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# 4MOST Low Resolution Spectrographs AIT at AIP

Florence Laurent<sup>\*a</sup>, Didier Boudon<sup>a</sup>, Eric Daguise<sup>a</sup>, Karen Disseau<sup>a</sup>, Steffen Frey<sup>b</sup>, Rémi Giroud<sup>a</sup>, Aurélien Jarno<sup>a</sup>, Jens-Kristian Krogager<sup>a</sup>, Jean-Emmanuel Migniau<sup>a</sup>, Matthew Lehnert<sup>a</sup>, Arlette Pécontal<sup>a</sup>, Emmanuel Pécontal<sup>a</sup>, Alban Remillieux<sup>a</sup>, Johan Richard<sup>a</sup>, Pasko Roje<sup>b</sup>, Carlos E. Rodriguez Alvarez<sup>b</sup>, Deborah Sobiella<sup>b</sup>

<sup>a</sup>Univ Lyon, Univ Lyon1, Ens de Lyon, CNRS, Centre de Recherche Astrophysique de Lyon UMR5574, F-69230, Saint-Genis-Laval, France ;

<sup>b</sup>Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, D-14482 Potsdam, Germany

## ABSTRACT

4MOST, the 4m Multi Object Spectroscopic Telescope, is an upcoming optical, fibre-fed, MOS facility for the VISTA telescope at ESO's Paranal Observatory in Chile. Its main science drivers are in the fields of galactic archeology, high-energy physics, galaxy evolution and cosmology. The 4MOST consortium consists of several institutes in Europe and Australia under leadership of the Leibniz-Institut für Astrophysik Potsdam (AIP). 4MOST is currently in its Assembly, Integration and Tests Phase with an expected start of science operations in 2025.

The design of 4MOST features 2436 fibres split into two low-resolution spectrographs (1624 fibres, three arms, 370-950 nm,  $R > 4000$ ) and one high-resolution spectrograph (812 fibres, three arms,  $\sim 44$ -69 nm coverage each,  $R > 18000$ ). The fibre positioner covers a hexagonal field of view of  $\sim 4.1$  deg<sup>2</sup>. The fibers are 85 $\mu$ m core with an output beam at  $f/3$ .

CRAL has the full responsibility of the two Low Resolution Spectrographs. Each of them is composed of a 200mm beam for an off-axis collimator associated to its Schmidt corrector, three "color" arms hosting  $f/1.73$  cameras with standard 6k x 6k 15 $\mu$ m pixel CCD detectors.

The local acceptance reviews at CRAL for the both 4MOST Low Resolution Spectrographs were successfully passed respectively in December 2021 and October 2022. In 2022, two SPIE papers described the process performed at CRAL from the integration and alignment of the sub-assemblies [10] up to the procedures developed to test the spectrograph and demonstrate its compliance with the requirements [11].

Then the two LRS were partially disassembled and sent to Potsdam. They have now been fully integrated, aligned and tested at Potsdam by the CRAL team. The integration of both LRS with the others sub-systems in order to validate the global end-to-end tests is foreseen in 2024 and an installation at VISTA telescope is expected in 2025. This paper describes the assembly, integration and performances achieved at Potsdam for the both Low Resolution Spectrographs. Special emphasis is put on the update of procedures and components to improve performances and meet the top-level requirements.

**Keywords:** 4MOST, VISTA, ESO, Spectrograph, Performances, AIT

\*florence.laurent@univ-lyon1.fr; phone +33 4 78 86 85 33; <http://cral.univ-lyon1.fr/>

# 1. INTRODUCTION

4MOST is a wide-field, high-multiplex spectroscopic survey facility under finalization for the VISTA telescope of the European Southern Observatory (ESO). Its main science drivers are in the fields of galactic archeology, high-energy physics, galaxy evolution and cosmology [2] and [13]. 4MOST will in particular provide the spectroscopic complements to the large area surveys coming from space missions like Gaia, eROSITA and Euclid, and from ground-based facilities like VST, DESI, LSST and SKA. The VISTA Wide Field Corrector design provides a focal surface at the conventional Cassegrain focus [3]. 4MOST features a 4.1 degree diameter field-of-view with 2436 fibres in the focal plane that are configured by a fibre positioner based on the tilting spine principle [4]. The fibres [9] feed two types of spectrographs; 1624 fibres go to two spectrographs with low resolution  $R > 4000$  and 812 fibres to a high resolution spectrograph with  $R > 18,000$  [5]. Both types of spectrographs are fixed-configuration, three-channel spectrographs. 4MOST will have a unique operation concept in which 5 years public surveys from both the consortium and the ESO community will be combined and observed in parallel during each exposure, resulting in more than 25 million spectra of targets spread over a large fraction of the southern sky [6].

This paper focuses on the LRS AIT in Europe at AIP premise which is under CRAL responsibility. The LRS AIT is driven by providing a high spectral resolution over a large spectral range. The section 2 of this paper introduces the LRS design and key requirements. The section 3 gives the strategy for this task. The section 4 summarizes the dismounting at CRAL and transport between Lyon and Potsdam. The re-alignment procedure is presented in section 5. The section 7 is focused on the performances. Finally, the section 8 compiles the conclusions and future developments.

## 2. 4MOST LRS DESIGN AND KEY REQUIREMENTS

The LRS is composed of two symmetrical unit spectrographs including the same optical components. Each unitary spectrograph should meet the key requirements listed hereafter. Each spectrograph is fed by an entrance slit of 812 science fibres. After collimation, the optical beam is separated in three spectral bandwidths, dispersed and reimaged in three different channels with  $F/1.73$  aperture. The separation in three channels provides the minimal resolution of 4000 (Figure 1). The Blue arm goes from 370 to 554 nm, the Green from 524 to 721 and the Red from 691 to 950 nm.

The LRS is composed of the 7 sub-assemblies:

- An Entrance Slit Unit -ESU- composed of 812 science fibres following focal plane curvature radius. A Slit Field Lens is glued onto the entrance slit. Note that the LRS MAIT/AIT/AIV phases will be performed with a Test Slit Unit, hosting a partially populated slit.
- A mirror acts as a Collimator collecting the  $F/3$  light from the fibres and generates a collimated beam of 200mm.
- A Dichroic: Dichroic beam splitters in front of the Schmidt corrector separate the three channels. There are two dichroics (Red and Blue).
- In addition, each channel includes a corrector, a VPHG for dispersion, a dioptric camera and a Field Lens Window. The spectral overlap of the channels is determined by the edge of the dichroic and here assumed to be 30nm. A 6k X 6k detector with  $15\mu\text{m}/\text{pixel}$  records the spectra.

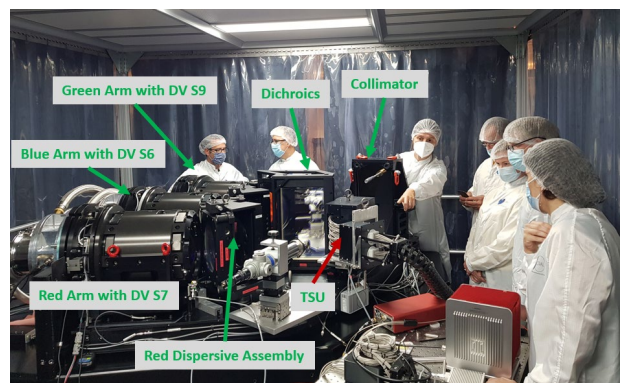
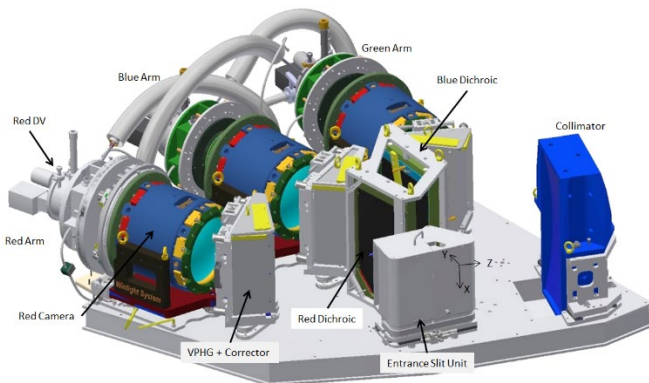


Figure 1: Left: LRS mechanical model. Right: LRS-A in operation

The LRS key design requirements are derived from the 4MOST top level requirements ([7] and [8]) and are listed below:

1. The LRS shall be able to accommodate a minimum of 812 science fibres and 10 calibration fibres. It shall accept  $f/3.0$ , with 85 micron core diameter fibre inputs. The LRS shall cover simultaneously the wavelength range from 400 nm to 885 nm (goal: from 370 nm to 950 nm). The LRS spectra shall be projected on 6k by 6k, 15 micron pixel detector(s).
2. The LRS spectral resolving power shall be  $R \geq 10 \times \lambda/\text{nm}$  for  $400 \text{ nm} \leq \lambda < 500 \text{ nm}$ , and  $R \geq 5000$  for  $500 \text{ nm} \leq \lambda \leq 885 \text{ nm}$ .
3. The LRS spectral sampling shall be  $\geq 2.5$  pixel (goal 3.0 pixels).

### 3. STRATEGY

The first LRS-A has successfully passed its Local Acceptance Review (LAR) in December 2021 in Lyon. The purpose of the LAR was to assess whether a subsystem is mature and complete before shipping it to the AIP for integration. The performance of LRS-A was found to be excellent and only minor issues were identified. After acceptance testing, it was disassembled and packed in preparation of shipment to the AIP. On 29 March 2022, the disassembled LRS-A arrived at the AIP on four trucks. A team from CRAL, supported by the 4MOST AIP integration team and two colleagues from MPIA Heidelberg spent the better part of the three following weeks to unpack and reassemble the spectrograph. The delivery of LRS-A was a major milestone for the 4MOST project and the team was very excited to receive it and follow its re-integration in the integration hall. In parallel, the integration of the second spectrograph LRS-B was on-going in Lyon. On October 26, 2022 the official Local Acceptance Review for the second Low Resolution Spectrograph (LRS-B) for 4MOST was held at CRAL in Lyon. Its reintegration at AIP was done in December 2022 on three weeks. One week before, the LRS-A was mainly retrofitted for the image quality and detector flat system where some requirements were partially compliant.

The paper [1] summarizes the approach for MAIT analysis, the manufacturing of optical and mechanical components and the technical requirements for each individual opto-mechanical component. The paper [10] focuses on the LRS MAIT at CRAL premise where the main MAIT tools used to align the LRS and the alignment procedure are presented. The performances for LRS-A achieved during the MAIT in Lyon are presented in paper [11].

In this paper, the methodology, the planning and the execution of each LRS reassembly and optical realignment is divided into six steps. Thanks to trihedral point/line/plane (PLP) system (sphere-cylinder-plane) interfaces, the LRS assemblies are remounted in plug and play mode. Only the Detector Vessel (DV) focus alignment has been performed. The MAIT has been designed in order to be the same at AIP and Paranal. The goal was to use the same AIT tools, mounting, alignment and verification procedures implemented at CRAL, well described in the paper [10], to minimize integration activities at AIP and then at telescope. Moreover, the performances are compared together between each phase. The Figure 2 presents the LRS AIT Flow Chart at AIP premise. The AIT for each LRS was carried out in three weeks by 4 qualified people supported by the 4MOST AIP integration team and two colleagues from MPIA Heidelberg.

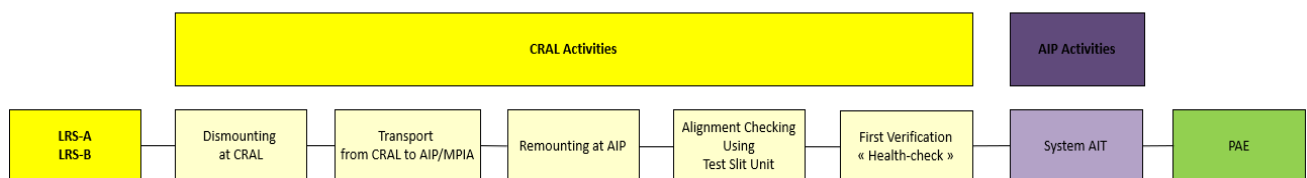


Figure 2: LRS AIT Flow Chart at AIP premise

#### 4. DISMOUNTING AT CRAL AND TRANSPORT FROM LYON TO POTSDAM

Thanks to PLP interfaces, each assembly is dismantled from its PLP interface. For LRS, the parts and assemblies have been delivered individually and packed on their individual transport boxes. Some of them have been packed together into another bigger transport box. The total weight is around 4 tons per LRS spread in 12 or 13 parcels representing 35m<sup>3</sup> in total. Note the all transport boxes will be re-useable for Paranal. All containers are equipped with appropriate sensors/indicators (temperature sensors, shocks recorder, tilt indicator...) to detect any mishandling of the equipment during transportation. For less sensitive components, the standard transport crates in wood or aluminum have been used for the transport. The very sensitive optics (Collimator, dichroic, dispersive assembly and Detector Vessel) are mounted on dedicated damping systems in plastic boxes (Figure 3). The Main Structure including Mounted Optical bench, PLP interfaces, Support Frame Interface and Cover assembly have been packed and transported together. This transport box is the only one with critical dimensions (L x W x H = 2950 x 2300 x 1400 mm) which fits the cargo plane - Figure 4. Due to the environmental constraints at CRAL and AIP, the 13 crates have been shared in 4 trucks.

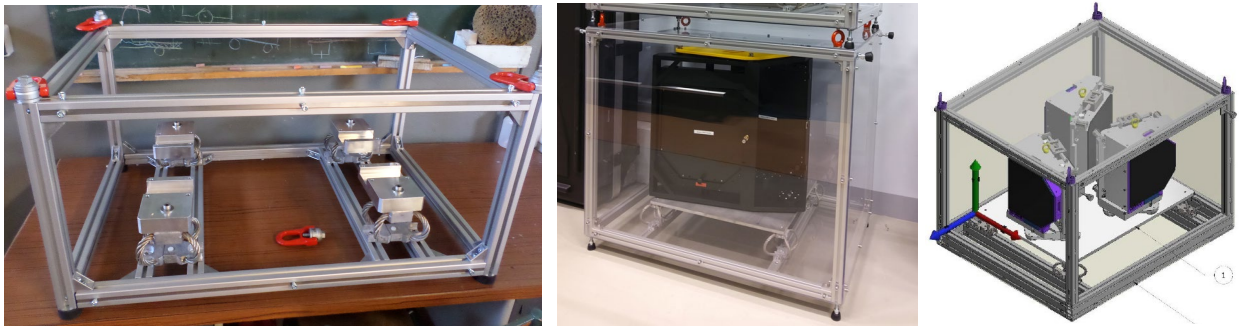


Figure 3: Dedicated damping system for Collimator, dichroic and 3 dispersive assemblies



Figure 4: Left: Parcel#1 - Main Structure. Middle: Parcel#2 – Frame. Right: Parcel#6 - Dichroic & Dispersive assemblies

#### 5. REMOUNTING AT AIP

The compatibility of AIP environment has to be done, by checking space available, cleanliness and handling capacity. All tools identified as mandatory have been shipped earlier and are available at AIP. Moreover, the crosscheck with the global end-to-end tests detailed in the AIT plan has been discussed. The safety aspects were aware by the team. The remounting at AIP takes place in the Leibniz-Haus Integration hall. All crates are unloaded from the truck by using a forklift in reverse direction.

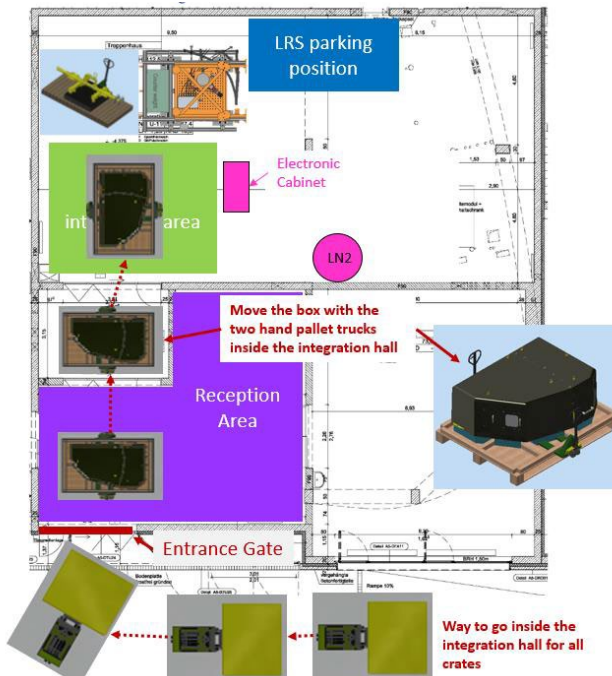


Figure 5: Left: Leibniz-Haus Integration hall with the reception, LRS integration and parking areas. Right: Unload LRS crates from the truck and go inside the integration hall

## 6. ALIGNMENT CHECKING USING TEST SLIT UNIT

### 6.1 Common Path Alignment

After the installation of the LRS Frame, the Mounted Optical bench without optics and the cabinet, the Common Path Alignment has been performed. The paper [10] described all the procedures on the LRS MAIT at CRAL premise where the main MAIT tools used to align the LRS and the alignment procedure are presented. This procedure allows to align and verify the common path which includes Optical Axis Definition, Test Slit Unit, Collimator and Dichroics installation. This procedure has been repeated during the AIT@AIP. Some internal verifications as near and far field measurements for the Test Slit Unit, check Pupil positioning and size with Pupil setup for the common path performed at CRAL are not reproduced here. Only differences in the results between the MAIT@CRAL and AIT@AIP are summarized hereafter. For that, we follow the procedure :

- Measurement of the PLP interfaces on the optical bench with Hexagon arm

The xyz positions are similar to the ones during MAIT@CRAL for LRS-A. For LRS-B, the xyz positions are similar except for the TSU z-axis and Collimator xy-axis which does not correspond perfectly to the alignment performed at MAIT@CRAL. A shift up to 0.2mm is measured. We have decided to stay with these values and checked after with the alignment targets.

- Optical Axis Definition

Both LRS: No issue with the installation of Target\_1&2 and the alignment telescope.

- Collimator Alignment

LRS-A: No re-alignment has been performed.

LRS-B: To validate the alignment, the reticle should stay in the first central ring of the Target. A re-alignment has been performed in order to be centred on the first central ring of the Target. For that, the collimator was shifted of 0.3mm towards -Y axis (towards the bench extremity). The vernier of collimator is now 14.85mm and is consistent with the hexagon measurement performed before. We do not know why the collimator positioning is not at the same location as

during MAIT@CRAL. That is due to the collimator locking which did not work perfectly. It should be retrofitted before AIV@Paranal by replacing the 3 washers by the new ones with a height of 12.85mm.

- Alignment of Dichroics

LRS-A: No re-alignment has been performed.

LRS-B: First, the 2 reticles were not centred along y-axis onto the targets. Second, as the collimator has been translated along y-axis, the Red\_Dichroic has been adjusted around x-axis by screwing the adjustment screw of 1/8 turn. Third, the 2 reticles were centred along y-axis onto the targets.

- Common path verification

No common path verification for both LRS because it was already done during the MAIT in Lyon.

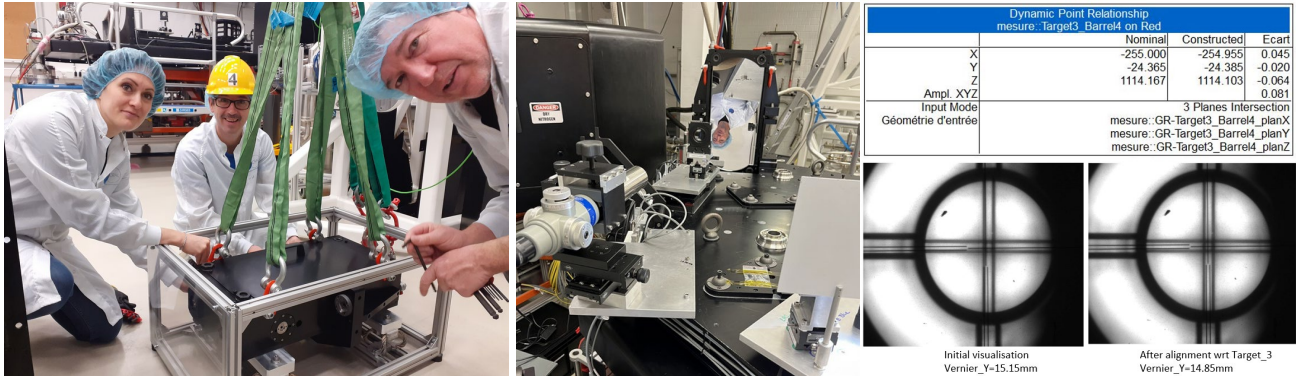


Figure 6: LRS-B Collimator. Left: Installation on the bench with the crane. Middle: View from the alignment telescope up to the Collimator. Right: Alignment verification on the targets

## 6.2 Arm & DV Alignment

This step allows to align and verify the “arm” which includes Corrector, VPHG and Camera alignment. We start with Blue arm and the procedure is repeated for the Green and Red arms. For that, we follow the procedure:

- Installation of the 3 dispersive assemblies including {Corrector + VPHG}
- Installation of the Blue/Green/Red {Camera + DV Interface Assembly}
- Installation of the Blue/Green/Red DV with pumping and cool down
- No optical or metrology verification were performed on these 3 installations
- Test Slit Unit -TSU- installation with AIP fibre feed team. The whole LRS MAIT/AIT/AIV phases are performed with the TSU, hosting a partially populated slit. The slit box is thus composed of only 6 slitlets, which are themselves only sparsely populated with 11 fibers each.
- Installation of the sources and Illumination Unit which injects light at the proper f-ratio into the bundle of fibers. The light sources are a Quartz-Tungsten-Halogen (QTH) lamp for the continuum source and Pencil Hg and Ne lamps for calibration arc lamps.
- Software functional checks
- Blue/Green/Red arm first exposures. Spectra positionings are correct. No re-alignment in Rz\_VPHG and (Rx, Ry) Camera to reach positioning requirements in using TSU Unit has been performed.
- To reach image quality requirements, the (z, Rx, Ry) DV in using Test Slit Unit has been performed. In fact, during the LRS-B MAIT@CRAL, the (z, Rx, Ry) DV alignment has been greatly improved. Now, these DV tip-tilt adjustments are based on the focus curves which allow us to determine the best focus plane. It is for this reason that the re-alignment of the 3 DVs for LRS-A has been redone at AIP.
- Adjust the tip/tilt of the DV in using the CRAL software tool results. The Figure 7 and Figure 8 illustrate the DV tip/tilt alignment from the beginning upto the final with an arc lamp for the FWHM in X-spatial and in Y-spectral direction.
  - A “fine” focus curve is performed (range 0.2mm with 50µm step) around the best focus determined by design with Test Slit Unit and arc lamps

- Run the software tool. This script is run on an arc line exposures formerly bias-subtracted. For each focus position, it maps the estimated fwhm of the arc lines all over the field of view assuming a 2D Gaussian profile and then plot estimated spectral resolution and sampling. It allows a quick estimate of the alignment status giving the corrected tip-tilt angle and the best focus position. As an illustrative example produced plots for FWHM mapping are shown here for a initial tilted optical alignment (Figure 7) versus a corrected optical alignment (Figure 8).
- If the tip-tilt is higher than one arcminute, proceed to the adjustment.
- Unlock by 1/8 turn and 1/8 turn more, the 6 locking screws on the DV Interface Assembly.
- Adjust the 3 adjustment screws by applying a number the turns following the results given by software tool.
- Lock by 1/8 turn and 1/8 turn more until reach 5N.m, the six locking screws on the DV Interface Assembly.
- Readjust the focus if necessary and take an exposure.
- Redo the tip tilt alignment if necessary. This is quite a lengthy and interactive procedure. It is a tricky part, it could take one day with more than a dozen iterations.
- Set the DV at the best focus.
- Take a set of exposures with Test Slit Unit and Light Source Module (arc lamps).
- Once the DV alignment is done, the Top and DV Covers are installed (Figure 9) and the Health checks for analysis can start (§7).

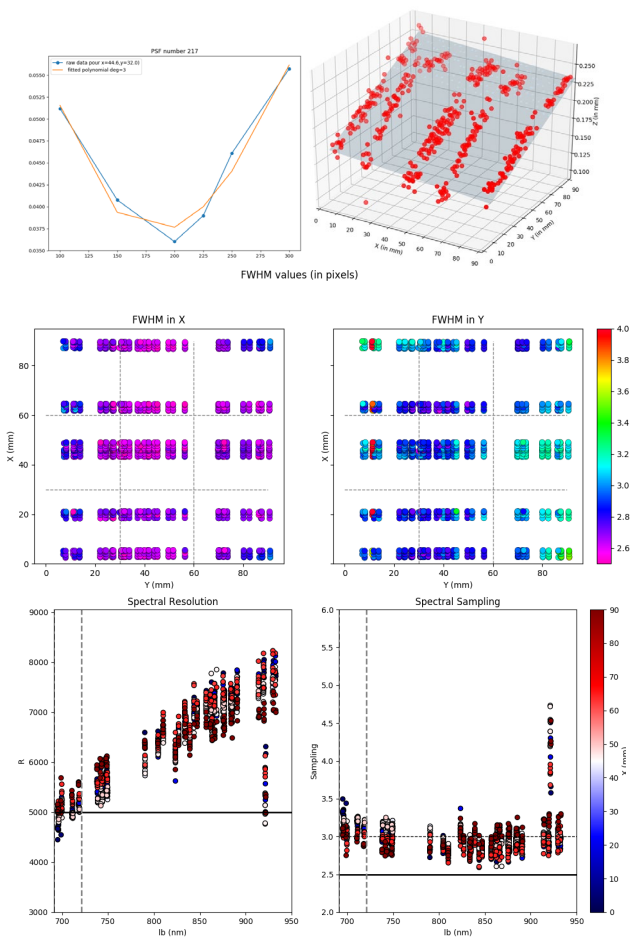


Figure 7: Original tilted optical alignment with  $Th\_X = -0.011 \text{ deg}$  /  $Th\_Y = 0.056 \text{ deg}$  /  $Z = 0.198 \text{ mm}$ . From top to bottom: Focus curve with best focus position; Tilted focal plane; Plots for FWHM mapping; Plots for spectral resolution and sampling

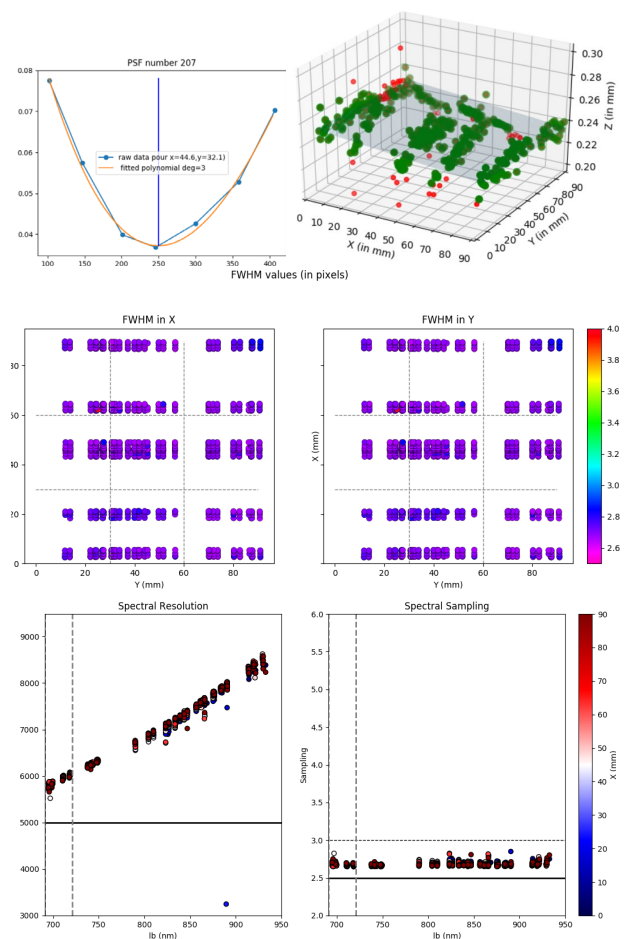


Figure 8: Corrected optical alignment with  $Th\_X = -0.009 \text{ deg}$  /  $Th\_Y = -0.003 \text{ deg}$  /  $Z = 0.242 \text{ mm}$ . From top to bottom: Focus curve with best focus position; Tilted focal plane; Plots for FWHM mapping; Plots for spectral resolution and sampling



## 7. FIRST VERIFICATION “HEALTH CHECK”

During the AIT@AIP, only the First Verification – « Health-Check » has been performed. That allows to validate the re-alignment with the image quality and spectra positioning. The Interface verification was partially checked at CRAL and will be finalized at Potsdam with the other subsystems by the system team [12]. The other verifications which allow performing specific tests onto the arm itself i.e. wavelength range, dichroic transition region, throughput, ghosts and straylight were not carried out again in Potsdam. The global tests for Spectrograph stability and Temperature difference requirement are not reproduced at Potsdam because they have already validated at CRAL. The whole performances reached during the MAIT@CRAL are fully described in the Karen Disseau et al. paper [11]



Figure 9: Left: Installation of the Top Cover. Right: Both LRS fully completed with all optical components and with the covers

### 7.1 Spectra position onto the detector

The positions of spectra onto the detector are measured on the first exposure on each channel. The spectra are well centered in both directions with a shift lower than 10 pixels compared to the nominal position which is not critical at all (no specification on the positioning, only the spatial centering can be critical since it can affect the available space for calibration fibre images on the top and bottom part of the detector). Consequently, the camera tip/tilt, as well as the Rz degree of freedom of the VPHG were not adjusted.

### 7.2 Performances using arc lamps: Spectral resolving power and sampling

The LRS Test Slit Unit is illuminated, through the Light Source Module, with Arc lamps (Hg lamp for the blue channel and Ne lamp for the green and red channels). First, a series of 10 bias is taken and a master bias is created by computing the median of the 10 bias exposures. Arc lamp exposures are then taken and bias-subtracted with the master bias.

The Spectral resolving power and its variation, Spectral sampling and its variation and Spectral purity have been checked using the arc lamps. The full analysis method is explained in details in the paper [11]. The performances are fully compliant with the requirements for both LRS. To improve the image quality, the LRS-A has been retrofitted in using the new detector vessel alignment process described in the section 6.2. The Figure 10 shows this improvement for green channel on LRS-A. For LRS-B, no adjustments were done between Lyon and Potsdam.

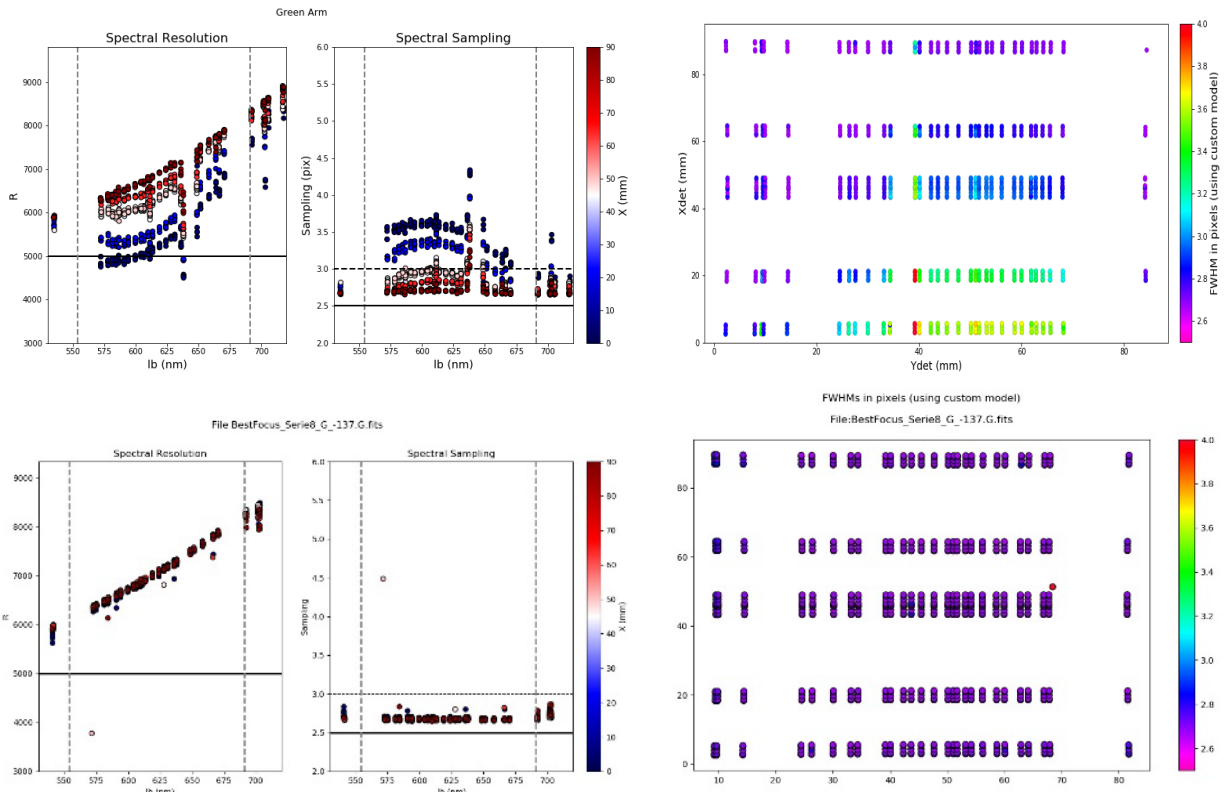


Figure 10: Performance for green channel on LRS-A. Spectral resolving power versus wavelength (Left side) and FWHM map over the detector (right side). Top: Degraded performance. Bottom: Corrected performance after DV re-alignment in using the new alignment procedure.

### 7.3 Performances using continuum lamps: Cross-talk between spectra and Homogeneity of spectral response

The LRS Test Slit Unit is illuminated, through the Light Source Module, with continuum lamp. First, a series of 10 bias is taken and a master bias is created by computing the median of the 10 bias exposures. Continuum lamp exposures are then taken and bias-subtracted with the master bias.

From fibre flat exposures, the cross-talk criterion is derived by computing the ratio between the flux contained in a 3x3 pixels box centered on the PSF, and the flux contained in the same box separated by 6.5 pixels along the spatial direction. For each arm, no value were found above the specified limit of 2%.

From the same exposures, the fibre spectra are extracted and the output flux at a given wavelength between all illuminated fibres are compared, using the median flux value for comparison. At any given wavelength, the variation in spectral response does not exceed 10% PTV which corresponds to the requirements.

### 7.4 Light-Tightness

In covering up incoming light from internal LEDs in the vacuum electro-magnetic valves on each DV that improves the light tightness. Taking several one-hour exposures to darkness, with the integration hall lights switched off overnight, show that the light-tightness is fully compliant with the requirement (Figure 11).

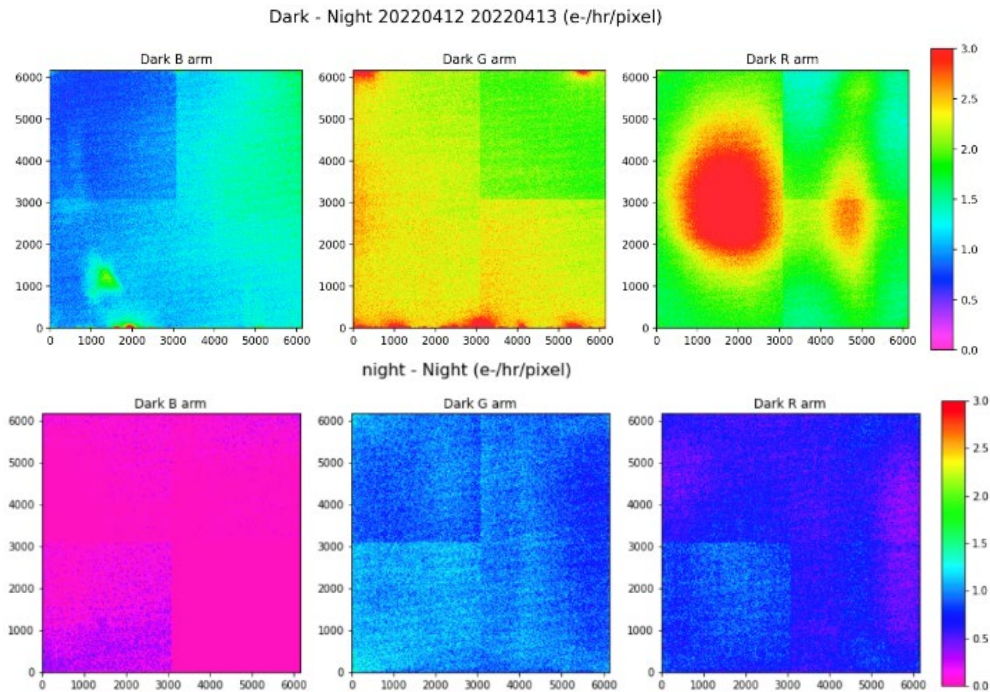


Figure 11: Results of dark exposures with lights off for LRS-A. The requirement is 3.0 e-/hr corresponding to the area colored in red. Top: Before retrofit. Maximum values in each channel are: [Blue] 2.48 e-/hr, [Green]: 3.09 e-/hr, [Red]: 3.93 e-/hr. Bottom: After retrofit. Maximum values in each channel are: [Blue] 0.84 e-/hr, [Green]: 1.60 e-/hr, [Red]: 1.47 e-/hr.

## 7.5 Detector Flats

To perform Detector flats, 3 set of 3 LEDs (2xFlatField + 1xUV) were installed into the focus tube between the camera and the detector vessel which acts as an "integrating" tube to illuminate the CCD (Figure 12, Left). Unfortunately, the LEDs were too bright and the pattern was not homogeneous leading to a violation of the requirement for homogeneous illumination on the detector (Figure 12, Right). A new optomechanical design for the LED system has been implemented on both LRS with LEDs now located in front of the camera instead of in front of the detector vessel (Figure 13, Left). The LED locations and the LED currents for the 3 arms have been adjusted. Now, the new design is compliant with the requirements (Figure 13, Right) except for the UV flat field source which is marginally out of specifications but acceptable for the instrument.

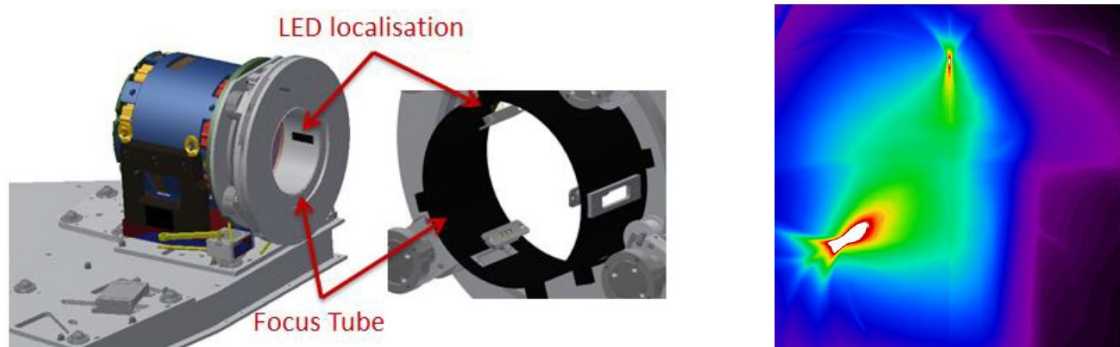


Figure 12: Left: Old illumination setup for the detector flats. The two groups of 3 LEDs (2xFlatField + 1xUV) are placed in front of the Detector Vessel in the focus tube. Right: Example for the Detector flat field LED exposures in the Green arm. With the old design, 55% CCD area are out of specifications corresponding to the green, yellow, red and white points.

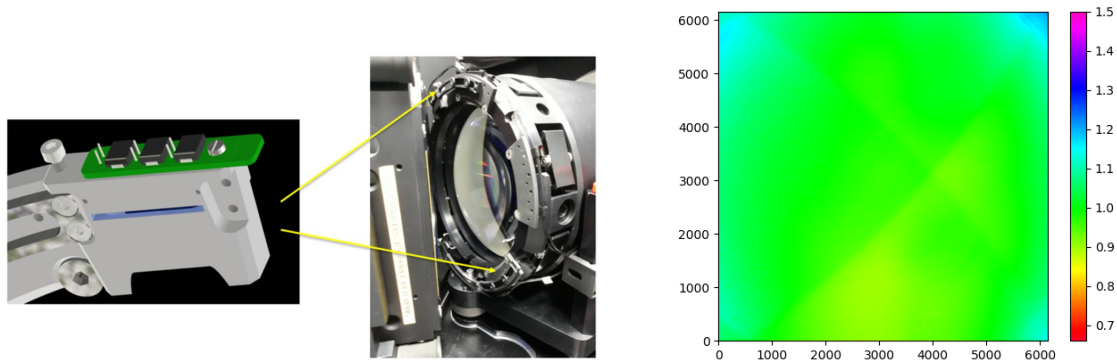


Figure 13: Left: New illumination setup for the detector flats. The LEDs are placed in front of the camera. Right: New design which is compliant to the requirement. Flux value normalized to the median over the detector area  $< 1.5$ .

## 8. CONCLUSION AND FUTURE DEVELOPMENT

During this AIT phase at Potsdam, all optical, mechanical, electronical, vacuum and cryogenic components have been integrated and aligned together in order to fulfil top-level requirements. Now, both LRS have been reassembled. The final reference exposures have been recorded for each arm after minor optimizations ie. camera focus or detector vessel tip-tilt optimization for LRS-A, detector flats retrofit and light tightness improvement. Health-checks were performed after re-assembly: we verified mainly the performances related to image quality (spectral resolving power and sampling, spectral purity, cross-talk). They were found to be similar to the ones we obtained during the first integration in Lyon, without any re-adjustment, proving the robustness of the opto-mechanical design and re-integration strategy. The results show good performances fully compliant with the requirements. During the summer 2023 and under the Andreas Kelz team's responsibility, the two Test Slit Units were replaced by the final Entrance Slit Units which is fully populated. Several intensive global end-to-end tests under AIP responsibility are currently carrying out with the Calibration Unit, the final Entrance Slit Units and the Spectrographs. The CRAL team supports these operations. The preliminary results are presented in the Genoveva Micheva et al. paper [12]. We are now preparing for the Preliminary Acceptance in Europe for the LRS, planned in autumn, 2024 for a telescope installation in 2025. There is then a good hope that the finally build LRS instrument will match its ambitious scientific performances.

I finally would like to particularly thank the members of the 4MOST CRAL team, AIP Project Office members and everyone working on 4MOST project for their support and invaluable contribution to this encouraging 4MOST LRS AIT phase.

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