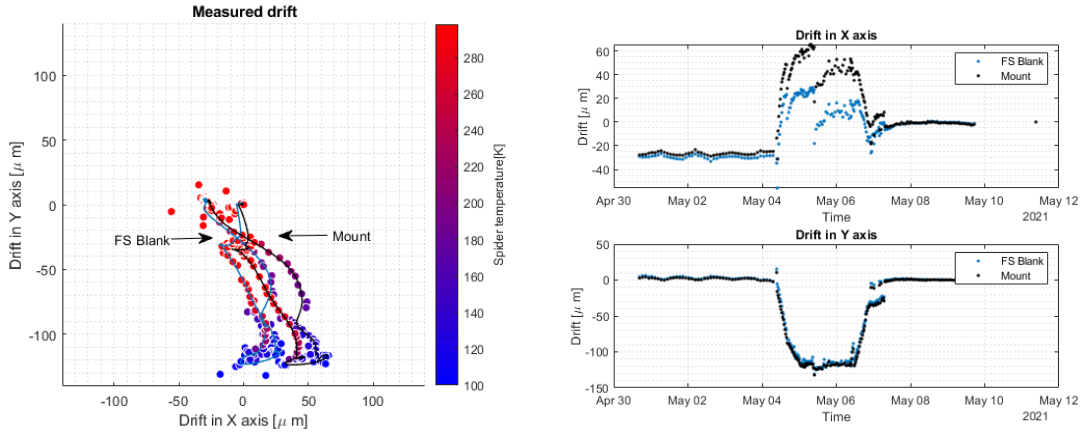


Figure 3.22: Measured drift for cycle 5: KMOS design + FS blank model. (left) Drift through temperature as seen from above. (right) Drift recorded through time in the x and y axes for the fused silica blank and the mount.

Given that the initial focus on the field of view is not maintained throughout the cycles, the image registration algorithm's quality varies throughout the cycle¹⁸. I fitted a spline to the drift data for each cycle, discarded clear outliers and smoothed the spline. I used these models throughout the analysis, and the fitting residuals were used to calculate each point's radial decentring error.

Figure 3.23 shows the measured drift for cycle 6. On all cycles, the tested lens mount assembly followed a drift path during cooldown and another through warm-up.

¹⁸Furthermore each C_i is a combination of more than one exposure; this was performed to ensure uniform illumination and CCD noise removal.

The captured hysteresis on the plot on the right shows evidence of a *lag* on how the energy flows inside the cryostat through cooling and warming.

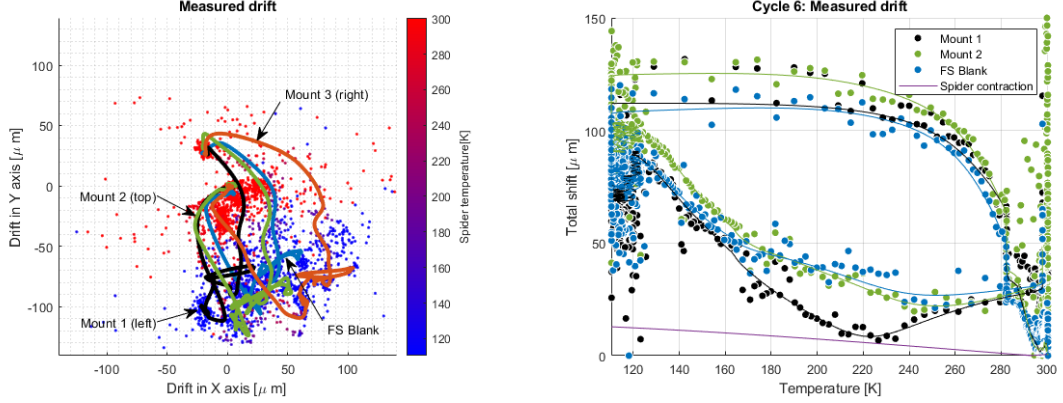


Figure 3.23: Measured drift for cycle 6: KMOS design + FS blank model. (left) Drift through temperature as seen with a top perspective, note that most points follow the splines and are not visible. (right) Absolute movement ($\sqrt{\Delta x^2 + \Delta y^2}$) through temperature shows a hysteresis. The top path corresponds to cool downs and the bottom to warm-up.

Given that the movement of the lens (or of the blank) is measured independently from the movement of the mount, the drift can be removed following a similar logic to equation 3.1. The relative movement of the mount with respect to the lens, δ_{+CTE}^i can be calculated as follows:

$$\delta_{+CTE}^i = \delta_M^i(t_j, T_j, P_j) - \delta_L^i(t_j, T_j, P_j), \quad (3.4)$$

where the notation $+CTE$ is a reminder that δ_{+CTE}^i has an additional movement due to the aluminium mount contraction towards the centre.

3.4.5 Spider contraction

The aluminium mount contraction towards the centre can be approximated considering linear thermal contraction:

$$L^{Al}(T_j) = \frac{dL^{Al}}{L^{Al}}(T_j) L^{Al}(T_0), \quad (3.5)$$

where $\frac{dL^{Al}}{L^{Al}}(T_j)$ is the change in length at a given temperature for 6061-T6 Aluminium and $L^{Al}(T_0)$ is the distance between the spider centre and the speckle pattern frame of

reference at room temperature. Figure 3.24 illustrates this equation for cycles 6, 7 and 8; cycle 5 has one mount speckle pattern. The contraction direction is considered for cycles with multiple mount patterns.

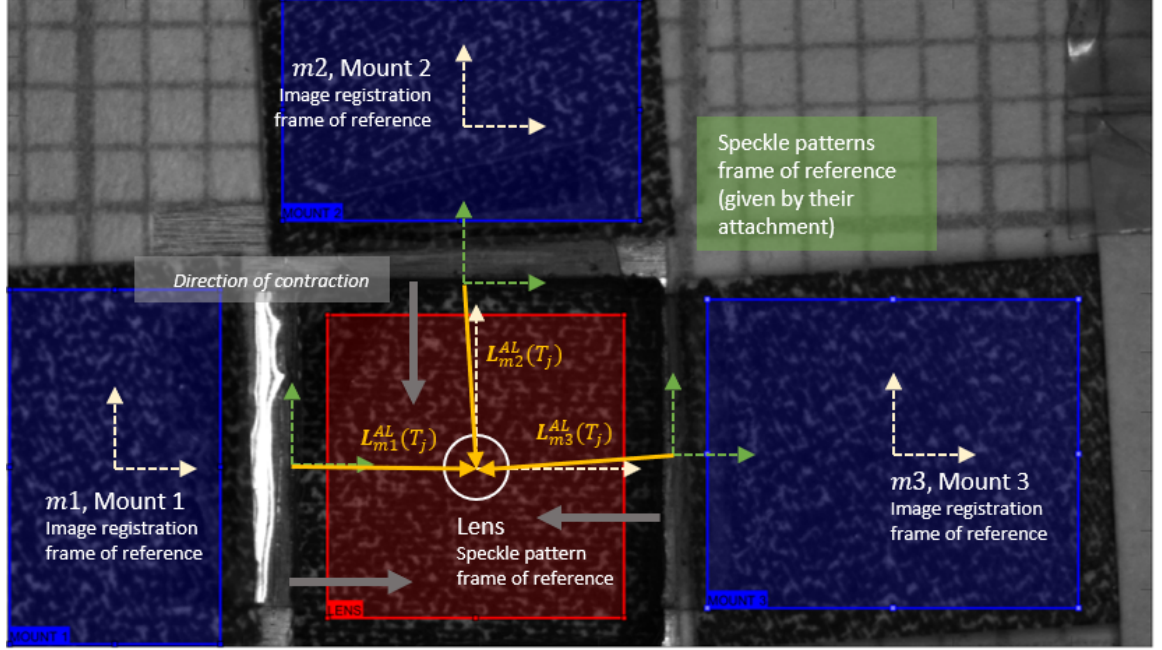


Figure 3.24: The spider contracts towards the mount centre; thus, the spider window changes size with temperature. The mount speckle patterns are attached with Kapton tape on the edges of the spider window and move along with its edge. L_{m1}^{Al} , L_{m2}^{Al} and L_{m3}^{Al} denote the aluminium mount contraction towards the centre for each speckle pattern, respectively. The lens speckle pattern frame of reference is assumed to intersect the centre of contraction of the mount.

$\frac{dL^{Al}}{L^{Al}}(T_j)$ is calculated as published by NIST[52] as:

$$\begin{aligned} \frac{dL^{Al}}{L^{Al}}(T_j) &= a + bT_j + cT_j^2 + dT_j^3 &> T_j \leq 18K \\ a &= -4.1277 \times 10^2 \\ b &= -3.0389 \times 10^{-1} \\ c &= 8.7696 \times 10^{-3} \\ d &= -9.9821 \times 10^{-6} \end{aligned} \tag{3.6}$$

The linear expansion factors are unitless and are specified for $[(L - L_{293})/L_{293}] \times 10^{-5}$ as part of their definition.

Figure 3.25 shows a plot of $\delta_{+CTE}^6(130K)$ on the left and $\delta_{+CTE}^7(130K)$ on the right along with their corresponding $L^{Al}(130K)$. The data in the plots corresponds to the

cold thermal equilibrium period during cycling. The tested model in cycle 6 is KMOS design with an FS blank, and in cycle 7 the model is the pre-HARMONI design with an HK9 lens. The impact of defocusing due to axial contraction can be seen in this figure in the measurement spread; for cycle 6, the fused silica blank barely changes size with temperature, thus producing less defocus through cycling. In cycle 7, the HK9 lens contracts more and produces more defocus, thus decreasing the quality of the image registration algorithm and increasing measurement uncertainty. Similar behaviour is observed in cycles 5 and 8. For all cases, δ_{+CTE}^i varies slightly for each mount reference.

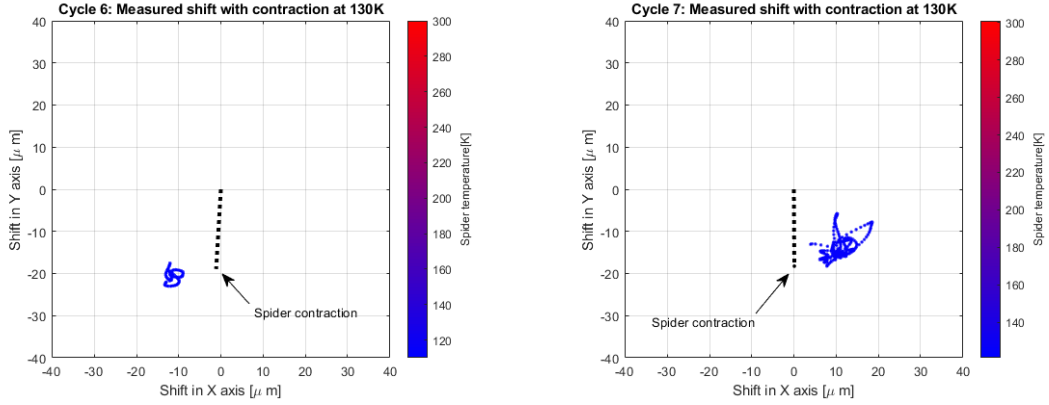


Figure 3.25: Recorded shift without drift for cycles 6 and 7.

3.5 Radial displacement

Radial displacement δ^i is the displacement with drift subtracted and displacement due to thermal contraction. It can be expressed as:

$$\delta^i = \delta_{+CTE}^i(t_j, T_j, P_j) - L^{Al}(T_j). \quad (3.7)$$

δ^i describes the change in position of the lens relative to the mount from thermal equilibrium at room temperature to cold thermal equilibrium at 130K. This change, expressed in 3.7, is a time, temperature and pressure dependent vector for this experimental setup.

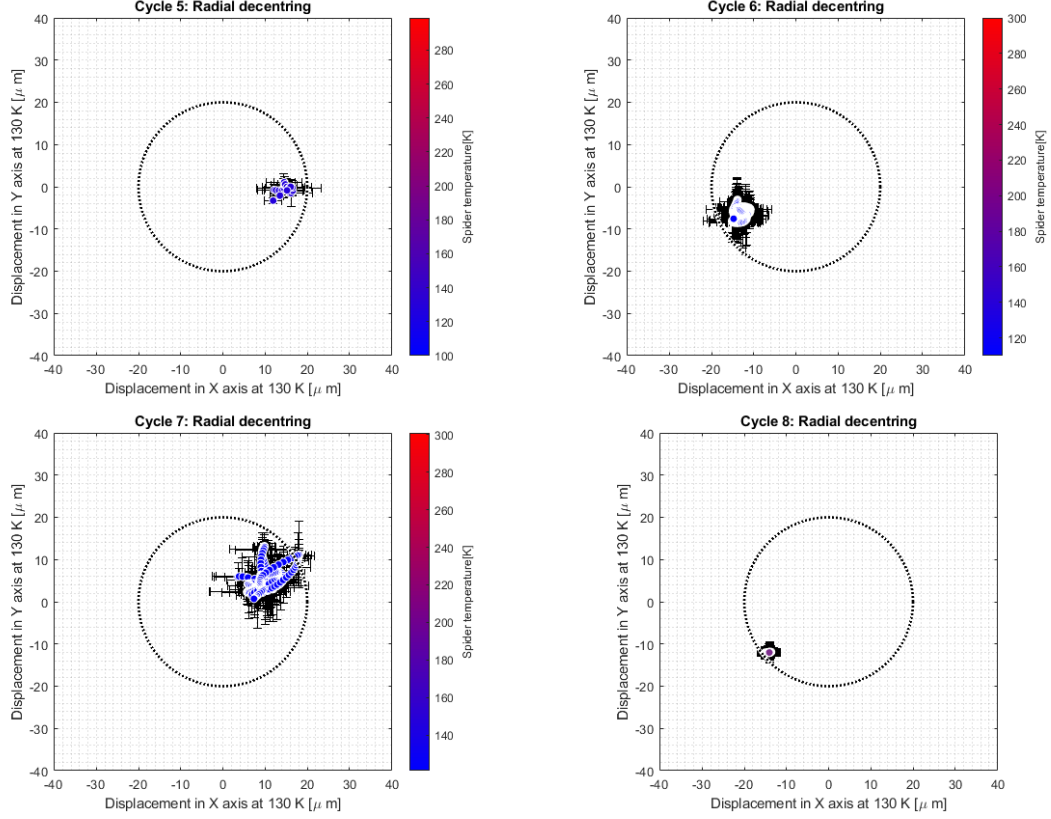


Figure 3.26: Recorded radial decentring per cycle at cold thermal equilibrium. The dotted circle outlines the $20\mu m$ expected tolerance.

Figure 3.26 shows radial displacement, δ^i , for cycles 5, 6, 7 and 8. Cycles 5 and 6 correspond to the KMOS design + FS blank model, and they actually show movement in the same direction, given that I rotated the lid by 180 degrees between these cycles. Similarly, cycles 7 and 8 correspond to the pre-HARMONI design + HK9 lens model and move in the same direction, considering that I also rotated the cryostat lid by 180 degrees between these two cycles. Surprisingly, the radial decentring on average on all cycles stays within the $20\mu m$ expected tolerance.

Figure 3.27 shows each cycle's magnitude of δ^i , along with its absolute error through time. From cycle 5 to cycle 8, I increased the measurement frequency from every hour to every ten minutes. During cycle 6, data was lost during cold thermal equilibrium due to an unexpected failure in the camera recording software, thus the gap in data. The most significant errors occur during cold equilibrium due to defocusing and are caused by poor feature extraction during image registration. During cycle 7, I analysed

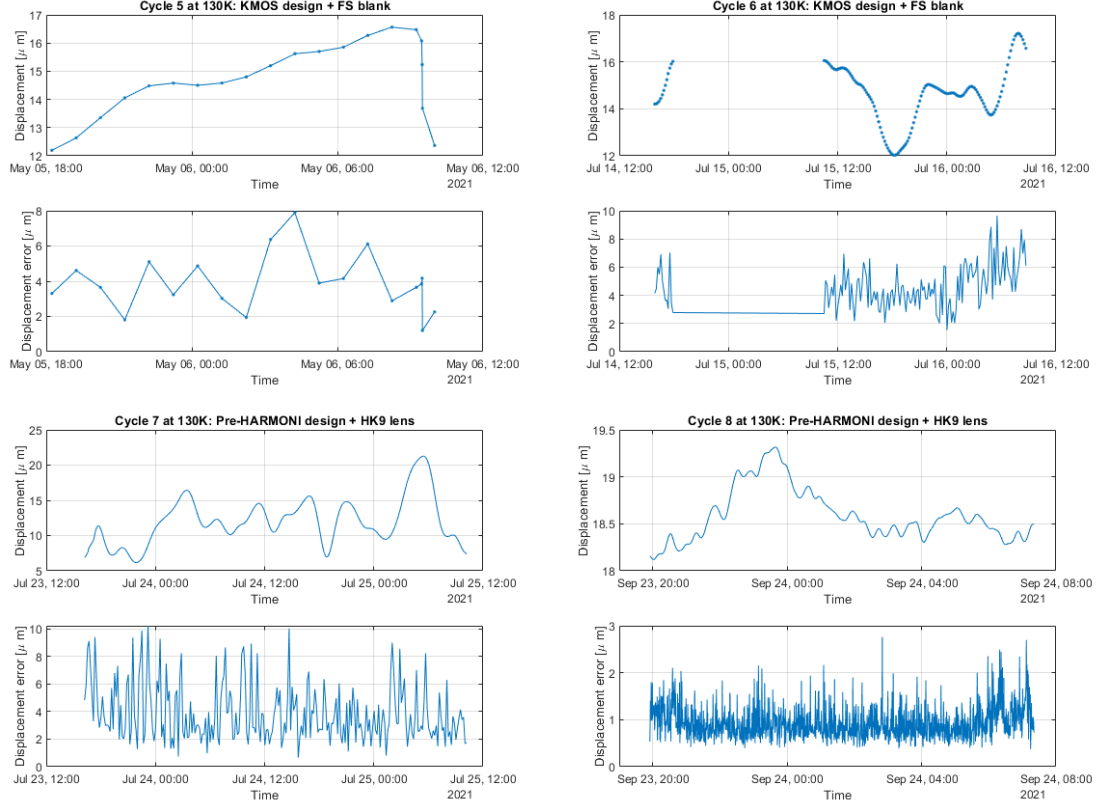


Figure 3.27: Total displacement per cycle at cold thermal equilibrium.

the poorest feature extraction. I decided to change the focus during cold thermal equilibrium for cycle 8 and analyse the data in two parts from room temperature to cool down and then from cool thermal equilibrium to room temperature. The accuracy of the measurement improved compared to cycle 7, as can be seen on the plot for cycle 8 on the bottom right.

The errors considered, e^i , can be expressed as:

$$e^i(t_j, T_j, P_j) = (s^i + \Delta e_s^i) \sqrt{e_{i,l}^2 + e_{i,m1}^2 + e_{i,m2}^2 + e_{i,m3}^2} \quad (3.8)$$

where s^i is the cycle i scale, Δe_s^i is the scale error for the cycle i , $e_{i,l}$ are fit the residuals of the raw lens or blank measurements and $e_{i,m1}$, $e_{i,m2}$ and $e_{i,m3}$ are the fit residuals of the raw mount measurements.

3.6 Conclusions

After having verified the alignment at room temperature in Chapter 2, I measured the change in radial alignment in thermal equilibrium at HARMONI's operational conditions. I did this for the engineering models that I assembled and reported in Chapter 2.

I marginally validate that a $\pm 20\mu m$ tolerance target for an FMOS/KMOS flexure mount design is a reasonable estimate. However, after analysing the total displacement measurements and their errors in detail for both models, I propose $\pm 30\mu m$ as a new tolerance target for this mount type for lenses in the 200+ mm range in diameter. I propose this new tolerance taking into account the level of uncertainty of my experimental setup, the number of cycles performed, and the limitations in the models' designs. A tolerance of $\pm 20\mu m$ for radial misalignment per lens at operational temperatures is too tight to describe this type of misalignment, including its assembly misalignment at room temperature. When maturing the camera AIV and performing a tolerance analysis on the camera's optical design, a traditional tolerance stack must be performed, and the displacement at operational temperatures must be considered independently from the lens mount assembly alignment to the camera optical axis at room temperature. Angular degrees of freedom θ_X and θ_Y of the lens in its mount are not tuned when inserted into the spectrograph mechanical structure, whereas X and Y position degrees of freedom are compensated by the spectrograph mechanical structure. Furthermore, I confirm that the assembled engineering models can survive HARMONI operational conditions, and that the blank and the lens do not present any fractures or degradation. I re-developed a measuring method to record radial misalignment of flexure mounts and reported my results as time-dependent. This chapter presents the information I generated while developing the experimental setup and performing the cycles.

Chapter 4

Dielectric mirrors

4.1 Introduction

This chapter studies the potential application of dielectric mirror coatings to the reflective surfaces in the science path¹ of the HARMONI instrument, along with the associated implications. This issue is of central importance because the overall throughput of the instrument is strongly dependent on the efficiency of its coatings. Depending on the chosen configuration, the scientific light is reflected 23 to 27 times throughout the instrument. The baseline design and analysis of the instrument consider metallic mirror coatings, and dielectric mirror coatings could significantly improve the overall throughput of the instrument. We considered dielectric mirrors because they have significantly higher reflectivity than traditional metallic coatings, even above 99%.

4.1.1 Light propagation: reflection and refraction

To understand how dielectric coatings are able to reflect more than 99% of the incident light, I will first introduce a few basic principles of how light propagates.

Incident light propagates in straight lines in a medium with an isotropic index of refraction.² When light propagates from a dielectric medium to another, part of the light is transmitted, and the other part is reflected. The transmitted beam is refracted and changes its direction of propagation. The reflected beam follows a mirrored path

¹The path that light follows through the instrument to produce a scientific detection is called the *science path*.

²There are optically anisotropic materials, and these can cause birefringence. A medium's refraction index can change with temperature or under mechanical stress.

normal to the incident plane. Figure 4.1 shows the path followed by the light when passing through air and another dielectric medium. From the figure, the incidence angle θ_i is the angle between the ray and the normal to the surface, θ_t is then the angle of the transmitted light, and θ_r is the angle of the reflected light. The angle of the reflected light is $\theta_r = \theta_i$, and the refracted light follows Snell's law: $n_2 \sin \theta_t = n_1 \sin \theta_i$, where n_1 is the index of refraction of the medium's incident light and n_2 is the index of refraction of the medium's diffracted light.³

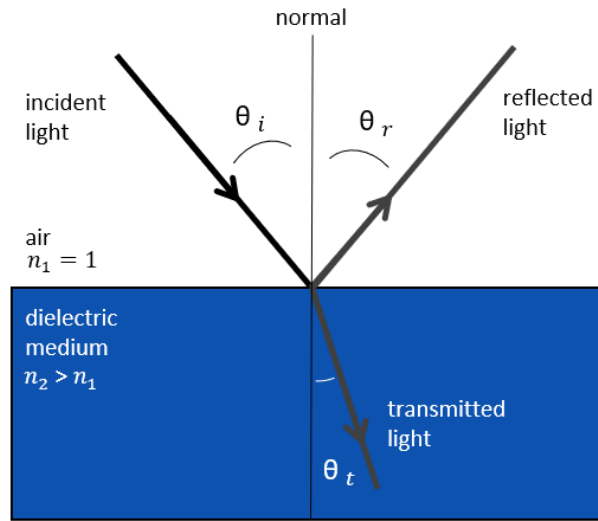


Figure 4.1: Light propagation at an air-dielectric medium interface.

The energy is conserved when light is refracted and reflected as it encounters a medium transition, i.e.:⁴

$$T = 1 - R, \quad (4.1)$$

where T is the relative portion of the beam energy that gets transmitted, and R is the relative portion that gets reflected.

Light being an electromagnetic wave, it carries a polarisation that can be characterised using two orthogonal polarisation states. The p -state has its electric field parallel to the incidence plane and the s -state perpendicular to it. Both polarisation

³Note that the index of refraction of a medium varies with wavelength, thus each wavelength will have a different refracted angle, θ_t .

⁴This equation describes the behaviour of unpolarised light in the absence of absorption.

states, p and s , propagate in straight lines and are similarly reflected and transmitted through isotropic dielectric mediums. However, the proportion of reflected and transmitted energy differs. The Fresnel equations give the p and s components:

$$R_p = \frac{(n_1 \cos \theta_t - n_2 \cos \theta_i)^2}{(n_1 \cos \theta_t + n_2 \cos \theta_i)^2} \quad R_s = \frac{(n_1 \cos \theta_i - n_2 \cos \theta_t)^2}{(n_1 \cos \theta_i + n_2 \cos \theta_t)^2} \quad (4.2)$$

where R_p and R_s are the reflection coefficients for each state⁵. From energy conservation, the transmission coefficients are:

$$T_p = 1 - R_p \quad T_s = 1 - R_s. \quad (4.3)$$

4.1.2 What is a dielectric mirror?

A dielectric mirror is an optical surface with a reflective coating made out of layers of dielectric and transparent materials. They can be optimised to a desired bandwidth and to a range of angles of incidence by tuning the number of layers and their thickness according to the layer materials' refractive indices [41]. Dielectric mirror coating layer combinations are designed to cause the highest possible reflection. Multiple layers of transparent materials can become reflective when the Fresnel reflections of these layers combine in constructive interferences. Figure 4.2 shows a conceptual diagram of how Fresnel reflections can interfere constructively to achieve reflectance.

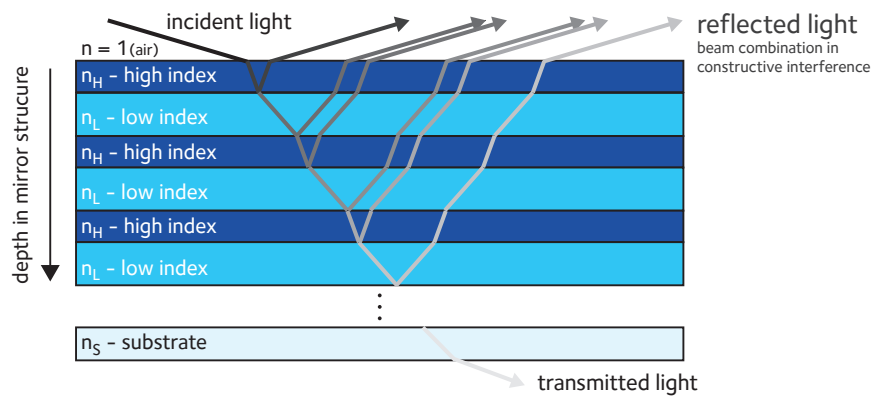


Figure 4.2: Example of a dielectric mirror layer structure, the image shows the concept of how high reflection can be achieved.

⁵A regular glass with $n_2 = 1.5$ has about 4% reflectivity for normal incidence.

The most prevalent design of dielectric mirrors is the Bragg mirror. In this design, the thickness of the layers is one-quarter of the design wavelength leading to the highest possible reflectance given the number of layer pairs and materials; this can be expressed as:

$$n_L t_L = n_H t_H = \lambda/4, \quad (4.4)$$

where n_L and n_H are the low and high index of refraction and t_L and t_H are the layer thicknesses for the low and high index materials, respectively. λ is the design wavelength [12]. Choosing materials with a high index of refraction contrast produces a more significant Fresnel reflection coefficient and reduces the number of layers required to achieve high reflectance. The reflectance of a Bragg mirror for unpolarised light at a given wavelength can be calculated as

$$R = \left[\frac{n(n_L)^{2N} - n_S(n_H)^{2N}}{n(n_L)^{2N} + n_S(n_H)^{2N}} \right]^2, \quad (4.5)$$

where N is the number of pairs of layers in the stack, and n , n_L , n_H and n_S are the respective indices of refraction of the originating medium, of the low and high index materials and of the substrate [28, 51, 16]. Similarly, a high index of refraction contrast produces larger bandwidths of high reflectivity [39, 37]. The bandwidth of the zone with high reflectance, $\Delta\lambda$ for a Bragg mirror can be calculated as

$$\Delta\lambda \approx \frac{4}{\pi} \lambda \arcsin \left[\frac{n_H - n_L}{n_H + n_L} \right]. \quad (4.6)$$

Another relevant characteristic of dielectric coatings is that their optical properties are very dependant on the angle of incidence. This effect is linked to how the wave vector components vary depending on the incident angle from the first reflection and through the layer's propagation. The larger the angle of incidence, the more the reflection spectrum is shifted towards shorter wavelengths [41]. Similarly, as the angle of incidence diverges from normal incidence, the s and p components vary, thus producing unequal reflection. Achieving an equal performance in polarisation for non-perpendicular incidence is a design challenge. The Fresnel equations in (4.2) indicate this behaviour. θ_i and θ_t from equation (4.2) would correspond to the incident angles for the high and low index of refraction layers. An example of a pair of dielectric substrates demonstrating the Fresnel equations behaviour is shown in Figure 4.3. Bragg mirrors have

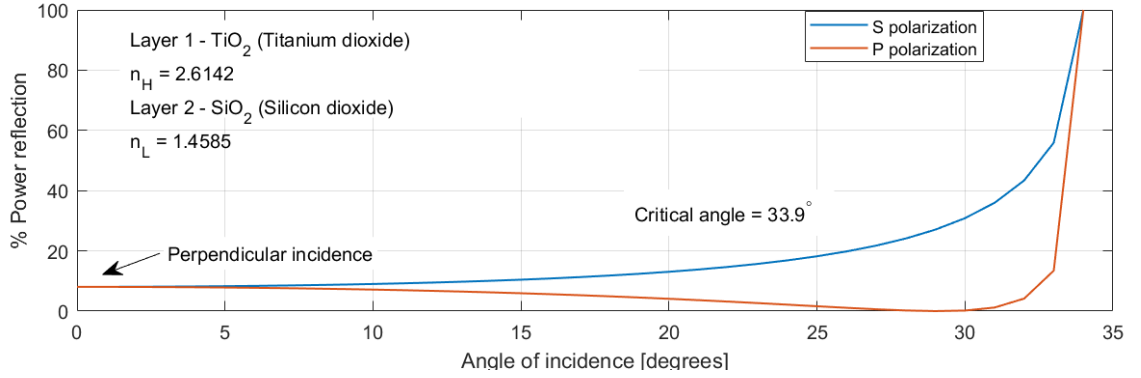


Figure 4.3: Example of a dielectric mirror layer pair with a high and low index of refraction combination. This plot shows that the power intensity reflectance varies for *s* and *p* polarisation and is dependant on the angle of incidence.

been widely used for various optical applications over many years, are well known for laser applications, and have reflectivities higher than 99%.

4.1.3 Previous research

Coatings with reflectivity beyond 99% have always been sought after in astronomy. Dielectric mirror coatings offer this but are used in astronomical applications only for specific purposes due to their cost, design limitations and manufacturing challenges. In 1966 Hysom et al. [21] already discussed the astronomical purposes for which such coatings were suitable, as well as the purposes for which they are not well suited. At the time, dielectric mirror coatings were used minimally for some applications but they were generally deemed too expensive and too difficult to make. Hysom argued that the number of layers required was out of reach and that the coatings could only be designed for extremely narrow bandwidths, thus limiting their applications for astronomy. Since then, significant technological improvements have led to better coating deposition techniques and facilities. Additionally, high reflectivity and durable coatings for the NIR domain of wavelengths beyond $1\mu m$ became possible by overcoating glass or metal mirrors with a layer of vacuum-deposited gold [56]. For the optical domain, it is widespread to enhance typical metal coatings with layers of dielectric materials. With this enhancement, coatings can achieve a 98% reflectivity. Coating companies offer them as a compromise between traditional all metallic mirrors and the

more expensive choice of entirely dielectric mirrors. By 2017, fully dielectric mirrors for astronomy had somewhat improved to cope with a 1-octave wavelength range, reasonable incidence angles and unpolarised lights by stacking up to ~ 100 coating layers [56]. The most relevant experience of the application of dielectric coatings for HARMONI is the MUSE instrument at the Very Large Telescope [49]. Four out of seven mirrors in MUSE had dielectric coatings applied, and the team modelled the mirror deformation due to coating stress on the substrate and tested their durability in environmental conditions. The coatings sustained and survived 24 cycles from 243.15 K to 358.15 K. The improvement in the overall throughput was significant and possible to implement for MUSE's requirements. In 2022 it was possible to buy 90-degree mirror diagonals for visible amateur telescopes from 99 USD. These diagonals have dielectric mirrors with an astounding 99% reflectivity [38] according to their advertisement. However, as stated earlier, these only work for one angle of incidence and a limited wavelength range.

4.1.4 Gap in research

HARMONI will be exploring a very broad range of wavelengths, covering the visible domain up to near-infrared wavelengths. It must handle a wide range of angles of incidence, unpolarised light, and operates in a vacuum at cryogenic temperatures. There were many open questions to determine whether dielectric mirror coatings can be applied to the reflective surfaces in the science path of HARMONI. At the start of my DPhil, the following points were unknown.

- How complicated would the design of the all-dielectric mirror be, given the wide ranges of wavelengths and of angles of incidence? Essentially, to make a coating for our surfaces, it would be needed to stack multiple Bragg mirrors (with different thicknesses to be effective at different wavelengths and angles of incidence) on top of each other, resulting in a huge number of layers.
- Could we find a coating company willing to accept the challenge and who would be capable of designing and manufacturing a coating for HARMONI's reflective surfaces?

- Could a coating like this survive the operational conditions of the mirror elements in the science path?
- Could a mirror element sustain a many-layered coating and the resulting compression stress?
- How would the resulting reflectivity curve look like and by how much would the performance differ for s and p polarisation?

4.1.5 Research aims and questions

The research aims of this chapter are:

- Confirm that coating manufacturing companies can make broadband dielectric coatings for HARMONI's wavelength range.
- Ascertain that the available coating options can endure HARMONI's operational conditions by testing their survivability.
- Identify surfaces throughout the science path that are eligible to be coated as dielectric mirrors.

This chapter answers several questions, from understanding the details about the reflective optics in the science path to examining the survivability of dielectric coatings in the various sub-systems. The list of questions is given below, roughly reflecting the sections in this chapter.

- How many reflective elements are in the science path? What are their shapes and sizes? What is the distribution of their angles of incidence?
- What are the coating requirements for the reflective elements in the science path? How many different coating types would we need for all reflective surfaces?
- Can reflective dielectric coatings be manufactured for our spectral range? Would a company be willing to design and manufacture these coatings for HARMONI?

- Are dielectric coatings feasible for HARMONI’s mirror surfaces and for its operational conditions?
- How can we know that a coating is able to survive HARMONI’s operational conditions? Would the coatings survive an accelerated lifetime test? Would their performance change before and after the test?
- What are the guidelines to select candidate surfaces to apply dielectric coatings? For each sub-system, which surfaces are eligible for these coatings?
- How much can the overall instrument throughput improve by using dielectric mirror coatings?

I developed this chapter envisioning a system-level perspective within the HARMONI instrument.

4.1.6 Chapter structure

In Section 4.2 (Reflective surfaces in HARMONI) I studied the latest available optics designs of the HARMONI sub-systems in the science path and identified their mirror elements and characteristics. In Section 4.3 (Feasibility study), my supervisor Dr Clarke and I engaged with coating companies to find out their capabilities as well as the current state of the art for dielectric mirror coatings. We asked the companies to propose a design for our requirements. We purchased coating samples. In Section 4.4 (Applicability to HARMONI), I found potentially suitable mirrors for every sub-system and showed the potential increase in reflectivity per sub-system and the overall instrument transmission. In Section 4.5 (Survivability tests), I carried out survivability tests on the purchased samples. To be able to perform the tests, I recommissioned a small cryostat owned by the HARMONI group and re-designed the inner and outer wiring. I tested coating degradation, adhesion, reflectance and cleaning resistance before and after performing an accelerated lifetime test. In Section 4.6 (Conclusions), I summarise the work carried out for this project, answer the research questions raised in the present section, discuss my work’s implications and give detailed recommendations

to implement dielectric mirrors coatings for the reflective elements in the science path of the HARMONI instrument.

4.2 Reflective surfaces in HARMONI

In this section, I give an overview of the reflective surfaces in the science path of HARMONI⁶ (see Figure 4.4) and categorise them by angle of incidence range and by size.

4.2.1 Mirrors in the science path

The HARMONI science path goes through four sub-systems, the focal plane relay (FPRS), the IFS pre-optics (IPO), the Integral Field Unit (IFU), and the Spectrographs (ISP). The latter three are located inside the IFS cryostat which is under vacuum with a controlled temperature of 130 K [54]. Throughout the science path, there are 23-27 reflections between the instrument entrance and the science detectors, depending on the instrument configuration⁷. See Figure 4.4 for guidance through this section.

4.2.1.1 Focal plane relay (FPRS)

The FPRS relays the focal plane of the ELT into the IFS and also redirects light of different wavelengths to the adaptive optics modules. This system combines reflective and refractive surfaces, including the LGS dichroic and its inner and outer container windows. The reflective surfaces comprise four mirrors with diameters ranging from roughly 160 to 700 mm, large curvatures ranging from -4000 to 2000 mm, a flat surface, and angles of incidence varying from 6 to 47 degrees on average. The detailed optical prescription of these surfaces is located in the appendix in Table F.1. The FPRS is chilled at -15°C and kept in a container with dry gas.

⁶These surfaces are studied as potential candidates for dielectric coatings to maximise the transmitted *science* light.

⁷More details about each of these sub-systems can be found in the HARMONI documentation. The optical design details and information about each sub-system references their design and analysis documents as of January 2019.

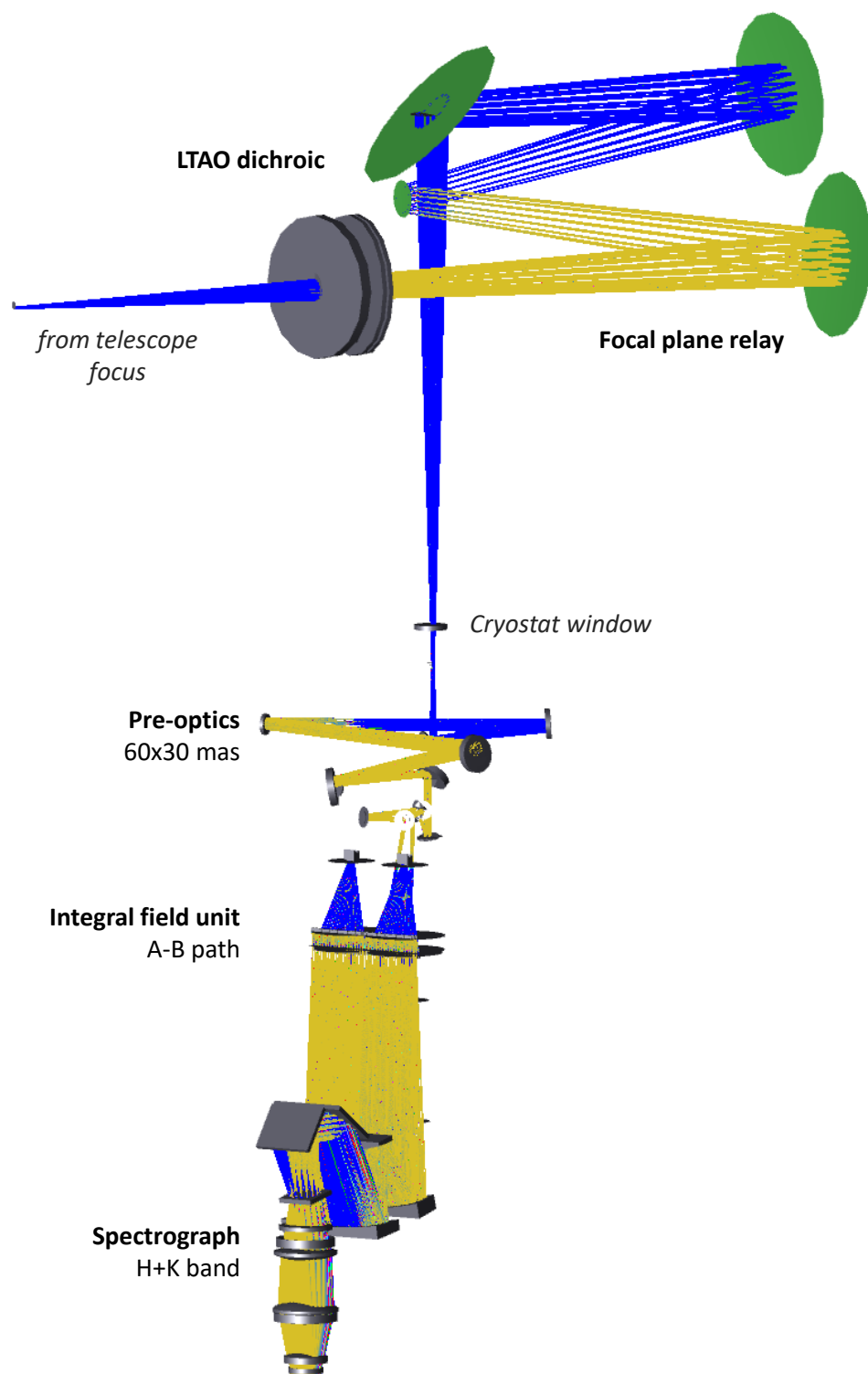


Figure 4.4: HARMONI Science path optics. LTAO model, 60X30 spaxel, AB IFU path, HK band.

4.2.1.2 Pre-optics (PO)

The pre-optics re-formats the field for the selected spatial scales and delivers it to the IFU. This system is almost entirely reflective, and it includes optics for four scales and pupil imaging.

The pre-optics science path includes 6 to 9 reflections, depending on the scale. These mirrors range from 22-160 mm in diameter and include toroidal, off-axis paraboloid, spherical, and flat surfaces. This sub-system's angle of incidence range is amongst the widest, encompassing from 0 to 51.4 degrees. Between its five scales (4 plate scales and one pupil imaging), the pre-optics includes 25 separate mirrors. The appendix in Table F.5 lists these elements per scale.

4.2.1.3 Integral Field Unit (IFU)

The IFU divides the field and reshapes it to provide four output slits arranged in a square at the input of each of the four spectrographs. To achieve this, it has a splitting and relay module (SRM) and four image slicer modules (ISM). The optics of this sub-system are entirely reflective. The relay module's science path includes 5 to 6 reflections depending on its path, as the relay module has eight light paths with 33 mirrors in total, considering its field splitter element. The mirrors in this module are flat prisms and flat and spherical mirrors with sizes ranging from ~ 15 to 90 mm. The incidence angles for each surface vary according to the path, ranging from 1 to 55 degrees. The image slicers (eight arranged in four pairs) include three reflections, and these pieces are highly complex structures. They are not considered for dielectric coatings due to their inherent assembled nature. The detailed optical prescription for the SRM and the ISM can be found in the appendix in Tables F.3 and F.2.

4.2.1.4 Spectrograph (ISP)

The spectrograph sub-system disperses the light from the ISMs with a chosen spectral resolving power and images the spectra onto a detector. The IFU divides the field into four parallel paths, each feeding one of four identical spectrographs. Each spectrograph has a collimator module with three large aspheric mirrors and a fold mirror module

with two mirrors comprising five reflective surfaces in the science path. This subsystem, per spectrograph, has five rectangular mirrors of various curvatures (three off-axis parabolas, the rest flats) ranging in size from 88-690 mm and with maximum angles of incidence ranging from 14 to 43 degrees. The complete optical prescription is in the appendix in Table F.4.

4.2.2 Angles of incidence distribution

To better understand how the angles of incidence are distributed among the mirror surfaces in the science path, I collected the angles and plotted them. Figure 4.5 shows the average angle of incidence of all reflective surfaces reflecting science light (for IFU paths C, D, G, and H). With the prior knowledge that the design of dielectric mirrors for our broad wavelength range requires many layers, increasing the difficulty by imposing a broad angle of incidence range from 0 to 55 degrees would make the coatings more challenging and more expensive to design and to manufacture. Thus, I split the incidence range into three categories before presenting the challenge to coating manufacturers. The first range corresponds to coating type A and encompasses 0 to 14 degrees, with 0 degrees as its design angle of incidence. Coating type A would be applied to most surfaces, 19 out of the 42 mirror types. The second range coating type B encompasses the range 14 to 35 degrees with a design angle of 21 degrees and is only applicable to nine mirror types. Finally, the third type, coating type C, encompasses the 35 to 55 degrees range with a design angle of incidence of 42 degrees and applies to 14 mirror types. To involve manufacturers in our project and to determine their capabilities as well as their limitations, we requested design curves at various angles of incidence for each coating type⁸. Details of the requested design curves for performance checks are shown in Table 4.1.

4.2.3 Size and curvature

We aim to apply dielectric coatings to as many surfaces in the science light path as possible across HARMONI's subsystems. However, the size and curvature of the

⁸These curves also allowed me to model each coating type across all our ranges of wavelengths and all our range of angles of incidences to then calculate a transmission model.

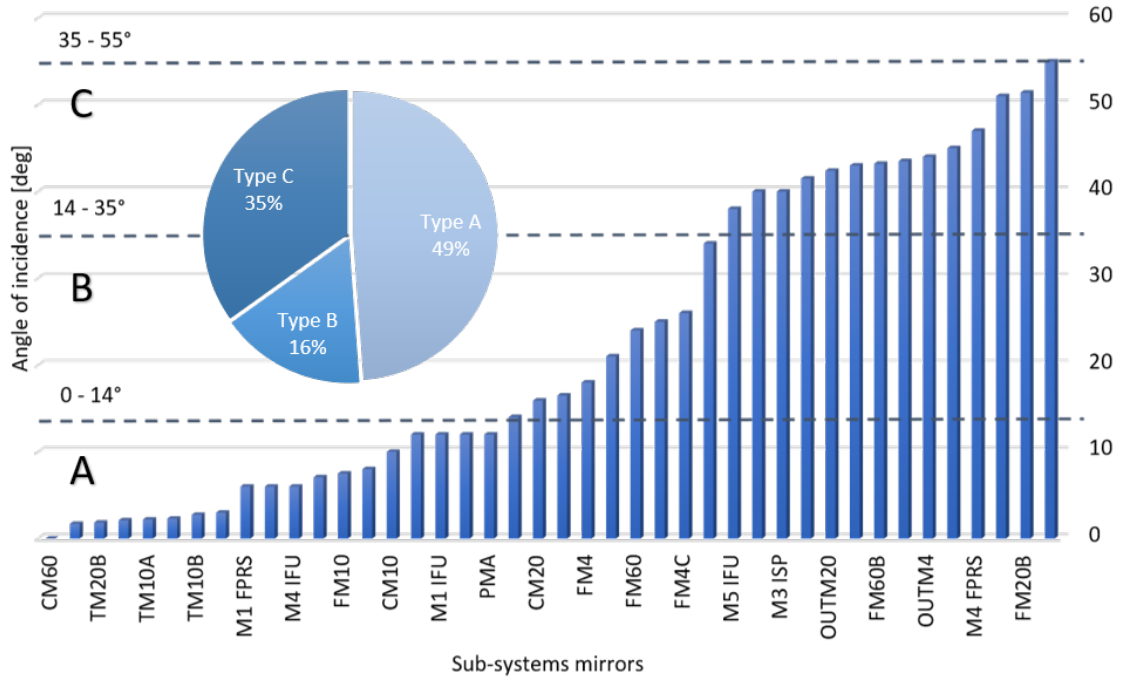


Figure 4.5: Angles of incidence distribution of HARMONI mirrors in the science path C, D, G, and H. (Design as of May 2021)

Coating type	Design AOI [°]	Performance check AOI [°]	AOI range [°]
A	0	0, 5, 10, 14	0-14
B	21	14, 21, 28, 35	14-35
C	42	35, 40, 45, 50, 55	35-55

Table 4.1: Proposed coating types and design angles of incidence for HARMONI’s angle of incidence ranges.

surfaces might pose a limitation. The larger the mirror, the more challenging it becomes to achieve a good dielectric coating due to a number of factors. One of the limiting factors is the coating area in the coating machine equipped to produce this type of coating. Early talks with manufacturers in March 2019 indicated a possible limit size of 400-800 mm depending on the available coating machine and required number of layers⁹. There are 24 mirror types with sizes smaller than 100mm, 11 between 100 and 400mm, and eight larger than 400mm (but under 800 mm).

⁹Considering that most of HARMONI’s mirror types are smaller than 100 mm, there could be some cost benefits to coating multiple mirrors in one go, although this would require more complex logistics to organise.

In terms of curvature types, most surfaces are flat or spherical with a large radius of curvature, but there are toroids and off-axis parabolas. Aspherical surfaces usually have more controlled surface forms and are more challenging to manufacture than spheres. Aspheres will only be considered candidates for dielectric mirror coatings if it can be ensured that the change in surface form induced by the compression stress from the coating layers can be counteracted successfully. Additionally, surfaces with a very pronounced radius of curvature might not be well suited for coatings with many layers because achieving uniform thickness layers throughout the entire surface is limited to the coating setup and size of the coating machine¹⁰.

4.2.4 Eligible surfaces

We started the engagement with manufacturers by selecting the most eligible surfaces in HARMONI, considering what had been achieved in the past and the commercially available options.

- Flats and spheres with a large radius of curvature(>800mm). Aspherical surfaces were deemed too risky to coat.
- Optical elements with a size range up to 200 mm. The majority of the commercially available coating options are for small optics.

4.3 Feasibility study

Having understood the potential impact that dielectric coatings could have in improving the overall throughput in HARMONI, we started to ground ideas and think how feasible would it be to apply these coatings to HARMONI. We set to search for coaters, discuss designs and manufacturing challenges, purchase samples, characterize them and test their survivability to HARMONI's operational conditions.

4.3.1 Coating requirements

The first step was to write down what we wanted from the coatings. I divided the requirements into two categories: reflectivity performance and operational conditions.

¹⁰This limit must be discussed with the manufacturer.

4.3.1.1 Reflectivity performance

We listed the following requirements for the coating design in our engagement with coating manufacturers.

Reflectivity over full wavelength range The coating should have high reflectance for the entire wavelength range (0.47 to 2.45 μm), with a primary focus on the 0.8 to 2.4 μm range.

Improved performance The reflectance performance should be higher than an enhanced silver coating design (i.e. >98%).

Dips and features Coating reflectivity within the atmospheric gaps at 1.1, 1.4, and 1.9 μm is less imperative, and coatings dips can be tuned to these areas (Figure 4.6 shows the used atmospheric transmission plot and the grating wavelength ranges available in HARMONI).

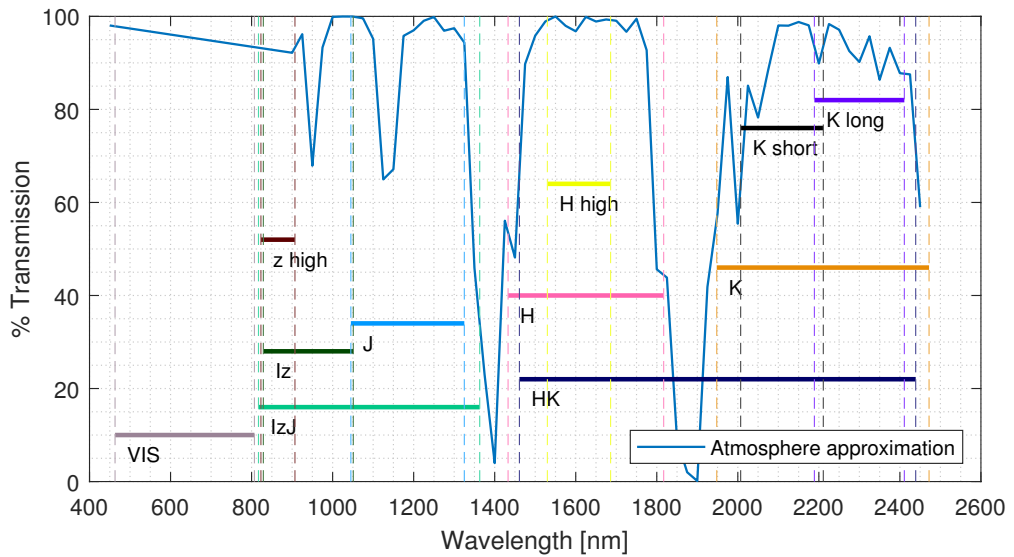


Figure 4.6: Atmospheric transmission approximation (as stated in the HARMONI transmission estimate).

Angle of incidence Design should be optimised to their design angle of incidence (AOI or AoI), and its performance checks AOIs (see Section 4.2.2).

We asked the coaters to propose three coating types for each of our angles of incidence ranges (see Section 4.2.2) following these main requirements. We requested design reflectivity data for all angles of incidence in Table 4.1.

4.3.1.2 Operational conditions

The operational conditions for reflective coatings vary throughout the instrument. The FPRS's optics is cooled down to -15°C and is inside an enclosure filled with dry gas. The IFS is a cryostat containing the PO, IFU and ISP sub-systems. The IFS will be under vacuum at 130 K. Additionally, during the lifetime of the instrument, we have calculated a minimum of 20 cool-down and warm-up cycles expecting a 15-year operation of HARMONI. We conveyed these conditions to manufacturers and asked them to consider this in the design to ensure the survivability to thermal cycling and optimal operation at cryogenic temperatures.

4.3.2 Engagement with industry manufacturers

I had an initial list of companies to contact that the MUSE instrument team and HARMONI optical team shared, and I included a few more that I found online. We sent initial emails to Asahi Spectra Co., Ltd., Optics Balzers, Viavi-OSP, Artemis Optical Limited and Materion Corporation. The companies with whom we were able to establish communication and who showed interest in working with us were [Optics Balzers](#), [Asahi Spectra Co., Ltd.](#) and [Viavi-OSP](#). In appendix A.1, I have included a reference to their contact details.

4.3.2.1 Asahi Spectra

Asahi Spectra have experience manufacturing dielectric coatings for astronomy but had not designed or manufactured a dielectric mirror covering our entire wavelength range. They confirmed having facilities for coating all of our surfaces, but they expressed concern over the compression stress caused by applying a large number of layers to an optical surface, thus likely limiting the size and shape of the suitable optics. We discussed possible scenarios to counteract such stress by applying a coating on the other side of the coated surface. After our technical discussions, Asahi Spectra

Co., Ltd. made three custom designs for each of our AOI ranges and provided us with theoretical reflection data for all our AOI checks (designs are shown in Figure 4.7¹¹). This gesture showed us that they were interested in developing this capability and wanted to collaborate with us in this feasibility study for HARMONI. We used the provided data to do transmission calculations and evaluated whether dividing the angle of incidence range into three categories had been useful or if the number of required coatings could be decreased. Initial results showed that the coating category B could be included in coating categories A and C when only considering the reflectivity performance. However, a more detailed discussion needed to occur when considering manufacturing, because coating category C had over 166 layers, and its compression stress considerably impacted the surface form. Having such stress applied to large surfaces could cause peeling or unexpected behaviour at cold temperatures.

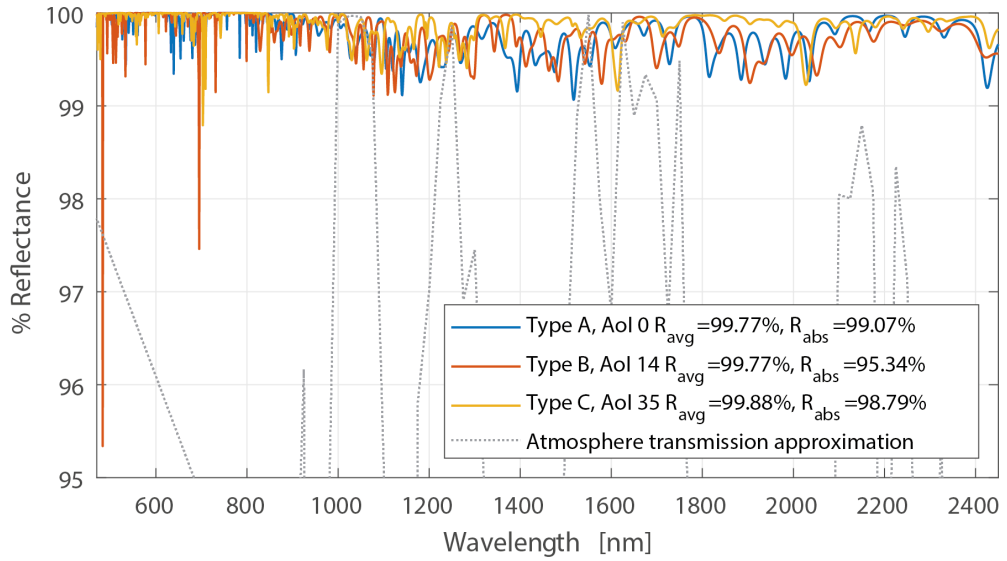


Figure 4.7: Reflectivity curves of coatings proposed by Asahi with selected angles of incidence.

Additionally, when applied to surfaces with curvature, the deformation caused by the stress would be more challenging to model and ensuring the performance in pronounced curvatures might be problematic given the difficulty in controlling layer uniformity over the entire surface. As technical discussions developed, we requested Asahi

¹¹ R_{avg} is the average reflectance over the wavelength range and R_{abs} denotes the minimum reflectance over the same range.

to provide a quote to manufacture samples for each proposed coating type for us to test. They provided us with a quote for eight samples per coating type, amounting to a cost of 4,000 USD, including shipping. The reference to this quote can be found in appendix [A.2](#).

4.3.2.2 Optics Balzers

Optics Balzers had previously worked with the MUSE teams to develop dielectric mirrors for their instrument and had a positive outcome. They have solid evidence of manufacturing dielectric mirrors, even including them in their catalogue as standard products called Diflex (though this coating is only specified to 2000 nm, rather than the 2400 nm we require).

We had several phone calls with the Optics Balzers team to explain our project and requirements. They came back to us with a proposal of three steps to study the applicability of their Diflex coatings for the HARMONI instrument.

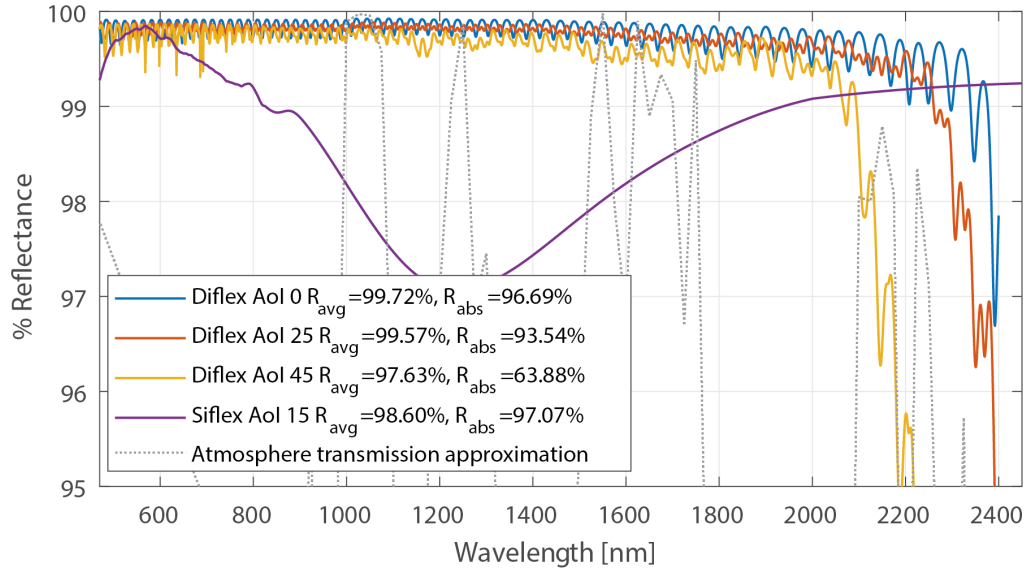


Figure 4.8: Reflectivity curves of coatings proposed by Optics Balzers with selected angles of incidence. The enhanced silver coating design Siflex is included for comparison.

- Step 1: Purchase a Diflex2000 mirror from their stock (their reflectivity curves are shown in Figure 4.8). Doing this was the first logical step when exploring the

survivability of dielectric mirrors. They had no evidence of previous tests and did not know what would happen to the coatings when cooled down or cycled. Thus we would use this first sample to determine the coating durability and suitability to HARMONI’s operational conditions. They would deliver one coated piece and its reflectivity data for 850 EUR.

- Step 2: Coating study design. Customised designs would be produced for the HARMONI wavelength range and for our range of angles of incidence. They would deliver design data per coating type and AOI for 2,500 EUR.
- Step 3: One batch of customised Diflex2000 coating. The goal would be to manufacture the customised design and produce coating samples. During this step, samples could be produced with and without back-side compensation to study the compression stress impact in the surface form. They would deliver test reports, reflectivity measurements and samples for 16,750 EUR.

Another crucial point that was discussed was the size ranges of HARMONI surfaces. They established a limit of 200 mm in February 2019. Since then, the company was bought by Materion. If discussions with Optics Balzers continue, I recommend reviewing this limit. We were only able to pursue the first step as part of this thesis, due to funding limitations. The reference to the project proposal and step 1 quote can be found in appendix [A.2](#).

4.3.2.3 Viavi

Viavi contacted Dr Fraser Clarke during a conference, and their details were shared with us by the optics team in the consortia. Similarly to Optics Balzers, we presented the project and explained our coating requirements, and they answered by sending us a sample reflectivity curve (see Figure [4.9](#)) with a statement of work. Their statement of work consisted of two phases.

- Phase 1: Complete design study to optimise and refine performance for HARMONI. During this phase, they would design coatings for our wavelength and

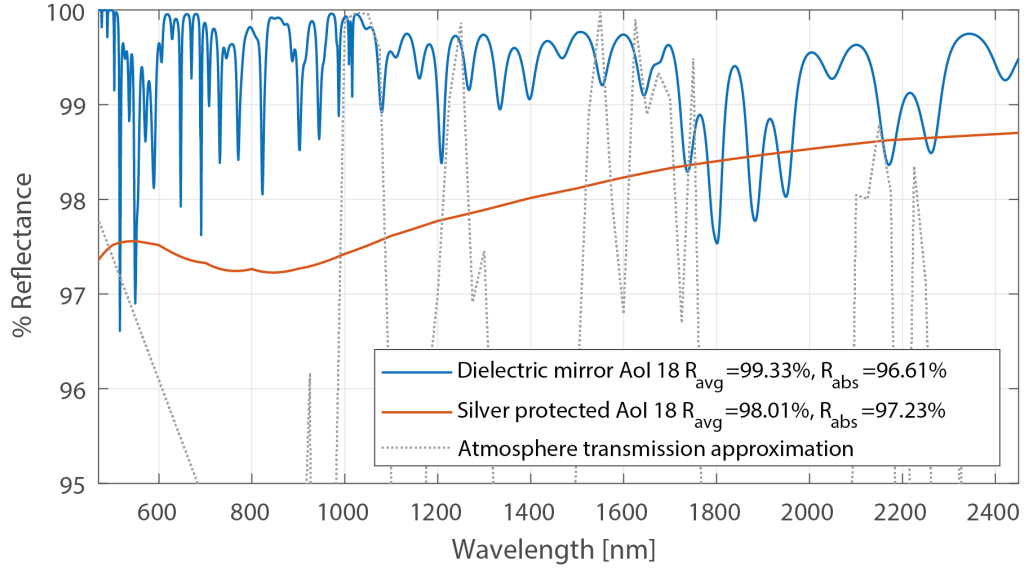


Figure 4.9: Reflectivity curves of coatings proposed by Viavi-OSP with an 18 degree angle of incidence. Their silver protected mirrors is shown as a comparison of the improved performance.

angle of incidence ranges starting from our request of three types and then evaluating the ideal number of designs. They would provide design performance curves, suggested specifications and estimated manufacturing costs for 9,700 USD.

- Phase 2: Coat samples of designs from Phase 1. This phase would consist of manufacturing samples of the proposed coatings. Each coating type lot of ten samples would cost 28,600 USD.

During our discussions, Viavi raised the issue of the reflectance spectra having structure or features and the induced stress on the mirrors being markedly higher than silver coatings due to the increased thickness of the coating. They mentioned that the structure in the reflectance spectra could be reduced by increasing the number of layers but at the cost of adding more stress to the mirrors. They explained that the induced deformation would likely be radially symmetric and manifest as a power term. Furthermore, they said that the mirror sizes we required were within their experience and capabilities.

Their quote reference, along with its statement of work, can be found in appendix [A.2](#). We did not pursue the Viavi options further during my thesis due to their cost.

4.3.3 Purchased coatings

The first step to carry out this project was to ensure that such coating could be designed and procured. Then, the second step was to test its survivability to HARMONI's operational conditions. Unfortunately, the budget for this project was limited to £10,000. We compared the three project proposals and quotes from Asahi, Optics Balzers, and Viavi against our objective. A summary of the proposals with the criteria that we took into account is shown in Figure 4.10. All designs from all companies had reflectivities higher than 99%, but we could not get a design and samples from all. We chose to purchase the manufactured samples of the three types from Asahi and a preliminary sample of Diflex from Optics Balzers. We would use these procured samples to test adhesion, surface quality, durability, cleaning ease and survivability to cryogenic cycling. The design studies and samples manufacturing possibilities from Optics Balzers and Viavi went beyond our budget and our scope.

		Options		
		Asahi	Optics Balzers	Viavi
Criteria	Experience	Dielectric coatings for industry and astronomy	MUSE instrument and dielectric mirrors standards product	Dielectric coatings for industry and astronomy
	Capabilities	Several size facilities, up to ~400 mm	up to ~200 mm	Small and large facilities
	Preliminary design	-	See figure 4.8	See figure 4.9
	Preliminary sample	-	850 EUR (exVAT) for 1 sample	-
	Design study	See figure 4.7	2,500 EUR (exVAT)	9,700 USD
	Samples manufacturing	4,000 USD (exVAT) for 8 samples for three types	16,750 EUR (exVAT) for one type	28,600 USD for 10 samples per coating type
	Exchanged data	Design reflectivity curves for entire AOI range for all types	Preliminary design reflectivity curve for three AOI	Preliminary design reflectivity curve for one AOI
	Additional information	Flatness measurements before and after coatings, manufactured reflectivity measurements at AOI checks, cleaning method	-	-

Figure 4.10: Comparison table for coating manufacturers options.

4.3.3.1 Asahi samples

We purchased eight samples per coating design (A, B and C). With the order, Asahi provided theoretical performance curves for our selected angle of incidence checks for the entire range for each coating. I used this data to do a 3D triangulation-based linear interpolation of the expected performance of each coating type over the entire AoI range. Figure 4.13 shows the resulting interpolation for each type. I later used this coating model per type to estimate sub-system and end-to-end transmission in Sections 4.4 and 4.4.5. Asahi used magnetron sputtering to coat a large mirror, and then, from this parent piece, they cut the samples they sent to us. All samples were coated only on one side.

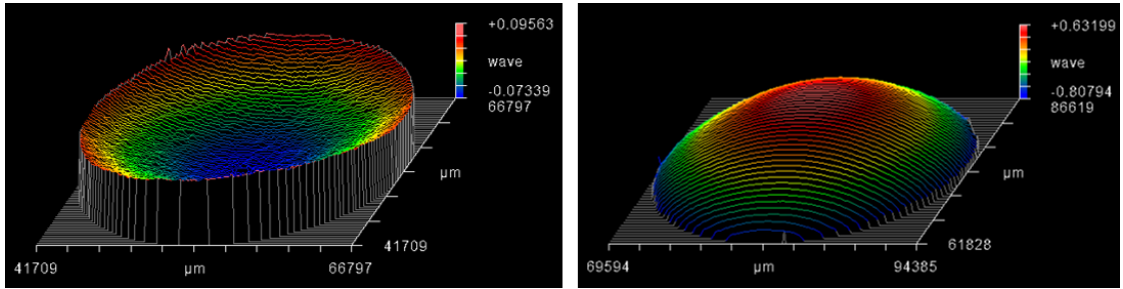


Figure 4.11: Interferometer measurements of a mirror before (left) and after (right) coating with coating type C. (Provided by Asahi Spectra Co., Ltd.)

The samples' substrate is fused silica with a diameter of 25 mm and thickness of 5 mm. Asahi measured the surface irregularity and power of the samples before and after coating application to better understand the impact of these coatings on their surface flatness. Figure 4.11 shows the change in surface form for coating C, where the most significant impact was observed. Table 4.2 shows the summary of the surface irregularity measurements for Asahi samples before and after coating application. The complete flatness measurements are in the appendix Section B. Before coating, all samples had at least a $\lambda/4$ flatness for $\lambda = 632.8nm$. Each coating type has about a hundred or more metal-oxide layers, with coating C being the thickest coating made by Asahi. P-V¹² irregularity changes from 0.169 to 1.440 waves over 25 mm for type

¹²Peak-to-valley

C. As suggested, however, the deformation is dominated by curvature, making it easier to predict and include in the design or even compensate with focus during assembly.

	Before coating			After coating		
	P-V [wave]	RMS [wave]	Power [wave]	P-V [wave]	RMS [wave]	Power [wave]
Type A	0.220	0.033	0.108	1.085	0.273	-0.954
Type B	0.220	0.033	0.108	1.139	0.292	-1.016
Type C	0.169	0.038	0.131	1.440	0.368	-1.315

Table 4.2: Summary of surface irregularity measurements for Asahi samples before and after coating application. P-V denotes peak-to-valley surface irregularity and power refers to power error. Both measurements describe the samples surface through the study of its wavefront.

Furthermore, Asahi also provided us with gonio-spectrophotometric measurements of their coatings (A, B and C) for each of the performance check angles we requested (see Table 4.1) that was within their capability to measure. Figure 4.12 shows the polarised and unpolarised reflectivity measurements of coatings C¹³. The figure shows that the coatings have consistent reflectivity S and P at their coatings design angle but not throughout their range, and the bottom right plot shows the most considerable departure. *P*-state, which has its electric field parallel to the incidence plane, is favoured as anticipated by the principles of light propagation. We expect this difference in performance per polarization state to have a minimal impact on HARMONI science light as the light interacts with many other refractive and reflective optical elements. The instrument is not designed to detect polarisation. The light throughout the science path optical surfaces is expected to be unpolarized¹⁴. Asahi demonstrated being able to manufacture their coatings to match their designs and provided us with an instructional video to clean the samples [3]¹⁵.

4.3.3.2 Optics Balzers sample

We purchased one sample of Diflex 2000 coating from Optics Balzers. Diflex 2000 coating is designed for high reflectance $> 99\%$ between 320 and 2,000 nm for an angle

¹³Reflectivity measurements for coatings A and B are included in appendix C.

¹⁴The caveat to that being that if you have a sequence of mirrors with common angles, you could end up polarising the light further into the instrument, but that is beyond the scope of this chapter.

¹⁵I followed this procedure throughout this work.

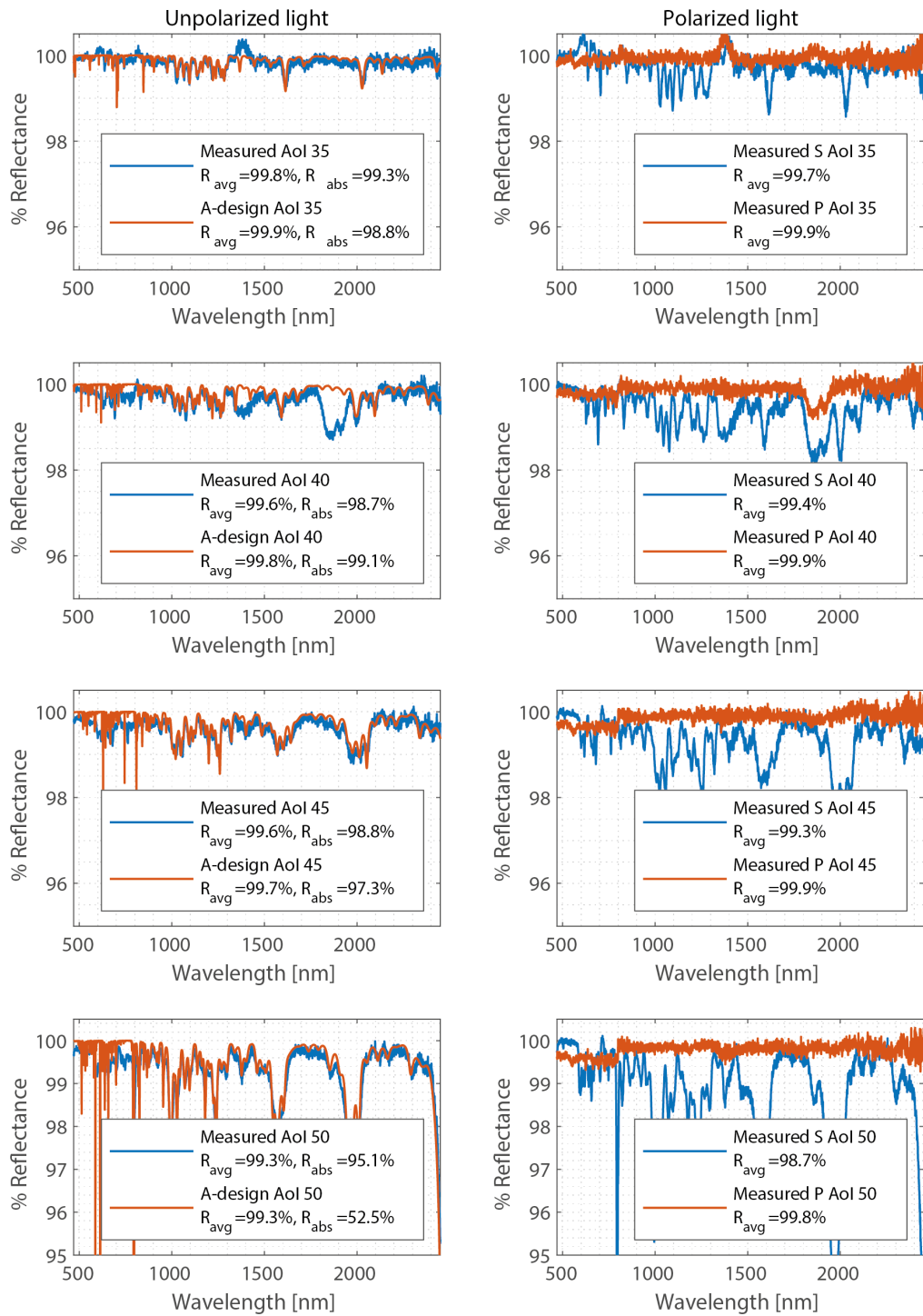


Figure 4.12: Coating C. On the left: unpolarized light reflectivity measurement at Aol checks. Comparison with design and as-manufactured curves. On the right: S and P polarization as-manufactured curves. (Provided by Asahi Spectra Co., Ltd.)

of incidence range of 0 to 50 degrees. It is composed of metal oxide layers, and it is advertised to withstand harsh environmental conditions and could be cleaned repeatedly [25]. The purchased sample substrate is fused silica and has a diameter of 25 mm with a thickness of 3 mm. The advertised specifications for Diflex 2000 are a reflectance of $> 99\%$ for any polarization, a flatness of $\lambda/2$, surface defects $5/1 \times 0.16$, parallelism < 5 arcmin and environmental stability for temperatures between -40 and $+150$ °C, as well as humidity up to 99%. The product datasheet reference can be found in appendix A.3.

4.3.3.3 Curve features

The dielectric mirror designs from all manufacturers show features or wiggles in their reflectivity curves due to minor imperfections in the constructive interference over hundreds of layers. The Viavi design is the most prominent and the Asahi the least. These features are concerning, as having an end-to-end transmission curve with much structure could complicate the analysis and error correction in the instrument. The ideal case would be that the features of each mirror would be smoothed when combined across the science path.

For this chapter, I multiply individual coating curves for a given angle of incidence¹⁶. This is a simplified analysis and is not the case for actual mirrors¹⁷. The simplified approach was chosen because, in most cases, we have incomplete or no coating models¹⁸. In Section 4.4, we will see that the features do not entirely smooth out when assigning individual coating curves to each surface; sometimes, the minimas or the maximas combine, resulting in more prominent features.

¹⁶This angle is the reported AOI for each surface in the HARMONI documentation; in very few cases, I selected the average angle from the optical design model.

¹⁷The reflection of a mirror is the product of the curves for a range of incidence angles, and the reflection over several mirrors does not behave in two dimensions.

¹⁸I only had the interpolated data from the Asahi coatings as a complete data set.

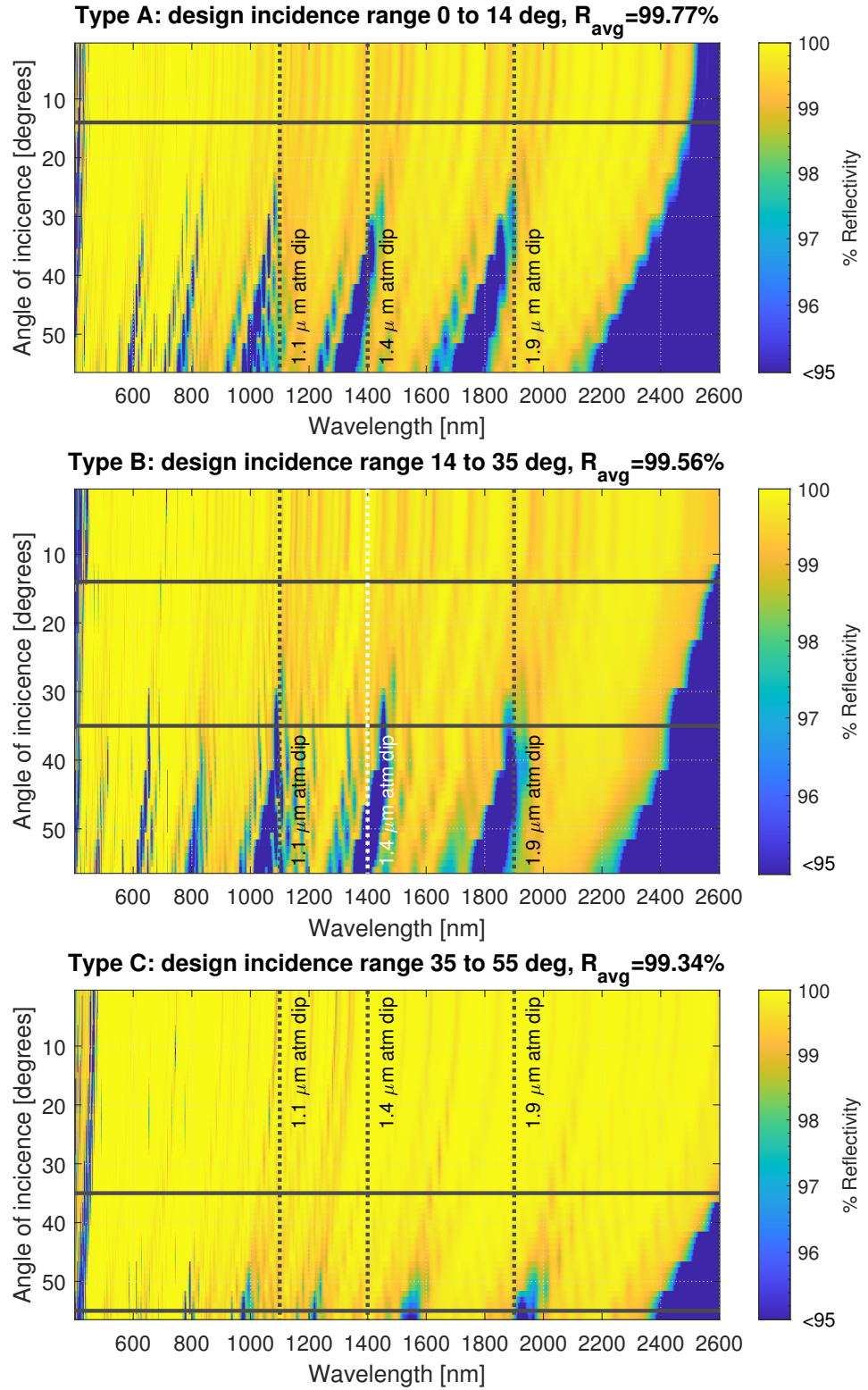


Figure 4.13: Reflectivity for Asahi coating model types A(top), B(middle) and C(bottom) over the entire angle of incidence range (unpolarized light).

4.4 Applicability to HARMONI

In this section, I quantify the impact in transmission when dielectric mirror coatings are applied to suitable reflective surfaces across HARMONI’s science path. First, I selected eligible surfaces. Then, I studied the increase in transmission per subsystem, only considering its reflective surfaces. I present three cases for comparison: the baseline case using only metallic coatings; a second, realistic case where I assign the corresponding dielectric reflective coating to every eligible surface, and a metallic (Siflex enhanced silver, shown in Figure 4.8) coating to the rest of the reflective surfaces; and thirdly an idealistic, but unfeasible case where all surfaces are dielectric mirrors. Finally, I modified the end-to-end transmission model from HARMONI. I included approximate transmission curves for the reflective surfaces based on their corresponding Asahi coating matching their chief ray angle of incidence. I present the estimated end-to-end transmission per grating bandwidth for the three cases.

4.4.1 Focal plane relay sub-system

As Section 4.2.1.1 mentions, four reflective surfaces exist in the focal plane relay subsystem. In the conservative case 1, all surfaces are deemed too large to apply a dielectric coating. In case 2, I assigned a dielectric coating to M2. Given its smaller size, M2 is the surface most likely to be assigned such a coating. In case 3, I assigned dielectric coatings to all surfaces and did not consider the size limitation. This last case is the least likely given that the sizes of M1, M3 and M4 are close to the limit above which a surface area is too large to be coated. Table 4.3 shows a summary of the characteristics of each surface and the assigned coating per surface per case.

Surface	RoC [mm]	Size [mm]	AoI [deg]	Assigned coating type		
				Case 1	Case 2	Case 3
M1	-4000	720	6	Silver	Silver	A
M2	2000	175	12	Silver	A	A
M3	-4000	720	6	Silver	Silver	A
M4	Plano	804x584	47	Silver	Silver	C

Table 4.3: Coating options for the reflective surfaces in the focal plane relay sub-system.

The resulting transmission estimate for each case is shown in Figure 4.14. Between cases 1 and 2, there is an improvement of 3.4% relative gain in minimum transmission.

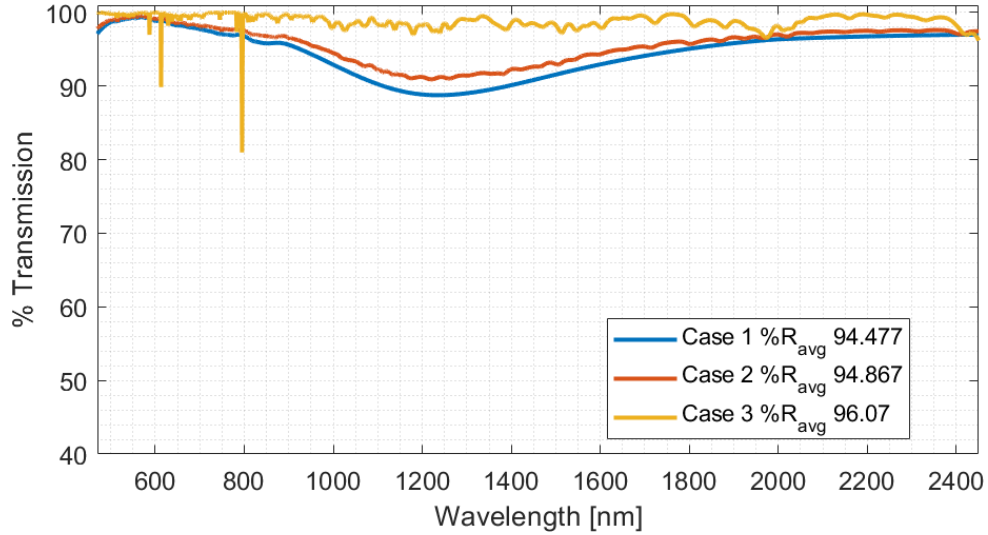


Figure 4.14: Simplified transmission model of the focal plane relay sub-system (only reflective surfaces are considered).

4.4.2 Pre-optics sub-system

The pre-optics subsystem has many eligible surfaces smaller than 100 mm that are either flat or slow spheres (see appendix Table F.5). For this subsystem applicability study, case 2 applies dielectric coatings to all the surfaces that are flat or slow spheres; toroidal and parabolic surfaces remain with a metallic coating applied. Cases 1 and 3 follow a similar logic as the FPR subsystem study. The full assignment of surface coatings is shown in Table 4.4.

Surface	RoC [mm]	Size [mm]	AoI [deg]	Coating type		
				Case 1	Case 2	Case 3
INPUTM	NA	100	41.5	Silver	C	C
COLLM	1598.44	130	7.07	Silver	Silver	A
FM60	NA	90	24	Silver	B	B
CM60	3249.99	160	0	Silver	Silver	A
FM60B	NA	160	43.2	Silver	C	C
OUTM60	NA	145	43.5	Silver	C	C
FM20	NA	80	16.5	Silver	B	B
TM20A	1830.37 / 1483.39	80	1.7	Silver	Silver	A

TM20B	552.15 / 900.11	50	1.85	Silver	Silver	A
CM20	2917.81	130	15.9	Silver	Silver	B
FM20B	NA	160	51.4	Silver	C	C
OUTM20	NA	145	42.4	Silver	C	C
FM10	NA	80	7.5	Silver	A	A
TM10A	1589.87 / 1428.31	68	2.2	Silver	Silver	A
TM10B	210.20 / 376.21	22	2.75	Silver	Silver	A
CM10	2600	130	10	Silver	A	A
FM10B	NA	130	40	Silver	C	C
OUTM10	NA	130	45	Silver	C	C
FM4	NA	80	18	Silver	B	B
FM4B	NA	90	21	Silver	B	B
TM4A	1627.99 / 1519.17	90	2.1	Silver	Silver	A
TM4B	124.15 / 233.58	22	2.3	Silver	Silver	A
CM4	3546.49	130	3	Silver	A	A
FM4C	NA	130	26	Silver	B	B
OUTM4	NA	130	44	Silver	C	C

Table 4.4: Coating options for the reflective surfaces of the pre-optics subsystem.

In Figure 4.15, I show the resulting plots of the calculated transmission for each case scenario per scale. I plotted the transmission model for each scale, considering only reflective surfaces to show the increase in reflectivity per case¹⁹. When comparing the average reflectivity per case in the plotted subsystem configurations, the difference in reflectance between the base case with only enhanced silver and case 2 with a combination of silver and dielectric coatings is clear. We can observe the overall increase in average reflectivity per case to evaluate the impact of applying dielectric coatings on eligible surfaces. However, the most visible impact is in absolute reflectivity. For example with the scale 60×30 mas, the absolute reflectivity has an increment of 7.1% from case 1 to case 2. In scale 20×20 mas, we see prominent features in cases 2 and 3 characteristic of dielectric coatings²⁰, but a significant increase in transmission is also visible from 850 to 2350 nm. In scales 10×10 mas and 4×4 mas, the relative gain in average reflectivity is more than 3% between cases 1 and 2. For this subsystem, case 2 presents the most down-to-earth scenario to implement dielectric coatings.

¹⁹Note that this subsystem model does not include any loss from filters.

²⁰These features are inherent to the Asahi coating type C beyond 50 degrees AOI.

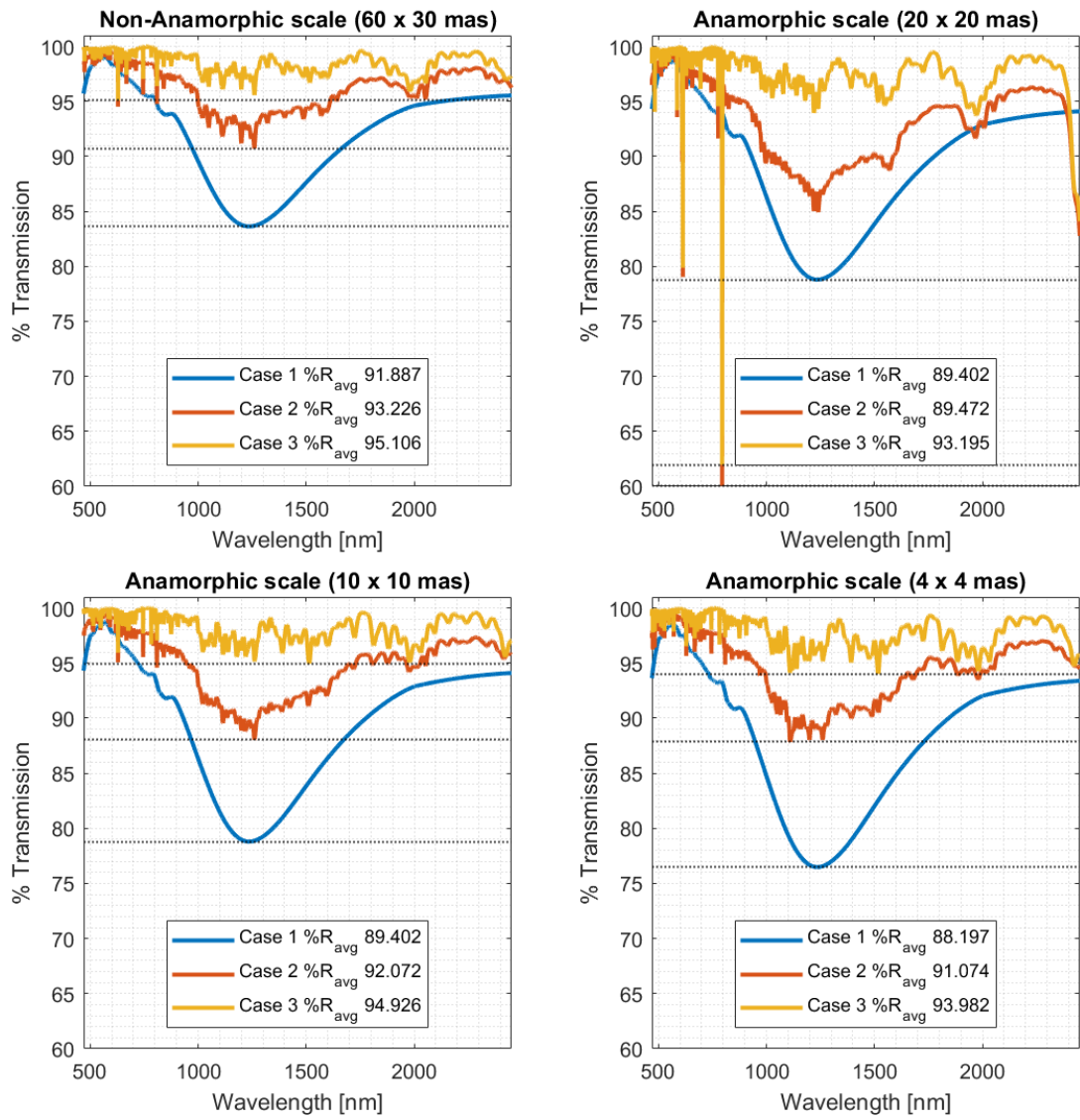


Figure 4.15: Pre-optics sub-system transmission estimate (only reflective surfaces are considered).

4.4.3 Integral field unit sub-system

The integral field unit subsystem includes two of the most complicated reflective elements in the instrument: the field splitter and the image slicer. Given its challenging manufacturing, the image slicer is not considered for dielectric coatings, while the field splitter only features in the idealistic case 3 scenario. Given their size and curvature, the mirrors in the splitting and relay module, as well as the pupil mirror assembly in the image slicer module are more suited for dielectric coatings.

I calculated the resulting transmission for this subsystem for three cases, similarly to the previous subsystems. Case 3 considers the possibility of applying dielectric coatings to M3 with a radius of curvature of 864 mm and to the field splitter as discussed in Section 4.2.3: the limit in the acceptable curvature radius depends on the optic size and the coating area of the selected coating machine. It can only be set via a detailed discussion with the coating company. Table 4.5 summarises the coating choice for each surface for each case.

Surface	RoC [mm]	Size [mm]	AoI [deg]	Coating type		
				Case 1	Case 2	Case 3
Field Splitter	Flat	19.9 x 14.9	5.5 θ X 12 θ Y	Silver	Silver	A
M1 IFU	Flat	38.7 x 36.5	51	Silver	C	C
M2 IFU	Flat	26.5 x 50.5	55	Silver	C	C
M3 IFU	864	50	6	Silver	Silver	A
M4 IFU	Flat	29.5 x 32.5	38	Silver	B	B
M5 IFU	2233	90 x 63	5	Silver	A	A
ISA	800	50.8 x 1	From -12 to 12	Silver	Silver	Silver
PMA	Flat	12x 7	From -12 to 12	Silver	A	A
SMA	105.27 to 109.01	13 x 7	From -8 to 8	Silver	Silver	Silver

Table 4.5: Coating options for the reflective surfaces of the integral field unit sub-system.

Figure 4.16 shows the transmission estimate for each case. The IFU, as a fully reflective sub-system, benefits from choosing dielectric coatings over traditional silver at the cost of pronounced features across the wavelength range. In this case, a slight increase in average transmission from case 1 to 2 impacts the overall instrument throughput and has a significant increase for the 900 to 2200 nm bandwidth.

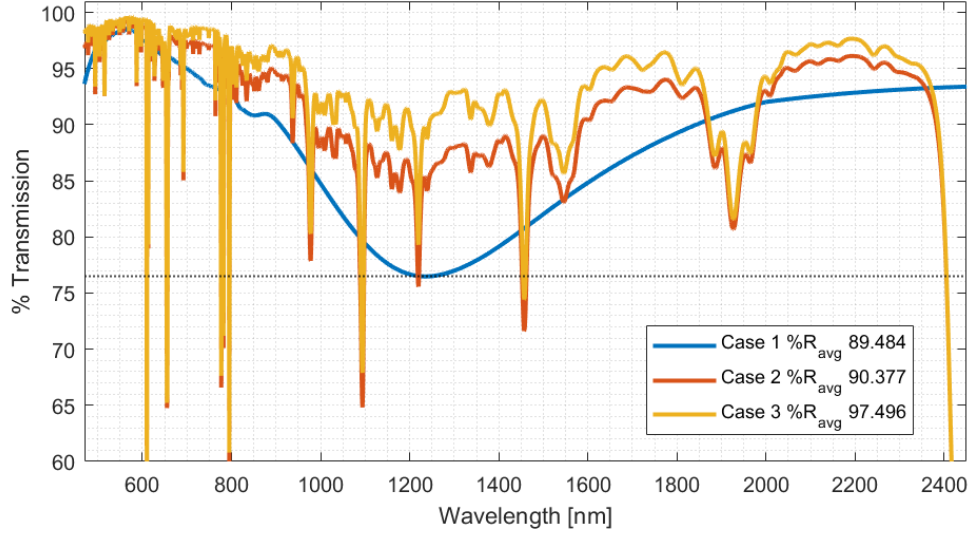


Figure 4.16: Transmission estimate of the integral field unit sub-system (only reflective surfaces are considered).

4.4.4 Spectrograph sub-system

The reflective surfaces in the spectrograph sub-system are large (diameter > 250 mm) and complex (aspherical) and are therefore likely to prove too challenging for dielectric coatings. However, given the various scenarios mentioned for all sub-systems, we have also considered three cases to implement dielectric mirrors. Case 2 challenges the limit in size and proposes both fold mirrors for dielectric coating application. Table 4.6 lists the reflective surfaces and their corresponding coating type per case. Figure 4.17 shows

Surface	RoC [mm]	Size [mm]	AoI [deg]	Coating type		
				Case 1	Case 2	Case 3
M1 ISP	-1240.4	646x126	34	Silver	Silver	B
M2 ISP	-630.56	414x100	25	Silver	Silver	B
M3 ISP	-1486.2	500x162	14	Silver	Silver	B
FM1	Flat	344x258	*	Silver	C	C
FM2	Flat	272x200	*	Silver	C	C

Table 4.6: Coating options for the reflective surfaces of the spectrograph sub-system.

*The angle of incidence of the fold mirrors depends on its grating selection.

the transmission estimate of the sub-system per case as if the non-reflective surfaces had a perfect transmission efficiency. The improvement from case 1 to case 2 is more

than 2% on average. This simplified transmission estimate allows us to see the potential benefit in gain from applying dielectric coatings. A further study to understand the behaviour of dielectric coating applied to large flat surfaces would allow surfaces like the fold mirrors in the spectrograph or the mirrors in the focal plane relay to be considered for these coatings.

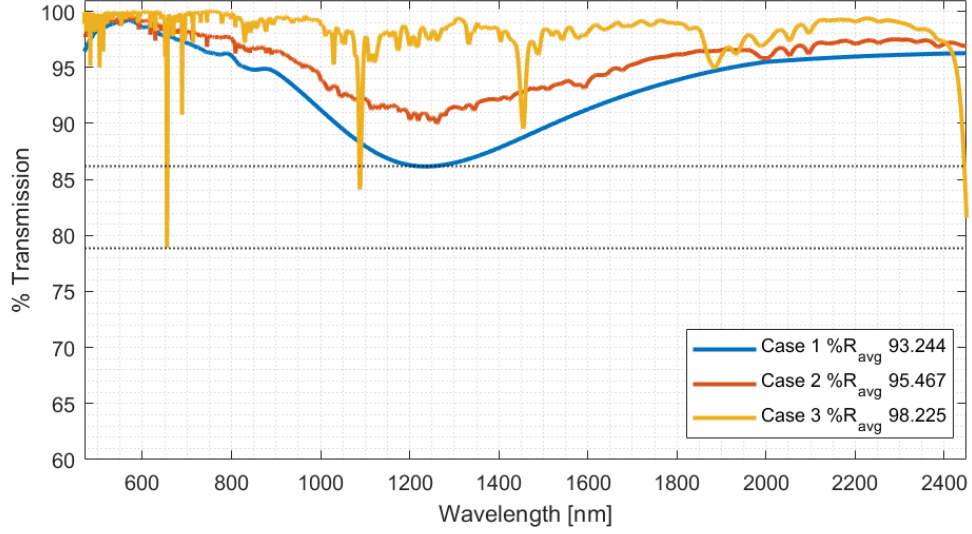


Figure 4.17: Transmission estimate for the spectrograph sub-system HK grating path. This model only considers reflective surfaces.

4.4.5 Simplified end to end transmission model

I constructed a simplified HARMONI science path transmission²¹ to showcase how much the instrument transmission would benefit from implementing dielectric coatings.

The instrument's transmission, T_{E2E} , (in line with the formal requirement for HARMONI) can be expressed as the product of the transmission or reflection curves of all the elements that refract or reflect light along the path:

$$T_{E2E} = T_{AO_{mode}} \times T_{FPR_{case}} \times T_w \times T_{PO_{scale,case}} \times T_{IFU_{path,case}} \times T_{ISP_{grating,case}} \times T_{misalignment}. \quad (4.7)$$

In equation (4.7), I defined the following elements:

²¹Based on the transmission model developed by Fraser Clarke which was used to prepare transmission budgets for the instrument Preliminary Design Review.

- $T_{AO_{mode}}$ is the estimated transmission of the AO modes (LTAO, SCAO, and noAO) considering the corresponding dichroic element relevant to the AO mode. The LTAO model considers AR coating on both sides, as well as bulk absorption. The SCAO model is the approximation for the current best estimate transmission model. No AO removes the dichroic element.
- $T_{FPR_{case}}$ is the estimated subsystem transmission of the focal plane relay per case.
- T_w is the IFS cryostat window: a broadband coating was selected following the instrument transmission model.
- $T_{PO_{scale,case}}$ is the calculated transmission of the pre-optics subsystem per scale per case. This subsystem has one refractive element in all scales (a filter).
- $T_{IFU_{path,case}}$ is the estimated transmission of the integral field unit subsystem per path per case. This subsystem is fully reflective; thus, the proposed transmission in Section 4.4.3 is the same used in this variable per case.
- $T_{ISP_{grating,case}}$ is the estimated transmission of the spectrograph subsystem per selected grating per case. $T_{ISP_{grating,case}}$ is equal to the only reflective transmission model presented in Section 4.4.4²² and multiplied by the transmission of the refractive elements in the subsystem.²³
- $T_{misalignment}$ is a given transmission estimate to describe the pupil misalignment. We assigned 98% over the entire wavelength range, in line with the HARMONI instrument level budget.

For total sensitivity calculations, the total transmission from the top of the atmosphere to the detected electrons can be expressed as:

$$T_{E2E+} = T_{E2E} \times T_{telescope} \times T_{atmosphere} \times T_{detector}, \quad (4.8)$$

²²The angle of incidence for fold mirrors configuration per grating was considered.

²³This subsystem has 11 gratings and two cameras, one for the visible and the near-infrared wavelength ranges. Each grating has an estimated transmission curve provided by a manufacturer. The cameras have seven lenses, and an anti-reflective coating was assigned to each element according to its material when a curve was available. We selected an estimation of an AR coating for the lenses where a curve was unavailable.

where T_{E2E} is given in equation (4.7). T_{E2E+} is called the *throughput* and it describes how much scientific light can be detected by the instrument. $T_{telescope}$ is the telescope's transmission, $T_{atmosphere}$ is the transmission from the atmosphere and $T_{detector}$ is the detector's transmission.

Where not explicitly mentioned, the refractive elements in all subsystems are accounted for as defined in the initial transmission model with placeholder coatings, given that the optical designs were undergoing development and their coatings had not been selected at the time of research.

Note that the instrument's transmission, T_{E2E} , as defined in equation (4.7) and the throughput, T_{E2E+} , in equation (4.8) represent the transmission of perfectly clean and new coatings, and do not include the effects of either dust or ageing, both of which will reduce the total transmission.

4.4.6 Improvement in the instrument transmission

To understand the impact of using reflective dielectric coatings in HARMONI, I analyzed the instrument transmission calculated with equation (4.7) for the LTAO mode, scale 60×30, IFU paths C, D, G and H. I want to compare that transmission to the instrument level requirement for HARMONI's transmission, which is defined as >27% over the central 80% portion of each of the considered wavelength ranges. Therefore, I calculated the average as well as the central 80% transmission for the instantaneous wavelength range of each grating. These calculations are summarised in Table 4.7, and the corresponding curve per wavelength range is shown in Figures 4.18, D.1 and D.2²⁴.

In Figures 4.18, D.1 and D.2, the curves for case 1 (C1) show the baseline transmission using an enhanced silver coating on all reflective surfaces. The curves for cases 2 (C2) and 3 (C3) show the transmission when assigning a combination of silver and dielectric mirror coatings. Case 2 selects the surfaces most likely suited for dielectric mirror coating, and case 3 selects surfaces that are, in theory, eligible for dielectric mirror coatings but present significant manufacturing challenges. As expected, when comparing case 1 with cases 2 and 3, there is a clear improvement in transmission gain due to the use of dielectric mirrors. The visible grating wavelength range (Figure D.2)

²⁴The last two grating curves are in the appendix.

Selected grating		Bandwidth		Case 1		Case 2		Case 3	
Name	R	λ_{min}	λ_{max}	$T_{E2E\rho}$ %	$T_{E2E\rho80\%}$ %	$T_{E2E\rho}$ %	$T_{E2E\rho80\%}$ %	$T_{E2E\rho}$ %	$T_{E2E\rho80\%}$ %
VIS	3000	463	807	47.3	49.7	48.7	51.3	50.5	53
IzJ	3500	817	1363	35.9	36.8	44.2	45.3	53.6	55
HK	3500	1461	2439	45	47.4	48.3	51.4	52.6	55.9
Iz	7000	829	1051	48.7	50.2	55.3	56.9	62.6	64.3
J	7000	1045	1325	37	37.2	48.1	48.4	60.7	61.1
H	7000	1433	1817	47.3	47.8	55.2	56.1	63.5	64.8
K	7000	1948	2472	58.2	58.9	59.1	61.9	62.5	65.8
z	18000	823	907	45.8	47.5	50.6	52.4	55.3	57.3
J	18000	1185	1305	30.4	30.8	40.5	40.8	52.2	52.7
H	18000	1530	1686	39.2	40.4	45.7	47.1	53.1	54.8
K	18000	2084	2296	50.3	51.9	54.3	56.1	58.3	60.3
K short	18000	2007	2211	51.3	52.3	55.1	56.3	58.8	60.2
K long	18000	2189	2411	48.1	51	50.6	54	53.8	57.4

Table 4.7: Simplified end to end transmission, T_{E2E} : LTAO 60×30 mas IFU Paths C, D G, H. Detector, atmosphere and telescope curves are not included.)

shows the smallest benefit from dielectric coatings, with a 3.2% relative increase in $T_{\rho80\%}$ between cases 1 and 2, and 6.6% for cases 1 and 3. The highest relative increase in transmission $T_{\rho80\%}$ with respect to the baseline case 1 is in the J band for both resolutions 7000 (Figure 4.18, 30.1% for case 2 and 64.2% for case 3) and 18000 (Figure D.1, 32.5% for case 2 and 71.1% for case 3). The simplified end-to-end transmission model demonstrates that it is imperative to consider implementing dielectric coatings for HARMONI. The potential improvement in the performance of the throughput is substantial. It is worth noting that the drop in performance at the end of the K band (see Figure 4.18) denotes the limit in broadband coverage of dielectric mirror coatings.

Figure 4.19 shows the throughput $T_{E2E+\rho80\%}$ for the two most realistic scenarios, cases 1 and 2. This calculation includes models for the transmission of the detector, telescope and atmosphere. For all grating wavelength ranges, it is possible to see a clear improvement in performance from cases 1 to 2. The J band (7000) shows the most significant improvement in absolute transmission with +7.2%, followed by H (7000) with +5.9% and IzJ (3500) with +5.4%. These results further motivate the use of dielectric mirrors in HARMONI.

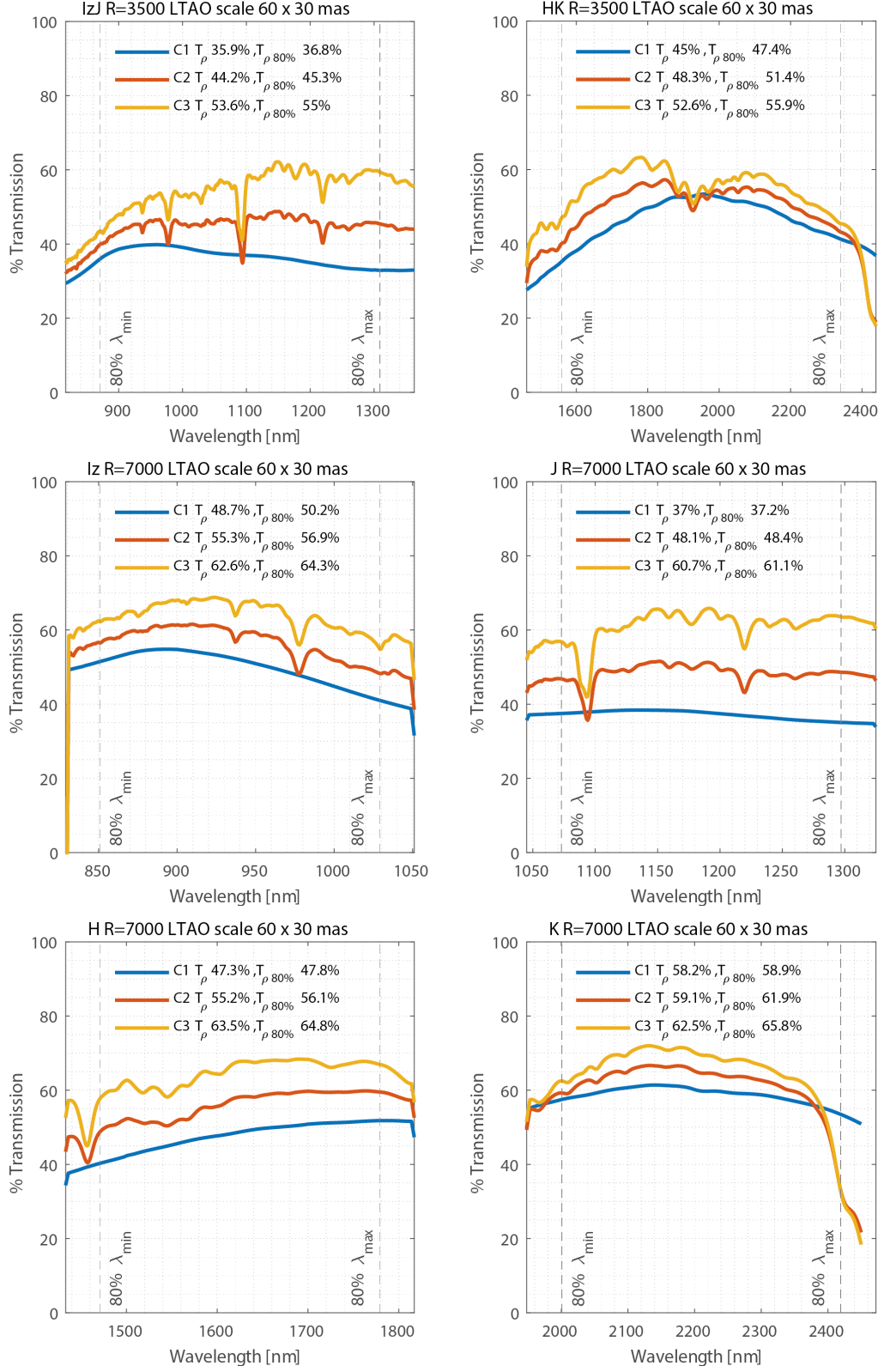


Figure 4.18: Estimated instrument transmission, T_{E2E} , per grating bandwidth for LTAO mode with a 60×30 mas scale, C, D, G and H IFU paths. The requirement is 27% averaged over the 80% band. (Detector, telescope and atmosphere curves are not included.)

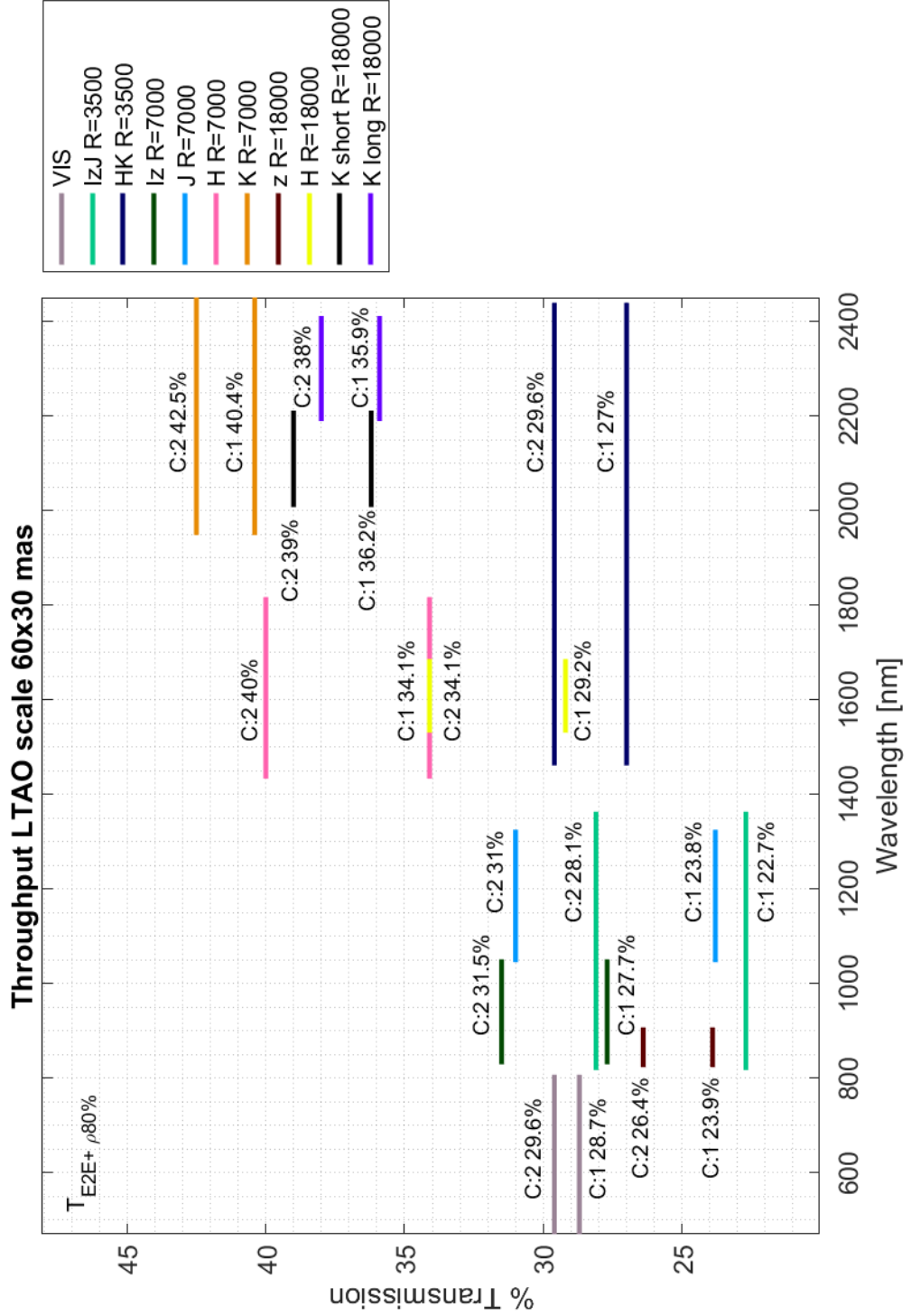


Figure 4.19: Calculated average throughput (from top of atmosphere to detector), T_{E2E+} , over the central 80% of each grating's wavelength range for the instrument configuration LTAO, scale 60x30 mas and IFU paths C, D, G, H.

4.5 Survivability tests

Survivability tests are meant to measure the endurance or suitability of dielectric coatings for HARMONI's operational conditions. It is the first assessment to determine the feasibility of incorporating dielectric mirror coatings to HARMONI's reflective surfaces.

4.5.1 Survivability definition

A coating sample is defined as having survived if its performance still meets requirements (see Section 4.3.1) after being subjected to an accelerated lifetime cryogenic cycle.

An *accelerated lifetime cycle* (also referred to as ageing or thermal cycling) intends to re-create the number of cool-down and warm-up cycles that are planned throughout the operational life of the HARMONI instrument, including its verification and its commissioning at system, subsystem and module levels. The estimated accelerated lifetime defined for the feasibility test of survivability of broadband coatings for HARMONI is 20 cycles.

To test the suitability for HARMONI, we evaluate performance changes in the following areas.

Coating degradation This is the first indicator of survivability. Before the accelerated lifetime cycling, coated surfaces are visually inspected for coating blemishes and for imperfections before testing. After cycling, degradation is recorded based on material deposited, new blemishes and imperfections, and evident deterioration. The coating survived when the degradation on the coating has minimal or no impact on its optical performance. There are two types of visual examination, by eye and by microscope. The visual examination by eye follows ISO 9211-4:2012(E) Annex C.

Adhesion The coating is said to have survived when it demonstrates to have good adhesion after ageing²⁵, following the test procedure defined in ISO 9211-4:2012(E).

²⁵An initial adhesion test was carried out to approve all deposited coatings on HARMONI optics.

Reflectance The key metric is that the reflectance should still be above 98% after cycling. There should also be no significant increments in absorption lines inherent ageing of the coating. Note that the reflectivity is measured before and after cleaning the surface from deposited particles during cycling. In this way, I determined the importance of cleaning the coating to regain reflectivity after ageing²⁶.

Cleaning resistance A coating should be able to be correctly cleaned with no performance degradation throughout its working life by following the manufacturer’s advice[3]. A coating survives when this is demonstrated to be true before and after ageing.

4.5.2 Accelerated lifetime cycle

4.5.2.1 Description

This cycling aims to recreate the conditions of what an optical surface inside the IFS cryostat would endure throughout its entire lifetime in the HARMONI instrument. To calculate what a lifetime means in terms of thermal cycling (TC), I considered that a mirror would undergo three warm-up and cool-down cycles for verification at module level, four cycles for AIT commissioning at subsystem and system levels in Europe, and a further three cycles for AIV commissioning in Chile. The target lifespan of the instrument is ten years, plus up to five additional years for AIT and AIV. I considered that there would approximately be two cool-down and warm-up cycles every three years, and that the instrument would be at the telescope’s operational temperature for the rest of the time. Thus, for the purposes of this test, a surface that sustains a total of twenty thermal cycles is classified as *aged* or *thermally cycled*. A key premise of this approach is that any ageing will happen during warm-up and cool-down cycles and not when the sample is sitting cold for a long time. It is worth mentioning that this is likely an overestimation; the instrument ideally would never be cycled unless something is not working adequately.

²⁶The amount of contamination is not directly related to the coating but to the cleanliness of the cryostat environment. The test cryostat used for the thermal cycling had been out of service for several years and was likely a significant source of contamination onto the test optics.

4.5.2.2 Setup

4.5.2.2.1 Cryostat

I used the same cryostat as in Chapter 3. The external setup had only a few differences from the setup described in Section 3.2. I did not set up a camera at the top of the cryostat and used the three-window lid. Figure 4.20 shows the setup in the HARMONI mechanical laboratory for testing the dielectric mirror samples.

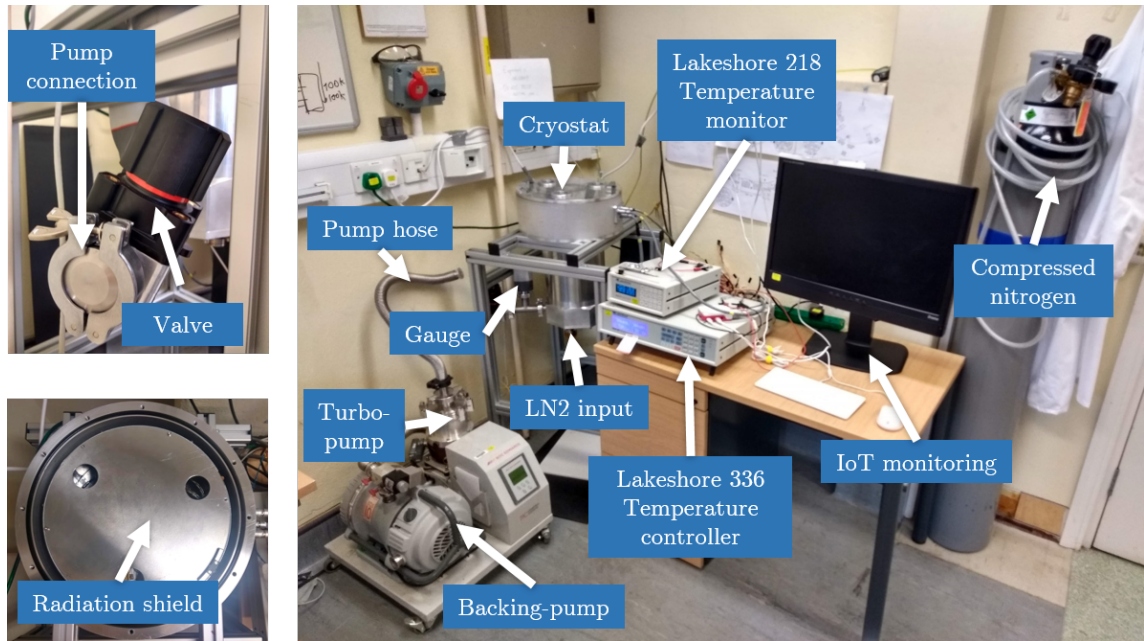


Figure 4.20: Cryostat setup in the HARMONI mechanical laboratory

Chronologically, the work of this chapter occurred before the lens mount cold testing presented in Chapter 3. Thus, I recommissioned the cryostat and cleaned the interior surfaces, lid, radiation shield and o-rings with isopropyl alcohol. I lubricated the connections with vacuum grease. I checked all the screws inside and outside the cryostat and re-screwed the required ones. I reviewed and double-checked inner and outer electrical connections. I searched for leaks and replaced a cryostat window. Moreover, I performed several mock cool downs and warm-ups to fully understand the setup before using it to test the coatings.

4.5.2.2.2 Sample cycling setup

Inside the cryostat, I placed an aluminium plate on thermally isolated stands fixed to the cold plate of the cryostat and thermally connected it with copper braids. Figures 3.6 and 3.8 show the internal chamber of the cryostat for the lens mount cold testing. I used the same thermally isolated stands, heaters and copper braids. I then placed the coating samples on the aluminium plate as shown in Figure 4.21.

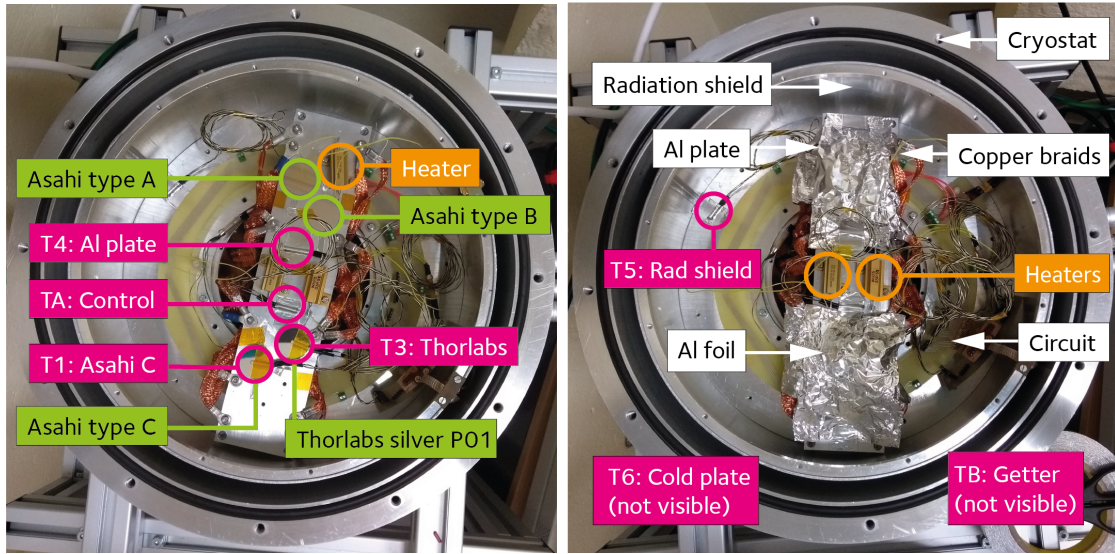


Figure 4.21: Samples setup version 1

To control the temperature of the coating samples during cooldown and warm up, I placed a PT-100 thermometer sensor and heaters in the plate. I connected the circuit to the temperature controller. Given that it was the first time I worked with the cryostat temperature control system, I tried two ways to control the temperature of the aluminium plate.

In version 1 of the setup, I placed three 25Ω heaters on top of the plate connected in parallel. See Figure 4.21. I put four coating samples: Asahi A, B and C, and a Thorlabs protected silver P01. I put two temperature sensors in the samples, one attached to the sample of Asahi type C and the other to the Thorlabs silver P01. I covered the samples with aluminium foil to shield the samples from the cryostat environment, given that I did not cool down the radiation shield. I performed three thermal cycles with this version. In this first version, the heat distribution across the

plate was not uniform, and the temperature control for the warm-up was not optimal. I changed the setup to improve the temperature control. I decided not to place the Optics Balzers coating sample for these initial thermal cycles as a precaution, given that I only had one sample.

For version 2, I attached six 25Ω heaters to the back of the aluminium plate. I connected three pairs of heaters in series and the pairs in parallel. This change resulted in a quicker thermal response and left plenty of space to place the coating samples on top of the aluminium plate. In this version, I included the Optics Balzers sample. See Figure 4.22. All other thermal cycles were performed with this version. I introduced the Thorlabs protected silver P01 coating sample to serve as a nominal reference to compare silver and dielectric mirror ageing and to calibrate my reflectivity measurements.

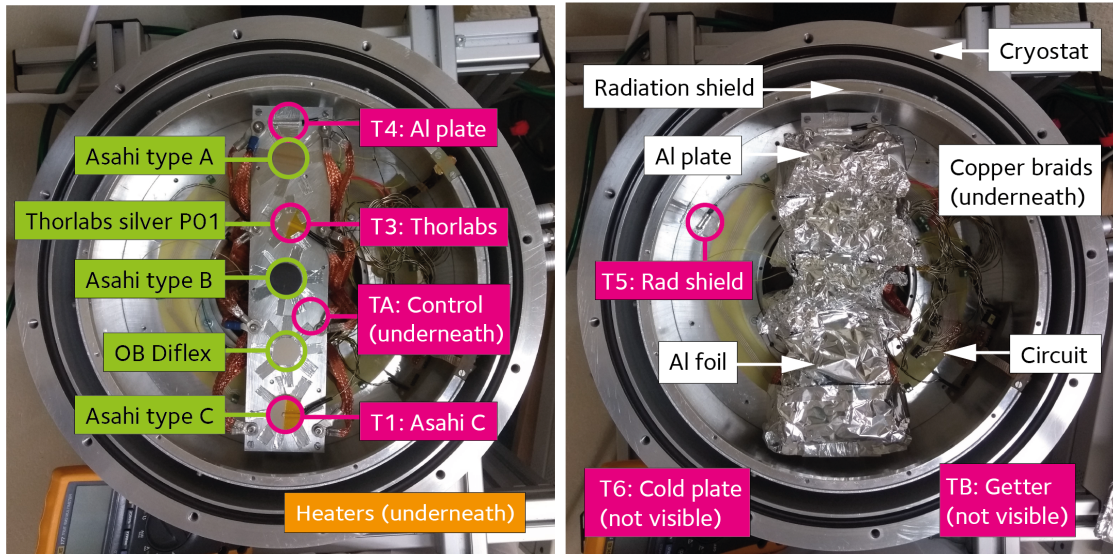


Figure 4.22: Samples setup version 2

4.5.2.3 Procedures

In order to age the samples using the set-ups, I followed these procedures:

- LN_2 dewar refill: see steps in appendix Section G.1. I repeated this procedure every eight thermal cycles.

- Thermal cycling: see steps in appendix Section G.1. I repeated this procedure 24 times.

4.5.2.4 Thermal cycles

I cycled coating samples of Asahi A, B, C and Thorlabs Silver C01 24 times, and the Diflex Balzers coating sample 21 times. Figure 4.23 shows the last 21 thermal cycles which occurred between the 4th and 22nd of December 2019. I opened the cryostat

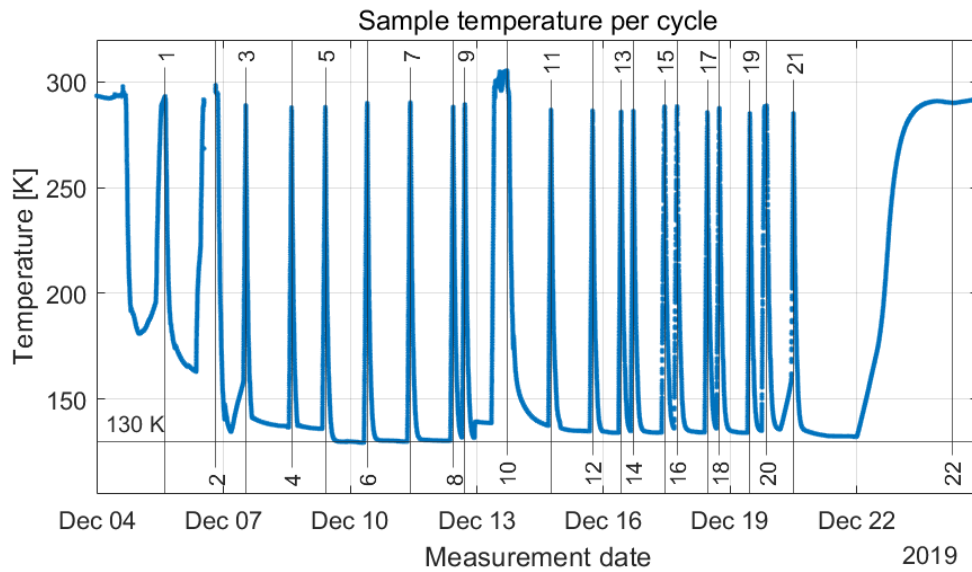


Figure 4.23: Completed thermal cycling for the dielectric coating samples.

after cycling the Asahi A, B, C, and Thorlabs Silver C01 three times to verify if the coating had survived and to modify the heater wiring as previously mentioned in the setups section. They did not show visible degradation or damage while still attached to the aluminium plate; thus, I added the Diflex coating sample to the setup and performed ten cycles. Then I opened the lid to inspect again (observe cycle 10 in Figure 4.23), and the samples showed no visible degradation or damage. I thermally cycled them for a further 11 cycles to complete the accelerated lifetime test. In the end, the samples showed no visible degradation or damage on initial visual inspection. I then performed the adhesion, cleaning resistance, coating degradation and reflectivity tests.

4.5.3 Coating degradation

4.5.3.1 Description

During our interaction with the coating manufacturers, we we asked if the coatings had been tested under cryogenic conditions. The manufacturers confirmed that no such tests had been done. At the time, there was no substantial evidence indicating that dielectric coatings would be compatible with cryogenic operation. The primary objective underlying the coating degradation test was to assess the coatings' ability to withstand the thermal stresses associated with thermal cycling. This examination was complemented by evaluations of cleaning resistance and adhesion before and after the accelerated lifecycle process. Collectively, these assessments enable a comprehensive assessment of coating degradation, encompassing considerations related to handling, storage and cleaning.

4.5.3.2 Setups

I did two visual inspections: the standard with the naked eye and another with a microscope. For the naked eye inspection, I used the setup I built for the visual examination of optical coatings following the ISO 9211-4:2012(E) Annex C standard (see appendix E.2). This setup can be seen in Figure 4.28. For the microscope inspection, I used the setup shown in Figure 4.25²⁷.

4.5.3.3 Procedures

4.5.3.3.1 Visual examination ISO 9211-4:2012(E) Annex C

I built an ISO 9211-4:2012(E) visual examination station (shown in Figure 4.27 on the left) in the cleanroom and placed it on the worktable in the laboratory area. Additionally, I placed an LED light source near the worktable, allowing for lighting with either the LED, the lamp, or the light torch. I performed all inspections with the general lab light off.

The steps to perform a visual examination are:

²⁷I performed the microscope inspection to look at the coatings in detail, though it is not part of the ISO 9211-4:2012(E) standard.

1. Place samples for examination on top of a soft and clean surface in the inspection area.
2. Take one sample and observe the coated surface at various angles at a maximum distance of 45 cm. Use gloves to handle the samples and only hold them from the sides. See Figure 4.24 on the right.
3. Shine a light torch or use a light bulb source to see through the coating and look for imperfections.

This straightforward procedure, combined with a trained eye, effectively finds coating blemishes, surface digs, and scratches.

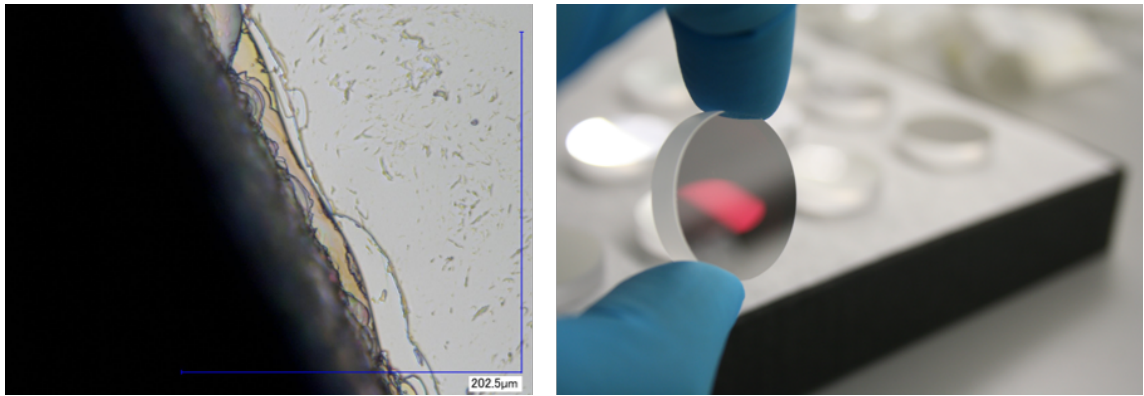


Figure 4.24: (left) Edge of an Asahi B coating sample observed with 1000x magnification. (right) Asahi C sample seen with a wide angle.

4.5.3.3.2 Microscope examination

1. Place a clean sample in the inspection area of the microscope.
2. Select the microscope magnification and move the sample stage to find the edge of the sample.
3. Focus on the edge of the sample (see Figure 4.24 on the left) and inspect the edges of the coating on the substrate surface.
4. Move the sample stage across the substrate surface and focus on the imperfections if found.

Moreover, I followed the procedure for microscope operation elaborated by Patricia Jacob[42].

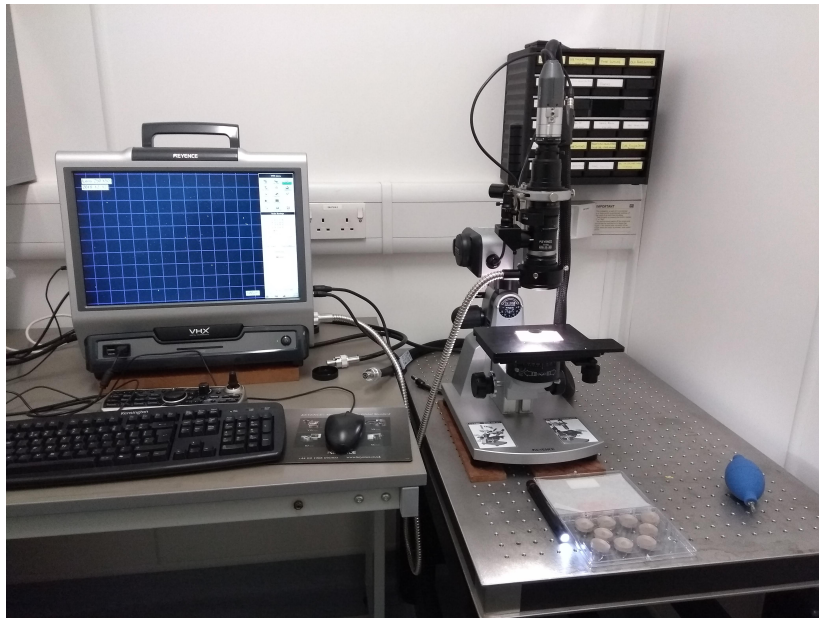


Figure 4.25: Coating examination with a microscope

4.5.3.4 Results

I performed a first inspection when I unpacked the samples. I found that the coatings did not degrade under standard laboratory conditions and appeared to be in excellent visual condition on arrival²⁸ for all samples.

I performed further inspections to look for coating degradations after one thermal cycle, ten thermal cycles, and after having fully aged the samples. This was the critical test to determine if this type of coating would survive cryogenic conditions.

Asahi A, B, and C, and Balzers coatings showed no degradation after one thermal cycle. After ten thermal cycles, the coatings showed faint blemishes due to dust and particle depositions inside of the cryostat. After the full ageing cycle, the samples showed clear blemishes but no sign of peeling or fractures (beyond the microscopic ones shown in Figure 4.24). For the test in Section 4.5.5, I discovered that the blemishes

²⁸Asahi coatings were shipped from Japan in cardboard boxes and individual paper pouches. The Balzers sample was shipped in a cardboard box from Germany and was packed in a custom made plastic container.

could be easily cleaned. Figure 4.26 shows the Asahi samples and Figure 4.29 the Balzer sample after ageing.



Figure 4.26: Asahi coating samples after being aged by thermal cycling.

4.5.4 Adhesion

4.5.4.1 Description

The objective of this test is to determine the durability of the coating in terms of adhesion. I tested the adhesion of the coatings as delivered by the manufacturer as part of the acceptance criteria. Then, I retested the coating after thermal cycling to determine its resistance to operational conditions and, depending on performance, to decide whether or not to recommend it for HARMONI's surfaces.

4.5.4.2 Setup

4.5.4.2.1 Adhesion test ISO 9211-4:2012(E)

This setup is straightforward; a clean work area would suffice (see Figure 4.27 on the right). I used narrow Kapton tape and cut a long enough strip. I held the sample firmly to achieve the best rate of tape removal.

4.5.4.3 Procedure steps

1. Inspect coating sample following ISO 9211-4:2012(E) Annex C procedure (see appendix E.2).
2. Follow procedure *ISO 9211-4:2012(E) Adhesion tests (conditioning method 02: adhesion)* with a degree of severity 03 (see appendix E.1).

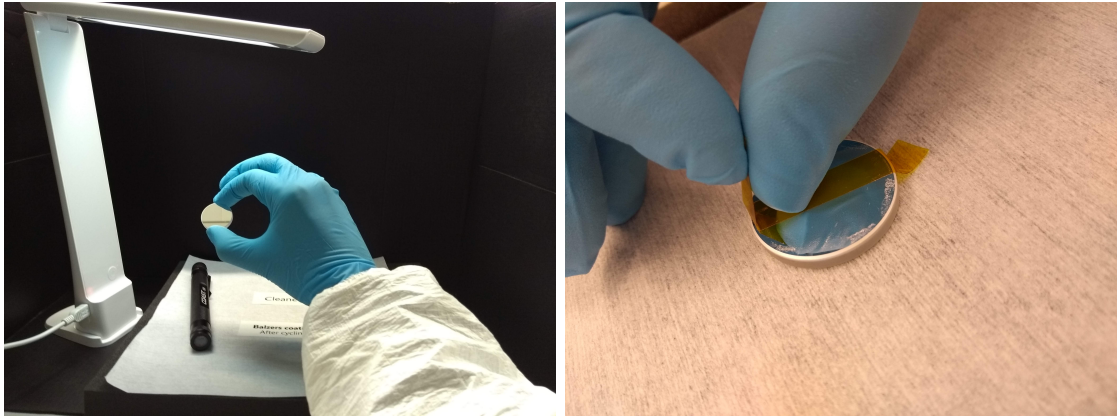


Figure 4.27: (left) Visual examination of optical coatings setup and (right) adhesion test setup

3. Evaluate the coating following ISO 9211-4:2012(E) Annex C procedure and look for any evidence of coating removal.

I followed this procedure for the as-delivered evaluation and after an accelerated lifetime. I did not clean the coating sample at any stage.

4.5.4.4 Results

I carried out the test for a sample of each Asahi coating. I tested the sample in cleanroom conditions at the Beecroft instrument lab. The samples were tested right after being unpacked and without prior manipulation. The Balzers sample of Diflex coating was not tested, given that it is a unique specimen.

I performed the adhesion test on one sample of each coating, and all sustained the maximum grade of 03 in severity²⁹. I then visually inspected the samples and found no evidence of coating removal. With this initial test, I determined that the Asahi coating samples A, B and C had good adherence and resistance before their accelerated lifetime ageing.

I tested again a sample of each Asahi and Balzers coating after the accelerated lifetime ageing process under the exact same conditions as for the initial adhesion test. In this case, the samples were only cleaned after the test. Again, all samples sustained a grade of 03 in severity. I found no evidence of coating removal. The Asahi and

²⁹Samples endure well the harshest grade of severity.

Balzers coating samples can survive a HARMONI accelerated lifetime ageing process without losing their adherence.

4.5.5 Cleaning resistance

4.5.5.1 Description

It is essential to consider the resistance to cleaning when choosing a coating, both to ensure optimum performance the longest possible, and to take this into account when issuing guidance for its handling and usage. For HARMONI, the most likely scenario when a surface might need cleaning is during its assembly and integration. Surfaces could become contaminated while being handled and they should therefore be cleaned prior to assembly to ensure the best performance. For long term maintenance, the coatings that remain under vacuum inside of the IFS cryostat throughout the instrument's lifetime will have depositions that will decrease their performance. Such depositions can be due to dust particles, outgassed materials from other components, or vacuum grease from the cryostat itself. Having a good cleaning resistance will give the option to later regain performance by cleaning the aged surfaces. I devised this test to check if the surfaces could be cleaned without visible degradation while handling them during AIT and after ageing. To achieve this, I cleaned a sample as it came out of its shipping box, cleaned a sample that I contaminated on purpose, and cleaned the samples that I aged with the accelerated lifetime test.

4.5.5.2 Setups

I carried out all cleaning resistance tests in the instrument assembly cleanroom. To clean the surfaces, I used cleanroom wipes with either distilled water, isopropyl alcohol or acetone. Figure 4.28 shows the setup I had for cleaning, part of the procedure and the visual inspection that I carried out.

4.5.5.3 Procedures

I developed this procedure following guidance from Asahi [3] and following my own experience cleaning optics at the optical workshop of INAOE³⁰. These are the steps

³⁰Mexico's National Institute for Astrophysics, Optics and Electronics.

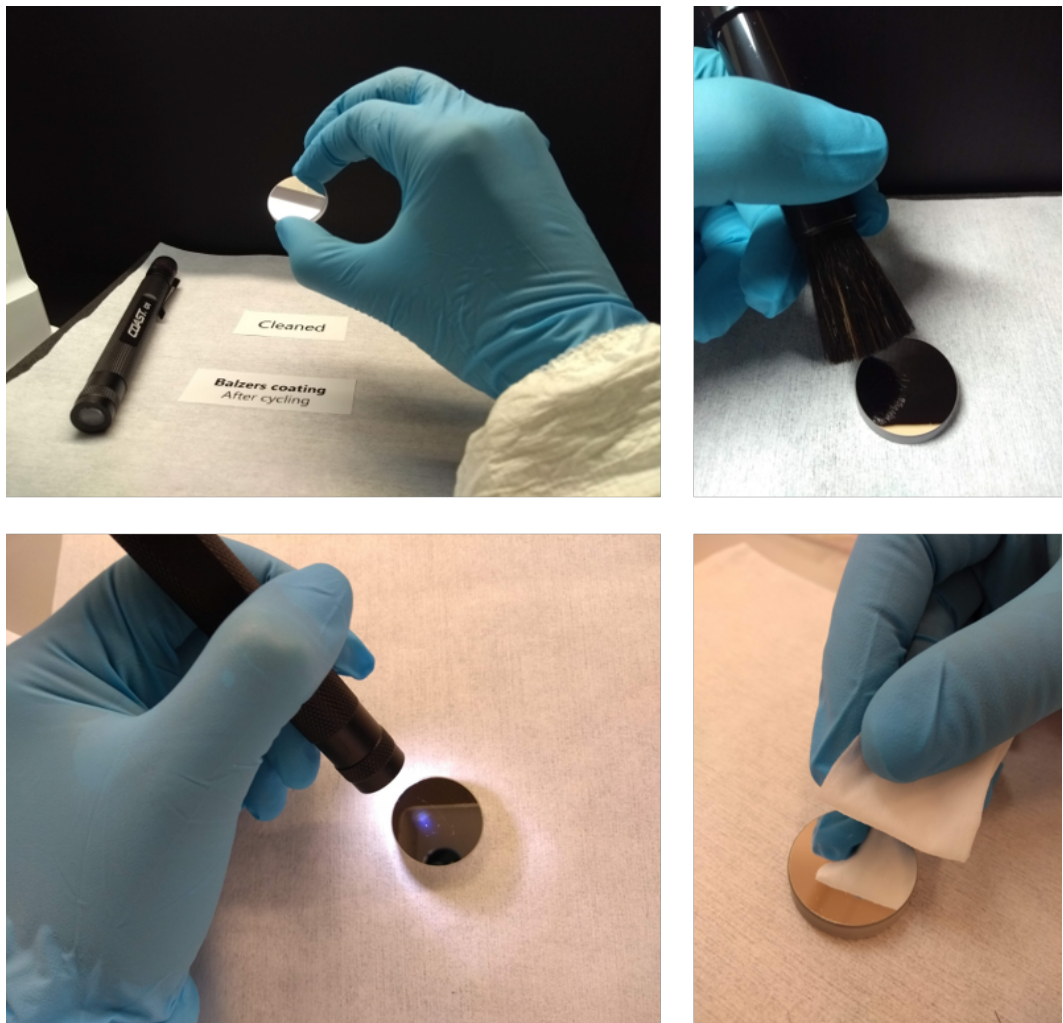


Figure 4.28: Cleaning resistance test setup. Pictures on the left: ISO 9211-4:2012(E) Annex C visual inspection setup. Pictures on the right: removal of large particles with a brush and a wiping example.

that I followed in cleaning the coated surface of the samples:

1. Inspect the sample and identify particles on the surface, stains and imperfections.
2. Remove particles. This can be done with a compressed air blower. The air must be directed parallel to the surface and not perpendicular to avoid scratching the surface with the particles you wish to remove; you must ensure not to spray too long. Large particles can also be removed with a clean anti-static brush. You should brush only once and in one direction and then clean the brush for re-use.
3. Moisten a wipe with distilled water and wipe the surface either from the centre outwards in a spiral motion or from one side to the other. Use each wipe only once and follow the same direction of movement (as if you were pushing the stains out).
4. Moisten a wipe with isopropyl alcohol and repeat the same motion and use each wipe only once. Repeat as needed.
5. Moisten a wipe with acetone and repeat the same motion as before, use each wipe only once and repeat as needed.
6. Inspect the sample following the procedure of visual examination of optical coatings ISO 9211-4:2012(E) Annex C (see appendix [E.2](#))

I carried out the procedure wearing well-fitting gloves to facilitate the handling.

4.5.5.4 Results

I handled and cleaned one sample of each type of Asahi coating and the Balzers sample as they came out of the container shipped by their manufacturer. Then I performed the accelerated lifetime procedure on these samples. I repeated the cleaning test on all samples (including a Thorlabs silver-coated sample that I used as a base comparison reference). Figure [4.29](#) shows results before and after cleaning of the aged the Balzers sample.

The dielectric mirror samples are well suited for cleaning before and after being aged. I found no sample for which the coating was damaged when put in contact with

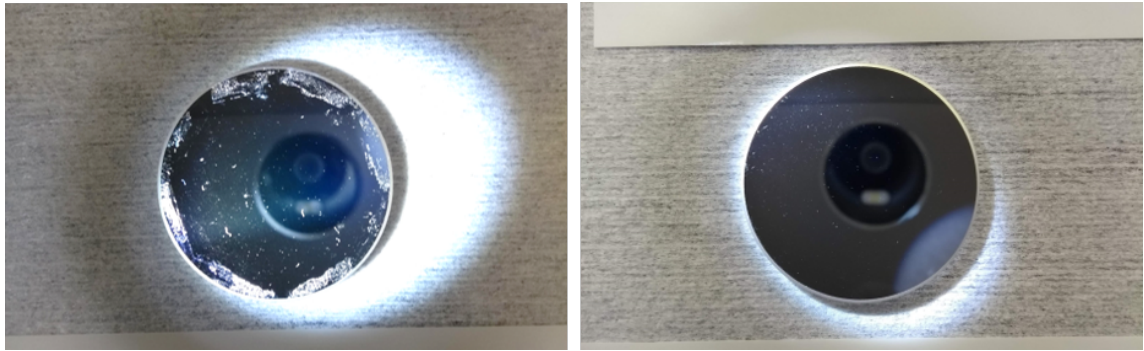


Figure 4.29: Aged Balzers sample. Left, before cleaning after cycling. Residuals from the aluminium tape used for fixation can be seen, as well as deposited dust particles. Right, after cleaning.

cleaning substances. The Balzers sample appears to be more resistant to scratching from cleaning than the Asahi samples. Table 4.8 summarises the results of my observations. Cleaning ease and resistance are characteristics that can describe this type of coating. In this aspect, the coatings are suitable for HARMONI and can survive its operational demands.

Sample	Cleaning at unpacking	Cleaning after cycling
Asahi A	Before: dusty surface; After: adequate cleaning resistance	Before: visible contamination due to ageing, side blemish; After: adequate cleaning resistance, surface as new with minor scratches. ³¹
Asahi B	Before: dusty surface, contaminated on purpose; After: adequate cleaning resistance	Before: visible contamination due to ageing, side stains; After: adequate cleaning resistance, surface as new with minor scratches.
Asahi C	Before: dusty surface; After: adequate cleaning resistance	Before: visible contamination due to ageing, blemished; After: adequate cleaning resistance, surface as new with minor scratches.
Balzers	Before: dusty surface; After: adequate cleaning resistance	Before: visible contamination due to ageing, adhesive marks (see Figure 4.29); After: adequate cleaning resistance, scratch-resistant.
Thorlabs Silver P1	NA	Before: visible contamination due to ageing, adhesive marks; After: degradation due to cleaning, significant scratching.

Table 4.8: Summary notes of cleaning resistance test carried out after unpacking and after undergoing the accelerated lifetime cycling.

4.5.6 Reflectivity

4.5.6.1 Description

This test aims to measure the change in reflective performance before and after ageing the dielectric coating samples³². Moreover, I also measured the performance recovery after cleaning the surfaces after being aged.

The sensitivity of the available equipment limits the results presented in this section. I could only discern that there was no measurable degradation of the coatings³³.

4.5.6.2 Setups

Depending on the availability of the spectrophotometers³⁴, I measured the sample's reflectivity for each coating with a Perkin Elmer Lambda 1050 Spectrophotometer or with a Perkin Elmer Lambda 750 Spectrophotometer. Both spectrophotometers have similar characteristics, wavelength ranges and lamp types. The spectrophotometers are equipped with an integrating sphere accessory to perform reflectivity measurements at an 8-degree angle of incidence. Figure 4.30 shows the setup for the Perkin Elmer Lambda 1050 Spectrophotometer in the Engineering Science department at the University of Oxford. I placed the coating samples in the sample reflectance port of the integrating sphere, as shown in Figure 4.30. I used a Spectralon reflectance standard for calibration and gloves for handling the samples in both setups.

4.5.6.3 Procedures

1. Place the integrating sphere accessory following the operator's manual.
2. Turn on the spectrophotometer and wait for 30 minutes to achieve full stability.
3. Set the measurement program to *total reflectance* with an 8-degree wedge.

³²Keeping in mind that measuring the change in performance indicates whether the coatings are suitable for HARMONT's operational condition and how they perform over time.

³³It turned out that measuring minor reflectivity variations on coatings with a very high reflectivity was a calibration challenge.

³⁴The Perkin Elmer Lambda 1050 Spectrophotometer was out of service for more than six months, and the Perkin Elmer Lambda 750 Spectrophotometer underwent recalibration in between testing.

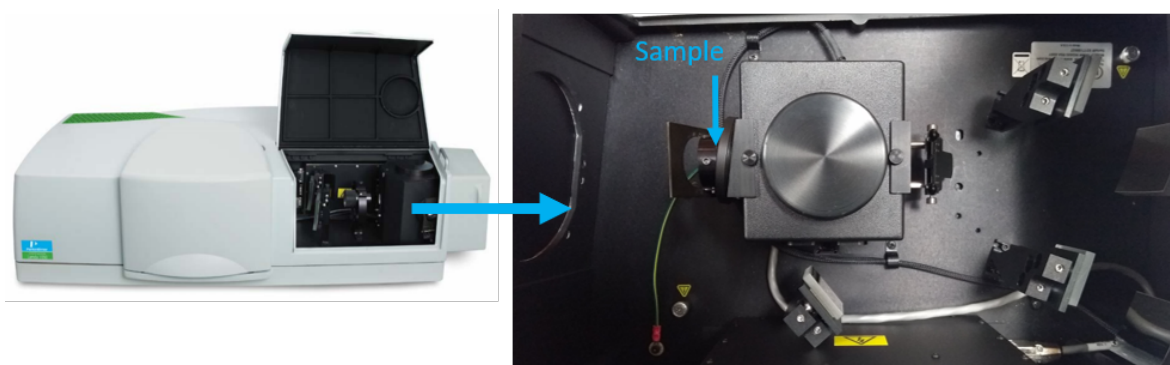


Figure 4.30: (left) Perkin Elmer Lambda 1050 Spectrophotometer (Credit: Perkin Elmer) (right) Integrating sphere accessory. The samples are placed on a sample holder in the aperture for a total reflectance configuration. The reference beam enters the module and reflects onto three mirrors (bottom mirrors) before entering the integrating sphere on the side. The sample beam enters the module, reflects onto two mirrors (top mirrors), and enters the integrating sphere through the 'transmission' port. The integrating sphere is equipped with an internal detector which records the measurements.

4. Place a Spectralon reflectance standard in the sample reflectance port of the integrating sphere and record the calibration baseline.
5. Clean and place a coating sample in the reflectance port of the integrating sphere, close the spectrophotometer compartment and record three measurements. Measure samples in the following order:
 - (a) ThorLabs silver coated sample.
 - (b) Asahi A.
 - (c) Asahi B.
 - (d) Asahi C.
 - (e) Balzers.
6. Place the spectralon reflectance standard in the sample reflectance port of the integrating sphere, close the spectrophotometer compartment and record three measurements.

4.5.6.4 Results

I measured the reflectivity at 8 degrees AOI of one Asahi A, Asahi B, Asahi C and a Diflex Balzers coating sample before thermal cycling (TC), after thermal cycling, and after cleaning the surfaces. Figure 4.31 shows the measurements for these three cases for each coating, along with either its closest available 8 degrees AOI model or measurement provided by the manufacturer³⁵.

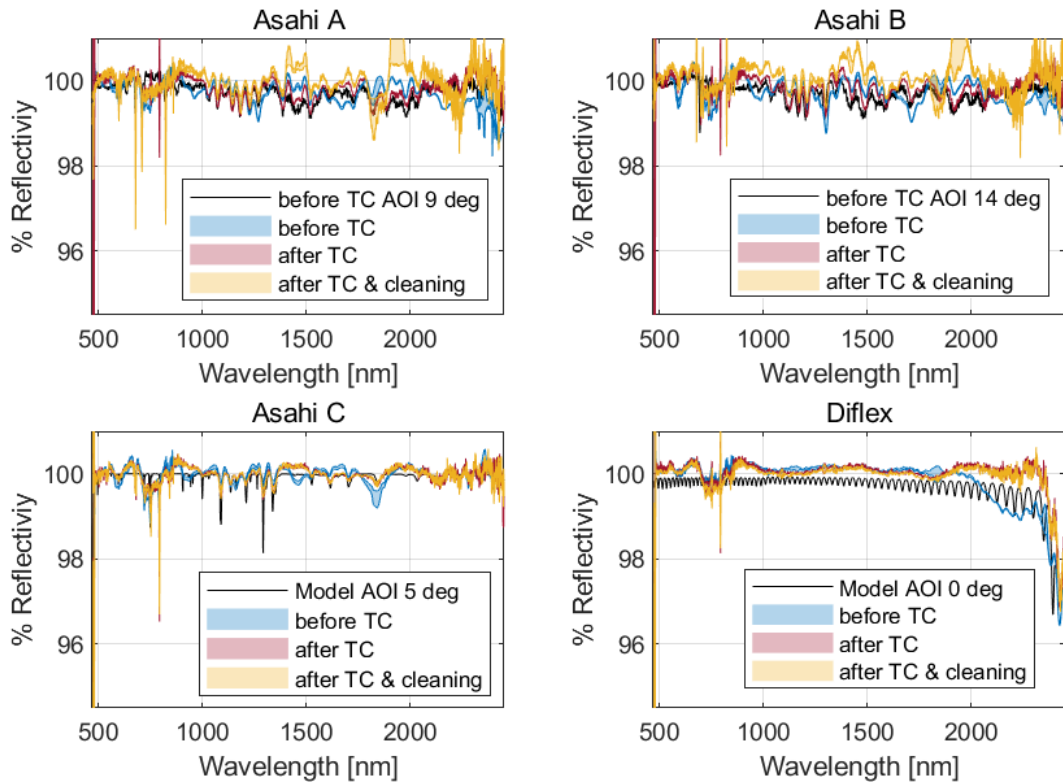


Figure 4.31: Reflectivity measurements of the coating samples Asahi A, B and C, and Diflex Balzers before and after thermal cycling, including after thermal cycling and cleaning. Most of the differences in reflectivity are due to the non-repeatability of the equipment rather than changes in the samples. Shaded areas indicate random errors in the measurements.

The measurements were carried out on the 4th of October 2019 (before TC), 20th of January (after TC) and 25th of January 2020. It is vital to mention that a Perkin Elmer engineer calibrated the spectrophotometer in engineering science between the 20th and 25th of January, making the measurements inconsistent for precise comparison; thus,

³⁵An indication of the systematic error is the measurements going above 100% reflectivity.

these measurements are only indicative. To compare the measurements, I calibrated the measurements with a Thorlabs Silver coating type P01 at 45-degrees [57]. The Thorlabs Silver coating data for 12 degrees AOI was not employed to calibrate for the band 470-1000 nm as it was impossible to differentiate the error from the spectrophotometer change in calibration and the calibration error itself. The 45-degree curve gave the best quality correction.

Given the change in spectrophotometer calibration between the after-thermal-cycling and after-thermal-cycling-*and-cleaning* measurements of the Asahi A and B samples, I applied a brightness correction based on the Thorlabs Silver coating to the after-thermal-cycling-*and-cleaning* measurements.

I calculated a spline with the Asahi C measurement, which I employed for shape correction for all measurements to remove the added errors of the spectrophotometer lamp change, monochromator and the Thorlabs Silver coating type P01 model deviation. I paid particular focus on the band 470-1000 nm.

The shaded areas in the plots of Figure 4.31 are the random measurement errors per case, given by

$$e_t = \sqrt{\sigma_m^2 + \sigma_t^2 + e_{fit}^2}, \quad (4.9)$$

where σ_m is the standard deviation calculated from 2-4 measurements per coating type per case, σ_t is the machine measurement repeatability which I calculated by measuring a Thorlabs samples 10 times and e_{fit} is the error on the spline fit for the Asahi C measurement per case. Note that these errors do not take into account systematic error terms covering the biases in the equipment which make up the largest errors in these measurements.

The main result of this test is that the reflectivity is not measurably degraded after thermal cycling. Something to note is that even after thermal cycling, the reflectivity is better than the typical silver coating with 98%. Considering the nature of the measurements, it is not possible to say how much reflectivity changes after thermal cycling and if there is a significant improvement in performance after cleaning the thermally cycled samples, though removing the dust particles and cryostat contamination should improve performance. Raw measurements of Asahi C and Diflex Balzers indicate a slight gain in reflectivity after cleaning.

4.6 Conclusions

4.6.1 Summary

In Section 4.2, I identified the reflective surfaces in HARMONI and found their shape, size and characteristics. In HARMONI, the science light is reflected 23 to 27 times³⁶ from the instrument's entrance up to the detectors. Throughout the instrument, in total, there are four mirrors in the FPRS, 25 in the PO, 1176 in the IFU and 20 in the ISP. The mirror's angle of incidence distribution varies from 0 to 55 degrees, which can be subdivided into three ranges, 0-14, 14-35 and 35-55 degrees (Section 4.2.2). Regarding size (Section 4.2.3), there are 24 mirror types smaller than 100 mm either in diameter or longest edge, 11 range from 101-400 mm and eight are larger than 401 mm. Most surfaces are flat or have slow spheres. There are toroidal surfaces in the PO and several parabolas in the PO and ISP.

In Section 4.3, I confirmed that there are companies that have the capabilities to design and make broadband dielectric coatings for HARMONI's wavelength range. I started by defining the coating requirements (Section 4.3.1) and organised them into two categories: reflectivity performance and survivability to operational conditions. For the reflectivity performance, the coating should have high reflectance over the 0.47 to 2.45 μm range with a primary focus on 0.8 to 2.4 μm . The reflectance performance should be higher than a typical enhanced silver coating design. The dips and features of the coating design are recommended to be tuned within the atmospheric gaps. The coating should cover the angle of incidence range and can be split into two or three ranges (I proposed three). For the survivability to operational conditions, the mirror coatings in the FPRS must survive and operate at -15°C in an enclosure of dry gas. Mirror coatings in the IFS must survive and operate at 130K in vacuum conditions. All coatings must resist a 15-year operation with a minimum of 20 cool-down and warm-up cycles. Then I contacted coating companies and found three who could design and manufacture a dielectric mirror coating for HARMONI's wavelength range: Viavi, Asahi and Optics Balzers. We purchased samples from Asahi and Optics Balzers.

³⁶The variation depends on the instrument's configuration.

Asahi had not manufactured a coating with so many layers before, and they developed this capability for this project.

In Section 4.4, I identified the eligible surfaces in HARMONI to apply a dielectric mirror coating (see Tables 4.3, 4.4, 4.5 and 4.6 in the case 2 column). The eligible surfaces are (Section 4.2.4): flats and spheres with a large curvature radius ($>800\text{mm}$) and with a size range of up to 200 mm. Then, I assigned a coating design to the eligible surfaces matching their angle of incidence range and found gain improvements per subsystem and in the E2E transmission when compared with an all-silver enhanced coating case. The FPRS shows an average reflectivity improvement of 0.39% (see Figure 4.14). The PO shows an average improvement per scale of 1.34% for 60×30 mas, 0.07% for 20×20 mas, 2.67% for 10×10 mas and 2.88% for 4×4 mas (see Figure 4.15). The IFU shows an average improvement of 0.85% (only the CDGH path was calculated; see Figure 4.16). The ISP shows an average improvement of 2.22% (see Figure 4.17). The overall instrument transmission improves for all grating wavelength ranges. For LTAO 60×30 mas with IFU paths CDGH, the improvement is at least 3% in the average transmission over the central 80% of each gratings wavelength range (see Figure 4.7). The most considerable improvement occurs for the J band R18000, with a 10% increase in the average transmission over the central 80% of the wavelength range.

In Section 4.5, I defined how I could evaluate the survivability of the purchased samples and aged a sample of each purchased coating through an accelerated lifetime test. I inspected the samples (Section 4.5.3) before thermal cycling, after thermal cycling and again after cleaning. I did an adhesion test (Section 4.5.4) on the samples before thermal cycling and after thermal cycling. I checked that the coating samples resisted cleaning without visible degradation before and after thermal cycling. Lastly, I measured the reflectivity of the samples over HARMONI's wavelength range before thermal cycling, after thermal cycling and again after cleaning. I confirmed that the samples survived HARMONI's operational conditions and did not degrade below the requirements. I could not find potential issues in the coatings after purchase nor significant deterioration due to the accelerated lifetime cycling.

4.6.2 Implications

This research has direct implications for the astronomical instrumentation field. It proves that broadband dielectric coatings can be designed and manufactured and provides experimental evidence of their survivability for HAMRONI’s operational conditions. This work opens the possibility of implementing such dielectric mirrors in HARMONI and in future astronomical instruments.

The presented transmission estimates represent the transmission of perfectly clean and new coatings and do not include the effects of either dust or ageing, which will reduce the total transmission. The initial assumption in the overall budget is that each surface will end up having 0.5-1.0% dust coverage, which is a direct hit of 0.5-1.0% on that surface’s transmission. Further work is needed to explore the impact of ageing and dust and produce improved instrument transmission and throughput estimates.

4.6.3 Practical applications

Dielectric mirror coatings are feasibly applicable to HARMONI’s reflective surfaces. In this chapter, I presented evidence that they will survive HARMONI’s operational conditions, that they perform efficiently throughout the instrument’s lifetime, and that they can significantly increase the instrument’s throughput. There are a few recommendations for applying these coatings that I would like to note.

Design We requested Asahi to match the inherent dips of the dielectric coatings with the atmospheric absorption windows, if possible. Some dips in Section 4.4 correspond to absorption bands between the gratings bands, thus not impacting the band’s transmission. Understanding the instrument’s transmission requirements and moving dips in the design to match these gaps can make designing easier and benefit the transmission.

Sizes and curvatures Manufacturers constantly improve their facilities, and projects like HARMONI have long developing timelines. What was true at the time of initial contact might not apply years later when the project is ready for purchase. Maintaining communication with the companies is fundamental as the eligibility

criteria might change. The eligible surfaces for case 2 in Section 4.4 follow criteria valid around November 2018 to July 2019.

Assemblies Optical elements made up of assemblies of surfaces are not considered eligible in this thesis because of their complexity, but could in theory be coated as dielectric mirrors. For example, the field splitter is an assembly of small flat mirrors; if the mirrors are coated before being assembled, there is a possibility of applying dielectric coatings to these surfaces, as applying the coating after assembly poses the challenge of achieving uniformity in flat surfaces at various angles. The coating method for the field splitter would need to be discussed with the optics manufacturer and the coater.

4.6.4 Evaluation and future work

4.6.4.1 Compression stress

This work confirmed that reflective dielectric coatings for our wavelength range were available on the market and could be purchased from different companies. It has provided experimental proof that an optical element sustaining hundreds of layers and the associated compression stress can be thermally cycled while maintaining its quality. To apply these coatings to HARMONI's surfaces, more work must be carried out to characterise the compressive stress on the coated surface and how this changes its surface form.

1. The impact of the coatings' compressive stress on the surface form can be modelled and quantified. The compression stress for the MUSE multi-dielectric coatings was modelled successfully (see Ref. [49]).
2. Dielectric mirror coatings can be applied on sample surfaces (flat and with curvature) to test the model's accuracy. The model's surface form predictions must be reliable because they will determine the surface manufacturing specifications, and they should predict the final surface from an initial form before coating.
3. The surface selection can be refined with these new eligibility criteria.

Another possible option to counteract the compression stress applied on the coated surfaces would be to coat the optics' back surface. However, this option would need to be modelled and tested; one might end up with a mirror deformed on both surfaces.

4.6.4.2 Eligibility criteria

The criteria to assign dielectric coatings to the reflective surfaces prioritise small, flat or slow spheres because these fit the manufacturer's facilities, and it is possible to easily control the layer thickness over the entire coated area for these surfaces. This could offer the best cost-benefit gain because several small surfaces could be coated simultaneously. Surfaces with more complex surfaces and larger sizes could be suited for dielectric coating if the manufacturer and interested parties prove that the surface form can be maintained within tolerance, including that the coating maintains its quality at operational temperatures. If this could be done, it would open up the possibility of applying coatings to large flat mirrors, such as the fold mirrors of the spectrograph subsystem. This research has fulfilled its goal of proving that dielectric mirror coatings can be manufactured and are suitable for HARMONI's operational conditions. However, the results are limited to samples of 25 mm diameter with a flat surface.

4.6.4.3 Polarisation

Dielectric mirror coatings have a different reflectivity performance for S and P polarisation. However, the instrument is not designed to detect polarisation. The difference in S and P reflectivity is not a concern due to the number and nature of the reflections and refractions involved in the instrument's science path. The caveat is that if you have a sequence of mirrors with common angles, you could end up polarising the light further along in the instrument. The optics team will examine this issue further in the E2E model analysis.

4.6.4.4 Radioactivity

For this research, I did not test if the coatings were radioactive. The coating manufacturers did not indicate this as a warning, but given that this could be a grave issue for

the instrument's detectors, it is essential to verify that this is not the case. This issue could be addressed in further work.

4.6.4.5 Curve structure or wiggles

The designs of dielectric mirrors from this research show structure or wiggles in their reflectivity curves. These wiggles have an angle of incidence dependence as shown in Figure 4.13. HARMONI being a spectrograph, a high-frequency structure in the coating performance could be problematic. However, the range of incidence angles in the HARMONI optics and the combination of various coatings means that the structure can smooth out the end-to-end reflectivity. This behaviour can be seen in the subsystem transmission curves for case 2 in Section 4.4 when dielectric and silver mirrors are combined. The transmission plots in Section 4.4 indicate that if a structure is a concern, a purely dielectric coating mirror system would not be optimal, and a combination with other coatings would smooth out the structure.

4.6.4.6 Laboratory conditions

The tested samples survive cryogenic conditions with temperatures from 320K to 130K and with a vacuum pressure range of 10^3 mbar to 10^{-6} mbar. For this research, experiments were carried out in similar conditions to how HARMONI optical surfaces would be handled. HARMONI optics will be stored and handled in a laboratory with cleanroom class 7 (ISO 14644-1) at a temperature of 20 ± 5 °C and a humidity of up to 50%.

Chapter 5

Conclusions

This Section presents a concise conclusion of my thesis. It demonstrates that my overall goal of providing a solid, reproducible and expandable base for the development of HARMONI and of future astronomical instruments has been met.

5.1 Summary

Chapter 1 describes HARMONI as a pioneering ground-based astronomical instrument due to its size, level of integration complexity and the fact that it will be the first IFS to operate on an ELT. The research gap that the thesis addressed focuses on two development challenges that the instrument faces: implementing a lens mount for HARMONI's spectrograph cameras which meets the challenging alignment tolerance at cryogenic operating temperatures, and evaluating the feasibility of implementing dielectric mirror coatings to enhance instrument throughput.

Chapter 2 demonstrated that flexure lens mount assemblies can be implemented for the HARMONI spectrograph cameras and proposes tangible steps for resolving identified design shortfalls to achieve alignment at room temperature. The Chapter comprehensively explains lens mount assembly technology, addressing factors influencing performance, alignment parameters, and integration considerations. The presented work regains and significantly increases the technology readiness level (TRL) of lens mount assemblies for HARMONI camera lenses. The Chapter defines alignment parameters for lens mount assemblies and how they interface with camera alignment. Detailed mounting and assembly procedures are presented, offering a step-by-step guide

for assembling lens mount assemblies in a repeatable and reproducible way. Furthermore, the Chapter presented a tolerance stack of two lens mount engineering models, providing an understanding of the factors impacting room temperature alignment. The Chapter provides valuable feedback to the D&A and AIT teams, contributing to improved lens mount technology for HARMONI. It also proposes a clear development pathway, addressing historical issues and providing a roadmap for future work in this field.

Chapter 3 validates two flexure lens mount engineering models in a HARMONI-simulated operational environment, characterising their radial alignment at 130 K thermal equilibrium as well as their survivability through thermal cycling. The measurement analysis presented in the Chapter concludes that the $\pm 20\mu m$ requirement is marginally met. Considering testing uncertainties and design limitations, I validate the flexure lens mount design to reliably meet $\pm 30\mu m$ for lenses with a diameter in the $\sim 200\text{mm}$ range. The Chapter verifies that the assembled engineering models can effectively survive HARMONI's operational conditions without causing lens fractures or bond degradation. Furthermore, to demonstrate radial alignment measurements, I presented a method for tracking radial misalignment of flexure mounts through thermal cycling.

Chapter 4 demonstrates that dielectric mirrors are a feasible technology at TRL 3 for the HARMONI instrument, and it provides insight into the potential throughput gain if dielectric mirrors were to be applied on eligible surfaces. The Chapter begins by identifying the reflective surfaces within the HARMONI instrument, categorizing them by their shape, size, and characteristics and assessing the applicability of dielectric coatings to each. The Chapter outlines coating requirements for dielectric mirror coatings based on reflectivity performance through HARMONI's wavelength range and survivability to HARMONI's operational conditions. The research project identified three companies capable of designing and manufacturing broadband dielectric coatings for HARMONI's wavelength range: Viavi, Asahi, and Optics Balzers. We purchased coating samples from Asahi and Optics Balzers to evaluate their performance and survivability. I present procedures and promising results for adhesion tests, cleaning resistance tests, and reflectivity measurements before and after thermal cycling.

5.2 Implications

The research presented in Chapters 2 and 3 has regained and increased the technological maturity of the flexure lens mount design for application in the HARMONI spectrograph cameras. Analysing the tip and tilt alignment of the two lens mount engineering models during assembly at room temperature provides concrete actions and parameters to improve the design and setup limitations. Then, the radial alignment measurements for these models elucidate for the first time the behaviour of the KMOS/FMOS flexure lens mounts in operational conditions, quantifying the lens displacement from room temperature to 130K equilibrium. The radial alignment results will provide feedback into the instrument design on what is feasible for the cold alignment of the lenses and, hence, what can be assumed in the optical design and performance analysis. The presented developments provide confidence in the camera design and its capabilities to be reliably adopted for the instrument. This thesis will further enable detailed design and AIT, and RALSpace will realise these work packages for HARMONI. Furthermore, this thesis provides an accessible basis for designing and developing future astronomical instruments.

The results presented in Chapter 4 quantify the substantial throughput gain when assigning dielectric mirror coatings to eligible surfaces, increasing the instrument's scientific potential. This thesis proved that dielectric coatings can be designed for broad wavelength ranges and withstand cryogenic conditions; therefore, further validation for larger surfaces and characterization of the coating compression stresses are worth exploring. Dielectric mirror coatings must be seriously considered for eligible surfaces in the HARMONI science path if a development timeline for further validation can be integrated into the manufacturing schedule. Moreover, if technology maturation timelines are incompatible with HARMONI's realisation, they are worth pursuing for future astronomical instruments. Throughout my DPhil, I have seen evidence that more and more companies are producing dielectric mirrors, making the market more competitive and accessible.

5.3 Evaluation and future work

The more you learn, the more you see your limitations and the potential for improvement.

The work presented in Chapter 2 requires further characterisation to validate the survivability of lens mount assemblies with the KMOS/FMOS flexure design during shipping. The test that J. Capone performed for the slotted mount ring design prototypes by Jamie Allen in the shaker table should be repeated for the lens mount engineering models that I assembled, to validate them for shipping. Additionally, detailed design work is needed on optimising bond area and thickness for each HARMONI lens to minimise alignment errors introduced by the elasticity of bonds, ideally validating it with a HARMONI lens. If a CMM is unavailable for assembly, it is worth investing in a high-quality rotary table *with well-characterised error motion* to ensure precise alignment during assembly. The existing mount jig would benefit from further developed to accommodate additional degrees of freedom for lens alignment. Future work should explore procedures for assembling and curing lens mount assemblies in series.

The limitations of the results presented in Chapter 3 lie in the convoluted challenge of measuring test parameters while developing the test setup. Every run carries improvement and lower measurement errors, making results difficult to compare. Further radial measurement tests employing image registration should change the camera focus when reaching 130 K to minimize measurement errors¹ at cold thermal equilibrium. Additionally, thermal cycles should be carried out with the final flexure design for the HARMONI lenses considering the improvements from Chapter 2 to confirm the presented radial misalignment.

For Chapter 4, future work should model and test for surface deformations at operational conditions, as the optical performance of the reflective surfaces has been designed at 130 K. Power error must be quantified through cooldown to set manufacturing specifications for eligible optical surfaces. Additionally, a more detailed transmission analysis with the instrument's end-to-end optical model should be carried out to calculate

¹A slower beam could also provide a larger depth of focus.

accurate transmission estimates, use 3D angles of incidence and review the potential impact of polarisation.

5.4 Final remarks

Throughout my DPhil, I shared my findings, trained others on the techniques I developed, organised the historical information I could gather, and did what I could to record my results to be repeatable and reproducible. I sincerely wish that the outcome of my work expressed in this thesis serves the HARMONI collaboration and future astronomical instruments beyond granting me a DPhil degree.

Appendix A

Dielectric coatings project

A.1 Manufacturers contact details

Optics Balzers

- Sales: Armin Rupp, armin.rupp@opticsbalzers.com
- Production: Dr. Thomas Weber, thomas.weber@opticsbalzers.com
- Optics Balzers Jena GmbH, Otto-Eppenstein-Straße 2, 07745 Jena, Germany
- <https://www.materionbalzersoptics.com/en/>

Asahi Spectra Co., Ltd.

- Sales: Toshihiko Kimura, t-kimura@asahi-spectra.co.jp
- Gardenia Bldg. 4F, 2-13-1 Kamijujo, Kita-ku, Tokyo 114-0034 Japan
- <https://www.asahi-spectra.com/>

Viavi-OSP

- Sales: Rick Zoborowski, rick.zoborowski@ViaviSolutions.com
- 1402 Mariner Way, Santa Rosa, CA 95407, USA
- <http://www.viavisolutions.com/osp>

A.2 Documentation

Table A.1: Project proposal

https://harmoni.physics.ox.ac.uk/_layouts/15/DocIdRedir.aspx?ID=4JY3FNXR53KP-2102554853-18133



Table A.2: Documents from industry manufacturers

Asahi, coating samples quote
https://harmoni.physics.ox.ac.uk/_layouts/15/DocIdRedir.aspx?ID=4JY3FNXR53KP-2102554853-18134



Optics Balzers, feasibility project quote
https://harmoni.physics.ox.ac.uk/_layouts/15/DocIdRedir.aspx?ID=4JY3FNXR53KP-2102554853-18136



Optics Balzers, coating sample quote
https://harmoni.physics.ox.ac.uk/_layouts/15/DocIdRedir.aspx?ID=4JY3FNXR53KP-2102554853-18135



Viavi feasibility project quote
https://harmoni.physics.ox.ac.uk/_layouts/15/DocIdRedir.aspx?ID=4JY3FNXR53KP-2102554853-18137



Table A.3: Diflex coating product information

Description https://harmoni.physics.ox.ac.uk/_layouts/15/DocIdRedir.aspx?ID=4JY3FNXR53KP-2102554853-18148



Datasheet https://harmoni.physics.ox.ac.uk/_layouts/15/DocIdRedir.aspx?ID=4JY3FNXR53KP-2102554853-18147



Table A.4: HARMONI transmission budget model

Model and non-reflective coatings https://harmoni.physics.ox.ac.uk/_layouts/15/DocIdRedir.aspx?ID=4JY3FNXR53KP-2102554853-7008



FPRS transmission model https://harmoni.physics.ox.ac.uk/_layouts/15/DocIdRedir.aspx?ID=4JY3FNXR53KP-2102554853-4117



Appendix B

Flatness measurements

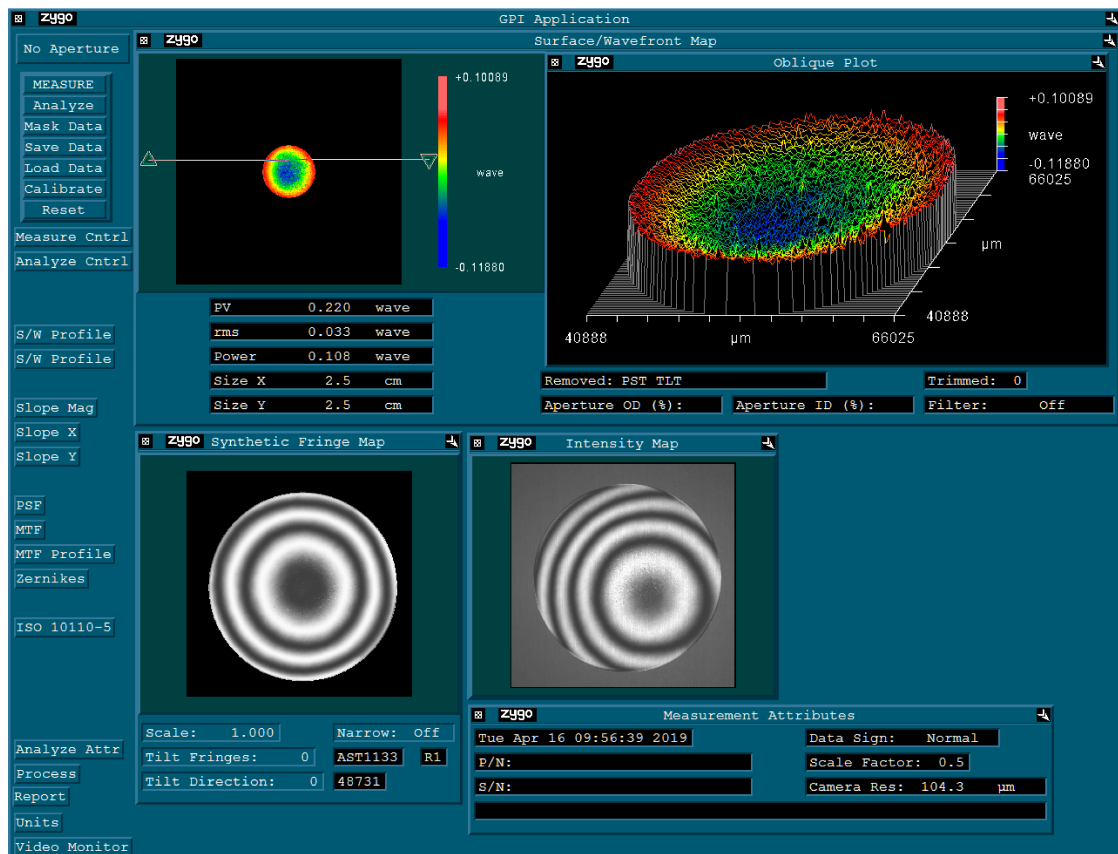


Figure B.1: Interferometer flatness measurement for Asahi coating samples prior to coating application for types A and B (Provided by Asahi Spectra Co., Ltd.)

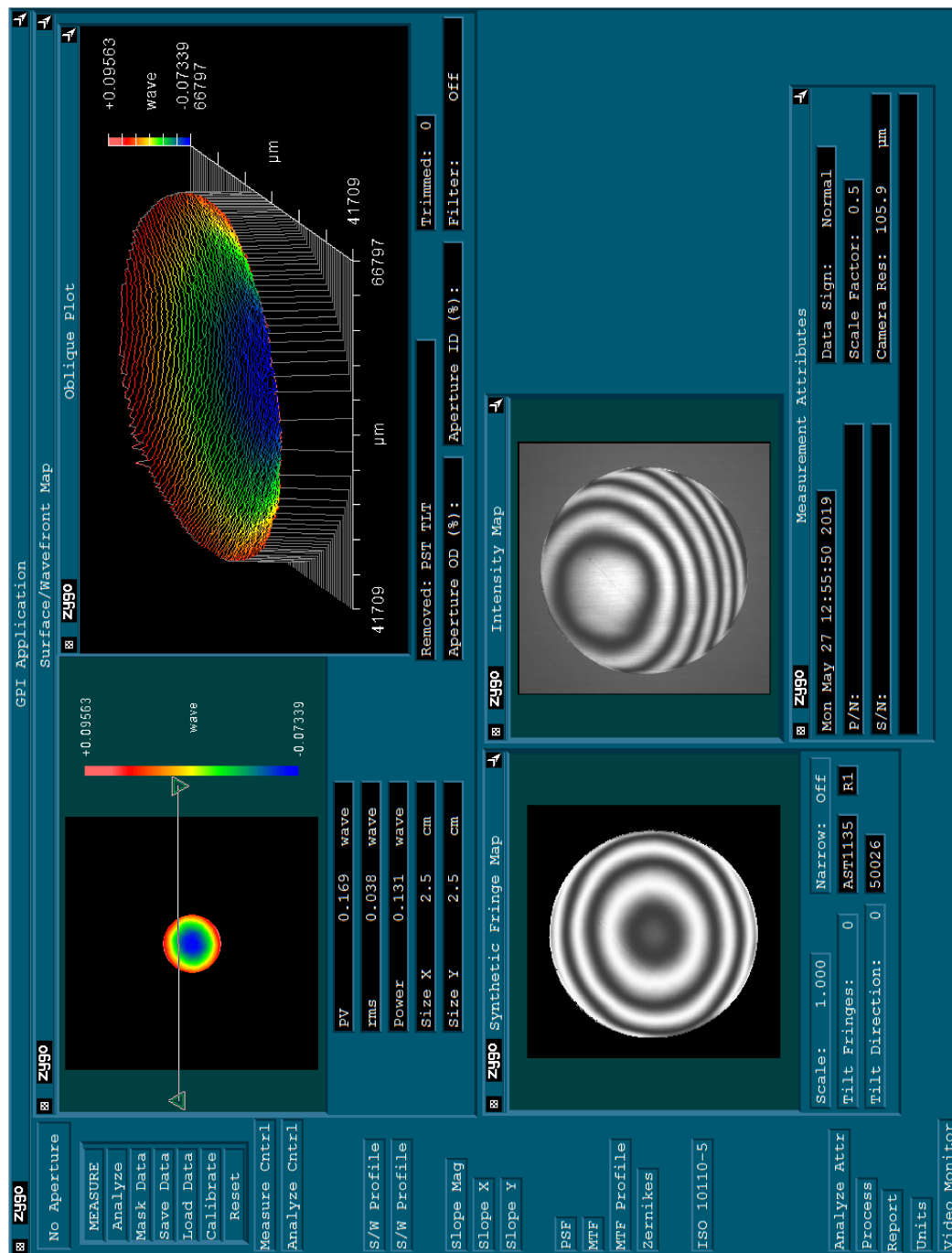


Figure B.2: Interferometer flatness measurement for Asahi coating samples prior to coating application for type C (Provided by Asahi Spectra Co., Ltd.)

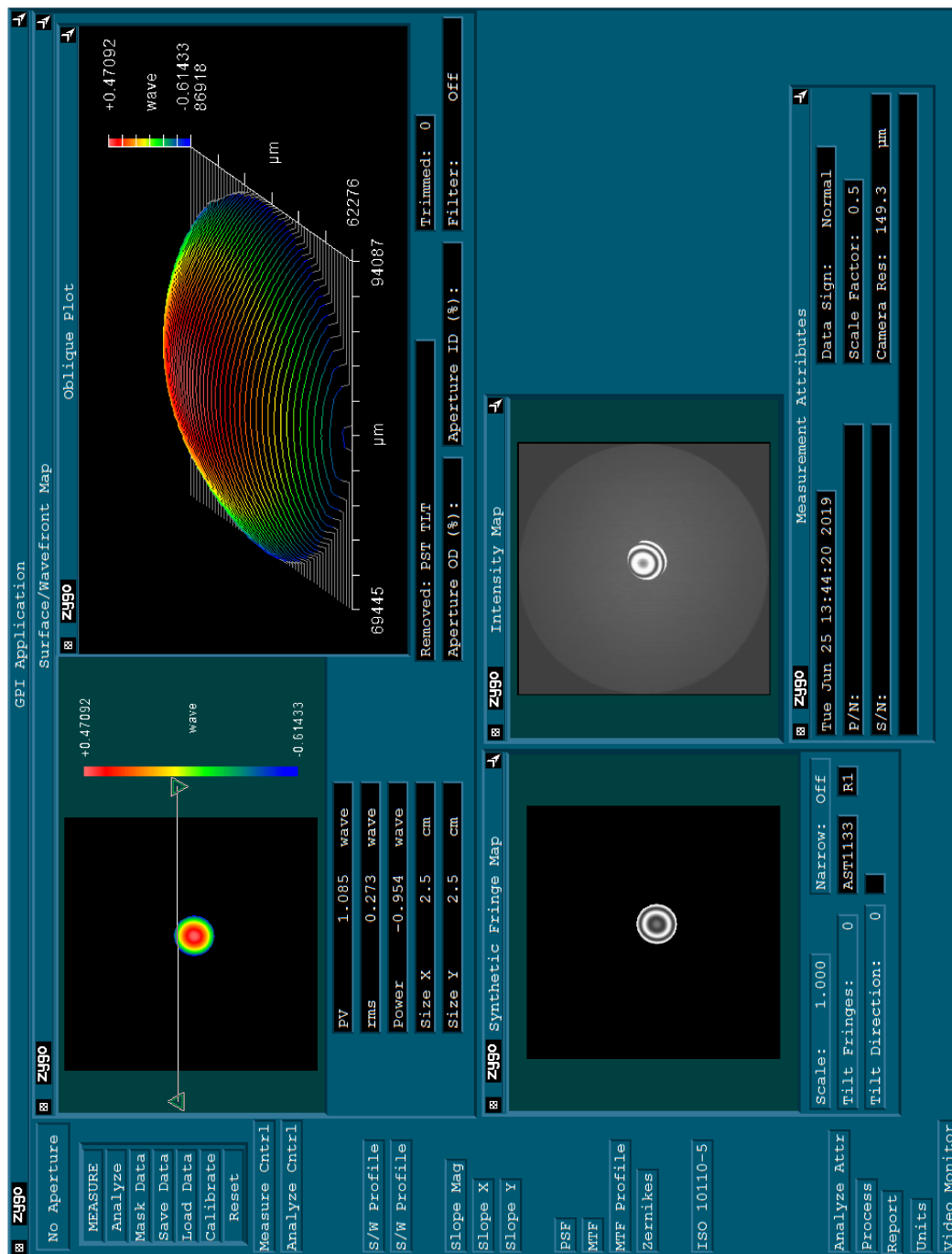


Figure B.3: Interferometer flatness measurement for Asahi coating type A after coating application (Provided by Asahi Spectra Co., Ltd.)

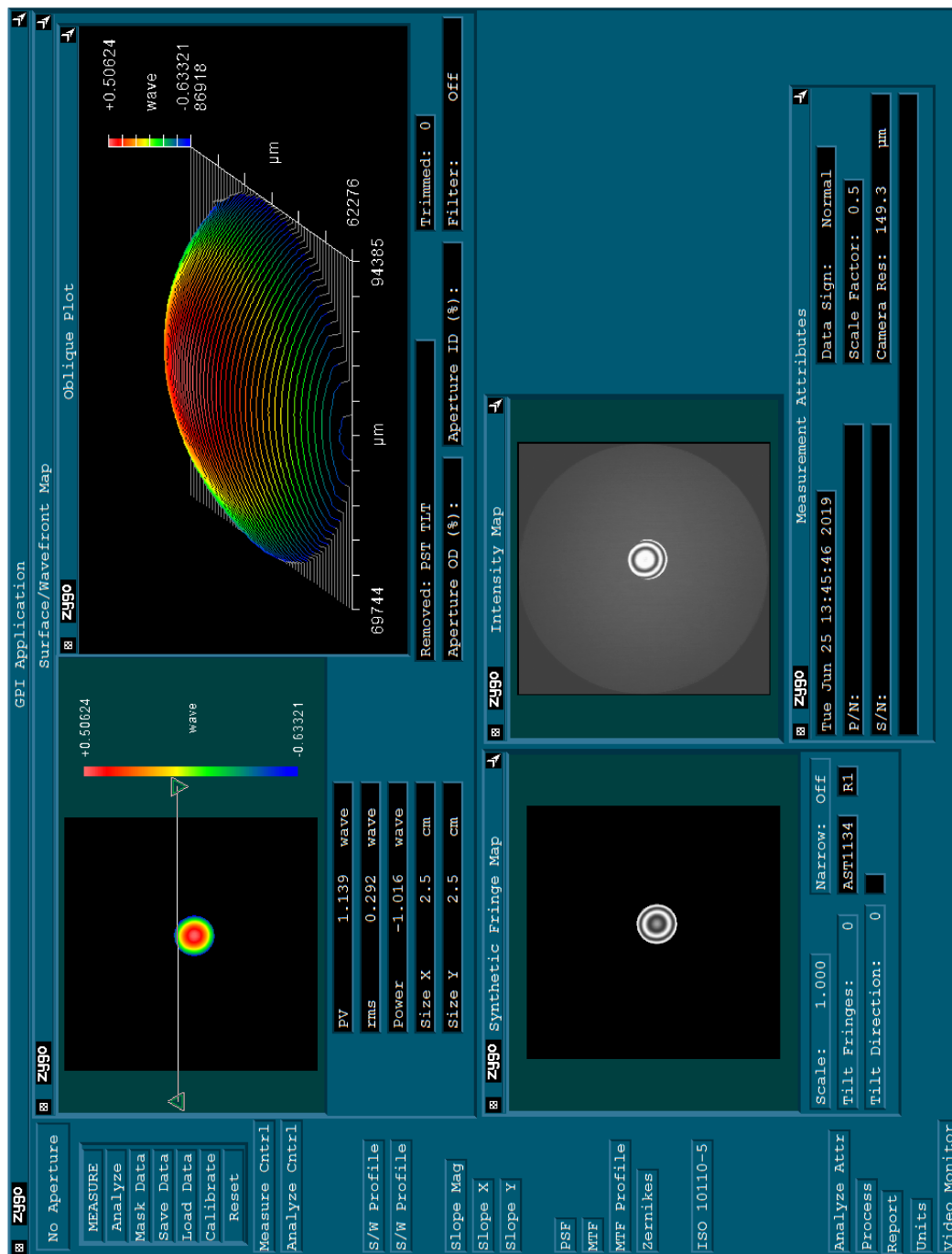


Figure B.4: Interferometer flatness measurement for Asahi coating type B after coating application (Provided by Asahi Spectra Co., Ltd.)

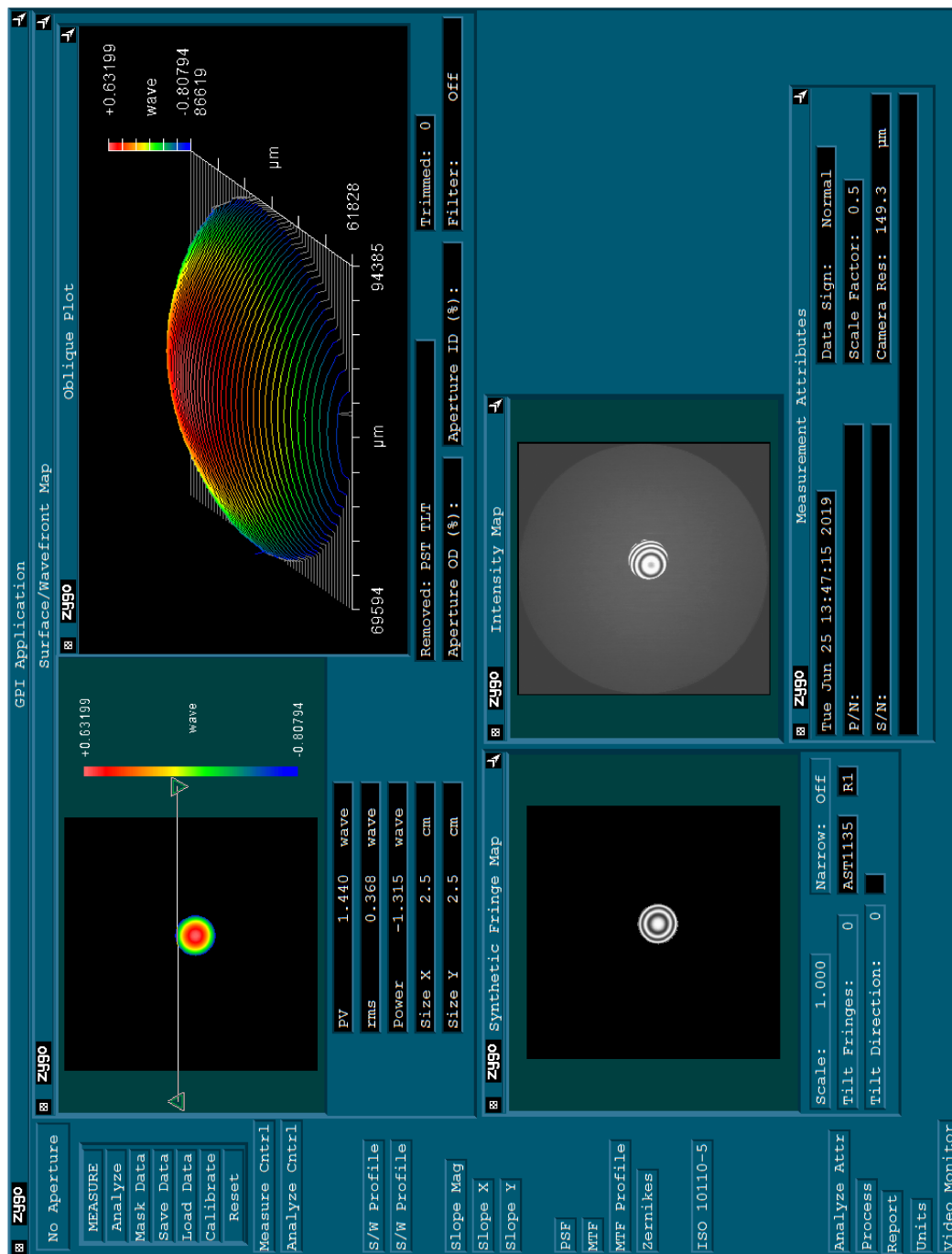


Figure B.5: Interferometer flatness measurement for Asahi coating type C after coating application (Provided by Asahi Spectra Co., Ltd.)

Appendix C

Reflectivity measurements

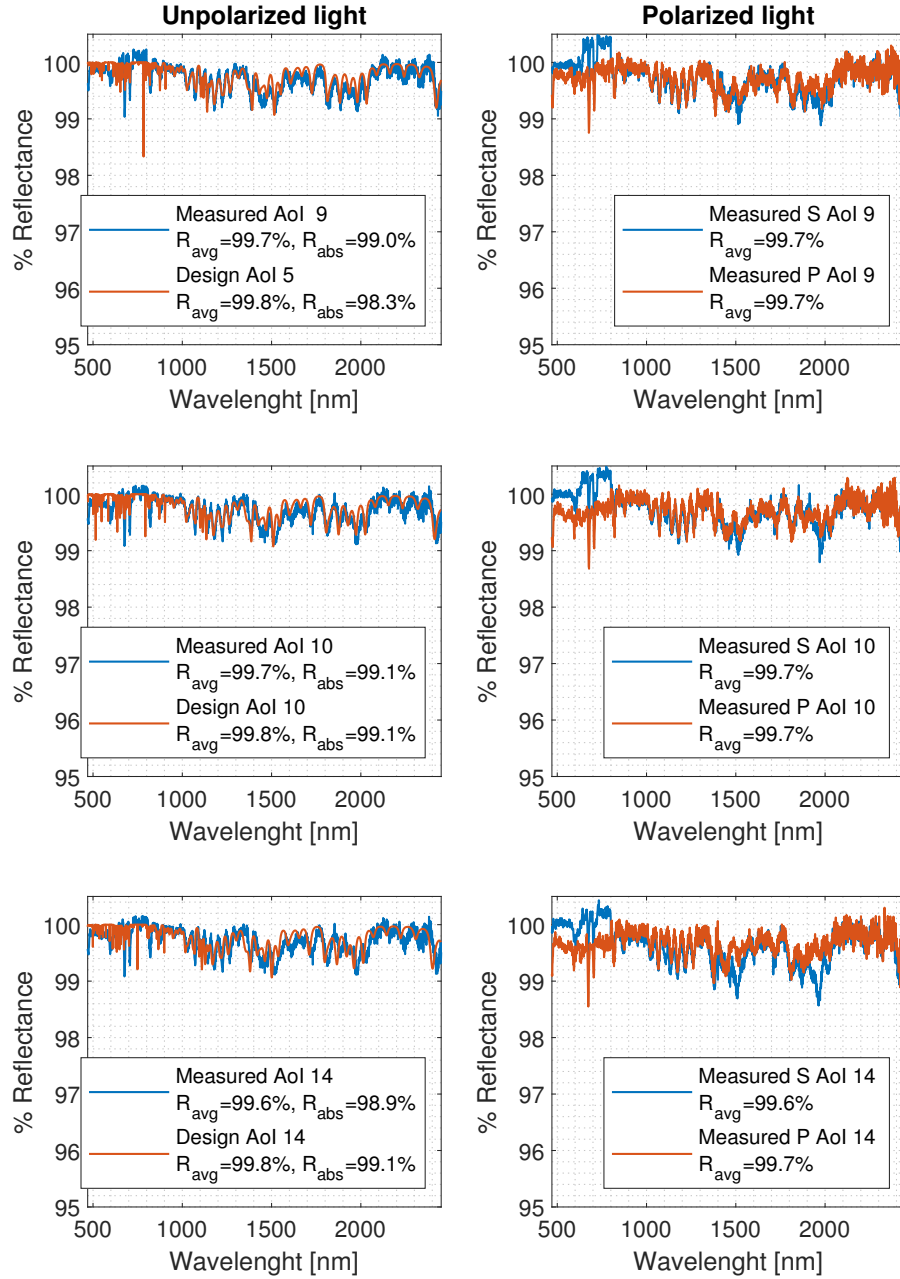


Figure C.1: Coating A. (left) Unpolarised light reflectivity measurement at AoI checks. Comparison with design and as-manufactured curves. (right) S and P polarization as-manufactured curves. (Provided by Asahi Spectra Co., Ltd.)

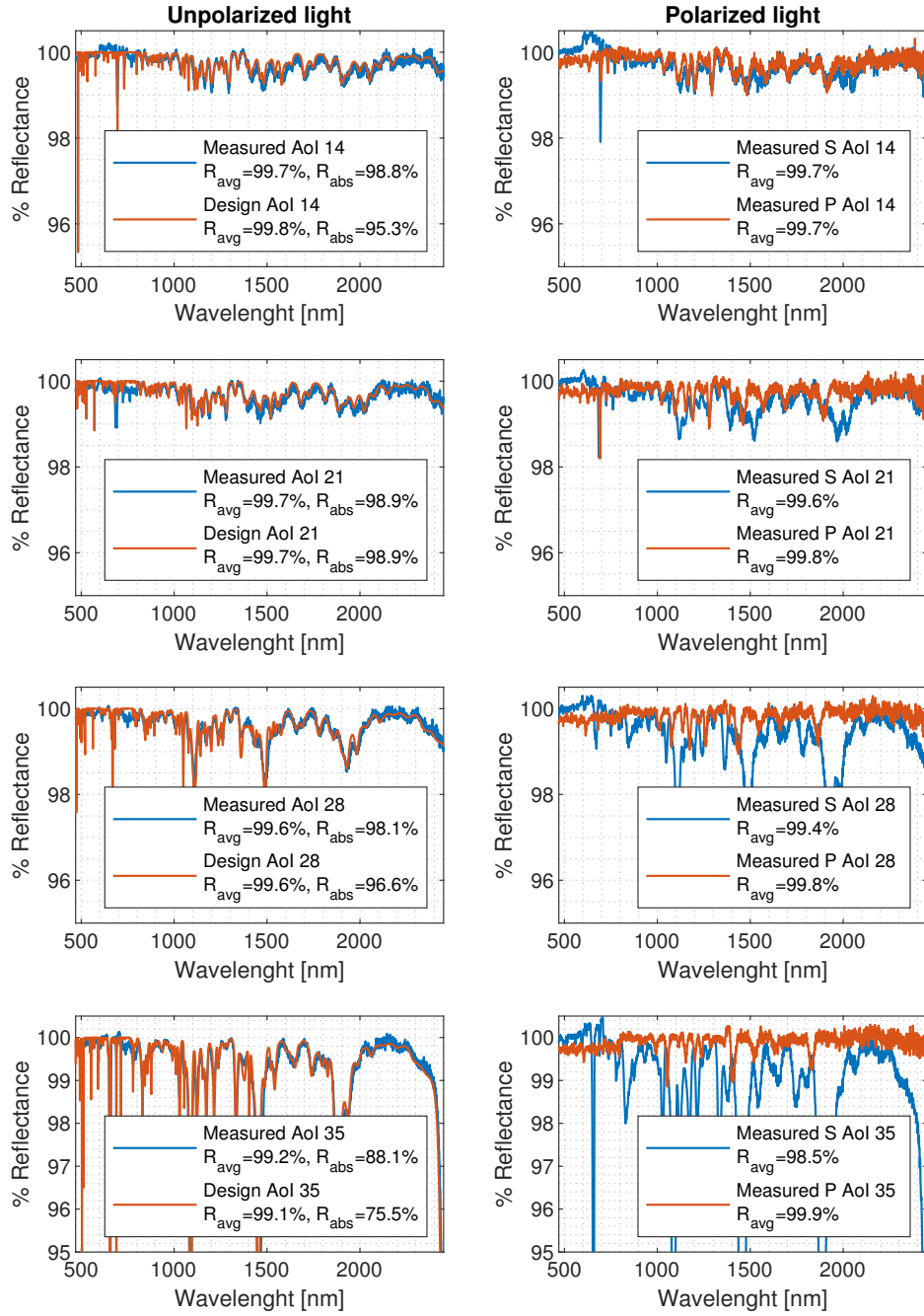


Figure C.2: Coating B. (left) Unpolarised light reflectivity measurement at AoI checks. Comparison with design and as-manufactured curves. (right) S and P polarization as-manufactured curves. (Provided by Asahi Spectra Co., Ltd.)

Appendix D

End to end transmission

Selected grating		Bandwidth		Case 1		Case 2		Case 3	
Name	R	λ_{min}	λ_{max}	T_ρ %	$T_{\rho 80\%}$ %	T_ρ %	$T_{\rho 80\%}$ %	T_ρ %	$T_{\rho 80\%}$ %
VIS	3000	463	807	46.8	49.3	48.2	50.8	50.3	52.9
IzJ	3500	817	1363	34.4	35.1	42.2	43.1	53.1	54.4
HK	3500	1461	2439	43.9	46.3	46.9	50.1	52.1	55.5
Iz	7000	829	1051	47.3	48.8	53.5	55	62.1	63.8
J	7000	1045	1325	35	35.2	45.4	45.6	60.2	60.4
H	7000	1433	1817	45.6	46.2	53.1	53.9	62.9	64.2
K	7000	1948	2472	57.2	58	57.7	60.6	61.9	65.3
z	18000	823	907	44.8	46.5	49.4	51.3	55.1	57.2
J	18000	1185	1305	28.6	29.1	37.9	38.3	51.6	52
H	18000	1530	1686	37.8	38.9	43.9	45.2	52.6	54.2
K	18000	2084	2296	49.4	51	53.3	55.2	58	60.1
K short	18000	2007	2211	50.4	51.4	54.1	55.4	58.5	60
K long	18000	2189	2411	47.3	50.2	49.6	53	53.5	57

Table D.1: Simplified end to end transmission: LTAO 20x20 mas IFU Paths C, D G, H. (No detector, atmosphere and telescope curves included)

Selected grating		Bandwidth		Case 1		Case 2		Case 3	
Name	R	λ_{min}	λ_{max}	T_ρ %	$T_{\rho 80\%}$ %	T_ρ %	$T_{\rho 80\%}$ %	T_ρ %	$T_{\rho 80\%}$ %
VIS	3000	463	807	46.8	49.3	48.5	51	50.5	52.9
IzJ	3500	817	1363	34.4	35.1	43.2	44.2	53.4	54.7
HK	3500	1461	2439	43.9	46.3	47.7	50.8	52.5	55.8
Iz	7000	829	1051	47.3	48.8	54.5	56	62.5	64.2
J	7000	1045	1325	35	35.2	46.7	46.9	60.4	60.7
H	7000	1433	1817	45.6	46.2	54.1	55	63.2	64.5
K	7000	1948	2472	57.2	58	58.6	61.3	62.4	65.7
z	18000	823	907	44.8	46.5	50	51.9	55.3	57.3
J	18000	1185	1305	28.6	29.1	39.2	39.5	51.9	52.4
H	18000	1530	1686	37.8	38.9	44.9	46.3	53	54.7
K	18000	2084	2296	49.4	51	53.8	55.7	58.2	60.2
K short	18000	2007	2211	50.4	51.4	54.6	55.9	58.7	60.2
K long	18000	2189	2411	47.3	50.2	50.2	53.5	53.7	57.3

Table D.2: Simplified end to end transmission: LTAO 10x10 mas IFU Paths C, D G, H. (No detector, atmosphere and telescope curves included)

Selected grating		Bandwidth		Case 1		Case 2		Case 3	
Name	R	λ_{min}	λ_{max}	T_ρ %	$T_{\rho 80\%}$ %	T_ρ %	$T_{\rho 80\%}$ %	T_ρ %	$T_{\rho 80\%}$ %
VIS	3000	463	807	46.6	49.1	48.5	51	50.5	52.9
IzJ	3500	817	1363	33.7	34.4	43	44	53.2	54.5
HK	3500	1461	2439	43.4	45.8	47.4	50.6	52.2	55.5
Iz	7000	829	1051	46.6	48.1	54.4	55.9	62.4	64.1
J	7000	1045	1325	34	34.2	46.4	46.6	60	60.3
H	7000	1433	1817	44.8	45.4	53.8	54.8	62.9	64.2
K	7000	1948	2472	56.8	57.5	58.4	61.1	62.2	65.5
z	18000	823	907	44.3	46	49.9	51.7	55.1	57.1
J	18000	1185	1305	27.8	28.2	39	39.4	51.7	52.2
H	18000	1530	1686	37.1	38.2	44.7	46.2	52.8	54.5
K	18000	2084	2296	49	50.6	53.7	55.5	58.1	60.1
K short	18000	2007	2211	50	51	54.4	55.6	58.5	59.9
K long	18000	2189	2411	47	49.8	50.1	53.4	53.6	57.1

Table D.3: Simplified end to end transmission: LTAO 4x4 mas IFU Paths C, D G, H. (No detector, atmosphere and telescope curves included)

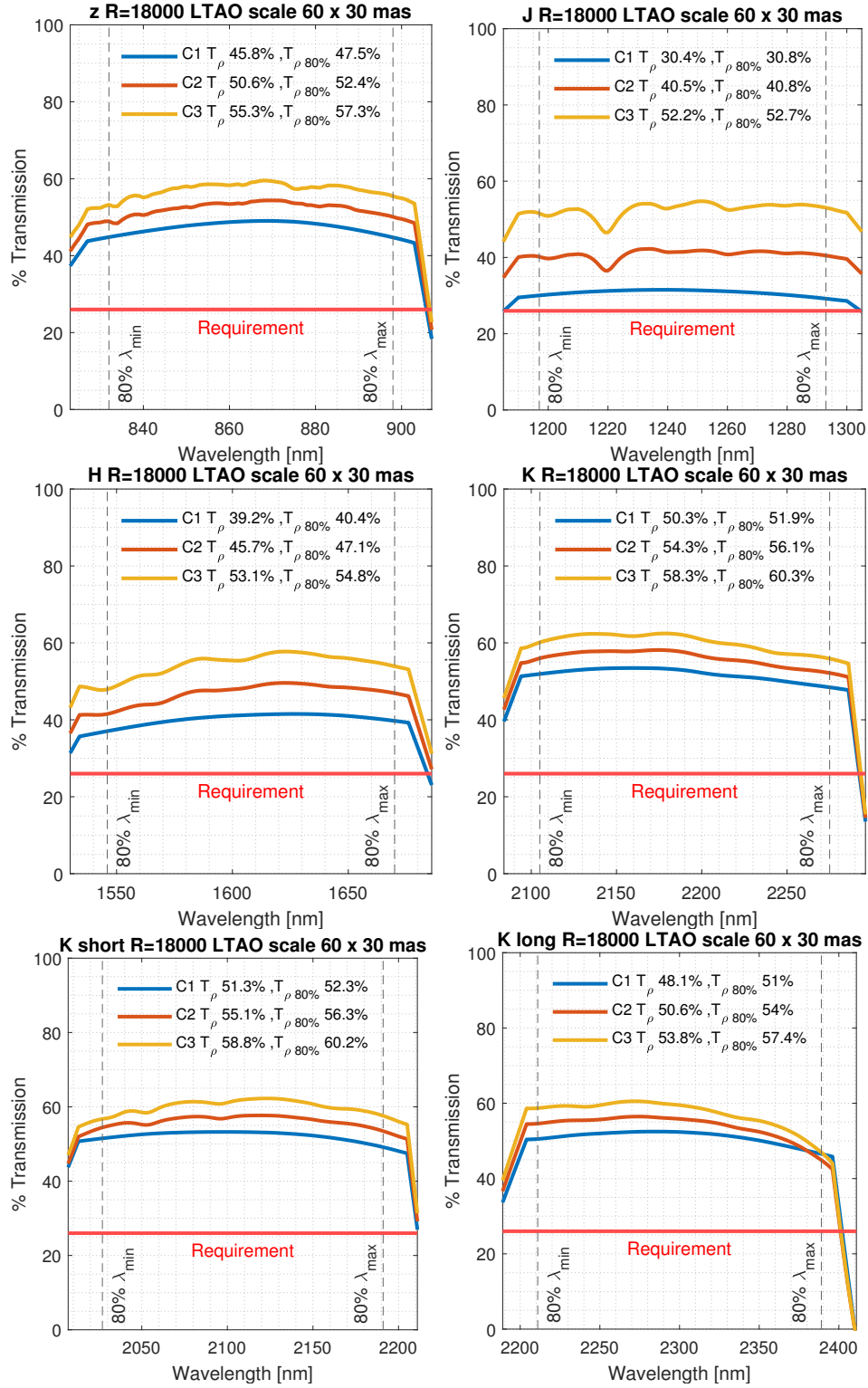


Figure D.1: Estimated end to end transmission per grating bandwidth for LTAO mode with a 60x30 mas scale, C, D, G and H IFU paths.

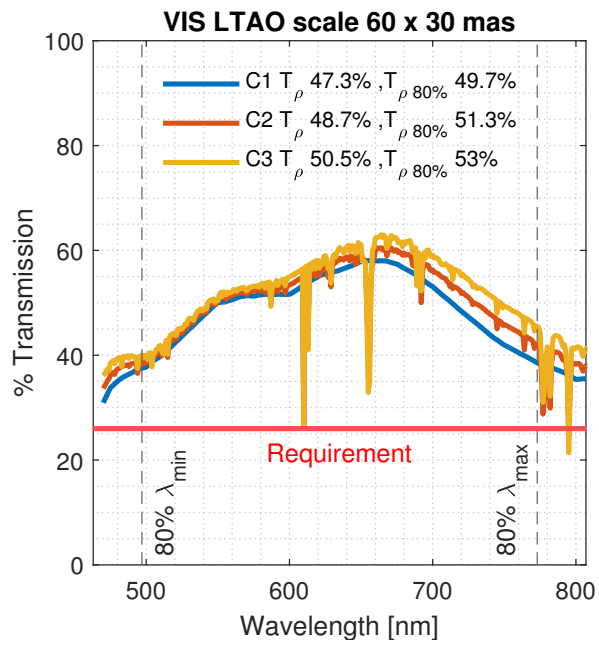


Figure D.2: Estimated end to end transmission per grating bandwidth for LTAO mode with a 60x30 mas scale, C, D, G and H IFU paths.

Appendix E

Adhesion test ISO 9211-4:2012(E)

This section is an extract from the standard ISO 9211-4:2012(E) section 6 and annex C.

E.1 Adhesion tests (conditioning method 02: adhesion)

E.1.1 General

The purpose of these tests is to evaluate to what extent the mechanical properties of optical coatings on components and substrates are affected when subjected to specific tensile or shear stress conditions at ambient atmospheric conditions.

E.1.2 Test conditions

1. The adhesive tape used for this test shall be clear in colour with an adhesive strength on steel of at least 9,8 N per 25 mm width when tested in accordance with ISO 29862, Method 1, 180° angle of peel. It shall be 12 mm to 13 mm wide. It shall show no evidence of deterioration and shall be capable of being unwound from the roll at a normal rate of speed without showing evidence of adhesive offsetting, adhesive splitting, or stringing out of adhesive, nor breakage or splitting of the tape backing. The tape shall be free of bare spots or foreign particles or any defect that may affect serviceability or appearance.

2. Apply approximately 25 mm of tape to the coated surface when the dimensions of the specimen permit, with sufficient tape remaining to securely grasp with a thumb and finger.
3. Press the tape firmly onto the coated surface. Rub the non-adhesive surface of the tape with a finger to ensure firm contact with the specimen and to work out any air bubbles that may be present.
4. Unless otherwise required in the relevant specification, do not apply the tape within 2 mm of any rim of the specimen.
5. Hold the specimen firmly in one hand, and in the other the end of the tape that protrudes beyond the edge of the test specimen.
6. Remove the tape at an angle perpendicular to the coated surface at one of the rates indicated in Table E.1.

E.1.3 Degree of severity (conditioning method 02: adhesion)

The degrees of severity for conditioning method 02 are given in Table E.1.

Table 2 — Degrees of severity for conditioning method 02: adhesion

Degree of severity	01	02	03
Rate of tape removal	Slow (approximately 2 s to 3 s per 25 mm)	Quick (approximately 1 s per 25 mm)	Snap (much less than 1 s per 25 mm)
NOTE The "snap" rate of removal refers to a snapping action of the wrist and fingers.			

Figure E.1: Degrees of severity for conditioning method 02: adhesion.

E.1.4 Recovery

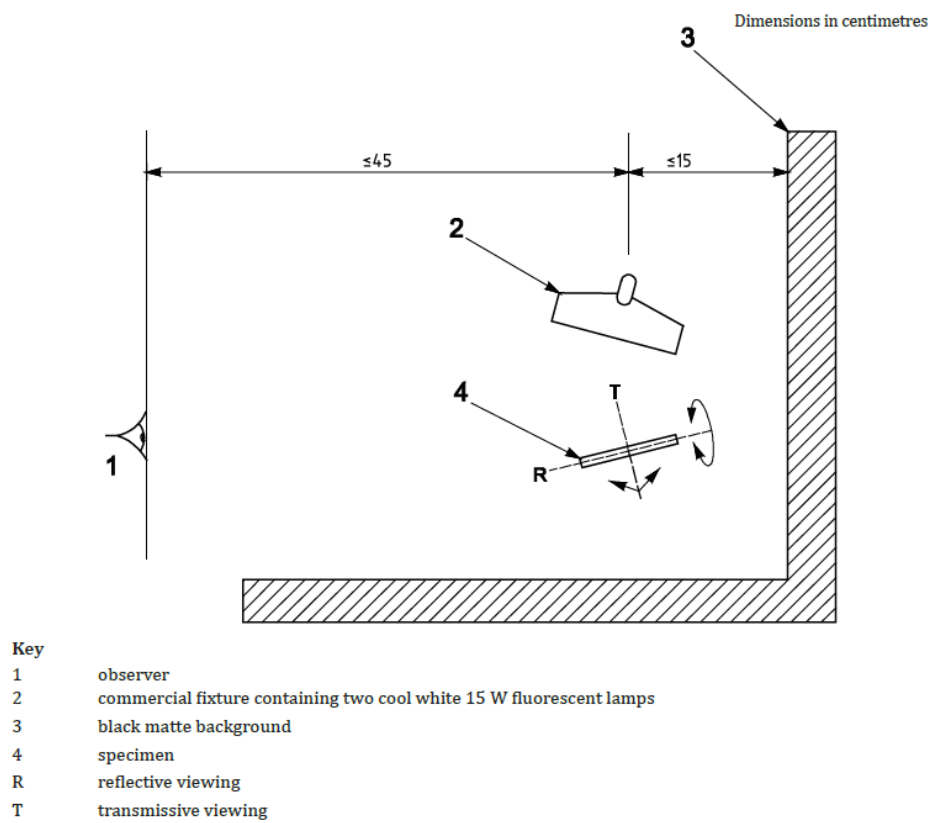
Do not clean the specimen prior to evaluation.

E.1.5 Evaluation

The film on the specimen shall be visually examined in reflected and/or transmitted light, with the unaided eye, for evidence of coating removal. The examination shall be performed using the method specified in Annex C, or that given in ISO 14997, or as agreed between the supplier and the user. The method used shall be stated. The coating shall not show any evidence of coating removal. Unless otherwise required in the relevant specification, visual discolourations of the coating such as stains, smears, streaks or cloudiness shall be acceptable if the specimen conforms to the optical and other environmental durability requirements of the relevant specification.

E.2 Visual examination of optical coatings ISO 9211-4:2012(E) Annex C

Visual examination of optical coatings by this method shall be performed using two cool white 15 W fluorescent light bulbs as the light source. The viewing distance from the coated surface to the eye shall not exceed 45 cm. The coated surface shall be viewed against a black matte background. The only illumination in the inspection area shall be from the light source used for examination. This method of examination is depicted in Figure [E.2](#).



NOTE The arrows indicate that the specimen is moved, tilted and rotated as appropriate to look for damage to the coated surface.

Figure E.2: Method of examination

Appendix F

Optical prescription for reflective surfaces in the science path

Element	RoC		Clear Aperture	Material	Centre Thickness	AoI
M1	-4000mm	CC	700 mm	Zerodur	104.7 mm	6 °
M2	2000mm	CX	160 mm	Zerodur	21.9 mm	6 °
M3	-4000mm	CC	700 mm	Zerodur	104.7 mm	12 °
M4	Plano	Fold mirror	780x560 mm	Zerodur	35.6 mm	47 °

Table F.1: Optical prescription for the reflective surfaces in the Focal Plane Relay Sub-System (FPRS).

Element	Quantity	Type	Clear aperture	Thickness	RoC [mm]		Angle of incidence	
					Paths A,B,E,F	Paths C,D,G,H	Paths A,B,E,F	Paths C,D,G,H
Field Splitter	1	8 flat prisms	(X,Y)=19.9 x 14.9 [mm]	~15 mm	Flat	Flat	12° (θ_X)	5.5° (θ_X)
M1	4	2 flat prisms	38.7 x 36.5 [mm]	~27 mm	Flat	Flat	1° (θ_Y)	12° (θ_Y)
M2 (CDGH only)	4	1 flat mirror	26.5 x 50.5 [mm]	10 mm	NA	Flat	55°	51°
M3	8	1 spherical mirror	50 [mm]	15 mm	824	864	NA	55°
M4	8	1 flat mirror	29.5 x 32.5 [mm]	10 mm	Flat	Flat	5°	6°
M5	8	1 spherical mirror	90 x 63 [mm]	20 mm	2122	2233	43°	38°
							6°	5°

Table F.2: Optical prescription for the reflective surfaces in the Splitting and Relay Module (SRM) of the Integral Field Unit sub-system (IFU).

Element	Quantity	Type	Size [mm]	RoC [mm]	Max. AoI
ISA	2	38 parabolic slices, adhered	50.8 x 1	800	From -12° to 12°
PMA	2	38 flat mirrors	12x 7	Flat	From -12° to 12°
SMA	2	38 spherical mirrors	13 x 7	From 105.27 to 109.01	From -8° to 8°

Table F.3: Optical prescription for the reflective surfaces in the Image Slicer Module (ISM) of the Integral Field Unit sub-system (IFU).

Element	RoC	Clear aperture half widths [mm]		Material	Shape	Max. AoI
		X	Y			
M1	-1240.4	318	58	Zerodur	Off-axis parabola	14 °
M2	-630.56	202	44	Zerodur	Off-axis parabola	43 °
M3	-1486.2	245	76	Zerodur	Off-axis parabola	40 °
FM1	Flat	344	254	Zerodur	Fold mirror	34 °
FM2	Flat	270	208	Zerodur	Fold mirror	25 °

Table F.4: Optical prescription for the reflective surfaces in the spectrograph sub-system (ISP).

Element	RoC	Curvature	Clear aperture	Outer diameter	Shape	Max. AoI
Shared optics						
INPUTM	Flat		80.18 mm	100 mm	Circular	41.5 °
COLLM	1598.44 mm	Off-axis paraboloid	86.7 mm	130 mm	Circular	7.07 °
Non-Anamorphic scale (60 x 30 mas)						
FM60	Flat		69.21 mm	90 mm	Circular	24 °
CM60	3249.99 mm	Off-axis paraboloid	129.6 mm	160 mm	Circular	0 °
FM60B	Flat		139.12 mm	160 mm	Circular	43.2 °
OUTM60	Flat		127.02 mm	145 mm	Circular	43.5 °
Anamorphic scale (20 x 20 mas)						
FM20	Flat		55.43 mm	80 mm	Circular	16.5 °
TM20A	1830.37 mm 1483.39 mm	Toroidal	75.91 mm	80 mm	Circular	1.7 °
TM20B	552.15 mm 900.11 mm	Toroidal	37.42 mm	50 mm	Circular	1.85 °
CM20	2917.81 mm	Off-axis paraboloid	104.42 mm	130 mm	Circular	15.9 °
FM20B	Flat		142.98 mm	160 mm	Circular	51.4 °
OUTM20	Flat		118.8 mm	145 mm	Circular	42.4 °
Anamorphic scale (10 x 10 mas)						
FM10	Flat		53.38 mm	80 mm	Circular	7.5 °
TM10A	1589.87 mm 1428.31 mm	Toroidal	67.32 mm	68 mm	Circular	2.2 °
TM10B	210.2 mm 376.21 mm	Toroidal	16.53 mm	22 mm	Circular	2.75 °
CM10	2600 mm	Spherical	94.68 mm	130 mm	Circular	10 °
FM10B	Flat		99.7 mm	130 mm	Circular	40 °
OUTM10	Flat		104.66 mm	130 mm	Circular	45 °
Anamorphic scale (4 x 4 mas)						
FM4	Flat		49.55 mm	80 mm	Circular	18 °
FM4A	Flat		59.94 mm	90 mm	Circular	21 °
TM4A	1627.99 mm 1519.17 mm	Toroidal	63.52 mm	90 mm	Circular	2.1 °
TM4B	124.15 mm 233.58 mm	Toroidal	8.44 mm	22 mm	Circular	2.3 °
CM4	3546.49 mm	Spherical	90.4 mm	130 mm	Circular	3 °
FM4C	Flat		94.54 mm	130 mm	Circular	26 °
OUTM4	Flat		103.91 mm	130 mm	Circular	44 °

Table F.5: Optical prescription for the reflective surfaces in the Pre-Optics sub-system (PO).

Appendix G

Testing

G.1 Thermal cycling procedure

G.1.1 Cooldown

The cooling-down procedure was developed during the first three cooldowns and optimised during the accelerated life cycle. The operation repeated following the following steps: When the cryostat has been opened:

1. check cryostat connections, thermometers, and heaters give expected readings.
2. check cold straps are not in contact with circuit tracks or radiation shield.
3. clean with isopropyl alcohol (IPA) radiation shield and place it in the cryostat.
4. clean with IPA cryostat lid, apply a small amount of vacuum grease to the o-ring, close the cryostat and secure the lid with four screws. (Screw radially symmetric.)
5. connect the pump. First, remove the caps from the cryostat pump connection and pump hose. Clean and carefully connect the pump hose to the cryostat connection. Make sure the cryostat valve is closed.
6. turn ON the backing pump and wait a couple of minutes until the pump seems to stabilise.
7. slowly open the cryostat valve. Pressure should go down to $\sim 10^{-3} - 10^{-4}$ mbar. If not, leave it to pump until it reaches these values. If it does not happen within a day, a leak inspection should be performed in the cryostat.

8. turn ON turbo-pump. The pump performs its routine procedure to reach 100% of the turbo-pump gradually. It may take up to ~ 10 minutes.
9. check windows, lid and port screws and re-screw if necessary¹.

All operations that require handling any internal part of the cryostat must be carried out wearing gloves.

Start here when the cryostat has not been opened²,

10. Connect LN_2 filling hose from dewar to cryostat and fill cryostat's liquid nitrogen bath. (If this is the first time it fills in the cycle, this process could take 2-3 hours; otherwise, about ~ 30 minutes.) The bath is full when the LN_2 spills and the cold plate temperature is stable at 82-84K. Close the dewar valve and wait a few minutes for the filling hose to unfreeze and remove it.
11. (Optional) Configure Lakeshore 336 controller to the current test plate temperature set-point and then set the desired cooling rate, turn ON the heater control to HIGH and change the set-point temperature to 90K.³
12. Configure Lakeshore 336 controller to set-point to 90K and turn heater control to HIGH. (Set default control to P 50, D 20 and I 0)

Only perform these steps when the pump is ON.

14. Wait until pressure reaches $\sim 10^{-5} - 10^{-6}$ mbar and stabilises.
15. Close cryostat valve. Pressure oscillates between $\sim 10^{-4} - 10^{-5}$ mbar and then stabilizes $\sim 10^{-5} - 10^{-6}$ mbar. If this does not happen, open the cryostat valve and wait longer.
16. Turn OFF turbo-pump, wait until it reaches 0%.
17. Turn OFF the backing pump.

¹Always screw radially symmetric.

²The pressure should be below $\sim 10^{-4} - 10^{-5}$ mbar.

³At first, I set the cooling rate to $\sim 1.7K/min$, but then I realised the setup could not achieve this cooling rate it rather cooled very slowly. Thus, I stopped setting a cooling rate and letting the cryostat cool as fast as possible to make the cycling more agile.

18. Disconnect the cryostat pump connection and put capping lids for protection.

The temperature in the test plate should eventually reach and stabilise at the set-point temperature of the controller.

G.1.2 Warm-up

This procedure was also developed during the first three warm-ups and optimised during the accelerated life cycle. The steps for warming up are the following:

When performing a warm-up and it is not required to open the cryostat if a cooldown is to happen right after,

1. Turn OFF heater control.
2. Configure Lakeshore 336 with a set-point temperature of 298 K plus P 50, I 10 and D 50 control.
3. Configure Lakeshore 336 with a warm-up rate of $\sim 2.0K/min$.
4. Turn ON the heater control and set it HIGH.
5. Wait until the test plate temperature reaches 298 K and then turn OFF the heater control.

Notice that LN_2 may not have run out, so the temperature will immediately drop. To continue to the next cycle, go to step 12 of the cooling-down cycle.

The procedure to open the cryostat after a cooldown and warm-up must follow these steps, additionally to the previous ones:

6. Configure Lakeshore 336 with a set-point temperature of 310 K plus P 50, I 10 and D 50 control.
7. Wait until there is thermal equilibrium inside the cryostat and turn OFF temperature control.
8. (if the pump is ON) Close valve.

9. (if the pump is ON) Turn OFF the turbo and wait until it stops.
10. (if the pump is ON) Turn OFF the backing pump.
11. Disconnect pump line.
12. Remove screws from the cryostat top lid.
13. Open the compressed nitrogen line up to a minimal flow and connect the compressed nitrogen line to the cryostat.
14. Open the cryostat valve slowly and wait until the lid is slightly lifted⁴.
15. Close compressed nitrogen line and close cryostat pump connection.
16. Place the blanking cap on the pump connection.
17. Open lid.

G.2 Documentation

Table G.1: LN_2 dewar refill

https://harmoni.physics.ox.ac.uk/_layouts/15/DocIdRedir.aspx?ID=4JY3FNXR53KP-2102554853-18150



⁴The cryostat has an overpressure valve. I followed this step to avoid hearing loud, unexpected noises.

Table G.2: Cryostat wiring

Designed by Andrea Hidalgo
[https://harmoni.physics.ox.ac.
uk/_layouts/15/DocIdRedir.aspx?ID=
4JY3FNXR53KP-2102554853-18151](https://harmoni.physics.ox.ac.uk/_layouts/15/DocIdRedir.aspx?ID=4JY3FNXR53KP-2102554853-18151)



Implemented by Rik Elliot [https:
//harmoni.physics.ox.ac.uk/
_layouts/15/DocIdRedir.aspx?ID=
4JY3FNXR53KP-2102554853-18152](https://harmoni.physics.ox.ac.uk/_layouts/15/DocIdRedir.aspx?ID=4JY3FNXR53KP-2102554853-18152)



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