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# 4MOST Low Resolution Spectrograph Alignment

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## 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 2023.

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 (LRS). Each LRS 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 final design review for the 4MOST LRS was successfully passed in May 2018. In 2020, a SPIE paper [1] focused on the definition of the technical requirements for all individual opto-mechanical components, the manufacturing and the deliveries up to the first assemblies in their mounts. The first LRS has now been fully integrated, aligned and tested, with both LRS foreseen for full system integration in 2022. This paper describes the long process from the integration and alignment of the sub-assemblies up to the “health-checks” performances for the entire LRS. Special emphasis is put on the procedures and tools used during this MAIT phase.

**Keywords:** 4MOST, VISTA, ESO, Spectrograph, Design, Performances, MAIT

## 1. INTRODUCTION

4MOST is a wide-field, high-multiplex spectroscopic survey facility under development 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]. 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].

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This paper will focus on the LRS MAIT which is under CRAL responsibility. The LRS MAIT 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 summarizes the main MAIT tools used to align the LRS. The alignment procedure is presented in section 4. The performances are briefly presented in section 5. Finally, the section 6 compiles the conclusions and future developments.

## 2. 4MOST LRS DESIGN AND KEY REQUIREMENTS

The LRS is composed of two identical (or 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 composed of 812 science fibres following focal plane curvature radius. A Slit Field Lens is glued onto the entrance 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 15µm/pixel records the spectra.

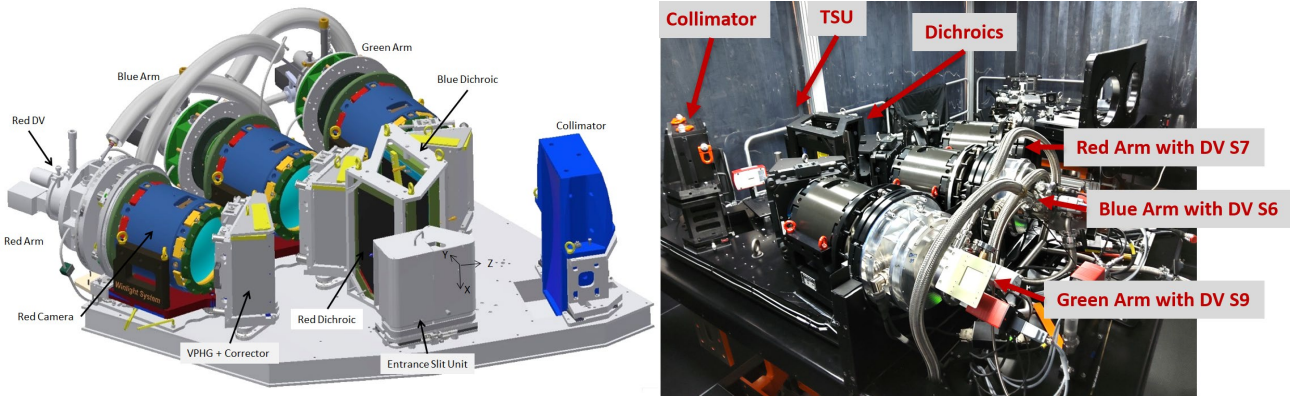


Figure 1: Left: LRS mechanical model. Right: LRS-A in operation

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. MAIN MAIT TOOLS DEVELOPED FOR ALIGNMENT

More than 20 MAIT tools are needed to achieve the 4MOST LRS MAIT Phase. The main MAIT tools are described here.

#### 3.1 Test Slit Unit with Light Source Module and Illumination Unit

The alignment and verification process of the LRS requirements needs a Test Slit Unit with Light Source Module and Illumination Unit.

The Light Source Module allows to provide all sources to perform the different tests. It is composed of 3 lamps: continuum lamp (Quartz-Tungsten-Halogen lamp), arc lamps (mercury and neon lamps) and monochromatic source (set of interference filters used with the continuum lamp). The light guides between sources and Illumination Unit and power supply is provided with sources.

An Illumination Unit (IU) for the fibre bundles is designed. The design is based on off-the-shelf components. It provides an input F-ratio of F/3.3. This design is based on VIRUS illumination unit, allowing to illuminate one or multiple ferrules at the same time - Figure 2.

Each of these tests requires a slit partially populated with pupil illuminated with a uniform illumination at F/3.3 beam. The Test Slit Unit is provided by AIP.

The Test Slit Unit is composed of:

- Slit Unit Support Structure which has the same interface as the final Entrance Slit Unit (kinematic mount). Note that the positioning/orientation is in concordance with tolerances defined in interface control document.
- Shutter Box and its associated electronic.
- Slit Box composed of:
  - 6 slitlets only at centre/middle/edge of slit with LRS slitlet location at positions 1, 6, 14, 15, 20, 28.
  - Sparsely populated slitlet containing 11 fibres each - 6 colored in blue and 5 colored in red fibres in Figure 2.
  - Connectors which are used for each slitlet in order to disconnect source/slitlet mapping following test configurations.

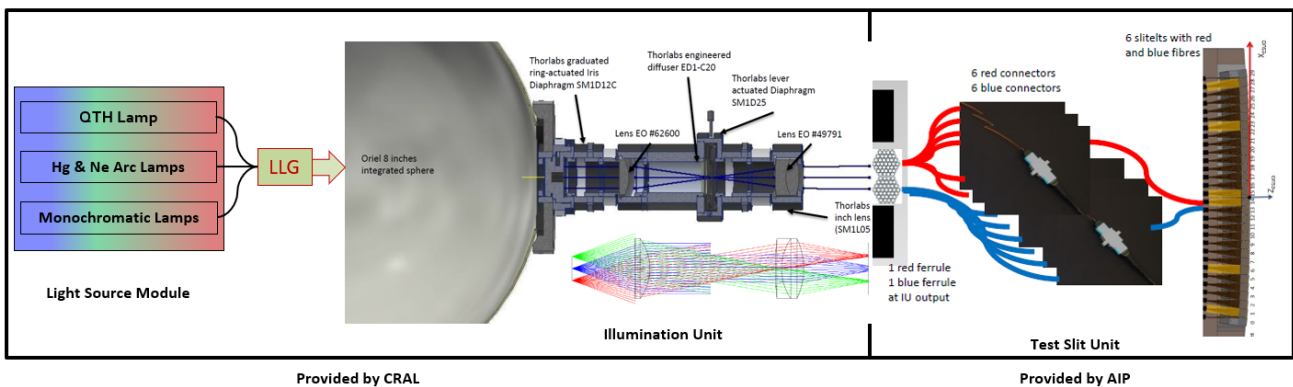


Figure 2: Light Source Module + Illumination Unit + Test Slit Unit

#### 3.2 References – Targets

The Global Reference Coordinate (Figure 3) is defined in order to be accessible at any time during the alignment. The Global Reference Coordinate is composed of 2 spheres (same as the trihedral Point-Line-Plane (PLP) used for other interfaces) and the Mounted Optical Bench. The Global Reference Coordinate (O, X, Y, Z) is defined as follows:

- O is the centre of the first sphere projected on the Mounted Optical Bench.
- Z is the line passing across the 2 centers of the spheres and is directed along the slit unit optical axis.

- X is the Mounted Optical Bench surface and is directed downwards.
- Y completes the right handed system.

Three other targets are defined in order to align each optical component together. The Figure 3 shows these alignment targets and their positions on the Mounted Optical Bench. Target\_1, Target\_2, Target\_3 are identical and are composed of 2 inches target.

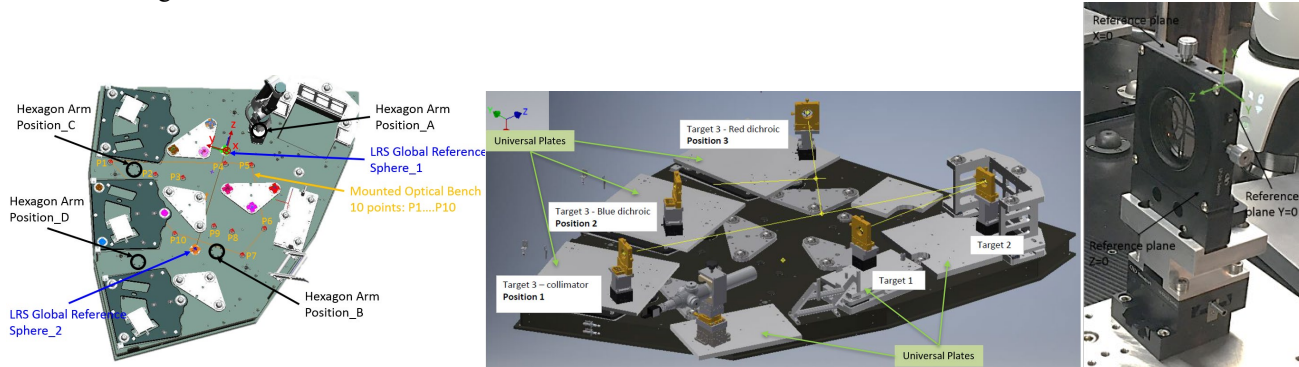


Figure 3: Left: Global References in yellow; Middle: Location of alignment targets in yellow. Right: Target in its mount

### 3.3 Metrology devices

An alignment telescope (AT) is used to align of optical components on the optical axis. Moreover, the HEXAGON Absolute Arm 8520 allows to measure the PLP interfaces, targets locations, PLP Interface wrt Mechanical components reference and Mechanical components reference wrt Optical components reference with an accuracy of  $\pm 11.5\mu\text{m}$  on a radius of 1000mm.

### 3.4 Software tools used during AIT

In order to facilitate the evaluation of the quality of the optical alignment and then to assess compliance to requirements specification a set of software tools were developed in Python. Two of them are particularly relevant for the description of the optical alignment steps.

#### 3.4.1 Rough estimate of FWHMs and spectral parameters

This script is run on an arc line exposure formerly bias-subtracted. 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. As an illustrative example produced plots for FWHM mapping are shown here for a still tilted optical alignment (while almost on focus) versus a good optical alignment (Figure 4).

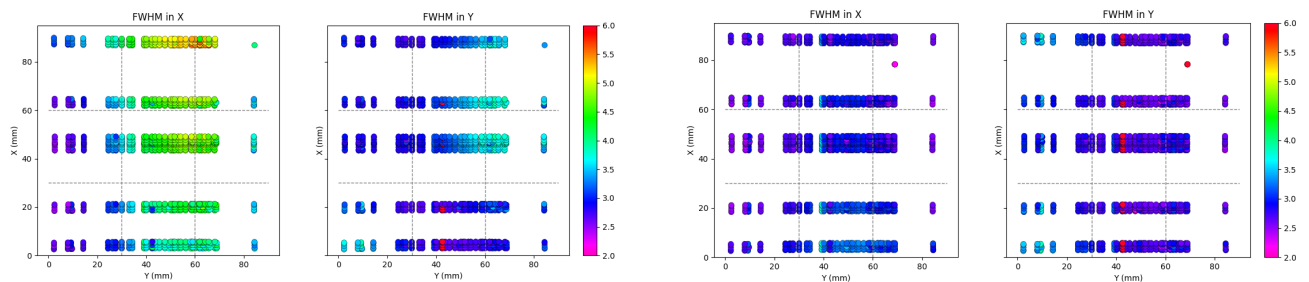


Figure 4: Left: Alignment still exhibiting a tilt in X and Y. Right: Alignment good enough to be kept as it.

#### 3.4.2 Check for compliance of the LSF parameters to requirement specification

This script evaluates the cross-dispersion fwhm but using a custom model acting as a fiber (simulated as an ellipse) convolved with a 2D Gaussian simulating the PSF. It takes longer to process and is then only used for final assessments on medianed bias-subtracted frames. More parameters are derived from these exposures to assess the critical performances. Input exposures may be arc line exposure to estimate criteria as the spectral purity or flat-field exposures to derive the crosstalk.



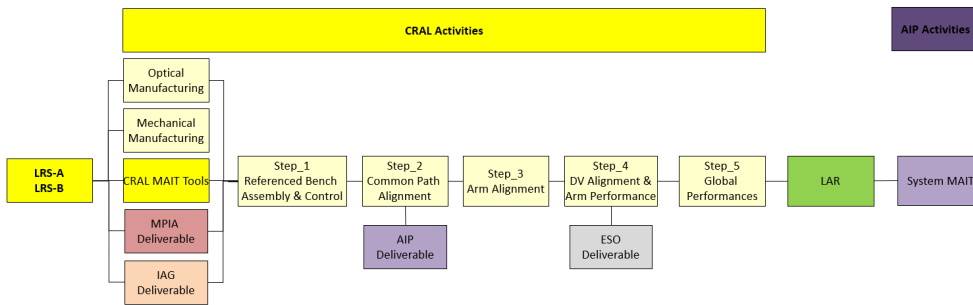
## 4. ALIGNMENT PROCEDURE

### 4.1 Strategy

Note that 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 methodology, the planning, and the execution of each LRS assembly and optical alignment are divided into 5 crucial steps described hereafter:

- Step\_1: Referenced bench assembly and control,
- Step\_2: Common Path Mounting & Alignment,
- Step\_3: Arms Mounting & Alignment,
- Step\_4: DV Mounting, Alignment & Arm Performance Tests,
- Step\_5: Global Performance Tests.



The system requirements where the tolerance analyses have been performed are the image quality, image positioning and vignetting (see [1]). Some of the optical components are manufactured and assembled with relaxed tolerance ( $\pm 0.5\text{mm} / \pm 5\text{arcmin}$ ) achieved with machine level precision. That is sufficient to reach a reasonable initial alignment of the system and guarantee the maximum stability after alignment. Other components have a compensation to nullify any degradation in image quality and/or image position/size due to the loose-tolerance elements as much as possible. To achieve these requirements, the following opto-mechanical components are separately adjusted: the Entrance Slit Unit as reference except along z-axis, the Collimator in (x, y), the Dichroics in ( $\theta_x, \theta_y$ ), the VPHG in ( $\theta_z$ ), the {Camera+DV} in ( $\theta_x, \theta_y$ ) and the DV in (z,  $\theta_x, \theta_y$ ). All these adjustment movements are permanently clamped once the correct alignment is reached.

	X ( $\mu\text{m}$ )	Y ( $\mu\text{m}$ )	Z ( $\mu\text{m}$ )	Tx (arcsec)	Ty (arcsec)	Tz (arcsec)
Slit						
Slit Field lens						
{Slit+Slit Field lens}			Home made stage			
Coll Mirror	Shimming	Home made stage				
Dichro_Red				Home made stage	Home made stage	
Dichro_Blue				Home made stage	Home made stage	
Corrector						
VPHG						Home made stage
Camera+DV				Home made stage	Home made stage	
Camera						
DV			Motorized home made stage	Home made stage	Home made stage	
FLW						
CCD						



Figure 5: Left: Foreseen adjustments to reach requirements. Right: Kinematic mounting based in PLP

In order to set up the LRS most similar to the conditions at the telescope, the LRS is mounted directly onto its LRS Frame equipped with LRS Instrument Cart in Lyon. The Optical Bench is equipped with kinematic mountings (Figure 5). They are used on each opto-mechanical assembly. This is important to the alignment process as it allows removal and replacement of components to micron repeatability (arc-second tilt). This methodology allows viewing of different optical components within the path at any time without interference of components upstream. They utilize a trihedral point/line/plane (PLP) system (sphere-cylinder-plane) and three “groove” arrangement. That allows adjustment under each through permanent shims, providing the most stable mount. For all components, the approach for manufacturing of

the opto-mechanical parts is to reference each optic wrt its interface with a sufficient accuracy and precision to provide already a good internal alignment from the start. Moreover, at any time, the optic is always measurable through its mechanics with Hexagon arm.

Due to the three arms in LRS, the goal was to secure the common path (i.e. Test Slit Unit, Collimator and Dichroics) before starting individual “arm” alignments. The tests onto pupil position are performed just after the common path alignment. Moreover, the alignment carries on with the Blue arm which allows aligning correctly the two dichroics in angle because it is more sensitive in reflection. After the Blue arm alignment, the first verifications are performed. The Green and Red arm are mounted and aligned following the same process as the Blue one. When the three arms are operational, the covers are mounted. The global verification could start (§5).

For the transport of the LRS to AIP as well as to Paranal, a dedicated set of containers will be used. For the transport, the mounted optics will be dismounted from the optical bench and separately packed. This will ease the further steps and minimize the integration activities both during integration at CRAL as well as at AIP and at ESO Paranal.

## 4.2 Global Alignment Budget

For each component, the global budget ( $\pm 0.5$  mm in X, Y, Z and  $\pm 5$  arcmin in  $\theta_X$ ,  $\theta_Y$ ,  $\theta_Z$ ) is shared in these 2 main levels and additional level for adjustment and margins. The components proper positioning and alignment are ensured by 2 main levels of tolerancing:

- The first level is done on Mounted Optical Bench wrt PLP Interface. Each optical component will be interfaced with the optical bench through a kinematic mount ensuring precise and reproducible positioning shown in Figure 5.
- The second level is done on PLP Interface wrt Mechanical components reference & Mechanical components reference wrt Optical components reference. That corresponds between the kinematic interface and the optical components reference surface.

The detailed alignment budget is presented in the paper in [1].

## 4.3 Procedure

### 4.4 Step\_1: Referenced bench assembly and control

This first step allows to assemble and control the optical bench without optics. The main goal is to be sure that all positioning/orientation of PLP interfaces are within the requirements wrt Global Reference Coordinate. For that, we follow the procedure:

- Mount the Mounted Optical Bench onto the LRS Frame with the lower cover.
- Install electronic, vacuum and cryogenic devices.
- Install the Global Reference Coordinate onto the Mounted Optical Bench. That will be the reference system coordinate for the Hexagon arm.
- Install all PLP interfaces onto the Mounted Optical Bench.
- Kinematic mounts are used on each optomechanical assembly. They are crucial for the alignment process since they allow removal and replacement of components to micron repeatability (arc-second tilt). This methodology allows viewing of different optical components within the path at any time without interference of components upstream. They utilize a trihedral PLP system (sphere-cylinder-plane) and three “groove” arrangement. That allows adjustment under each thanks to permanent shims, providing the most stable mount.
- Measure the positioning/orientation of PLP interfaces with Hexagon arm wrt a Global Reference Coordinate
- Adjust them by shimming under the 3 spheres ( $x$ ,  $\theta_y$ ,  $\theta_z$ ) and/or re-manufacturing all the 3 slots ( $y$ ,  $z$ ,  $\theta_x$ ) if necessary (nominal positioning ( $\pm 0.25$ mm /  $\pm 2.5$ arcmin)).
- Result on LRS-A: The  $x$  &  $z$  positions ( $\pm 0.08$ mm) are within the specifications. The  $x$ -positioning ( $\pm 0.05$ mm) is also within the specifications.

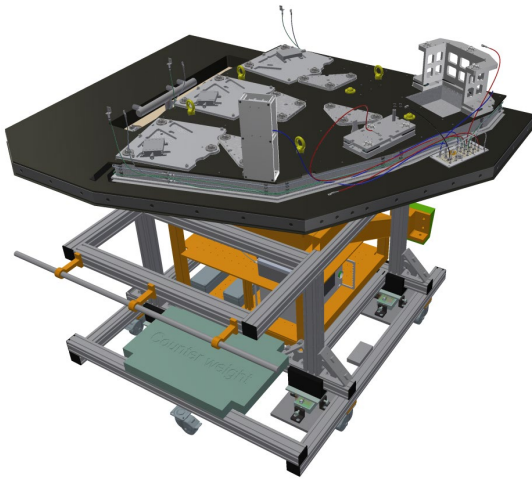


Figure 6: From design to reality: Referenced Bench Assembly & Control

#### 4.5 Step\_2: Common Path Mounting & Alignment

The second step is to align and verify the common path which includes Optical Axis Definition, Test Slit Unit, Collimator and Dichroics. For that, we follow the procedure:

- Optical Axis Definition - Figure 7
  - Set Target\_1 onto the theoretical position of the slit center and Target\_2 onto the theoretical position of the collimator with Hexagon Arm.
  - Here, the optical axis is defined with two referenced points formed by these two target centres.
  - Install AT on the universal plate such that the distance between AT and Target\_2 is at least 1200 mm.
  - Align AT wrt the 2 targets.
- Test Slit Unit (TSU) Verification
  - Step 1: Near field measurement ( $x, y, z, \theta_z$ ).
    - Acquire an image of Target\_1 by installing a detection module (Apogee Camera and Nikon 200mm Photo Lens) on a translation stage (along  $z$  direction) between Target\_1 and the collimator, at about 300 mm from Target\_1.
    - Image analysis: compute position of Target\_1 centre and arms onto the detector ( $x, y$  optical axis reference and  $\theta_z$  reference).
    - Install of Test Slit Unit at the location of Target\_1 and illuminate it with continuum lamp.
    - Acquire an image of TSU output with the detection module.
    - Image analysis: Consider the 2 central slitlets imaged onto the detector; compute the ( $x, y$ ) position of each fiber and fiber sizes. The  $z$  positioning will be validated by comparing the fiber image size with the known fiber size, or at least by checking that inside one slitlet, all fiber size are within an acceptance range.
    - Results: The ( $x, y$ ) positioning is lower than 0.1mm; the  $\theta_z$  is  $\sim 10$  arcmin but this setup is not accurate enough for  $\theta_z$  computation. The  $z$  positioning verification was finally not conclusive: a shift was noticed between the extrema of both focus curves obtained on the fibre images and the Target image due to the slitlets, which changes the optical system in case of imaging the fibre with the camera+photo objective. This could be modelled with Zemax, but not accurately enough without providing a model of the photo objective.
  - Step2: Far field measurement ( $\theta_x, \theta_y$ )
    - In this step it is necessary to change the f-ratio fiber injection that should be set at  $f/6$  instead of  $f/3$ .
    - Acquire an image of autocollimator reticle by installing a detection module (Apogee Camera alone) at 100mm from the theoretical position of the slit center.
    - Image analysis: Compute the position of target image centre on the detector ( $x, y$  optical axis position reference).



- Re-install TSU and illuminate only one slitlet of TSU with continuum lamp at  $f/6$ .
  - Image analysis: Compute the beam centroid position and compare with expected values.
  - Results on LRS-A: These results suggest a tilt around Y axis of  $\sim 15$  arcmin, close to (maybe a bit out of) the limit of the tolerance range. The tilt around X is around 2 arcmin. Due to the difficulty to compute the flux center of mass, these results are more indicative as final.
- Collimator Alignment - Figure 7
    - Remove Target\_2 & TSU.
    - Re-Install Target\_1 onto the theoretical position of the slit center (kinematic mount).
    - Install Target\_3 at the red VPHG location with Hexagon Arm.
    - Mount the collimator with the crane.
    - Measure collimator optical surface with Hexagon Arm wrt its PLP interface, check with theoretical value.
    - Align collimator (x, y) by imaging Target\_3 with AT (x position adjustment by shimming, y position adjustment with a micrometre).
    - Results on LRS-A: Shims of 0.42mm are placed below the spheres in order to reach x-positioning. The collimator has been translated along +y-axis of 0.945mm.
    - Measure the distance between Target\_1 (slit center) and collimator with Hexagon Arm. Adjust if necessary by translating TSU along z-axis.
    - Results on LRS-A: The TSU was moved away from the collimator thanks to the translation stage (translation of 1.08 mm along Z axis, towards negative Z values).
    - Once the collimator is aligned, clamping screws are locked.

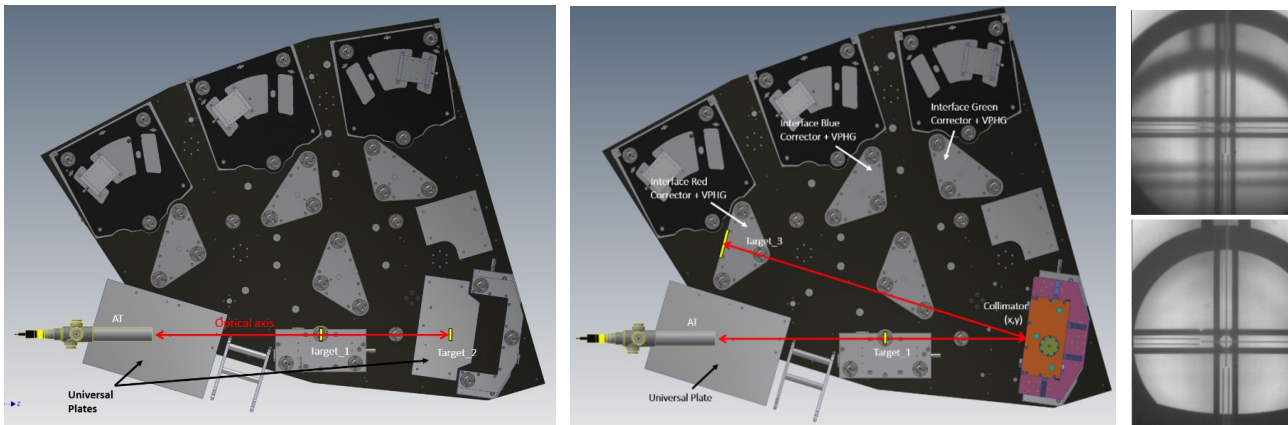


Figure 7: Optical axis definition and collimator alignment. Target\_1 and \_2 images with Alignment Telescope

- Alignment of Dichroics - Figure 8
  - Install the dichroic assembly in its PLP interface with crane.
  - Install one Target\_3 at the location of the Blue Camera with Hexagon Arm.
  - Install another Target\_3 at the location of the Green Camera with Hexagon Arm.
  - Note that the image of Target in transmission is completely insensitive to any tilt applied to the dichroic. Consequently both dichroics can be placed on the bench and aligned simultaneously in only one step by imaging both Target\_3, which are placed where each dichroic is reflective.
  - Align Red\_Dichroic ( $\theta_x, \theta_y$ ): check its positioning/orientation by imaging Target\_3\_GreenCamera with AT.
  - Align Blue\_Dichroic ( $\theta_x, \theta_y$ ): check its positioning/orientation by imaging Target\_3\_BlueCamera with AT.
  - Note: A 0.5 mm displacement of the target center (the central circle of the target pattern is 1 mm diameter) corresponds to a tilt of about 1.5 arcmin on the red dichroic (a tilt around Y induces a displacement of the target in X direction and vice versa). Similarly, a 0.5mm displacement of the target center corresponds to a tilt of about 2.5 arcmin on the blue dichroic. This means that the alignment stays acceptable (given the angular tolerance on the dichroics alignment) as long as the shift between the target centre and the AT reticle does not exceed the central circle diameter.
  - Once the dichroics are aligned, clamping screws are locked.

- Common path verification - Figure 8
  - Remove Target\_1 and re-install TSU.
  - Illuminate TSU with continuum lamp.
  - Check Pupil positioning and size with Pupil setup (Apogee Camera with Nikon 200mm Photo Lens and diffusing screen):
  - Align and focus the detection unit of Pupil setup by imaging Target\_3.
  - Remove Target\_3 and replace it with the diffusive screen.
  - Take an exposure and compute the pupil centre position and size.
  - Check Pupil positioning and size with Pupil setup onto Green&Red arms. As before with this Pupil setup, the results are not accurate enough. The results are just informative.

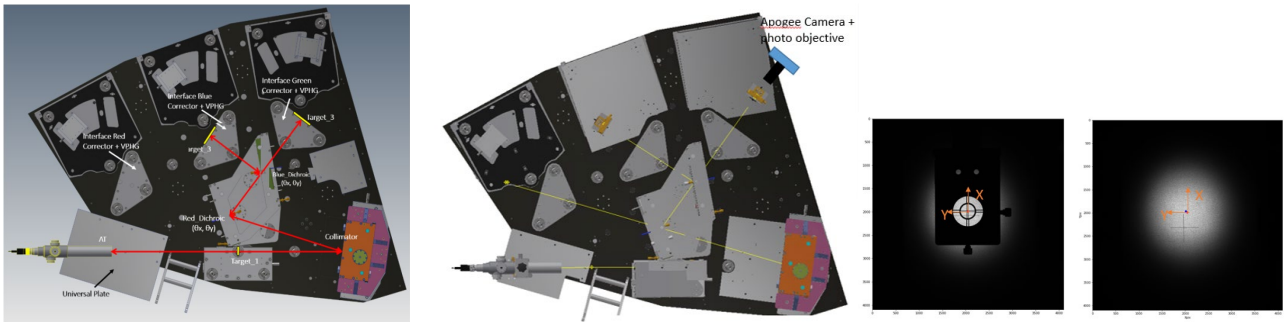


Figure 8: Left: Alignment of Red\_Dichroic and Blue\_Dichroic at the same time. Middle: Pupil setup configuration on green arm. Right: Examples of recorded images of Target\_3 and beam for the common path verification

#### 4.6 Step\_3: Arms Alignment

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

- Corrector & VPHG Alignment

For the corrector and VPHG, we apply the same philosophy as previous in imaging Target\_3 on the alignment telescope. As this assembly is in the transmissive path, its alignment is not relevant. No adjustment is foreseen both for the corrector and VPHG. Note that the final optical alignment of the VPHG is performed later by the rotation around z-axis to align the spectra wrt CCD column.

- Camera Alignment

- Mount {Camera + DV Interface Assembly} onto its PLP interface.
- Measure {Camera + DV Interface Assembly} references with the Hexagon Arm wrt its PLP interface.
- Adjust {Camera + DV Interface Assembly} in (z, Rx, Ry, Rz) until the theoretical position is reached.
- Once the Camera is adjusted, clamping screws are locked.
- Mount {Camera + DV Interface Assembly} onto the LRS optical bench.

#### 4.7 Step\_4: DV Alignment & Arm Performance

The fourth step is to align the DV and to perform the first tests onto the whole arm from the Test Slit Unit up to DV. The procedure is repeated for the Green and Red arms. For that, we follow the procedure:

- Electronic setup and external cabling.
- Mount and operate the Detector vessel.
- Align Rz\_VPHG, (Rx, Ry) Camera and (z, Rx, Ry) DV to reach image quality and positioning requirements in using Test Slit Unit.
  - The DV alignment is provided by observing arc and continuum lamps illuminating the Test Slit Unit.
  - Take a first set of exposures with Test Slit Unit and Light Source Module (arc lamps) - Figure 10.

- A macro focus curve is performed (range 2mm with 250 $\mu$ m step). The translation stage is located into DV Interface Assembly (interface between the camera and the DV). Therefore the whole DV can move over +/-2 mm. In reality, we do not need a “real” focus curve. An analysis by “eyes” is accurate for the macro focus.
- A “fine” focus curve is performed (range 0.3mm with 25 $\mu$ m step) around the best focus of the macro focus curve. In reality, we do not need a “real” focus curve. Evaluate using the software tool mapping the FWHMs how far we are from the focus (the smaller the FWHM the better) and if a tilt still remains - §3.4.1.
- Set the DV at the best focus.
- Unlock all degrees of freedom on the Camera (the 3 PLPs, Rx and Ry) and on the VPHG (4 locking screws) - Figure 9.
- Adjust the “smile” angle on the CDD with Rz Camera. Move the 2 rear PLPs on the Camera in order to have the same y-CCD position on the outermost fibres at central wavelength.
- Adjust the “spectra” angle on the CDD with Rz VPHG using the adjustment screw in order to have the same x-CCD position on one of the central fibre along the whole spectrum.
- Adjust the x-positioning on the CDD with Ry Camera using the 2 rear PLPs in order to have the theoretical x-CCD position (3080px) on the “virtual” fibre.
- Adjust the y-positioning on the CDD with Rx Camera using the adjustment screw in order to have the theoretical y-CCD position of the brightest spectral line on one of the central fibre (Blue=2178px corresponding to Hg line at 435.8nm; Green=2621px corresponding to Ne lines at 640.225nm; Red=3384px corresponding to Ne lines at 837.75 nm).
- Lock all degrees of freedom on the Camera and on the VPHG.

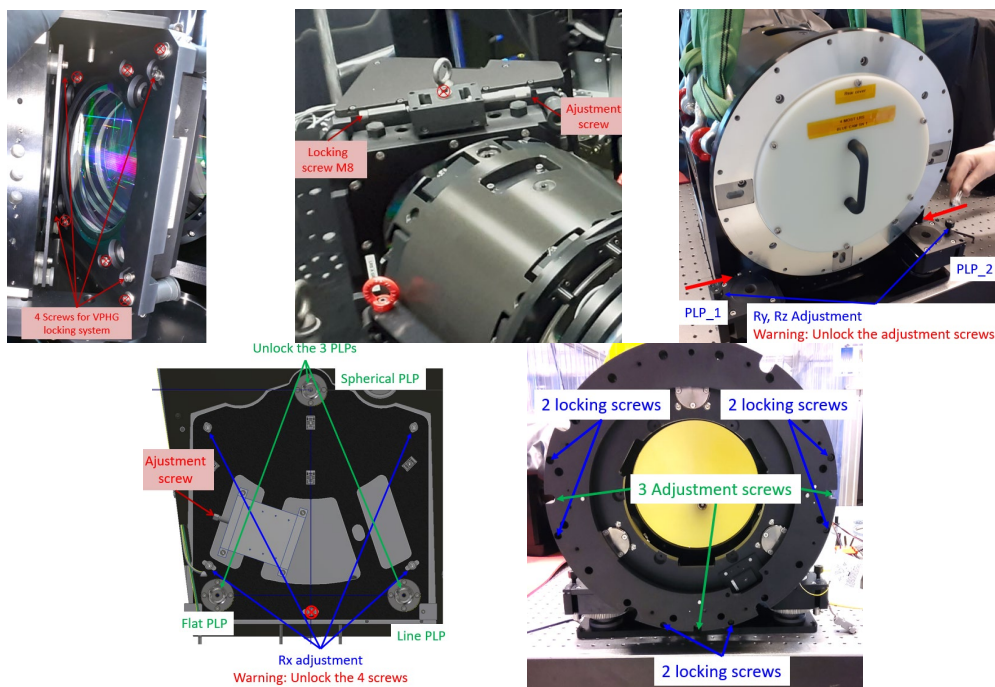


Figure 9: Locking system and adjustment screws on VPHG, camera and DV Interface Assembly

- Adjust the tip/tilt of the DV in using the CRAL software tool results. The Figure 4 illustrates 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.
  - Take a set of exposures with Test Slit Unit and Light Source Module (arc lamps). The Figure 10 shows an arc lamp exposure where there are 6 slitlets along the spatial direction (vertical) and the wavelengths along spectral direction (horizontal).
  - Run the software tool. If the LSFs are higher than 3.25pixels, proceed to the adjustment. The Figure 4 shows the results of the software tool when the DV is misaligned (left) and after the DV tiptilt adjustment (right).
  - Unlock by 1/8 turn and 1/8 turn more, the 6 locking screws on the DV Interface Assembly - Figure 9.

- 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 three days with more than one hundred iterations.
- Readjust the focus if necessary.
  - Set the DV at the best focus.
  - Take a set of exposures with Test Slit Unit and Light Source Module (arc lamps).
  - Redo the positioning alignment if necessary.

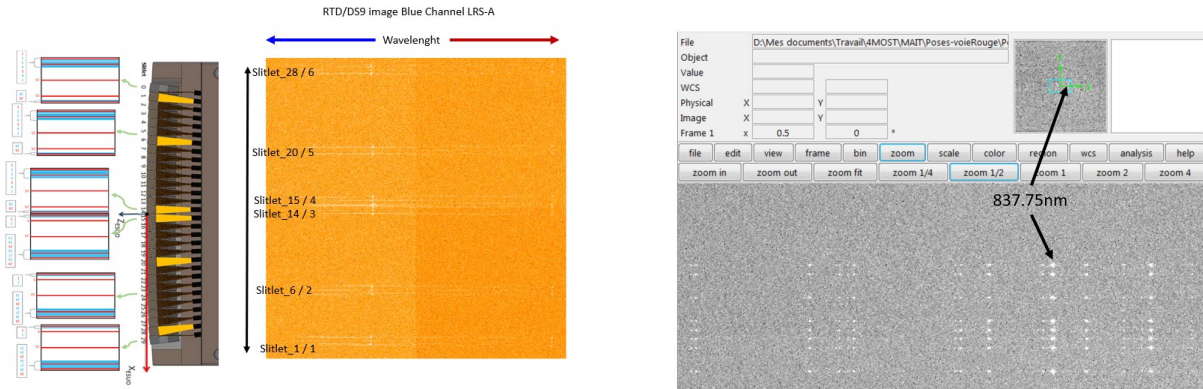


Figure 10: View of an exposure with a zoom on the right

## 5. PERFORMANCES

The fifth step is to perform the global tests onto the whole LRS. All of the verification tests are performed at CRAL integration hall as part of the Local Acceptance Review (LAR), before shipping the LRS to AIP for System AIT.

The LRS verification plan is composed of 3 steps:

- Interface verification mainly LRS-Fibre Feed interface and LRS-Detector Systems interface
- First Verification which allow to validate the alignment for each arm (§ 4) ie. image quality and positioning. That is communally named “health-checks”. For that, the software tool is used (§ 3.4.2)
- Second Verification which allow to perform specific tests onto the arm itself as throughput, ghosts, straylight.
- Third Verification which allow to perform other tests onto the whole LRS when the covers are closed. That is communally named “global tests”.

Note that, there are 88 verifications. For LAR, there are 4 verifications by Design, 1 by Analysis, 33 by Inspection, 23 by Tests and 27 are Not Applicable.

The paper [10] details how the requirements for the Low Resolution Spectrograph subsystem have been verified. It presents the results on the whole performances which have been validated.

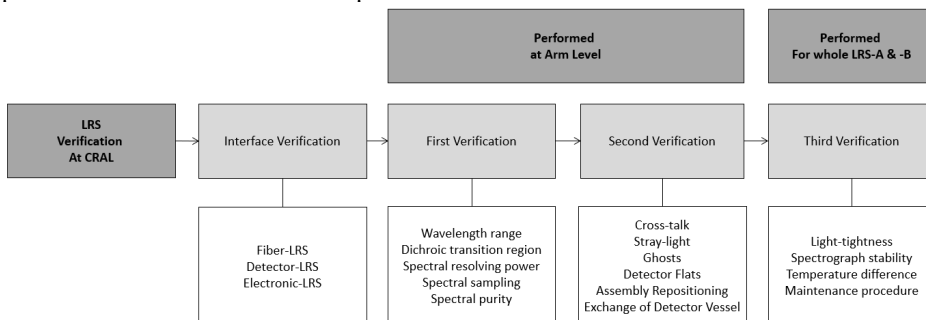


Figure 11: Schematic view for verification plan

## 6. CONCLUSION AND FUTURE DEVELOPMENT

During this MAIT phase, all optical and mechanical components have been integrated and aligned together in order to fulfil top-level requirements. An alignment procedure for 4MOST LRS in Lyon Integration Hall has been performed to allow a compliance with requirements and an integration in safe conditions. This alignment procedure includes a list of more than 20 MAIT Tools used for the alignment and integration procedures and for the verification plan. Today, the first LRS-A has successfully passed its Local Acceptance Review in December 2021. 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 no major 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 is on-going in Lyon. The first results are very encouraging. We expect a Local Acceptance Review for LRS-B in autumn, 2022. 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 MAIT phase.

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