The calibration unit and detector tests for MUSE

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ABSTRACT

The Multi-Unit Spectroscopic Explorer (MUSE) is an integral-field spectrograph for the ESO Very Large Telescope. After completion of the Final Design Review in 2009, MUSE is now in its manufacture and assembly phase. To achieve a relative large field-of-view with fine spatial sampling, MUSE features 24 identical spectrograph-detector units. The acceptance tests of the detector sub-systems, the design and manufacture of the calibration unit and the development of the Data Reduction Software for MUSE are under the responsibility of the AIP. The optical design of the spectrograph implies strict tolerances on the alignment of the detector systems to minimize aberrations. As part of the acceptance testing, all 24 detector systems, developed by ESO, are mounted to a MUSE reference spectrograph, which is illuminated by a set of precision pinholes. Thus the best focus is determined and the image quality of the spectrograph-detector subsystem across wavelength and field angle is measured.

Keywords: Integral-field spectroscopy, 3D-spectroscopy, calibration, spectrographs: MUSE, VLT

1. INTRODUCTION

The Multi Unit Spectroscopic Explorer MUSE [1] is one of the second-generation instruments for the Very Large Telescope (VLT) in Chile, which belongs to the European Southern Observatory (ESO). For an integral field spectrograph (IFS), it offers a wide field of view of 1 arcmin^2. Combined with a spatial sampling of 0.2 arcseconds, this results in a total of 90,000 spatial elements or spaxels. During an exposure, a spectrum ranging from 465nm to 930nm is produced for each spaxel. As to record this large amount of information, the total field of view is split into sub-fields first and then directed to two dozen individual spectrographs that operate in parallel.
The major aim of this effort is to obtain spectra of very distant galaxies as to study the progenitors of normal nearby galaxies out to redshifts z of around 6. These galaxies are extremely faint and therefore require the large light collecting power of the VLT, a high instrumental throughput and long integration times. To reach flux levels of a few 10^{-19}erg s^{-1} cm^{-2}, which is an order of magnitude more sensitive than what currently can be achieved with narrow band imaging, long integration times (of around 80 hours per field) will be required, imposing high stability and good calibration onto the instrument. Thus calibration procedures, the spectrograph transmission and the image quality as well as the treatment of the resulting data are of great importance to achieve the science goals.

This ambitious project is carried out by a consortium of seven major European research institutes, led by the Centre de Recherche Astrophysique de Lyon (CRAL). Further partners are the Laboratoire d'Astrophysique de Toulouse-Tarbes, (LATT), the Institut für Astrophysik Gottingen (IAG), the Astrophysikalisches Institut Potsdam (AIP), the Leiden Observatory (NOVA), the Institute for Astronomy at ETH, and the European Southern Observatory (ESO-ODT).

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The work-packages are distributed in such a way, that the existing expertise of the partners is used at best. CRAL manages the project, is in charge of the integration of the overall instrument and for the development of the spectrographs. IAG builds the instrument main structure and the splitting and relay optics that feed the individual spectrographs. The optical detector team of ESO provides the 24 CCD detector vessels with controllers, and the vacuum and cryogenic system to operate these. LATT designs the fore-optics and is in charge of the MUSE instrument control electronics. AIP developed the calibration unit, undertakes the detector system acceptance testing and is in charge of the data reduction pipeline. The contribution of NOVA is GALACSI, the adaptive optics system upstream of the actual MUSE instrument.
All teams, including ETH, are engaged with observational and theoretical astrophysicists to develop and exploit the scientific use of MUSE.

This paper focuses on the development of the calibration unit and the acceptance testing of the detector subsystems as these are the major hardware-related contributions by AIP.

2. THE MUSE INSTRUMENT

To provide an integral-field with relative large size, high spatial resolution and broad wavelength coverage, MUSE [2] uses a modular structure of 24 identical field-units, each one consisting of an advanced mirror-based slicer, a fully refractive spectrograph and a CCD detector with 16 million pixels. To feed these units, a series of fore-optics and splitting and relay optics is needed to de-rotate, to anamorphic magnify and to split the square field of view into 24 sub-fields. These sub-fields are relayed using a set of mirrors to guide the light into the spectrographs. The entire instrument is placed on the Nasmyth platform of the VLT (see figure 1). For stability reasons, the instrument main structure is a monolithic block that houses all 24 field-unit in an arrangement of 4 rows of 6 units each. A so-called extension beam above the main structure provides the mechanical interface for the fore-optics, consisting of de-rotator, wide- and narrow-field magnification optics, the instrument main shutter and the image splitter. The calibration unit (CU resides on top of the extension beam. AO correction will be performed by the VLT deformable secondary mirror. Four sodium laser guide stars are used, plus a natural star for tip/tilt correction.
The instrument concept and science goals are described in detail in [3]. This paper describes the design and development status of the calibration unit and the first performance validations of the detector subsystem. Other aspects of the instrument are described in more detail in a series of papers [4-9] in this issue, while up-to-date information can be found at the MUSE website [11].

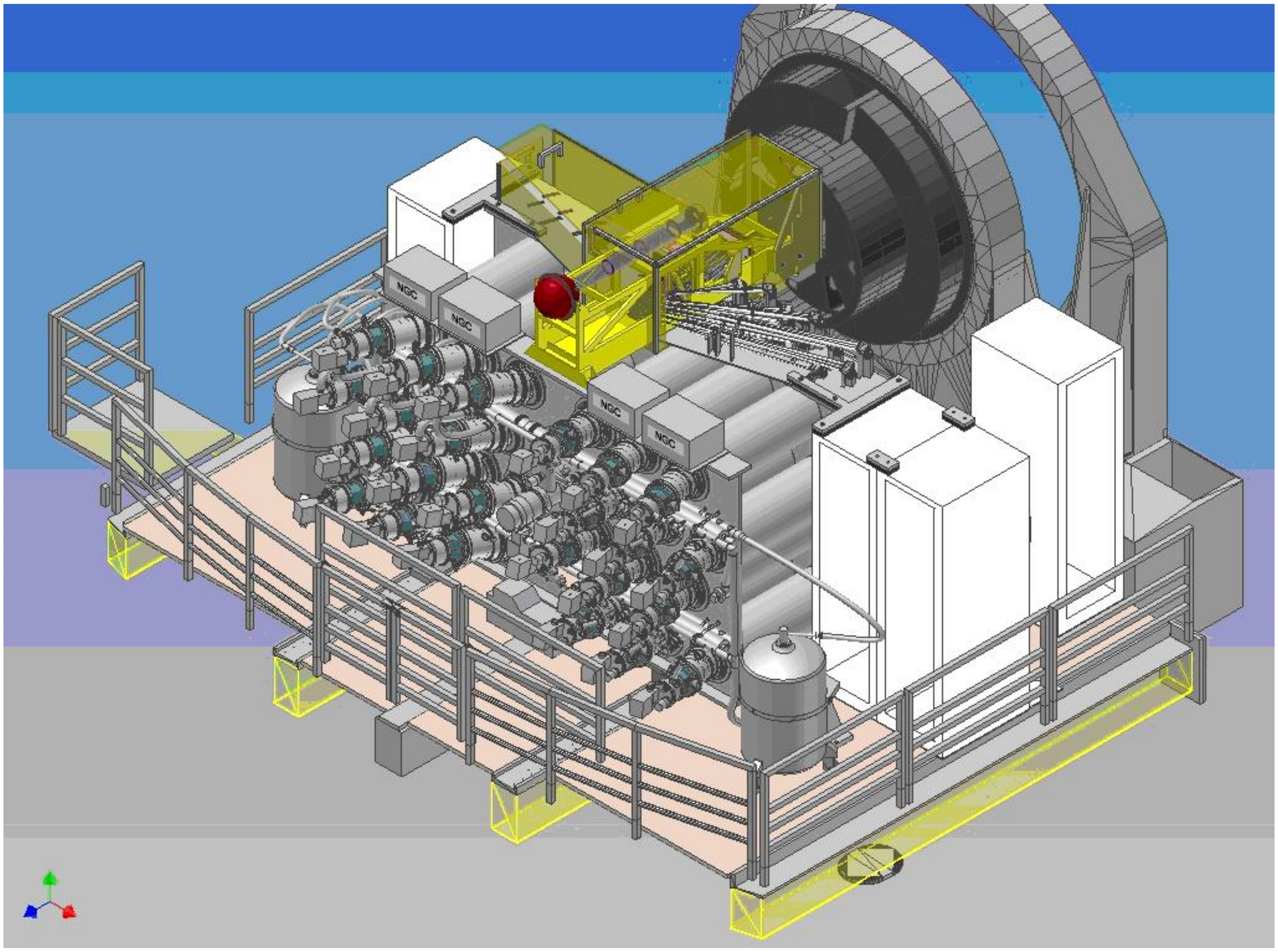

Figure 1: CAD view of the MUSE instrument at the VLT Nasmyth platform [6]. From the Nasmyth rotator, the light travels through the fore-optics and is distributed to the 24 spectrographs and recorded by as many detectors at the back of the instrument. The calibration unit sits on top of the instrument.

3. THE CALIBRATION UNIT

The Calibration Unit (CU)[10] of MUSE shall provide the instrument with an input beam that mimics the beam provided by the telescope. The calibration light sources include both, a continuum source to measure the instrumental response and spectral arc lamps for wavelength calibration. In addition, the CU provides precision masks for image quality and geometrical calibration of the instrument. The CU injects the light at the very front end of the instrument, immediately after the telescope focal plane, so that the calibration light follows the same path as the light from the telescope through all optical components of MUSE.

In essence the CU features:

- Various calibration light sources (CLS) for white light and spectral illumination.
- An integrating sphere (CUis) for homogenous illumination (to simulate a flatfield screen).
- A calibration relay lens (CUrl) to mimic the VLT beam (using a telescope objective).
- A fold mirror (CUfm) to fold the beam.
- A set of precision masks at CU focal plane (for image quality calibration).
- A calibration pick-up mirror (CUpm) to insert the CU beam into MUSE.

3.1 Optical Design

The aim of the calibration unit is to mimic at best the VLT Nasmyth focus from the optical point of view, and therefore provide the MUSE spectrographs with a reference field similar to what is expected from the field generated by the VLT. Optically, the VLT Nasmyth focus can be described by a limited amount of purely geometric parameters:

- a beam f-number of F/# = 15 (image-side),
- a telecentric system with a 8000mm entrance pupil (the VLT primary mirror)
- a 120 meter effective focal length

Furthermore, the calibration unit optics has to provide the same high quality imaging as the VLT.

- achromatic system
- a flat field illumination in the image plane
- across an image plane of at least 50mm diameter in physical size

The flatness of the focal plane produced by the calibration unit and its size are of critical importance. A set of precision masks can be inserted at the location of the CU focal plane, e.g. using pinholes to trace the PSF or line-masks to only illuminate certain sections of the overall field as to evaluate aberrations and straylight levels.

For reasons of footprint (the image plane being located in the focal plane of the calibration unit lens system), it is necessary to perform a scaling of the system, within keeping the same image plane geometric characteristics. Therefore, the actual calibration unit lens system has the following characteristics:

- a beam opening at F/# = 15,
- a telecentric system with a 80mm entrance pupil (a stop located at the exit of an integrating sphere)
- a 1200 millimeter effective focal length (given by the calibration relay lens)
- a flat and telecentric image plane of at least 50mm diameter in size, corresponding to the maximum
- the image focal plane of the lens

This longitudinal scaling of the system characteristics provide the calibration system with parameters similar those of the VLT Nasmyth focus, as shown in figure 2.

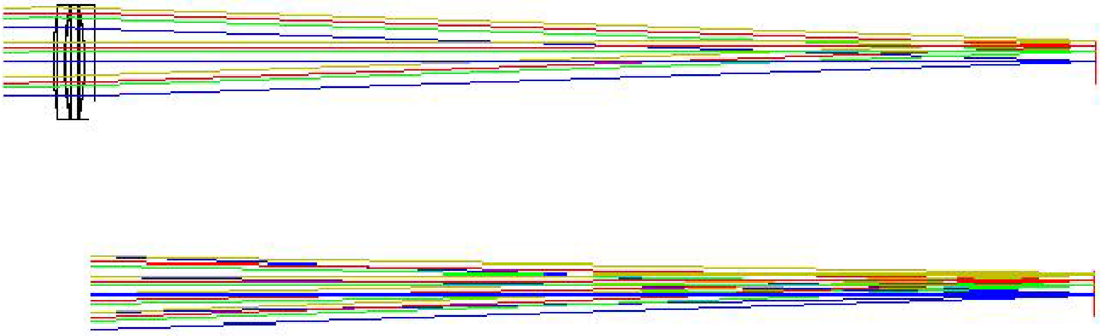

Figure 2: Sketch of the CU optical concept. The top part shows the ray tracing for the VLT, the bottom part the CU beam, using an integrating sphere (left) and a relay lens (center) to closely mimic the VLT beam and to provide a sufficiently large focal plane (right).

Those general geometrical considerations lead to a paraxial approximation of the design as shown in figure 3.

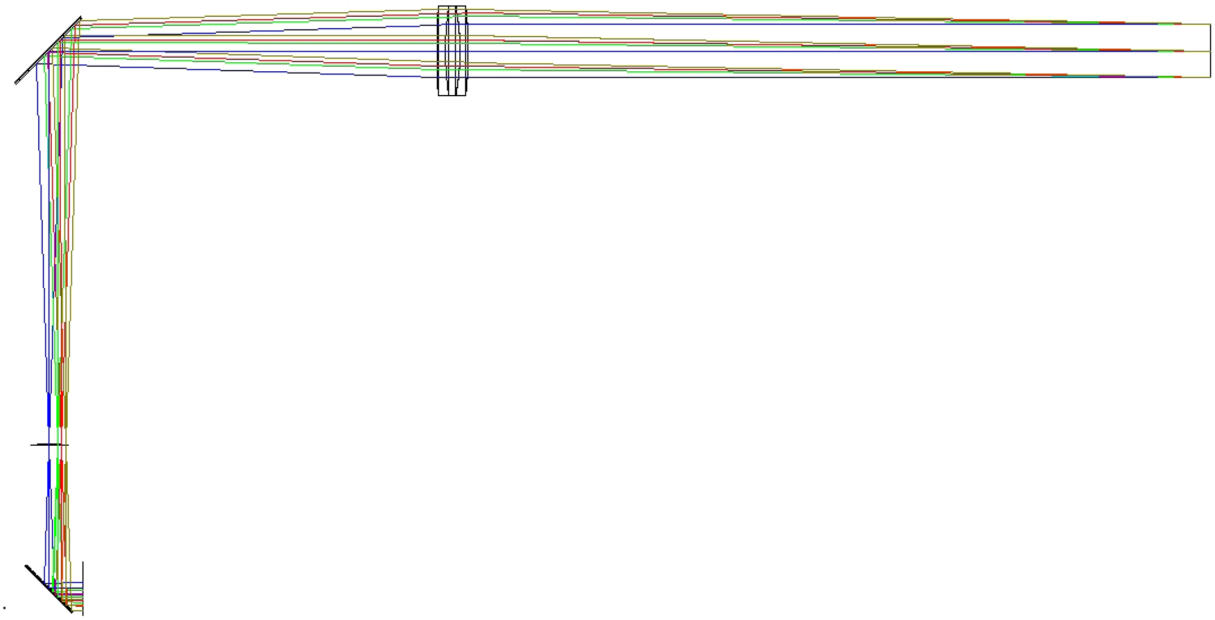

Figure 3. Ray tracing through all elements of the folded version of the calibration unit beam (in the travel direction of the light): from the entrance pupil plane (top right), the relay lens, fold mirror, focal plane, and the pick-up mirror (lower left) towards MUSE.

As the system is telecentric, all chief rays are parallel, resulting in a very limited angular dependency of the illumination, thus in combination with using the exit port of an integrating sphere as input pupil plane, creating a good flat field. For the CU lens three designs were evaluated, a singlet made of BK7, an achromatic doublet made of BK7/F2 and an apochromatic triplet using K5/CaF2/K5. Due to the requirement to minimize the CU chromatics given that the reflective VLT is achromatic by default, the triplet lens was chosen. The lens is supplied with a broadband anti-reflection coating to avoid any ghosts.

For practical reasons, especially regarding the high thermal dilatation coefficient of CaF2, the company fabricating the lens (Lichtenknecker Optics) proposed an equivalent air-spaced design, using infrared Ohara glasses. The manufacturing tolerances are similar to commercial refractor telescopes of this size. The prescription data of the design can be found in table 1.

Table 1. Prescription data of the CU lens system [all distances are in millimeters]

Surface	Radius	Thickness	Material	Half-Diameter	Comment
0	Infinity	1115	Air	80	aperture stop
1	423.627	12.5	S-BSL7	67	lens surface 1
2	310.610	1.446	Air	67	lens surface 2
3	354.210	22	S-FPL53	67	lens surface 3
4	-319.700	0.107	Air	67	lens surface 4
5	-337.451	12.5	S-BSL7	67	lens surface 5
6	-2684.000	1167.333	Air	67	lens surface 6
7	Infinity			25	image plane

This design provides the expected geometrical parameters, as stated in table 2.

Table 2. System data of the calibration unit lens

Effective focal length	1199.9 mm
Working F/#	14.998
Paraxial image height	24.75mm (for 1.182° field)
Exit pupil position	-17110mm

The relative illumination at the focal plane created by the CU optics shows a 0.2% (peak-to-valley) illumination variation only, fulfilling the requirements of a flat field across the size of 50mm (see figure 4).

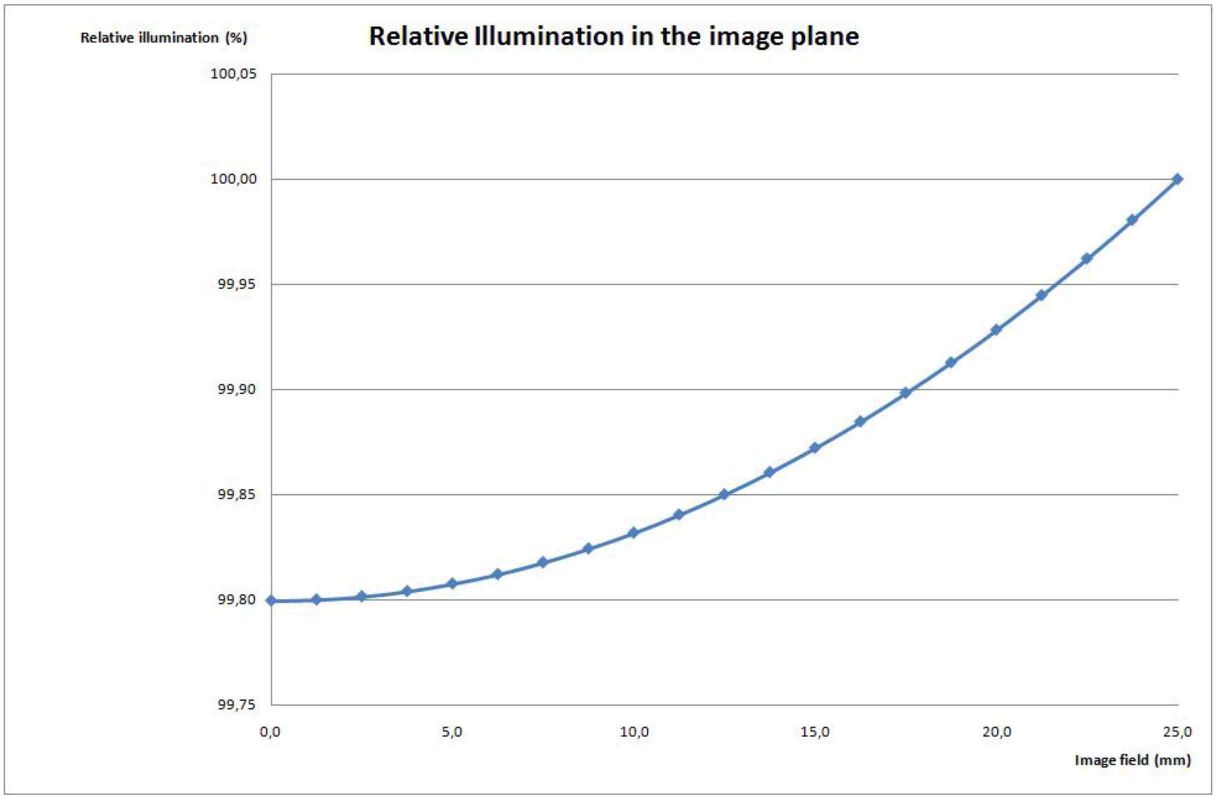

Figure 4. Relative illumination at the CU image plane, from centre to edge of field.

While the CU image quality is a less important parameter, the design yields good spot diagrams as shown in figure 5, which are compared to the ones of the VLT in figure 6.

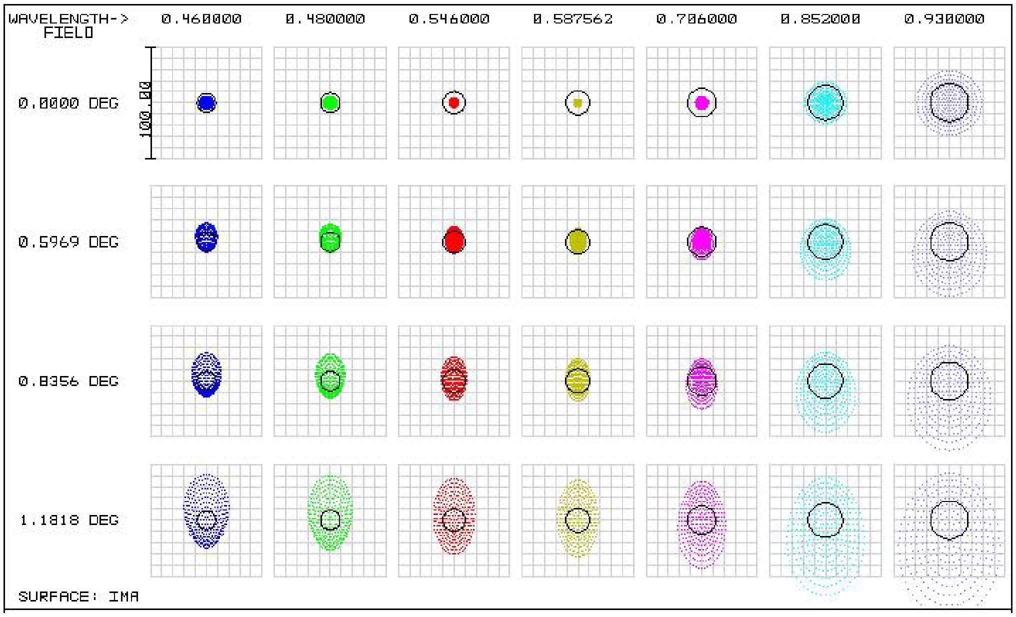

Figure 5. Spotdiagrams at the CU focal plane (box size=0.06mm) across wavelengths from blue (left column) to red (right column) and field angle from centre (top row) to edge (bottom row). For comparison, the VLT Airy disk is shown as circle in each box.

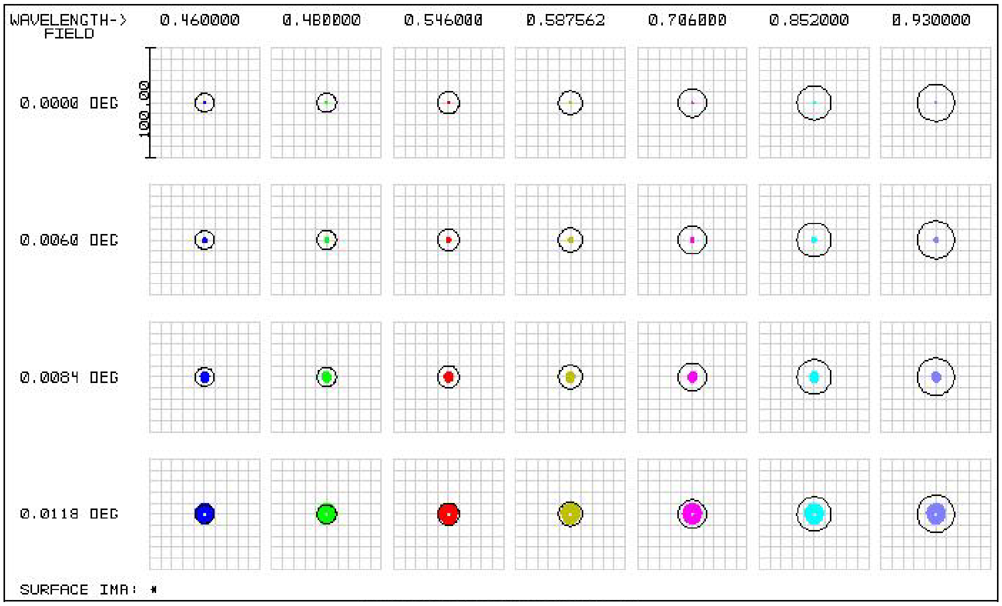

Figure 6. Spotdiagrams at the VLT Nasmyth focal plane (box size=0.06mm) across wavelengths from blue (left column) to red (right column) and field angle from centre (top row) to edge (bottom row). For comparison, the Airy disk is shown as circle in each box.

Apart from the optical design, one of the main challenge for such a big diameter lens consists in the practical fabrication of the lens and the design of a mount capable of compensating the dilatation of the glass for the quite broad functional temperature range (-5°C to +25°C) which may be encountered during transport, integration and operation of the instrument. A modified solution of our design was provided by the lens manufacturer (Lichtenknecker Optics) that compensates any thermal effects through spring-loading (see figure 7).

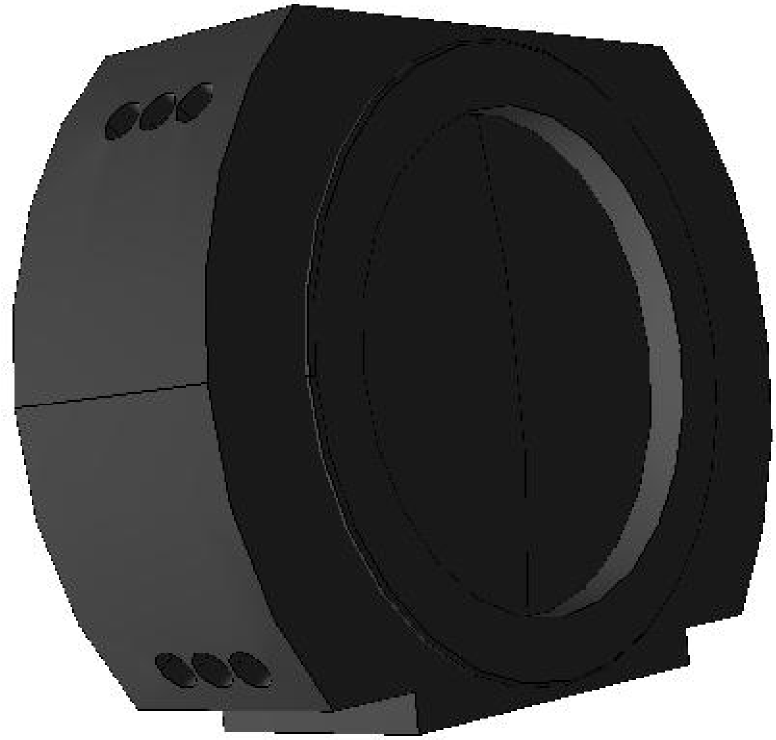

Figure 7. CAD view of the mount for the apochromatic triplet, compensating any thermal effects.

3.2 Mechanical Design

The entire CU is mounted onto a single mechanical support (see figure 8), called the extension beam that sits on top of the instrument main structure [6].

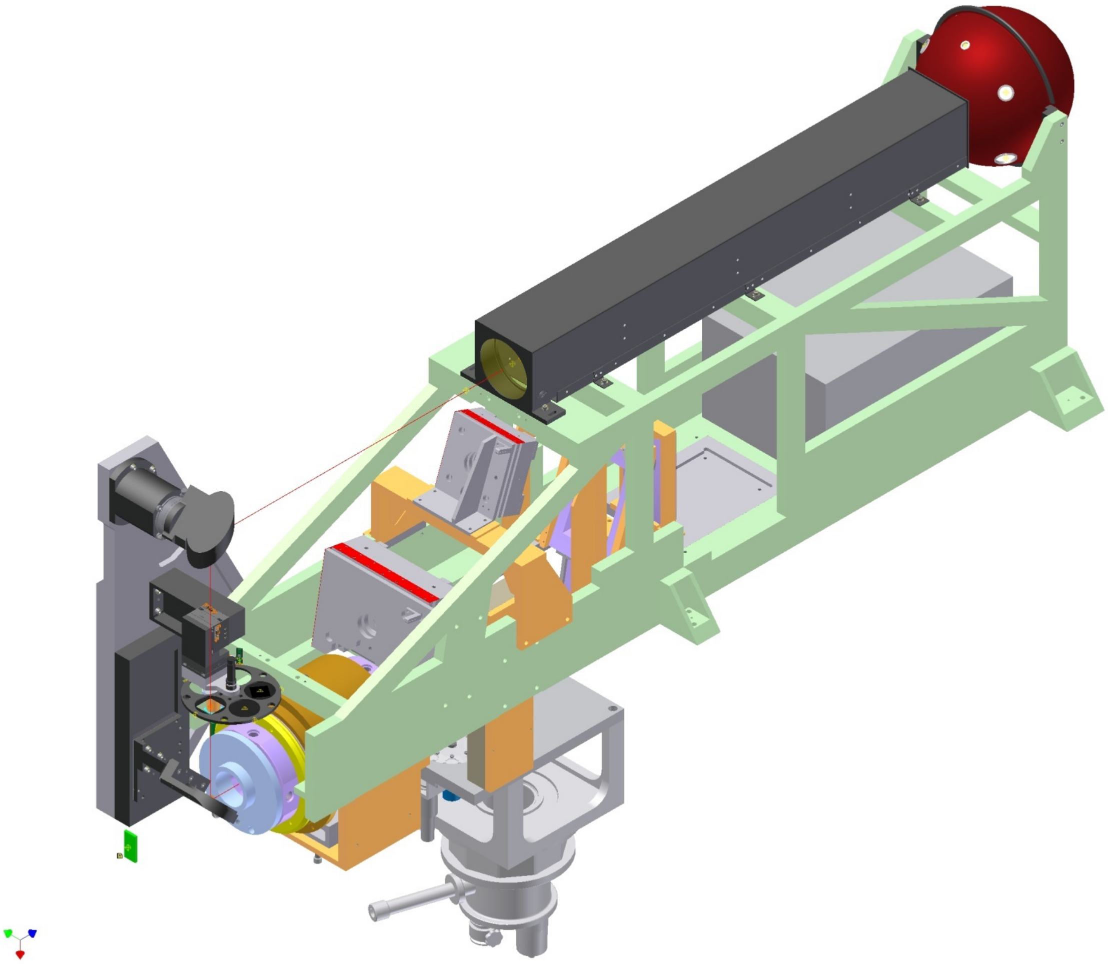

Figure 8. CAD view of the MUSE CU components mounted in the extension beam that also houses the fore-optics inside.

3.3 Calibration Light Sources

The concept of the CU allows flexible combinations of up to 6 Calibration Light Sources (CLS) to be coupled into the instrument. The design foresees 2 continuum and 4 spectra arc lamps that are into the CU integrating sphere in parallel. The light sources are located in individual housings that are placed remotely within the electronics cabinet. In this way heat sources are kept away from the instrument. The connection to the integrating sphere is done with a bundle of light guides (figure 9). Thus, it is possible to provide a “mix” of up to 6 calibration light sources in a single calibration exposure.

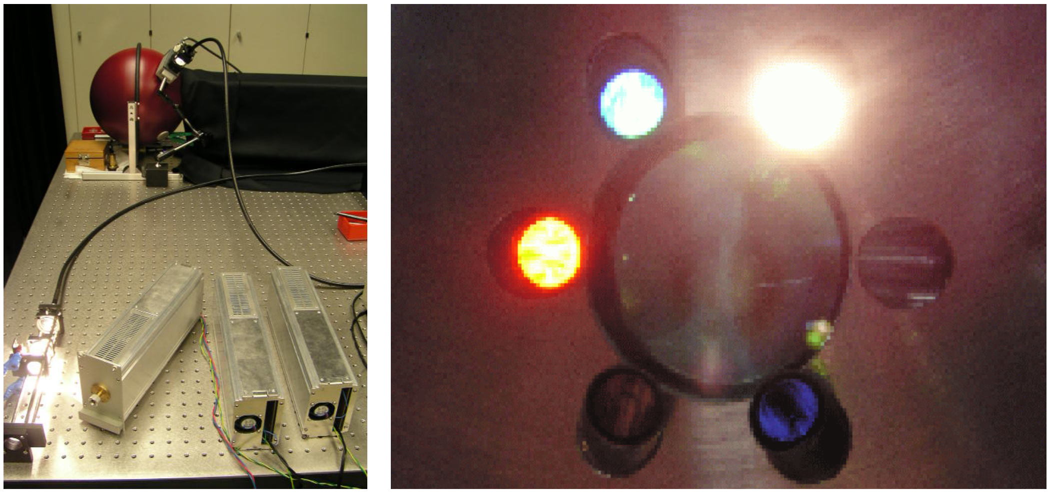

Figure 9. The calibration lamps units are connected with light guides to the MUSE CU during flux tests (left). The output ends of the light guides shine into the integrating sphere (right), allowing

3.4 Calibration Masks

The concept of the CU allows the insertion of various calibration masks at the focal plane (figure 10). The operational masks are defined as follows: a) square field mask for Wide-Field-Mode, b) circular field mask for WFM+guide fields, c) multi-pinhole mask for PSF calibration, d) slit mask for spectra tracing, e) square field mask for Narrow-Field-Mode

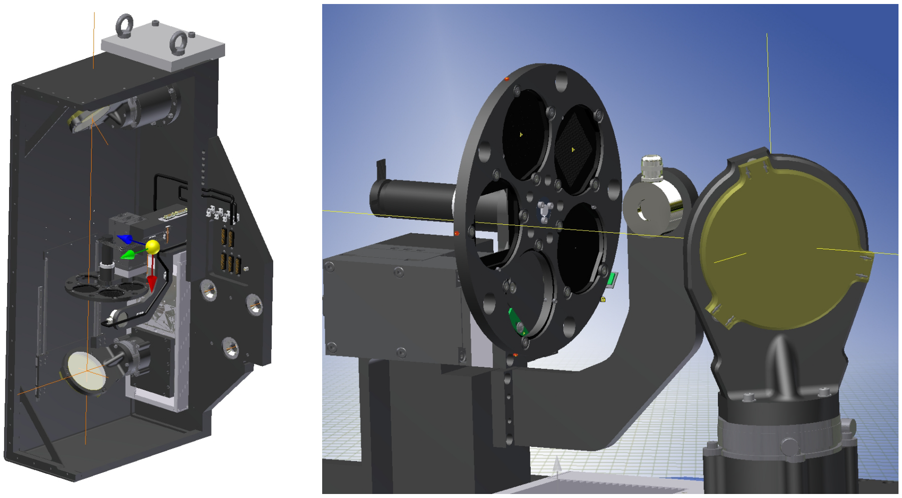

Figure 10: Left: CAD view of the CU front part, which includes the fold mirror, the mask wheel, and the pick-up movable mirror all mounted to a common plate. Right; Detailed CAD view of the CU mask wheel which has 5 ports to hold the calibration masks. Also shown is a calibrated photodiode that can be illuminated by the CU beam to flux-calibrate the instrument.

4. DETECTOR SYSTEM TESTING

4.1 Test Setup

The first (out if a series of 24) spectrographs was built and extensively tested at CRAL[9]. After evaluation of the spectrograph performance, the system was send to AIP as a reference, as to measure the correct CCD integration with respect to the detector head and spectrograph optics. Given the tight tolerances resulting from the optical design and the specification that 80% of the ensquared energy of the IFU point-spread-function (PSF) should essentially be contained in 2 pixel, a careful alignment of the CCD detectors, in particular in tip-tilt, need to be ensured. While a measurement jig at ESO is used to align the CCD chip correctly to the detector outer flange, the purpose of the tests at AIP (see figure 11) is to verify the overall good image quality across the chip with the attached spectrograph, to establish a common best focus and to ensure that all detector systems are interchangeable at all spectrographs.

To perform the tests, the spectrograph front end is illuminated by a set of pinholes with a diameter of 10 microns, corresponding to 1/10 of a slicer width. Illuminating the pinholes with arc lamps (Hg, Ne, Xe) results in over 500 PSFs across the detector. However, using pinholes of this size, the PSF at the CCD (with pixels of 15 microns) is actually under-sampled. This causes some difficulties to measure the ensquared energy (A80) value directly. Instead, a re-sampling onto a finer grid and an interpolation is needed.

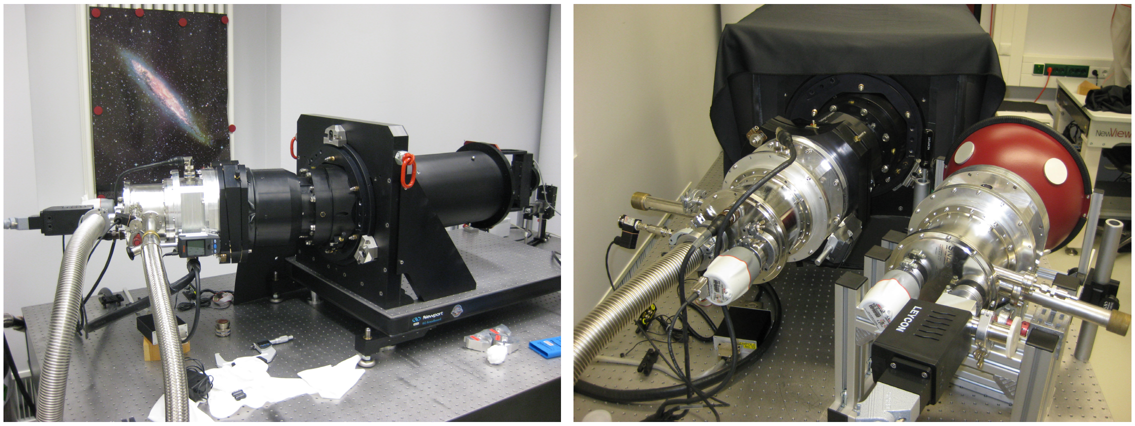

Figure 11. The MUSE spectrograph with attached detector vessel on the test bench at AIP (left). Two MUSE detectors, attached to the spectrograph for image quality tests and an integrating sphere for flat-fielding.

4.2 Test results

As the detector testing has just commenced, only preliminary results are available at this stage. These indicate that it is possible to obtain a common best focus for the majority of the points across the field angle and across the wavelength range. The 80% ensquared energy value was measured to be within 2.6 pixels (see figure 12).

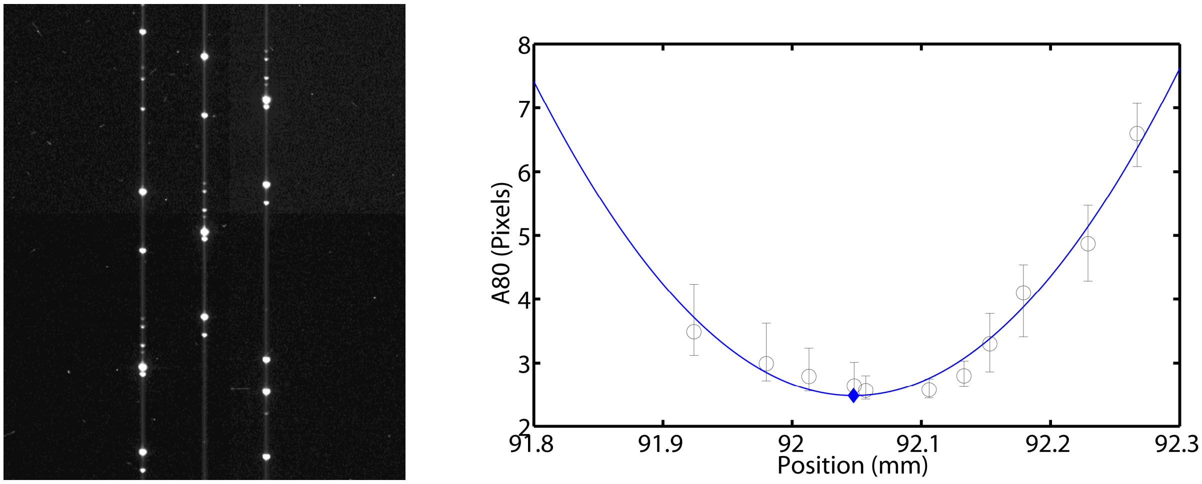

Figure 12. Left: raw frame of an image quality test exposure, showing the emission line spots of an Hg/Ne arc-lamp. Right: Measured 80% ensquared energy (A80) values of the median PSFs across the detector versus different focus positions. The A80 value at best focus is 2.5 pixels.

5. CONCLUSIONS

For the MUSE calibration unit an optical design, including an apochromatic triplet, was chosen that closely mimics the VLT beam. The use of precision masks at the focal plane allows an accurate calibration of the image quality of the entire MUSE optical train. With the first spectrograph and detectors systems being manufactures, real testing of the image quality of individual IFU has commenced. The preliminary results indicate an overall good image quality of the MUSE spectrograph-detector subsystem.

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