MUSE Image Slicer: Test results on largest slicer ever manufactured

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ABSTRACT

An image slicer breadboard has been designed, manufactured and tested for MUSE (Multi Unit Spectroscopic Explorer) instrument, a second generation integral field spectrograph developed for the European Southern Observatory (ESO) for the VLT. MUSE is operating in the visible and near IR wavelength range (0.465-0.93 m) and is composed of 24 identical Integral Field Units; each one incorporates an advanced image slicer associated with a classical spectrograph.

This paper describes the original optical design, the manufacturing, component test results (shape, roughness, reflectivity, microscopic visualization) and overall system performance (image quality, alignment) of the image slicer breadboard. This one is a combination of two mirror arrays of 48 elements each. It is made of Zerodur and uses a new polishing approach where all individual optical components are polished together by classical method. This image slicer constitutes the first one which has the largest number of active slices (48) associated with strict tolerances in term of positioning. The main results of the tests on this image slicer breadboard will then be presented. Most of them are compliant with requirements. This demonstrates that the manufacturing process is mature and gives good confidence for serial production applied to MUSE instrument.

Keywords: Integral Field Unit, Advanced Image Slicer, MUSE instrument, Classical polishing, Zerodur

1. INTRODUCTION

Integral Field Spectroscopy (IFS) is a technique that gives simultaneously the spectrum of each spatial sampling element of a given field. It is a powerful tool which rearranges the data cube represented by two spatial dimensions defining the field and the spectral decomposition (x, y, λ) in a detector plane. In IFS, the “spatial” unit reorganizes the field, the “spectral” unit being composed of a classical spectrograph. For the spatial unit, three main techniques – microlens array, microlens array associated with fibres and image slicer – are used in astronomical instrumentations.

The advantage of imager slicer system compared to the others is data-packing efficiency which is around 90% and which is also more compact. The principle of an image slicer system is based on the concept proposed by R. Content in 1997 [1]. The two main optical functions of the image slicer are to transform a rectangular Field of View (FoV) in a series of mini-slits at the spectrograph entrance plane and to reimagine the telescope pupil at infinite distance. It is originally composed of three reflective elements (a slicer stack, pupil and slit mirrors), each of them made of different mirrors which passes different geometrical characteristics (mirror tilts and curvature radius).

Proposed to the European Southern Observatory (ESO) for the second generation VLT–instrumentation, MUSE (Multi Unit Spectrograph Explorer) will be installed on the VLT Nasmyth platform B for a first light in 2012. The MUSE consortium consists of seven European Research Institutes – Centre de Recherche Astronomique de Lyon, Astrophysikalisches Institut Postdam, ESO, Swiss Federal Institute of Technology Zürich, Laboratoire d’Astrophysique Toulouse Tarbes, Sterrewacht Leiden and University of Goettingen – all managed by CRAL. MUSE is an innovative
IFS which combines a 1’×1’ FoV, with a spectral resolution reaching 3000 and a spatial sampling of 0.2’ matching the spatial resolution provided by a ground layer adaptive optics system named GALACSI. MUSE operates in a large visible and near IR spectral range (0.465 – 0.93 µm). It will be especially optimized for the study of the progenitors of normal nearby galaxies out to high redshift. A detailed description of MUSE and its scientific applications is presented by Bacon et al. during this conference [2]. The MUSE instrument is composed of a Calibration Unit [3], a Fore-Optic which includes an optical derotator and an anamorphoser by 2, a splitting optics cutting the FoV in 24 parts and 24 relay optics [4] which feed 24 identical IFS. Each IFS is composed of an original advanced image slicer associated with a high-throughput spectrograph with a Volume Phase Holographic Grating (VPGH) and a 4k×4k CCD detector. Although different experiments have been carried out on image slicer system [5], [6], [7] and [8], MUSE IFS represents a major difficulty for MUSE. The Figure 1 gives a mechanical overview of MUSE with all subsystems.

Figure 1: MUSE Mechanical Overview

A Conceptual Design Phase (Phase A study) was performed by the MUSE Consortium and finished with a review in February 2004. In 2006, an Optical Preliminary Design Review of the instrument optics (OPDR) was performed where the frozen optics design was presented and reviewed. ESO was agreed at the time to come to the MUSE Preliminary Design Phase (PDR) with a working image slicer sub-system (ISS) which is the most critical component of the MUSE instrument. Although some ISS contracts were in place, the ISS itself was not a subject at the MUSE PDR which has been granted in July 2007. But, the ISS feasibility shall be shown at the Optical Final Design Phase (OFDR) in December 2007.

To pass a successful OFDR, an image slicer made of two arrays of spherical mirrors has been designed, manufactured and tested. The remainder of this paper is organized as follows: the optical design is presented in section 2, the ISS component manufacturing is described in section 3, the optical integration is illustrated in section 4, the ISS individual tests and performances are discussed in section 5, and a conclusion with future developments are presented in last section.
2. MUSE SLICER OPTICAL DESCRIPTION

The technical performance of the MUSE image slicer derives from the top-level requirements of the instrument. The MUSE ISS magnification ratio of 0.076 and input and output focal ratios are related one to each other. To respect Shannon criterion on the CCD plane, an anamorphic ratio is introduced by MUSE Fore Optic. These characteristics lead to a nominal output focal ratio of 4.35 along the x-axis and 8.7 along the y-axis. This is a consequence of the large on-sky geometrical etendue that must be transmitted by the MUSE instrument (i.e. 0.2” angular resolution on an 8 m-diameter telescope), and could be critical with respect to the image quality performance. The input pupil characteristics are given by the input focal ratio of 57.4 along the x-axis and 114.8 along the y-axis. It is located at infinity distance (=60m) from the slicer stack. Moreover, 90% of the enclosed energy at the pseudo-slit plane should be included within one spatial sampling element along the x-axis (35 μm at pseudo-slit plane) and two spectral sampling elements along the y-axis. The required ISS average optical efficiency is 0.925 in middle wavelength range. The projected FoV of the IFU, corresponding to the dimensions of the image to be sliced, is 133.6 x 11.1 mm. This has additional consequences on the global image quality of the subsystem and on pupil aberration. Consequently, the number of slices is 48. In order to avoid diffused light, micro-roughness of optical surfaces should be less than 3.5 nm RMS. These major ones were controlled as described in section 5.

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- Image Dissector Array (IDA)
- Focusing Mirror Array (FMA)
- Pupil / Slit mask (PSM)

Figure 2 : ISS Product Tree

The Figure 3 shows the optical design.

Figure 3 : Optical Design. In order to simplify the drawing and the understanding, only the configurations n°1, 4, 7 and 10 are represented.

The ISS consists in:

- An Image Dissector Array (IDA) - Figure 4: This key component is composed of 4 identical stacks of 12 slices cutting the entrance Field of View (FoV) in thin, narrow strips, redirecting the beams in different directions, and imaging the telescope pupil at different places following a “staircase arrangement”. The 4 stacks of slices are placed side-by-side. Each slice is an off-axis spherical mirror around x and y-axes with a useful rectangular aperture of 33.40 mm (optical useful area of 33.245mm) along x-axis by 0.925 mm along y-axis containing a 15” x 0.2” sky image. IDA is mounted on a support in order to put it on a specific optical bench. Each slice has the same curvature radius of 300mm. Then, the intermediate pupil plane is located at 150 mm from IDA on a spherical surface. IDA makes an angle of 5.16 degrees around x-axis between the incident and reflected beam.
A Focusing Mirror Array (FMA) - Figure 7: It is placed in front of IDA. It is constituted of 48 identical focusing mirrors (each being associated to one slice). The focusing mirrors ensure the triple function of deflecting the optical beams from the IDA so that they are parallel one to each other, creating a demagnified image of its associated slice in the ISS image plane which is tilted around x-axis with an angle of -6.23°, and re-imaging all the images of the telescope pupil at a common location that will be the entrance pupil of the MUSE spectrograph. Each focusing mirror is an off-axis spherical mirror tilted around both axes with a rectangular aperture of 9 mm along x-axis by 2.6 mm along y-axis. FMA is mounted on a support in order to put it on a specific optical bench. Each focusing mirror has the same curvature radius of 22.8 mm and is shifted along z-axis in order to image all slices in the tilted pseudo-slit plane located at 12.4 from FMA. The 1.38 degrees angle is located between incident beam coming from IDA and reflected beam going to Spectrograph entrance. IDA and FMA are roughly 160 mm apart. In the pseudo-slit plane, mini-slits are arranged in four staggered rows, within ±30μm accuracy along both axes.

A pupil/slit mask (PSM) - Figure 5. This mask is put in the pseudo-slit plane in order to limit any scattered light on MUSE CCD detector. It is constituted of 48 elliptical holes where the telescope pupil light is coming through and 48 rectangular holes, which are located in the ISS image plane. Due to the optical design, four slit baffles are into those elliptical holes.

For the Optical Final Design Phase, the breadboard is composed of a full IDA and FMA with 48 spherical mirrors each. The PSM is not part of this breadboard.

3. MUSE SLICER FABRICATION

This ISS breadboard was manufactured and assembled by Winlight Optics in France using classical polishing techniques. All slices, focusing mirrors, wedges and heels are made of Zerodur.

3.1. IDA Manufacturing

The IDA manufacturing constitutes a WINLIGHT Optics/CNRS patent. Recent innovative methods, developed conjointly by LAM (Laboratoire d’Astrophysique de Marseille, France) and WinLight Optics (Marseille, France), allow reaching high performances (accurate roughness, sharp edges, surface form, etc.) with standard glass manufactured components while saving costs and time by an order of magnitude compared with classical techniques. Last developments and applications are presented in details in a paper presented in this conference by Vives et al., on “New technological developments in Integral Field Spectroscopy” [9].

All slices are assembled using molecular adhesion process. IDA is coated after its assembling with protected slicer. In Figure 6, the final IDA is shown.
3.2. FMA Manufacturing

All focusing mirrors are identical then the offset will be given by a decentring of mirror directly on FMA support. One mirror is extracted from one blank of Zerodur. First, the optical surface is polished. Second, a lens is glued on the optical surface to avoid chips on edges. Third, the lateral surface is polished in order to have correct size of 9x2.6mm. After that, all 48 focusing mirrors are coated with protected sliver in the same time. A hole is located into the lateral surface of each focusing mirror (Figure 7, Right). That is to hold them during the coating. The reference surface is the back one with respect to the optical surface. A centred optical surface is polished onto active surface. A prismatic wedge is glued onto the back of the heel giving a tilt around x-axis for a line of 3 mirrors (Figure 7). Sixteen prismatic wedges are manufactured and assembled. This assembling is placed on a special optical bench equipped with an autocollimator with a microscopic objective. It worked in confocal configuration measuring the positioning of the curvature centre. This equipment was mounted on 3 translation stages with feelers with accuracy better than 1 µm. Each focusing mirror is glued in a correct positioning when the reflected spot into autocollimator is located at the correct positioning. This process is repeated for the 48 focusing mirrors.
In Figure 8, the final FMA with these 48 spherical mirrors is represented.

![Figure 8: The FMA composed of 48 focusing mirrors](image)

### 4. MUSE SLICER INTEGRATION

#### 4.1. General View - Optical Bench Composition

The test bench is composed of three main modules:
- ISS Illumination Unit,
- ISS Detection Unit,
- ISS Unit.

For each test, three modules are separately set up and adjusted, and then they are aligned together on the optical bench. The ISS Unit is mounted step by step following the different tests.

#### 4.1.1. ISS Illumination Unit

The main functions of ISS Illumination Unit are to:
- Mimic the ISS/IFU input focal ratio (f/57.4mm along x-axis, f/114.8mm along y-axis),
- Image the input FoV onto the ISS Unit (133.6mm in X, 11.1mm in Y),
- Magnification by 3.

The ISS Illumination Unit is composed of (Figure 9):
- Interchangeable sources (spectral or continuum, if needed) with hot mirror and filter wheel,
- An integrating sphere (Exit Port=50mm),
- Two interchangeable diaphragms (a rectangular aperture and a grid of pinholes) located in the object focal plane,
- An achromat (f=300mm, D=40mm),
- A folding mirror at 45°,
- A pupil mask glued onto folding mirror. The dimensions of the pupil mask shall respect the ISS input focal ratio. It is located in the focal plane of the parabolic mirror.
- A Parabolic Mirror (f=800mm, D=200mm)
4.1.2. ISS Detection Unit

The ISS Detection Unit works following different configurations. Each one is set up in function of the test to be realized. The main differences between these configurations are the conjugation and the magnification with the CCD camera. The ISS Detection Unit has been already used and validated in previous slicer tests [10] and is composed of:

- CCD camera (Apogee, 1536×1024 pixels of 9µm each)
- Collimator lenses working with magnification by 0.7,
- Microscope objectives (x 4 and x 10) associated with last collimator lenses.

All elements except collimator lenses are placed on a common mount with 3 motorized translation stages (x, y and z) and a manual rotation stage around y-axis.

4.1.3. ISS Unit

A manual rotation stage around x-axis is located below IDA and FMA. Two translations stages along y and z-axes are below FMA too. A pre alignment in positioning of that has been performed using Romer metrological Arm.

4.2. Alignment Procedure

The full ISS Detection Unit is aligned wrt ISS Illumination Unit and ISS Unit. The optical bench has been mounted step by step. The ISS Illumination Unit has been aligned as following:

1. The pre-positioning of all elements of ISS Illumination Unit has been performed with Romer metrological Arm.
2. The fine adjustment in centring and tilt of each component has been performed with a Helium-Neon laser using autocollimation principle (Figure 9). The optical reference was the achromat (accuracy better than ±20 arcseconds).
3. The adjustment of the pupil mask location has been made thanks to a theodolite used at infinity.
4. Positioning of the parabolic mirror by laser autocollimation and rotation at the correct angle thanks a rotation stage (accuracy better than ±20 arcseconds).
5. Magnification, image quality and uniformity of the entrance pupil on all FoV of the ISS Illumination Unit have been measured.
6. Prepositioning of the ISS Support with Romer metrological Arm at correct location. Two holes are located in the same location as the reference targets onto the ISS Support. They are the references for the ISS Support prepositioning.
7. IDA Integration into ISS Support.
8. Autocollimation onto heel in the location of the reference target (accuracy better than ±20 arcseconds)
10. Integration of FMA.
11. Translation along z-axis of an autocollimator in order to tilt FMA with the same angle as IDA (±30 arcseconds accuracy).
12. Global tilt of FMA of an angle of 0.69° using Romer metrological arm (±30 arcseconds accuracy).
13. Check positioning of IDA wrt FMA thanks to Romer metrological arm. Fine adjustments if needed (±25µm accuracy).
14. Prepositioning of the ISS Detection Unit with Romer metrological arm at correct location wrt IDA positioning
15. Optical Alignment of the ISS Detection Unit using an autocollimation onto CCD window because the laser pass trough heel which is no coated.
16. Tests in different planes.
17. Qualification of ISSDetection Unit in magnification and quality image for all configurations.

5. MUSE SLICER TESTING

5.1. Component Testing

5.1.1. Roughness Measurement
The roughness measurement was performed by Winlight, on the centre and on the extremity of one slice on a minimum square side of 0.45×0.45mm (Figure 10). Moreover, it has been measured on the FMA n°1, 25 and 35. The average PTV value is 13.7 nm and the RMS one is 0.6 nm. It is 6 times better than requirement which was 3.5 nm RMS.

5.1.2. Shape Measurement (Interferogram)
The shape measurement was performed with an interferometer on IDA and FMA and is illustrated on the Figure 11. The shape on full aperture both on IDA and on FMA is compliant with requirement. It has been measured better than 0.25 µm PTV for IDA and 0.15 µm PTV for FMA. Moreover, the shape on a square aperture of 0.93 mm side on IDA is near to the requirement (8.8 nm for 8 nm for the requirement). It is acceptable for this component.

Figure 10: Roughness Measurement on IDA

Figure 11: Shape measurement on slice square aperture of 0.93 mm side
5.1.3. Coating Measurement
The coating measurement was performed by Winlight on samples located in the same vacuum chamber as IDA and FMA. The coating measurement for both components is higher than requirement of 0.98 on all wavelength range.

5.1.4. Microscope Visualization
Due to an original manufacturing method of IDA (polishing of all optical surfaces in the same time), the risk to have a lot of scratches and digs on slice edges was very important. After microscopic inspection, only two minor scratches are visible on the 24 slices. Their size is less than 50 µm.

5.2. Overall System Performance

5.2.1. Measurement of the relative locations of the pseudo-slit
Five images of the mini-slit are simultaneously on the detector. Then, the reconstructed pseudo-slit is presented on the Figure 12. Only 24 mini-slits are represented in order to simplify the drawing and the understanding.

Figure 12: Reconstructed pseudo slit composed of 24 mini slits
The FWHM geometric centroid giving the relative location of the centroid along both axes, the gap between two mini-slits and the mini-slit length are computed. The magnification is also derived from the length of each mini-slit. The uncertainty of this measurement is ± 15 µm on the centroid positioning in the pseudo slit plane. It is represented by the error bars on Figure 13 and Figure 14. Note that on all graphs, right boldface lines indicate requirements.
At 578 nm along x-axis (spatial direction), the relative positioning is compliant with the requirement (Figure 13). Along y-axis (spectral direction), it is partially compliant (38 mini-slits out of 48 are compliant including uncertainty of measurement - Figure 14). The maximal error on the relative positioning along y-axis is 120±15µm. Nevertheless, we can consider that these errors are acceptable because they are along the spectral direction and they represent a displacement less than 2 pixels on MUSE CCD.

Figure 13: Relative positioning of the mini-slits along x-axis.
The gap between two mini-slits is deduced to the mini-slit positioning. It is compliant with the requirement (Figure 15). No overlapping between each mini-slit appears in the pseudo-slit plane. Note that the central gap between the two stacks is smaller by design.

The magnification is computed thanks to the length of each mini-slit. Because of a poor magnification of ISS Detection Unit (0.62), the uncertainty of measurement is high and the magnification is computed only along x-axis. But this calculation gives a first idea of the ISS magnification. ISS magnification has been measured at 0.0077±0.0005 which coincides with requirement (0.076±0.001). To obtain correct magnification, only one mini-slit shall be recorded in a camera CCD. That means the use of an ISS Detection Unit with a magnification by 5.

In conclusion, the alignment between the mini-slits is very accurate and in concordance with the requirements. The only minor compliances are acceptable and some requirements could be relaxed.

### 5.2.2. Point Spread Function Measurements

In order to evaluate the image quality of the prototype, the PSF is studied in the pseudo-slit plane. For different slices, either at the centre or at the extremity of slices, several PSFs are recorded onto detector. With a magnification x 5 on ISS Detection Unit, several PSFs of the slice-slit imagery are simultaneously on the detector. A grid of pinholes is located on the telescope focal plane in the ISS Illumination Unit. Nevertheless, this test is very time consuming because of the required exposure times. Then the Enrectanguled Energy (EE) is computed for each PSF. The uncertainty of this measurement is ± 3 % of EE due to the uncertainty in the background estimation.
For all measured PSFs, the average EE measured in a rectangle of 35 ×70 µm in the pseudo-slit plane is 89±3 %. On the Figure 16, few typical PSF images are shown. Note that the rectangle represents the requirement rectangle (35×70 µm side) centred onto measured PSF. It shall contain 90% of energy. The PSF of the slice 1_1 has been sliced along spatial and spectral directions and compared to Zemax file (Figure 16). The measured PSF is larger than the Zemax one but it is conform to requirements in EE. The measured geometric form is roughly the same as the Zemax ones.

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Figure 16 : Left: PSF on the four slices. Right: PSF sliced along both axes compared to the Zemax file

6. CONCLUSIONS AND FUTURE DEVELOPMENTS

The results and analysis of the tests on the ISS prototype for the MUSE instrument have been presented and summarized in this paper. The roughness measured on all components is 6 times better than the requirement. It corresponds to the classical polishing technique on glass material. The shape on full aperture on both IDA and FMA is compliant with requirement. The measured shape on the slit width is slightly higher than requirement (8.8 nm against 8 nm for requirement) but it is acceptable. The coating efficiency measured on the sample is compliant to the requirement. Even if no measurements were performed in the intermediate pupil plane, the visual inspection of this plane shows no apparent vignetting onto the focusing mirrors.

The measurements performed in the pseudo-slit plane demonstrate that the angular tilts on FMA are on specifications. There are no overlaps between neighbouring slits and the alignment of the pseudo-slit is excellent. The geometrical characteristics of each mini-slit validate the magnification of the system. The PSF measurements demonstrate the high image quality of the ISS at 578 nm.

This Image Slicer Subsystem with 48 slices and 48 focusing mirrors is not only the largest we had in hand and in the world but it is by far the best from the half dozen we have tested since the very start of the project. It is compliant with our specifications and was build and assembled by the manufacturer and delivered almost in time and in a relatively short time scale (6 months). It demonstrates that the manufacturing process is mature and gives good confidence for the series production.

The next step consists of the manufacturing and testing of a full Integral Field Unit – IFU- for MUSE Instrument (Figure 17, Left). It is composed of a new Image Slicer Subsystem, a spectrograph including a Volume Phase Holographic Grating (VPHG) and a 4k×4k CCD detector provided by ESO ODT. These three subsystems are already ordered and will be delivered in CRAL, Lyon in February 2009. Integrated together, several tests (Image quality, Spectral resolution and sampling, spatial sampling, Spectrum positioning and tilt, Throughput measurement, Diffused
light measurement, Ghosts measurement, Vignetting and mechanical tests) will be performed. The final acceptance of this first IFU integrated in MUSE Instrument is scheduled in May 2009.

The ISS subsystem looks like this one. It is composed of two arrays of 48 mirrors each. The mirror arrangement is slightly different from this one giving three staggered rows into pseudo-slit plane instead four. A mechanical support made of Invar will be manufactured in CRAL mechanical workshop using a four axes machining center (Figure 17, Right).

Figure 17: Left: IFU Mechanical Drawing. Right: ISS Support foreseen for the final IFU in MUSE Instrument

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