A **M**ulti **U**nit **S**pectroscopic **E**xplorer for ESO Very Large *Telescope*

MUSE User manual

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0.6	01/02/14	All	Pre-commissioning version: includes comments from PAE, from V. Mainieri / J. Vernet / F. Selman
0.9	21/02/14	All	Includes changes made during commissioning 1 - New transmission - New flat-field measurements - Updated TSFs - Updated acquisition procedure - Updated order of slices, channels and shape of the SGS regions - Reorganisation of sections - Updated calibration plan - Definition of offsets with rotator offsets and illustrated examples, definition of blind offsets - Added real views of the instrument together with diagrams - Figure and Table captions + cross references checked
1.0	28/02/14	All	Version made available for P94

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1 Introduction

1.1 Scope

The MUSE User Manual provides extensive information on the technical characteristics of the instrument, its performances, observing and calibration procedures and data reduction. The goal is to provide all pieces of information and advice necessary for MUSE users to prepare their observations. It is intended for MUSE users, and as such it is written from an astronomer's perspective.

1.2 MUSE in a nutshell

MUSE, the Multi Unit Spectroscopic Explorer, is a second-generation VLT instrument located on the Nasmyth platform B of the VLT UT4. It is a large-format integral-field spectrograph, based on image-slicing technology, and has a modular structure composed of 24 identical Integral Field Unit modules that together sample a contiguous 1 arcmin^2 field of view in Wide Field Mode (WFM) sampled at 0.2 arcsec/pixel. Spectrally, the instrument samples most of the optical domain, with a mean resolution of 3000. MUSE will initially be used in seeing limited WFM only.

MUSE will later exploit the VLT Adaptive Optics Facility in combination with the GALACSI AO module. When offered, it will provide Ground Layer AO correction for the WFM. In the future, a Narrow Field Mode (NFM) will also be made available, and will cover a ~7.5 arcsec^2 field of view sampled at 0.025"/pixel with Laser Tomography AO correction.

A view of the instrument attached to the telescope is shown in Figure 1: View of the MUSE instrument at the Nasmyth focus of the VLT UT4. The main instrument characteristics are summarized in

Table   1. MUSE
was   built by a

Figure 1: View of the MUSE instrument at the Nasmyth focus of the VLT UT4.

Consortium involving institutes from France, Germany, The Netherlands, Switzerland and ESO. Name of the institutes and their respective contributions are given in Table 2.

Table 1: MUSE characteristics and observing capabilities

Number of modules	24
Wavelength range	480-930 nm (nominal) 465-930 nm (extended)*
Resolving power	1770 (480 nm) – 3590 (930 nm) (WFM) 1740 (480 nm) – 3450 (930 nm) (NFM)
Spectral sampling	0.125 nm/pixel
Detectors (per module)	4k x 4k e2V CCD
Field of view	59.9" x 60.0" (WFM) 7.42" x 7.43" (NFM)
Spatial pixel scale	0.2" / pixel (WFM) 0.025" / pixel (NFM)
Throughput (total atmosphere, telescope and instrument)	14 % (480 nm) 35 % (750 nm) 14 % (930 nm)

*only available for WFM instrument modes. Suffers from 2nd order contamination.

1.3 More information on MUSE

All MUSE Manuals are available on the MUSE instrument WEB pages together with the most updated informations on the instrument:

http://www.eso.org/sci/facilities/paranal/instruments/muse/

Information and software tools for the preparation of service and visitor mode observations with MUSE are available at:

http://www.eso.org/sci/observing/phase2
http://www.eso.org/sci/observing/phase2/SMGuidelines.html

Visiting astronomers will find further instructions on the Paranal Science Operations WEB page and the Paranal Observatory home page:

http://www.eso.org/sci/facilities/paranal/
http://www.eso.org/sci/facilities/paranal/sciops/

1.4 Version notes, change track

The first version of this manual has been delivered by the MUSE consortium, P.I. R. Bacon., for Phase I, P94, on 28 Feb 2014.

1.5 List of Abbreviations & Acronyms

This document employs several abbreviations and acronyms to refer concisely to an item, after it has been introduced. The following list is aimed to help the reader in recalling the extended meaning of each short expression:

- ADC: Atmospheric Dispersion Corrector
- ADU: Analog / Digital Unit
- CCD: Charged Coupled Device
- CU: Calibration Unit
- DQ: Data Quality
- DRS: Data Reduction Software
- ESO: European Southern Observatory
- FO: Fore Optics
- FOV: Field Of View

- GALACSI   Ground Atmospheric Layer Adaptive Corrector for Spectroscopic Imaging
- IFU: Integral Field Unit
- IRLOS: Infrared Low Order Sensor
- LGS: Laser Guiding System
- LSF: Line Spread Function
- MUSE: Multi Unit Spectroscopic Explorer
- NFM: Narrow Field Mode
- NGC: New Generation Controller
- OGS: On-axis Guide Star
- P2PP: Phase 2 Proposal Preparation
- QE: Quantum Efficiency
- RTD: Real Time Display
- SGS: Slow Guiding System
- SNR: Signal to Noise Ratio
- SRO: Splitting and Relay Optics
- TBC: To Be Confirmed
- TSF: Template Signature File
- TTS: Tip-Tilt Star
- UT: Unit Telescope
- VLT: Very Large Telescope
- WFM: Wide Field Mode

Table 2: collaborating institutes and their contributions

Collaborating institutes	Contribution
Leibniz-Institut für Astrophysik Potsdam	Development of the Calibration Unit, testing of the preassembled spectrograph-detector units, data reduction software
Centre de Recherche Astrophysique de Lyon	Overall management of the project, image slicer sub system, spectrograph opto-mechanical design and integration, data analysis software.
ESO	Detector systems (24 detectors and their cryogenic environment), GALACSI
ETH – Institute of Astronomy (Zurich)	Procurement of the 24 spectrographs
Institut für Astrophysik Göttingen	Design, analysis and procurement of the instrument mechanics, the support and handling structures as well as for the optics that apply the field splitting and the relay optics.
Institut de Recherche en Astrophysique et Planétologie (Toulouse)	Electronic and Software Control of the whole Instrument, Opto-mechanical development of the Fore-Optics module.
Leiden Observatory	Interface between the MUSE spectrograph and the adaptive optics system, definition of the top-level requirements for the adaptive optics system.

2 Technical description of the instrument

2.1 Overview of the opto-mechanical design
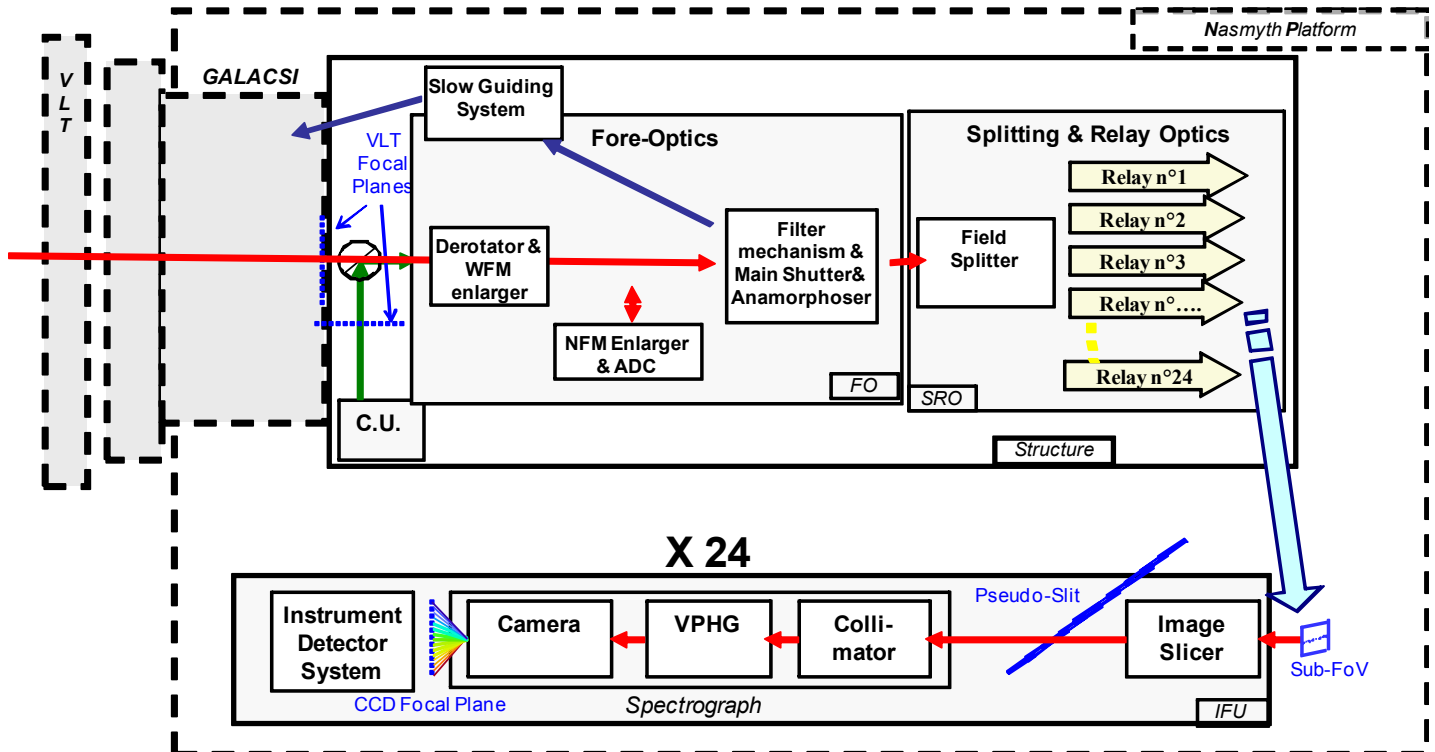
Figure 2: Overview of MUSE subsystems

Figure 2 shows a schematic view of the layout of MUSE. The instrument is composed of the following sub-systems:

- The **Calibration Unit** (CU) provides different illumination fields to calibrate MUSE instrument. It includes functions to switch on and off the lamps, motors to position the chosen mask and to insert a Calibration Pick up mirror in the MUSE instrument lightpath. These functions are controlled through calibration and maintenance templates.

- The **Fore Optics** (FO) reshapes the VLT focus image to adapt it to the next sub-system which splits the image in 24 channels. It rotates the field, magnifies it, and reshapes it into a 2:1 ratio.

- The **Splitting and Relay Optics** (SRO) sub-system divides the Field of View in 24 horizontal sub-fields, and feeds each Integral Field Unit.

- Each of the **24 Integral Field Units** (IFU) is composed of 3 sub-systems: the Image Slicer, the Spectrograph, and the Detector. Each slicer separates a 1/24 sub-field into 48 slices.

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2.2   Description of the instrument sub-systems

This section describes the different sub-systems of MUSE in the order they are encountered along the optical path going from the telescope to the detectors (see Figure 2 and **Figure 3**).The functionalities of the different sub-units are explained and reference is made to their measured performance.

2.2.1   Calibration Unit

The calibration unit (CU) is a mechanical structure with calibration lamps, an integrating sphere, and a set of masks used to produce calibration fields for MUSE. A calibration pick-up mirror allows to select between the Telescope and the CU as the MUSE entrance light beam.

The CU allows for a choice of **6 calibration lamps** as input light sources:

- Two flat-field halogen lamps providing uniform continuum flux over the MUSE wavelength range

- 4 arc lamps used for wavelength calibration:
    - One Ne pencil-ray lamp
    - One Xe pencil-ray lamp
    - One HgCd pencil-ray lamp
    - One Ne High Power lamp

Two pico-ampere meters placed at the CU focal plane are used to monitor the absolute flux sent by the lamps into MUSE. Details on the line wavelengths and relative fluxes produced by each lamp are provided in Section 8.2.

The **focal plane mask wheel** allows for a choice of 5 masks covering the CU field-of-view. Two positions are used in regular operation: CLEAR and WFM_SMP.

- The CLEAR (no mask) position is used for flat-field and wavelength calibrations.

- The WFM_SMP is a mask containing a grid of small (50 µm diam.) pinholes covering the WFM FOV. It is used to perform the geometrical calibration (see Section 6.1.4).
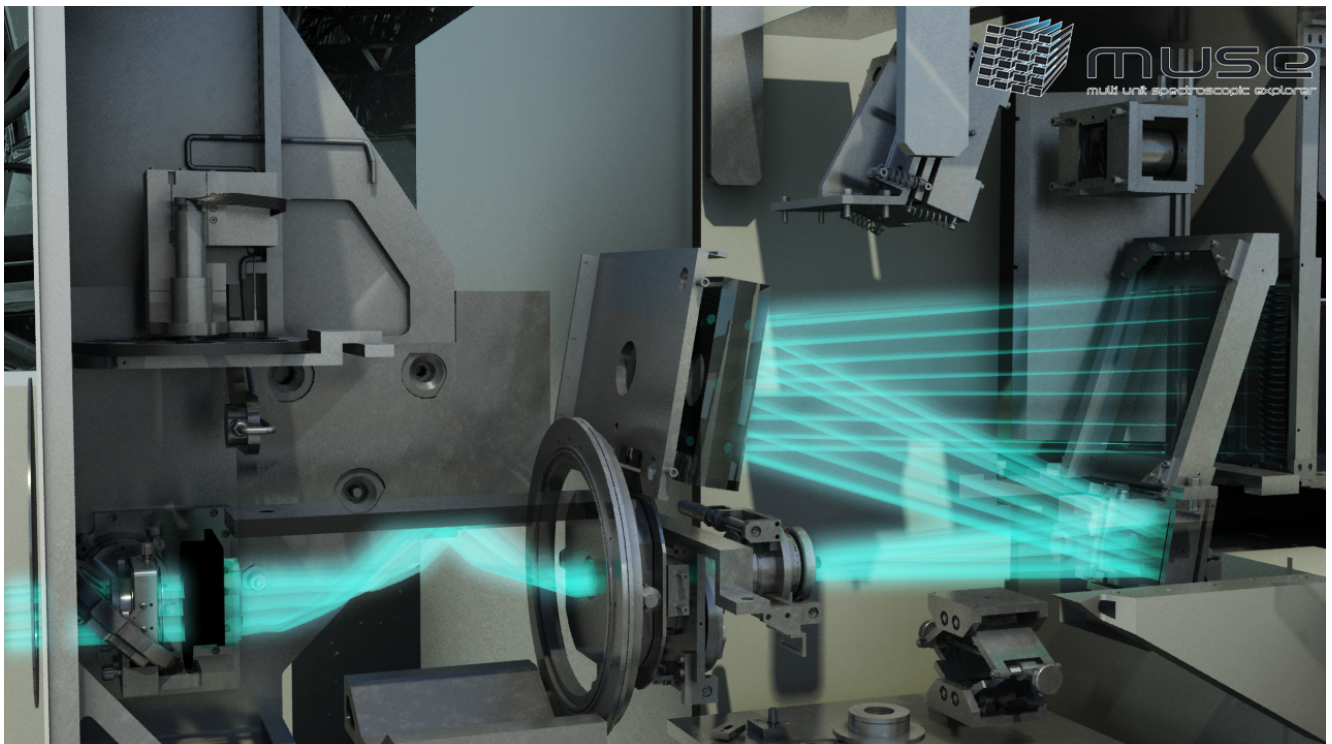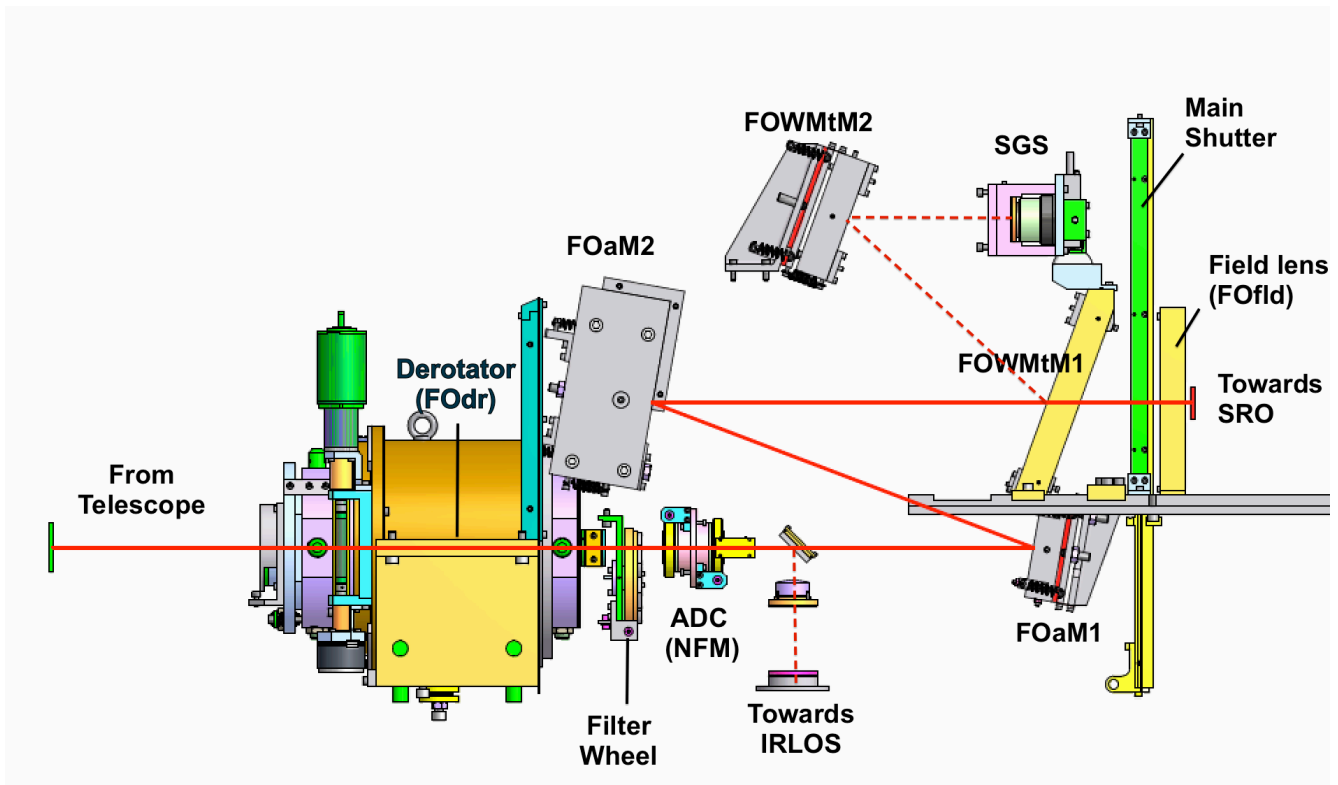
Figure 3: schematic view of the subsystems in the Fore-Optics. The top panel presents the optical elements (details in the text), and the bottom 3D view shows the path of light rays.

2.2.2 Fore Optics

The fore-optics system comprises the following subcomponents (see also **Figure 3**):

- **Derotator**

    The derotator compensates for the field rotation at the VLT Nasmyth focus. It is a classical derotator based on two prisms: when rotated by an angle α, the image plane rotates by the angle 2α.

- **Mode-switching unit and Atmospheric Dispersion Corrector (NFM only)**

    The Mode-switching unit prepares the field-of-view when the instrument is used in Narrow-Field Mode. It adds a magnification of x8 in each direction and includes the Atmospheric Dispersion Corrector (ADC). The ADC will be used, in NFM mode only, to correct for atmospheric dispersion. It consists in two Amici prisms working in counter-rotation.

- **IRLOS (NFM only)**

    In NFM, a dichroic reflects the infrared light towards IRLOS, with the InfraRed Low Order Sensor measuring the wave front errors invisible to the LGS-AO system. It is a Shack Hartman sensor with 2 by 2 sub apertures working in the MUSE field of view at a wavelength range of 980nm to 1800nm. It senses image drifts occurring in NFM and corrects them by means of the AO loops.

- **Filter Wheel**

    A filter wheel is included in the fore-optics to adjust the spectral coverage according to the desired instrument mode:

- The nominal wavelength range of MUSE corresponds to 480-930 nm, which allows for suppression of second-order contamination in the red.
- An "extended" wavelength range is available in WFM only, allowing observations down to 465 nm. However, strong second-order contamination appears in that case at $\lambda>900$ nm (see Section 2.5.3 for details).
- In AO modes only, the range 584-594 nm is blocked to avoid contamination by Na light from the LGS.

    In total, 5 filters are available in the wheel. The relationship between instrument mode and filter name is provided in Table 7 (Section 5.2).

- **Anamorphoser**

    Two cylindrical mirrors (FOaM1 and FOaM2, **Figure 3**), provide a magnification of 0.5 to the beam in the horizontal direction within the fore-optics to ensure sufficient sampling in the dispersion direction.

- **Slow Guiding System (SGS)**

  When in WFM mode, an elliptical pick-up mirror (FOWMtM1, **Figure 3**) separates the central field-of-view (corresponding to 1 x 1 arcmin^2 on sky) from the four metrology fields surrounding it, which are reflected towards the WFM Slow Guiding System (**Figure 3**) after removing the magnification using the FOWMtM2 mirror. Incoming light is recorded by the SGS using a NACE 1k x 1k Technical CCD (having a 0.09" pixel scale). The system automatically detects astrophysical sources in the metrology fields (Figure 4) and corrects for small motions by sending commands to the Telescope in a closed loop.

WFM metrology Fields

WFM scientific Field of View
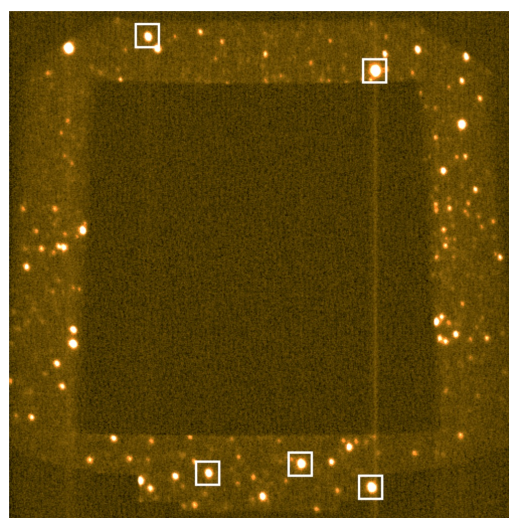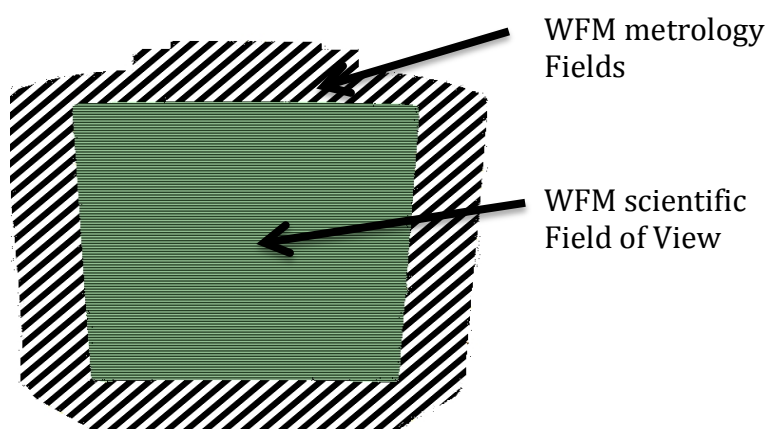
Figure 4: (left) location of the four metrology fields used by the SGS, as seen on the detector. (right) example of SGS image showing the detected stars used to monitor small motions (white squares). Note that the SGS image is flipped vertically when oriented on sky (right panel).

- **Exposure shutter**

  This shutter is located between the SGS pick-up mirror (FOWMtM1) and the exit beam. It is a Bonn shutter with a rectangular aperture moving along the vertical direction.

2.2.3 Splitting and Relay Optics (SRO) system

The SRO system splits the MUSE field-of-view into 24 channels and redirects the light of each channel towards the entrance of an IFU. It is composed of a field-splitter and a field separator, which separate the field into 24 horizontal beams (Figure 5). These sub-fields feed 24 relay optics, which correct for the variations in optical path from one channel to another (Figure 6).

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Figure 5: MUSE Field splitter and field separator optics. The 24 mirrors positioned at varying angles split the MUSE field-of-view in 24 horizontal bands.
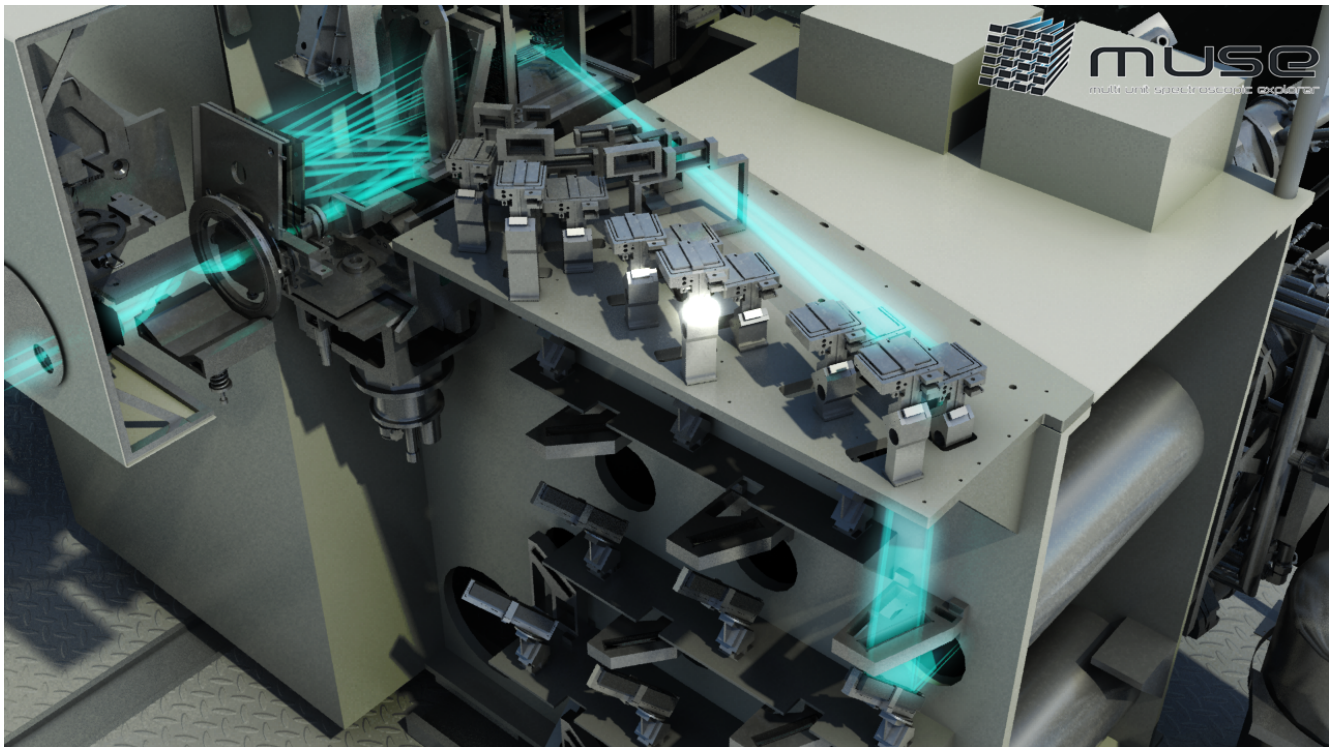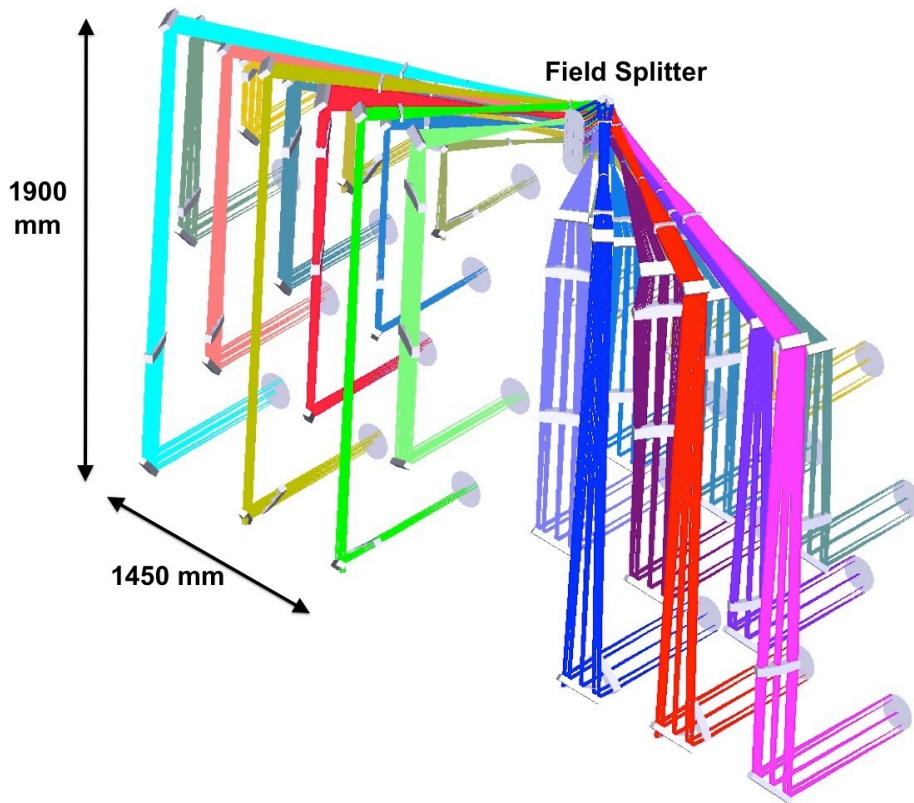
Figure 6: 3D view of optical paths for all channels due to the relay optics splitting of the field-of-view into 24 channels. The bottom figure shows the path of lightrays for one of the channels, as seen from the Fore-Optics

2.2.4   Integral Field Unit

Each of the 24 Integral Field Units (each assigned to a given channel) is formed by the combination of an image slicer, a spectrograph, and a detector, which we describe below. The optical layout of one of the IFU is presented in Figure 7.
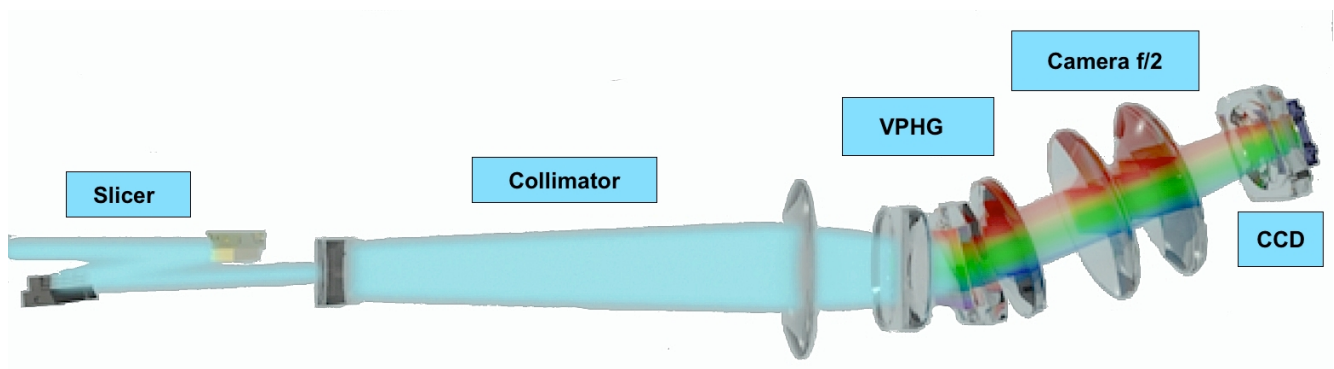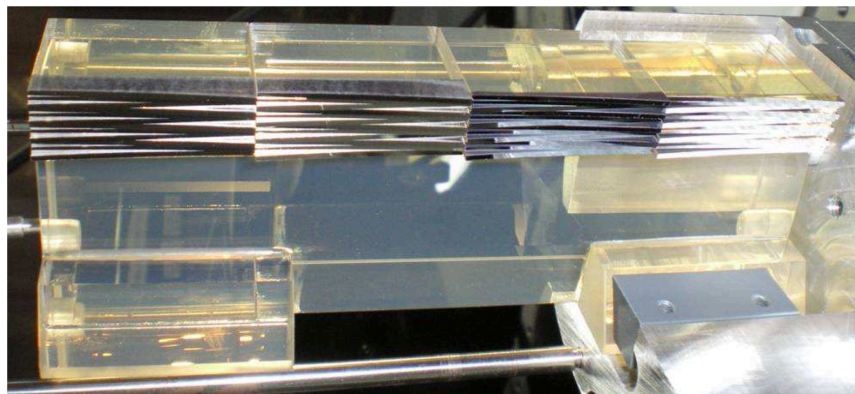
Figure 7: Overview of the optical layout for one of the IFUs. The top panel shows one of the slicers, which cuts the FOV of each channel into 4 stacks of 12 slices. The bottom panel shows the optical elements in the IFU and the path of light to the CCD.

2.2.4.1 Slicer

The slicer cuts and rearranges the 2D sub field of view in a 1D pseudo slit of 0.2arcsec width. The main function of the image slicer is to slice the fraction of the field-of-view coming from the SRO into 48 slits that are rearranged in a long slit at the entrance of the spectrograph. The slicer is composed of:
- an image dissector array separating the beam in 48 slices (as represented on top of Figure 7)
- a focusing mirror array, which rearranges and aligns the slices
- a pupils / slits mask reducing scatter light and ghost images before entering the spectrograph.

2.2.4.2 Spectrograph

The main function of the spectrograph is to produce the spectra of the mini slits and image them onto a detector. It is composed of a collimator, a Volume Phase Holographic Grating and a camera. The grating disperses the mini slits in the perpendicular direction and achieves a spectral resolution of 1750 at 465nm to 3750 at 930nm (Figure 11).There is no moving part in the spectrographs and all 24 spectrographs are identical.

2.2.4.3 Detector

The light exiting each of the 24 spectrographs is sent onto a 4k x 4k, 15 μm pixel CCD, operating at 163 K. The full characteristics of these detectors are given in Table 3.

Table 3: Properties of the MUSE detectors

Parameter	Value
CCD Type	E2V Deep depletion, AR graded coated
Active pixel format	4096*4112 pixels (X*Y)
Pixel size	15*15 microns
Pre-scan pixels in X direction	32
Overscan pixels	32
Detector gain	1.1 ADU / e-
Saturation	65000 e-
Linearity	<0.5% non-linear residuals
Binning factor	1x1 only
Readout noise	2.6 e-
Number of readout ports	4
Readout speed	100k pix.s-1
Readout time to RTD	40 sec
Dark current at 160K	3 e-.pix-1.hr-1

Table 4: Properties of each CCD.

The twenty-four scientific detectors of MUSE are controlled using four New Generation Controllers (NGC). The readout is always used without binning during observation.

The detector image is formed of 4 quadrants of 2048 x 2056 pixels (X x Y) each, separated by prescan and overscan regions. In the normal (science) readout mode, both prescan and overscan regions have 32 pixels in size (Figure 8).
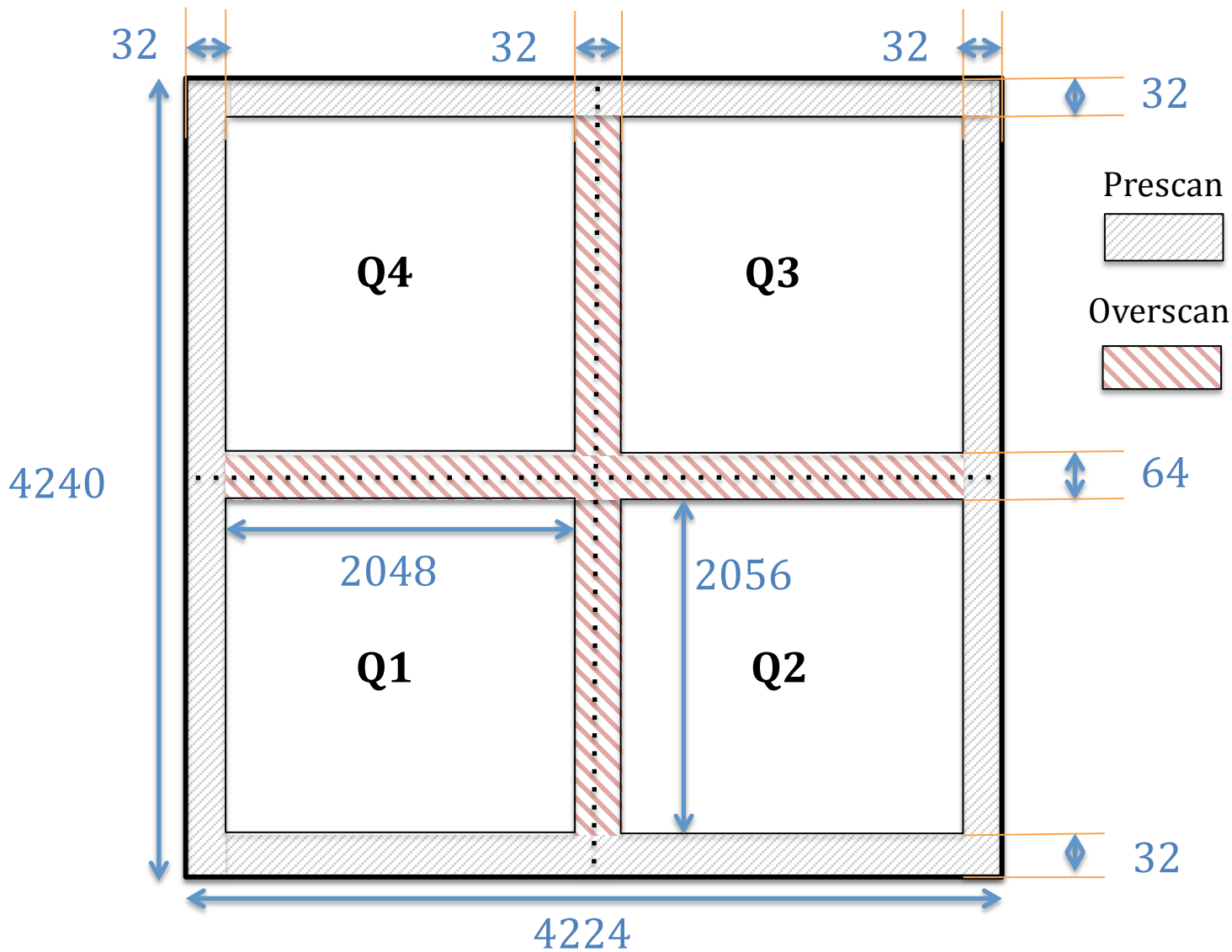
Figure 8: Overview of the pixel map of one for one of the detector, showing the 4 quadrants and the prescan / overscan regions. All scales are given in pixels.

2.2.5 Spectral format
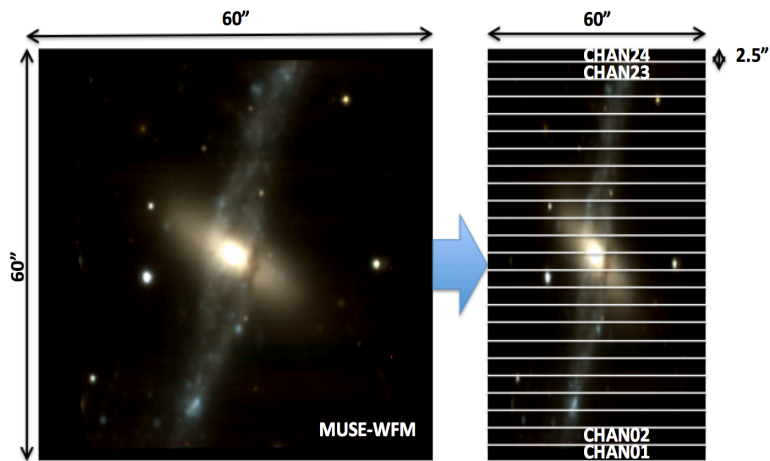
Figure 9: Overview of the splitting of the field-of-view from the fore-optics to one of the MUSE detectors. Left: splitting of the MUSE FOV into 24 sub-fields entering each channel. Center: shape of the entrance slicer on sky, with 4 stacks of 12 slices (numbered in red from 1 to 48) covering a 2.5 x 60" field. Bottom: location of each slice on the detector, with the corresponding wavelength range.
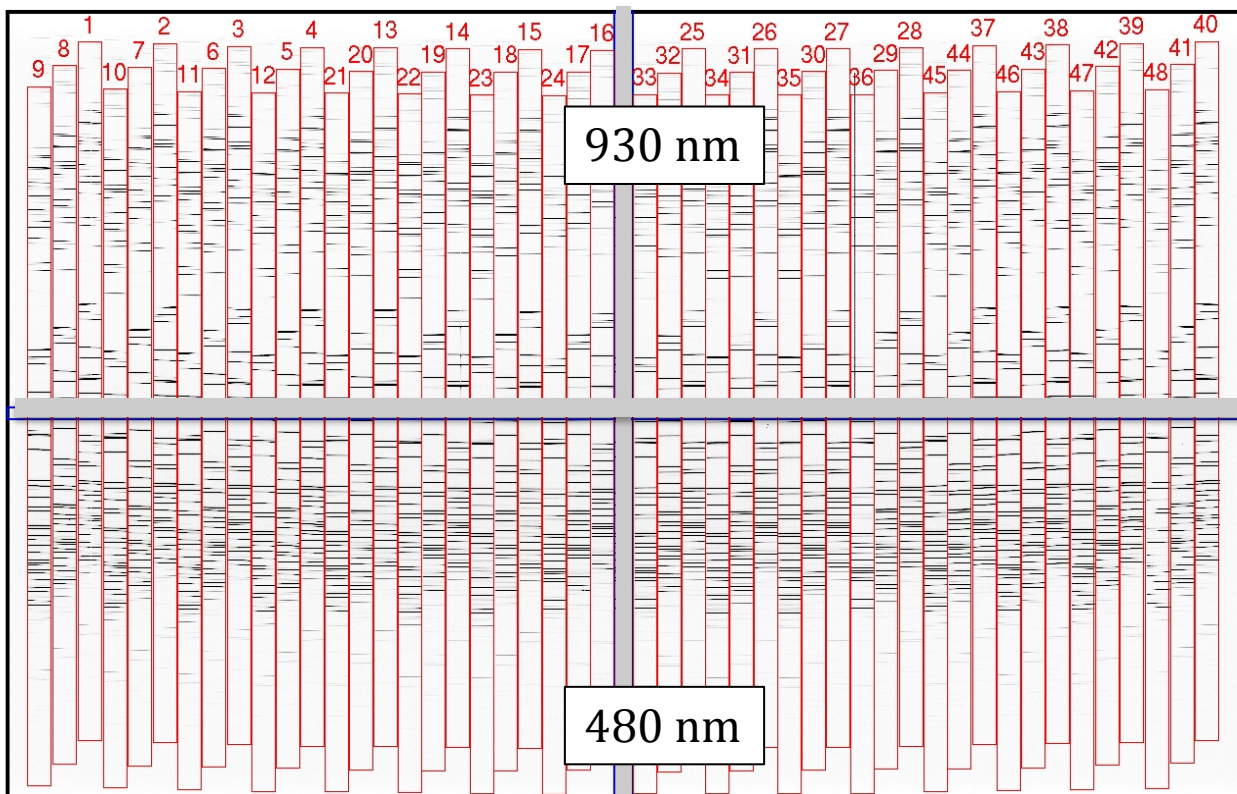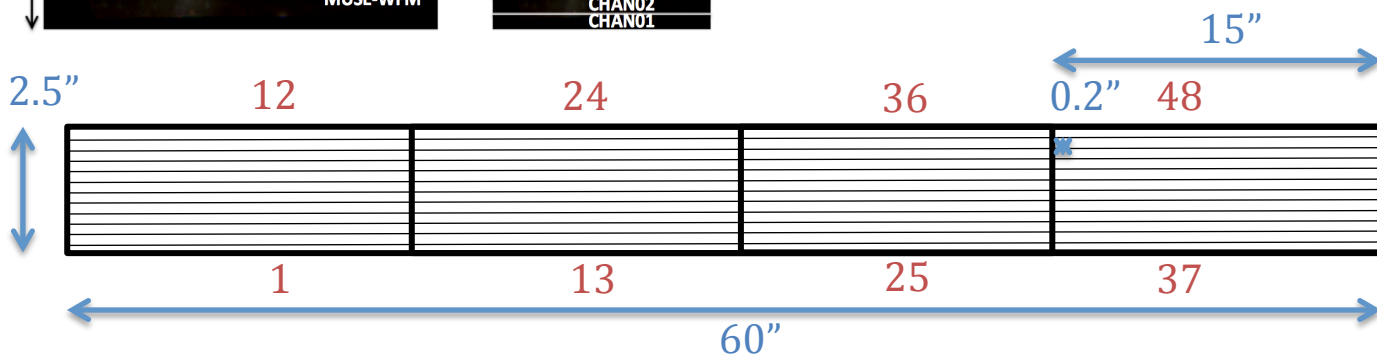
Figure 9 gives an overview of the spectral format as seen on one of the detector, and the relationship with the splitting and slicing of the field of view in the sky frame, when used in WFM. The spectral format is identical in NFM, except that the field-of-view is 7.5" x 7.5".

After splitting the magnified field-of-view into 24 sub-fields entering each of the 24 IFUs, the image slicer separates a sub-field into 48 slices (upper-right panel), and aligns them along the horizontal axis of the detector (bottom panel). The numbers 1-48 show the relationship between the image slicer mapping and the CCD mapping. Each slice is ~ 75 pixels wide, and dispersed in the spectrograph along the vertical axis of the CCD, with the bluest wavelengths located the bottom of the detector and the reddest wavelength at the top. The 48 slices are offset vertically from one another by ~ 125 pixels, following a repeating pattern of 3 slices.

3 Overall performances and characteristics

3.1 Absolute throughput and limiting magnitude

Absolute throughput of the overall system (MUSE+UT4) has been measured by observing spectrophotometric standard stars during commissioning. The throughput in both modes peak to a high value (35%) around 700 nm, and is overall > 15% (Figure 10). At shorter wavelengths, the throughput in the nominal mode (WFM-NOAO-N) drops around 480 nm, while the extended mode gives a high throughput down to 465 nm.

Figure 10: end-to-end MUSE+VLT/UT4 throughput, as derived from spectroscopic standard observations.

We have used this measured efficiency curve to predict the performances of the instrument in spectral continuum observations. We are assuming a 1 **hour observation of a point source at airmass = 1.0 and a seeing of 0.8" in V**. The limiting magnitude at S/N=10 per spectral resolution element, in regions free of sky lines, is reached for the following AB magnitudes (Table 4):

Table 4: Limiting magnitude of MUSE per spectral resolution element:

Filter	Wavelength	AB mag (S/N=10)
V band	550 nm	22.64
R band	640 nm	22.70
I band	784.9 nm	22.28

Similar results for different sources / conditions, as well as more detailed performances, can be obtained using the dedicated Exposure Time Calculator available on the ESO website (**currently a beta version**):

http://www.eso.org/observing/etc/bin/gen/form?INS.MODE=swspectr+INS.NAME=MUSE

3.2   Spectral resolution and sampling

In all instrument modes, spectral resolution increases between 1600 at the bluest wavelengths (480 nm) and 3600 at the reddest wavelengths (930 nm). This was measured on wavelength calibration data (Figure 11). Each resolution element is sampled by 2.5 pixels along the spectral direction.
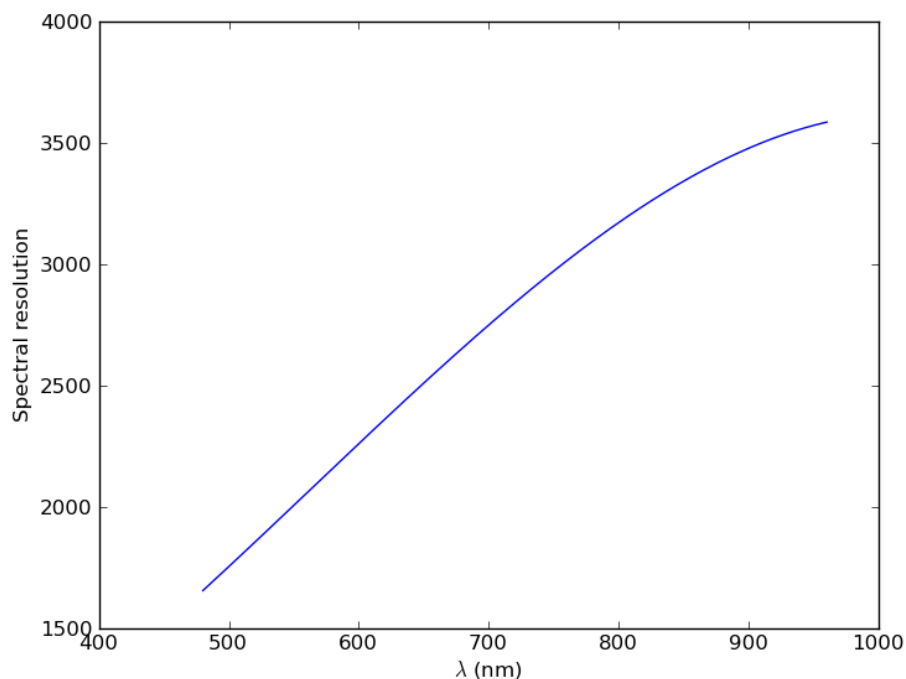
Figure 11: Spectral resolution achieved as a function of wavelength, as measured in the lab using calibration lamps

3.3   Exposure timing

The performances of the Bonn shutter have been estimated to provide an error < 300 μs on the total exposure time. In addition, and due to the shutter mechanisms, variations in the exposure time across the field of view are possible, but have been estimated to be < 1ms over the entire field of view.

3.4   Overall illumination and uniformity

There are some factors that are decreasing the MUSE throughput in some specific area. The first factor is the Field Splitter: the gap between the Field Splitter lenses cause a small light loss that affects the 4 slices at the bottom and the 4 slices at the top for each channel. The gap is smaller than 50μm for a spaxel size of 580μm, so the light loss is lower than **8.3%** for these channels. The effect is visible as horizontal regions of lower illumination in a continuum flat-field image (Figure 11).

The second factor is the gap between the 4 stacks of 12 slices in each channel that is 20μm for spaxel size of 465μm in this direction. The **4.3%** of light loss affects only the spaxels at the edges of the slices, and is visible as vertical regions of lower illumination in the continuum flat-field image (Figure 11).

Finally there is the geometrical shadowing of some slices by the neighbouring slices at the slicer level . In the worst case, there is **7%** of light loss. But integrated over the entire slicer stacks, the light loss is only **0.4% per channel.**

Very high SNR flat-field exposures obtained in the lab have been used to characterize the global illumination as a function of position (Figure 12). The median flux value is used as a reference to measure the flat-field variations. The main characteristics are the following:

- The small vertical distortion is visible as the global trapezoidal shape of the FOV: slices from the top channel have a smaller horizontal extent than the bottom channel.
- In general, the flat-field is quite uniform, with variations of +/-2% within a given channel / stack.
- At the top/bottom edges of each channel, a horizontal drop of ~ 10% in illumination due to the field splitter vignetting.
- In between the 4 stacks in each channel, a vertical drop of ~ 30% in illumination is visible, due to the inter-stack vignetting.

- A small flux variation (~2-3%) is visible between the central 2 stacks and the leftmost and rightmost stacks. This is predicted by design.
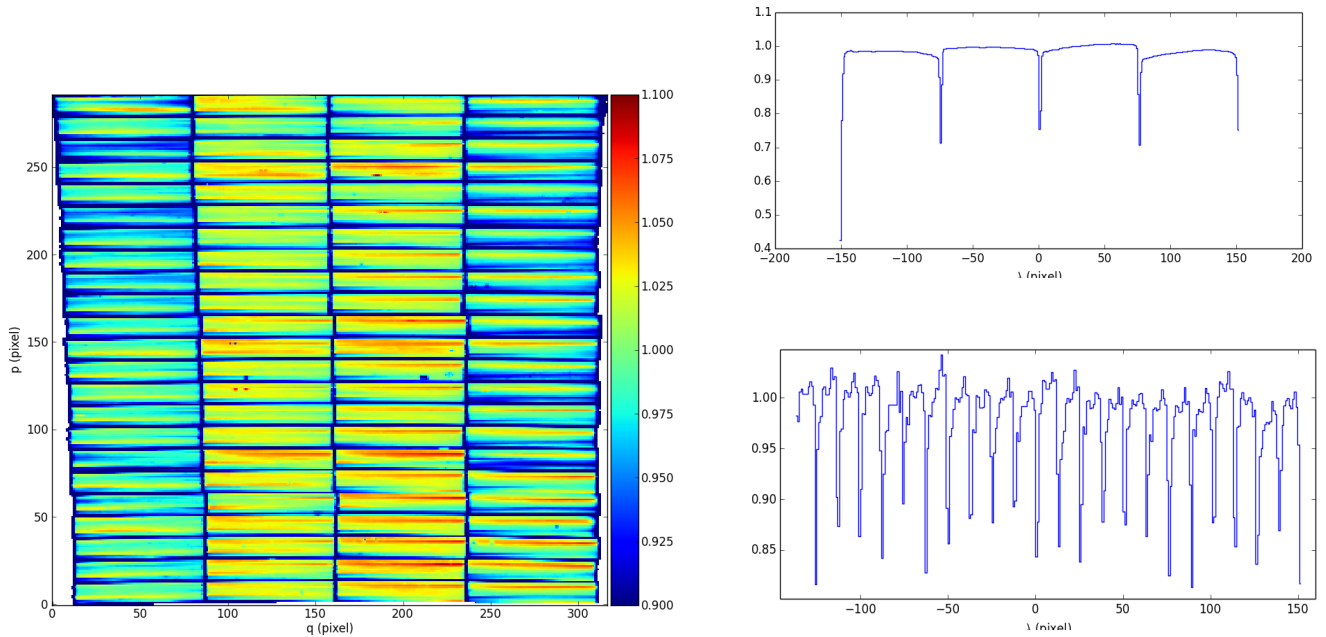
Figure 12: (left) normalized reconstructed image of the continuum flat-field in WFM. (right) vertical (top) and horizontal (bottom) cuts through the normalized image showing the horizontal and vertical variations in illumination.

3.5 Distortion and astrometric precision

Instrument distortion is calibrated by using a regular multi-pinhole mask as part of the overall calibration plan (see Table 10). The overall field of view of the instrument shows a trapezoidal shape (Figure 11), with channel 01 having a 3.5" smaller angular view in the horizontal direction.

Astrometric precision is also calibrated on a regular basis by observing stellar cluster fields with a high astrometric precision. The astrometric solution has been obtained during commissioning 1 on these fields with an overall rms precision of 0.04" in each direction.

3.6 2nd order

In the **nominal** wavelength range (i.e. using the cutoff blue filter at 480 nm), the second orders appear, as expected, above the 930 nm wavelength limits (as shown as the red boxes in Figure 13). One can nevertheless see a faint contamination in the 920-930 nm region. In addition, the second orders are defocused and therefore extend beyond the slice. Because of the 3 steps pattern, the slices extending higher on the detector are impacted by the adjacent second orders. The impact is nevertheless very limited.

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In the **extended** mode (i.e. without any blocking filter), the impact of second orders is significant and starts already at **790 nm**. The contamination reaches levels of **~ 12%** at wavelengths redder than 850 nm.
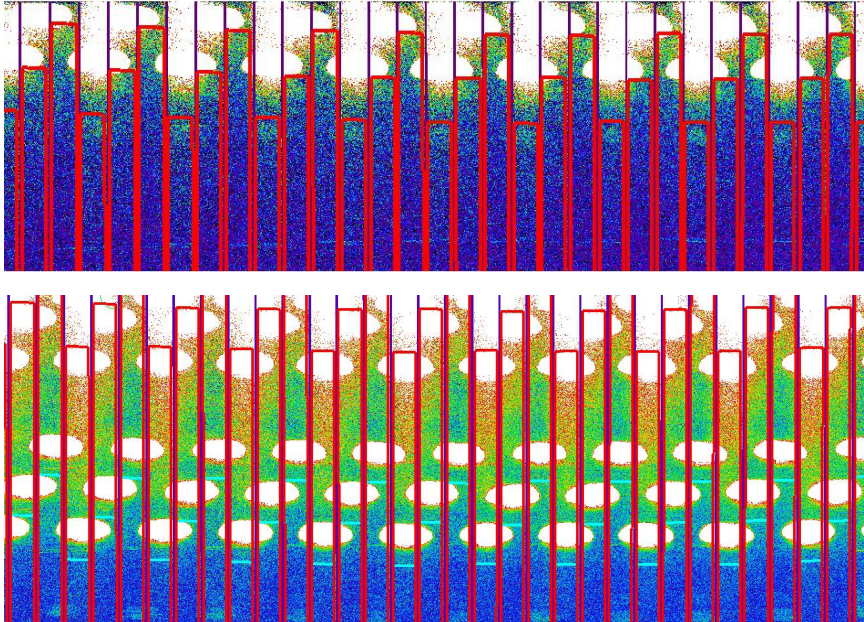
Figure 13: second order effect in nominal (top panel) and extended (bottom panel) modes, shown here for a bright exposure with arc lines. The red boxes mark the slice limits up to 930 nm. The impact of second order is visible as the white ellipses illuminating the top of the detector. The nominal instrument mode is not affected by contamination, but it is more significant in the extended instrument mode.

3.7 instrument stability

We present here some of the results on instrument stability, as known at the end of Commissioning 1. The long-term stability of the instrument is still to be verified in Commissioning 2 and this section will be later updated.

Wobble:

The MUSE derotator produces a residual mechanical wobble, which produces a repeatable pattern as a function of the derotator position. When the instrument is used in WFM, the effect of this wobble will be compensated by the SGS.

In the case when the SGS will not be available (e.g., no suitable stars in the metrology fields), the impact of this wobble is estimated in the worst case of 1 hour observation in a target close to the zenith (4 deg. Zenithal distance). We can reach a total displacement of 0.28", which has an impact of 10% on image quality in good observing conditions (0.6" seeing). In most cases, the impact will be much smaller.

Thermal stability:

MUSE has been submitted to thermal tests in the lab to assess its stability with regards to the ambient temperature. The resulting displacements in the spatial and spectral directions are provided in the Tables below. To predict the effect of temperature changes on observations we have used the Paranal statistics that give the median and peak DT for various periods (1 hour, 1 night, 1 season, see left columns in Table 5 and Table 6).

The stronger impact appears in the wavelength direction. During 1 hour exposure the inferred motion is still small (<0.05 resolution element) and the impact on the LSF is negligible: e.g. assuming a Gaussian shape its FWHM will increase by a maximum of $(1+0.03^2)^{1/2}$ = 1.0004, i.e. 0.04%.

During 1 night, the offset is larger and can reach 0.4 Å. However it is always possible to use sky bright emission lines to correct for this offset. This is currently implemented in the sky subtraction pipeline recipe.

Table 5: thermal stability in the spatial direction

Conditions	Maximum offset in spaxel
1 hour median ΔT (0.5 °C)	0.01
1 hour peak ΔT (1.5 °C)	0.03

Table 6: thermal stability in the spectral direction

Conditions	Maximum offset in Å	Maximum offset in resolution element
1 hour median ΔT (0.5 °C)	0.06	0.03
1 hour peak ΔT (1.5 °C)	0.19	0.08
1 night median ΔT (3.2 °C)	0.42	0.17
1 night peak ΔT (6.0 °C)	0.78	0.31
Seasonal median ΔT (7.0 °C)	0.91	0.36
Seasonal peak ΔT (20.0 °C)	2.60	1.04

4 Problems to be aware of

4.1.1 Ghosts and straylight

Ghosts : a ghost analysis has been performed on the detectors when illuminating the slices with bright saturated emission lines. The only detected ghosts have been observed at a very low $< 10^{-5}$ ($<$ 0.001%) level.

Straylight : similarly, contaminating straylight appears at a very low level ($< 10^{-5}$) when illuminating a channel with a very bright light source. This effect is seen at the level of the detector, with a background affecting the neighbouring slices.

This ghost / straylight analysis is still preliminary at this stage, and will be updated after a full analysis of all data acquired during the commissioning of the instrument.

4.1.2 Remanence

Remanence of the detectors has been measured by performing long dark exposures shortly after a saturated exposure. Remanence measured in these dark exposures is very low (0.04+/-0.23 e-) and its effect can be ignored.

4.1.3 Detector defects

Fringing: The choice of detectors for MUSE keeps the effect of fringing to a very low level. Fringing is apparent on very high signal-to-noise flat-field exposures in the 7500-8700 A wavelength range, and is measured at a peak-to-peak level of 0.3% in WFM and 0.6% in NFM (Figure 16).
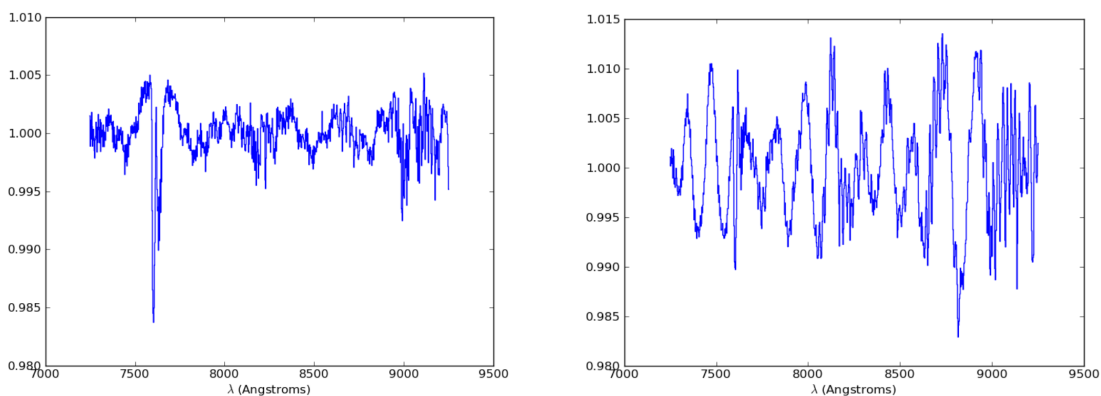
Figure 14: Fringing measured in the red part of the spectrum, as measured on normalised flat-fields in WFM (left) and NFM (right). The absorption visible around 7600 Angstroms is a telluric feature.

Bad colums / pixels:

MUSE detectors are generally of high quality, with only very limited regions of bad pixels. 17/24 detectors do not show any strong defect automatically flagged by the pipeline as a data quality (DQ) issue, and the remaining 7 detectors show between 1 and 3 bad columns. The full details of bad pixels flagged are given as reference for each detector in Table 11 in Section 8.1.

5 Observing with MUSE

5.1 General information

As for all ESO instruments the P2PP software is used to prepare MUSE observations. The generic guidelines for Phase 2 and the P2PP software that can be found at the following links:
http://www.eso.org/sci/observing/phase2/SMGuidelines.html
http://www.eso.org/sci/observing/phase2/P2PP3.html

The User shall provide during Phase 2 the OBs containing acquisition and observation templates, fill the README information, and provide the corresponding finding charts following the rules given at
http://www.eso.org/sci/observing/phase2/SMGuidelines/FindingCharts.html.

To help with MUSE preparation, we have created a MUSE-FOV template to use with ds9. One can create such a template by copying/pasting the code provided in Section 8.4.

5.2 MUSE Observing modes

MUSE is primarily a survey instrument, with two basic modes: Wide Field Mode (WFM) for surveys and general use; and Narrow Field Mode (NFM) for achieving unprecedented spatial resolution across a sizeable field. For the moment, **only WFM without AO** is available to the users.

In addition there are two choices of wavelength range, the nominal (N) one suppressing 2nd-order overlap of blue light at red wavelengths (see Section 3.6). The available instrument modes (WFM-NOAO-E and WFM-NOAO-N) are presented in Table 7, as well as the 3 additional instrument modes which are expected for the future.

Table 7: Summary of MUSE instrument modes. Filter names and spectral ranges. Only WFM-NOAO-N and WFM-NOAO-E instrument modes are available at the moment, with 3 additional instrument modes expected in the future (hatched).

MUSE instrument mode	Spatial setting	Filter name	Spectral range (nm)
WFM-NOAO-N	WFM	Blue	480-930
WFM-NOAO-E	WFM	Clear	465-930$^{(*)}$ with 2nd order contamination at 850-930 nm
WFM-AO-N	WFM	Blue-Na	480-574, 604-930
WFM-AO-E	WFM	Na	465-574, 604-850$^{(*)}$
NFM-AO-N	NFM	Blue-IR	480-930 Nota: Na Notch in Galacsi

(*) See Section 2.5.4 about 2nd order contamination in the red for WFM-NOAO-E instrument mode.

5.3   MUSE Target acquisition

The first template to be included in the OB is the **acquisition template**. For both available instrument modes (WFM-NOAO-N and WFM-NOAO-E), the template to be used for acquisition is **MUSE_wfm-noao_acqfast.**

The main parameters of the acquisition template are the following:

- Instrument Mode
- WCS position of the FOV center (RA,DEC)
- Position Angle on the sky (measured from North through East). The convention for position angles with respect of the FOV is detailed in Figure 16.
- *(Optionally)* Position and magnitude of the VLT Guide Star. The VLT Guide Star must be between R band magnitudes 8 and 12 (in Vega), and located within the VLT guide star area (Table 8). Providing the VLT guide star is not mandatory but is useful when combining observations taken at different days or when doing mosaic observations with MUSE. The quality of the astrometry in the headers of the raw data depends directly on the quality of the astrometry of the guide star.
- Exposure time of acquisition exposure. Typical integration times vary between 10 sec. (if there is a V<17 point source in the FOV) and 2 min. (when the brightest point source is V<20). If there is a need of precise (<1" error) pointing in fields where only faint extended sources are present, blind offsets are recommended.
- *(Optionally)* Blind offsets. The user has the possibility to apply some offsets with respect to a bright reference star centered in the FOV of MUSE, in case no bright source is visible in the FOV for direct acquisition and precise pointing is necessary. The convention is to provide telescope offsets (arcsecs in RA and DEC) to **move the telescope from the target to the reference star**.

RA_REFSTAR   = RA_TARGET + ΔRA
DEC_REFSTAR = DEC_TARGET + ΔDEC

Figure 15: convention for blind offsets during acquisition

In that case, the sequence is the following:
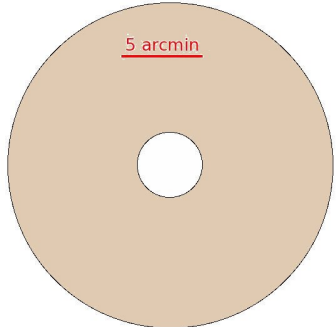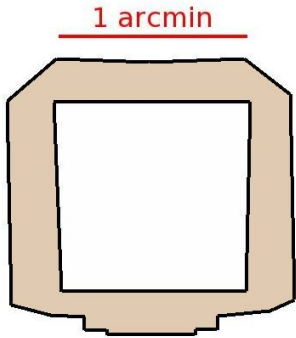
- o The telescope points to the reference star by including offsets from the target
- o The reference star is centered in the MUSE FOV.
- o The offsets are cancelled and the telescope moves to the target position.
- o For those familiar with the instruments, this definition of blind offsets is identical to the one used for HAWK-I and CRIRES.

- Slow Guiding (True/False): the user can choose to use the secondary slow guiding system (SGS). In this case, the SGS will acquire a reference image and detect guide stars, which adds a small overhead in the acquisition (Table 9). The SGS will lock on these stars and correct for small motions such as derotator wobble, which is important for long exposures, in particular close to the zenith. The user does not need to provide secondary guiding stars in acquisition, these are automatically found by the system.

Table 8: Description of the different guide stars used for acquisition, and their corresponding region of sky with respect to the centre of the MUSE FOV

	Guide Star Area	Shape
VLT guide star	10 arcmin radius circle inside the unvignetted Nasmyth FOV 4 arcmin diameter circle excluded	
SGS guide stars	SGS metrology fields, ~ 1.5 arcmin square field, MUSE FOV excluded	

5.4 MUSE science observations

5.4.1 Science templates

Two science templates are available for each mode, allowing to perform stare observations or to include a sequence of offsets.

5.4.1.1 Stare observations (MUSE_wfm-noao_obs_stare)

When using this template, a number of exposures are taken without any offset of the telescope between them. This allows to keep the SGS in closed loop during the entire sequence.

5.4.1.2 Offset sequence (MUSE_wfm-noao_obs_offset)

This template allows the user to perform a number of exposures and offset the telescope and/or the instrument derotator to adjust pointing and PA in between each exposure sequence. The list of offsets is provided in P2PP. In addition, the user should specify a list of exposure types ("O(BJECT)" or "S(KY)") and a list of exposure times. The science mode of MUSE to be used for this OB, as defined in Table 7 (e.g. WFM-NOAO-N), has been defined in the corresponding acquisition template in P2PP.

Similarly to other VLT instruments, telescope offsets are defined relative to the previous telescope position, therefore the offsets are cumulative, e.g. a sequence of [0, -2, 4, -2] will finish at the original position. The offsets are defined in units of arcseconds in the reference frame selected (DETECTOR or SKY). The convention is detailed below in Figure 16: Offset conventions for MUSE. We summarize here the main definition. If the first image is to be taken at the preset coordinates, the first set of offsets should be 0,0. If there are less offset values than the defined total number of exposures, the template will return at the beginning of the list of offsets and apply them again. However, **the number of offsets provided should be identical in x and y directions**.

Figure 16: Offset conventions for MUSE. We summarize here the main definitions
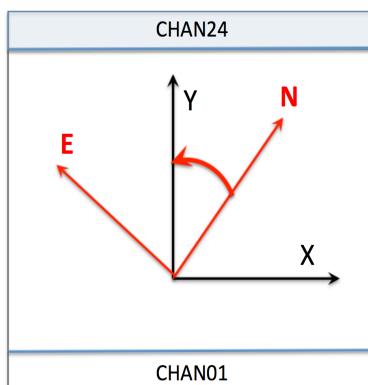
- If the user offsets are given in"SKY" convention, telescope offsets are sent in arcsecs, positive in the direction of East (RA) and North (DEC), respectively.

- If the user offsets are given in "DETECTOR" convention, telescope offsets are sent in arcsecs, positive in the X and Y directions, respectively, where the X and Y axes are defined relative to the 24 channels of MUSE.

- The position angle of a MUSE observation is measured positive East from North (red oriented angle). Positive position angle offsets are sent to the derotator in the same direction (see examples below).

Return to Origin (True/False): this parameter determines whether the telescope is sent back to the original position (before any offset was applied) at the end of the template. Default="True"

For example, if the number of exposures is 5 and the series of offsets (in "SKY" convention) is:

ΔRA	0	-10	5
ΔDEC	2	7	3

Then the offsets applied to the telescope will be:

ΔRA_{VLT}	0	-10	5	0	-10
ΔDEC_{VLT}	2	7	3	2	7

In addition, the user can provide a list of PA offsets to be sent to the instrument before an exposure. Like telescope offsets, PA offsets are cumulative. When in "DETECTOR" framework, if both telescope

offsets and PA offset are provided, the telescope offsets are sent with respect to the current PA of the instrument, before applying the PA offset.

Example 1: Telescope offsets only, "SKY" convention

Total number of exposures:	5
List of exposure types:	O,S,O,O,S
List of integration times:	1200,20,1200,1200,20
Offsets coordinate type:	SKY
List of ΔRA offsets:	0,-30,30,-1,-29
List of ΔDEC offsets:	0,-20,20,3,-23
List of PA offsets:	0
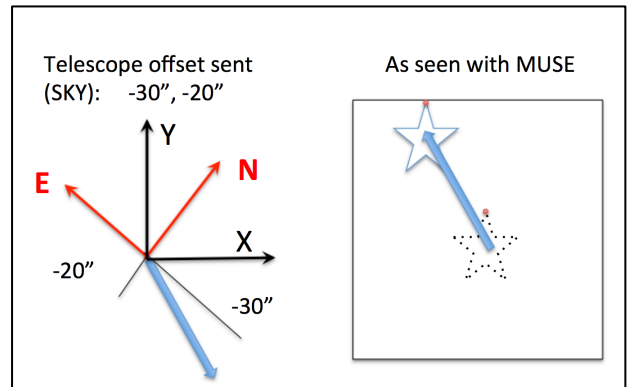
⇨ The telescope will (1) not move but make an 'object' exposure (1200s), (2) move and make a 'sky' exposure (20s), (3) move back to the origin and make an 'object' exposure (1200s), (4) move slightly and make an 'object' exposure (1200s), (5) move to the previous 'sky' position and make a 'sky' exposure (20s).

An illustration of the effect of the second offset is given in the figure.

Example 2: Telescope offsets only, "DETECTOR" convention

Total number of exposures:	7
List of exposure types:	S,O
List of integration times:	20,1200
Offsets coordinate type:	DETECTOR
List of ΔX offsets:	-30,30
List of ΔY offsets:	-20,20
List of PA offsets:	0
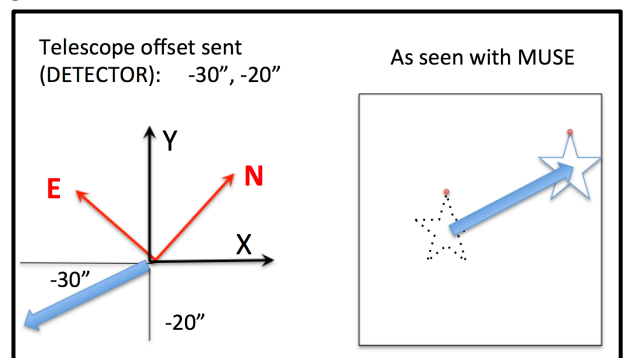
⇨ The telescope will (1) move and make a 'sky' exposure (20s), (2) move back to the origin and make an 'object' exposure (1200s), (3) to (7) repeat (1) and (2) until 7 exposures have been taken: therefore the last exposure will be of 'sky' type, and the telescope will finish the template at the 'sky' position, shifted from the preset coordinates.

⇨ Note that the list of integration times could be '20,1200,20,1200', the result would be the same, as well as if the ΔX list was '-30,30,-30,30,-30,30': each list is repeated as many times as required by the total number of exposures, and only the ΔX and ΔY offsets list lengths are linked.

An illustration of the effect of the first offset is given in the top-right figure.

Example 3: Telescope offsets and PA offsets, "SKY" convention

An illustration of the effect of a (-30",-20") sky offset combined with a PA offset of 20 degrees is given in the figure:

Telescope offset sent (SKY): -30",-20"

PA offset: + 20 deg

As seen with MUSE
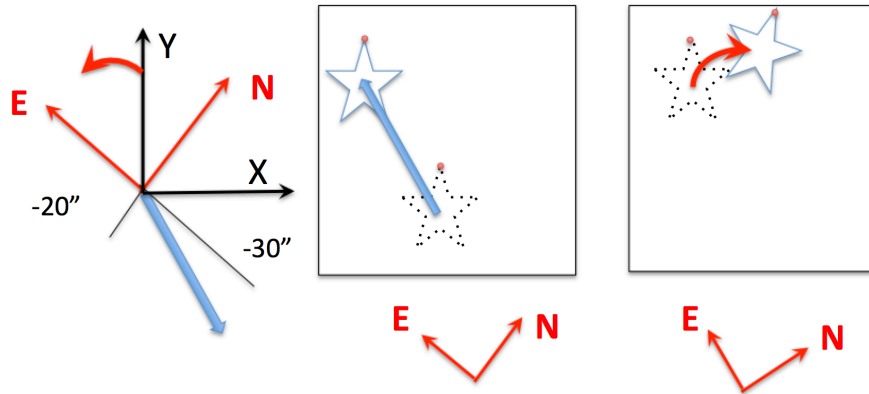
Example 4: Telescope offsets and PA offsets, "DETECTOR" convention

An illustration of the effect of a (-30",-20") detector offset combined with a PA offset of -100 degrees is given the figure:

Telescope offset sent (DETECTOR): -30", -20"

PA offset: - 100 deg

As seen with MUSE

5.4.2 Attached calibrations

The daytime calibrations (Section 6) provide flat-field and arc exposures, which could be slightly shifted compared to the night-time science observations due to thermal variations repeatability (Section 2.5.7). If the user requires more accuracy it is possible to include arc and flat calibration in an observing OB as an attached calibration template, directly after the corresponding science template. Attached calibrations are charged to the user program.

5.5 Instrument and Telescope Overheads

The overheads on acquisition and observation depend on the integration time set. We provide here a summary of the telescope and instrument overheads (Table 9).

Table 9: Summary of overheads.

Acquisition and setup		
Telescope pointing, guide star acquisition (Preset)		6 min
Interactive acquisition loop		2 min
SGS loop closure		90 s
Observations		
Detector setup		15 s
Detector readout + FITS file merging		80 s
Each telescope offset		15 s
SGS loop closure for large offsets		90 s
Derotator offset		0.11 s / degree
Attached calibration	Attached flat-field calibrations	250 s + 106 s / flat-field
	Attached wavelength calibration	180 s + 112 s / arc lamp exposure (1 per lamp)

Overhead computations:

Example 1: not using the SGS

The total duration of a simple acquisition and a stare (no offsets) observation is :

T_{total}= 360 s (preset)+ T_{acq} + 120 s (acquisition, 1 iteration) + N x (15 s + UIT + 80 s)

With T_{acq} the integration time of acquisition and UIT the integration time of each of the N exposures.

Example 2 : using the SGS with small telescope offsets, no PA offsets

T_{total}= 360 s (preset)+ T_{acq} + 120 s (acquisition, 1 iteration) + 90 sec (SGS loop closure) + N x (15 s + UIT + 80 s + 15 s (telescope offset))

With T_{acq} the integration time of acquisition and UIT the integration time of each of the N exposures (assuming identical UITs).

Example 3: using the SGS, with large telescope offsets and rotation offsets.

In that case, we are (conservatively) assuming that the SGS has to close the loop after each offset / rotation because it has lost the current guide stars.

T_{total}= 360 s (preset)+ T_{acq} + 120 s (acquisition, 1 iteration) + 90 sec (SGS loop closure) + N x (15 s + UIT + 80 s + 15 s (telescope offset) + 20 s (rotation) + 90 s (SGS loop closure))

With T_{acq} the integration time of acquisition and UIT the integration time of each of the N exposures (assuming identical UITs).

6 Calibrating and Reducing MUSE data

6.1 MUSE calibration

We summarize below the main calibrations performed as part of the standard calibration plan for MUSE. These calibrations are performed on a regular basis. The the definition of the calibration plan is still work in progress at this stage.

Table 10: Overview of the MUSE calibration plan.

Calibration	Number of exposures (per mode)	Frequency	Phase	Purpose
Bias	5	Daily	Day	Master bias, bias characteristics
Dark	3	Monthly	Day	Master dark, dark current
Geometrical calibration: multi-Pinhole mask with arc lamps	80	Monthly	Day	Relative location of the slices
Flat-field with sky	>3	Weekly, still under investigation	Twilight	Illumination correction
Flat-field with continuum lamp	5	1-3 nightly (a)	Day	Illumination correction Tracing solution Background light Instrument throughput
Attached Flat-field with continuum lamp	N (c)	On request.	Night	High-precision flat-fielding
Wavelength	1 per lamp	Daily	Day	Wavelength solution Dispersion characteristics
Attached Wavelength	N (c)	On request.	Night	High-precision wavelength solution
Spectrophotometric calibration	1	(b)	Night	Absolute flux calibration Optional: Telluric correction
Astrometry	1	Monthly	Night	Astrometric model

(a) The actual frequency of flat-field calibrations is currently under investigation, but is foreseen to happen between 1 to 3 times per night.
(b) During clear or photometric nights in which MUSE science OBs are executed
(c) The number of exposures is defined by the user.

6.1.1 Wavelength calibration

Wavelength calibration is performed on a daily basis. For each MUSE instrument mode used in science observation, 1 exposure is taken with each of the 3 available arc lamps (HgCd, Xe, Ne)

illuminating the entire FOV. The location of these reference emission lines on the detector is used by the DRS to derive an overall wavelength solution. Details on the emission line wavelengths are provided for each lamp as a reference in Table 12 to Table 14, Section 8.2.

MUSE observers can submit an "attached" wavelength calibration to be performed directly following their science observation.

6.1.2 Flat-field calibration

Flat-field calibration is performed on a nightly basis, at a frequency of 1 to 3 times per night (TBD). For each MUSE instrument mode used in science observation, 5 exposures are taken with the continuum lamp illuminating the entire FOV. If possible, observations of the twilight sky taken in the morning / evening can also be used for calibration. The data reduction software uses these exposures to estimate the tracing solution, as well as the illumination and throughput as a function of position and wavelength.

MUSE observers can submit an "attached" flat-field calibration to be performed with the continuum lamp directly following their science observation.

6.1.3 Sky flat calibration

This calibration takes evening or morning twilight exposures to correct for overall illumination on sky. Exposures are taken according to the sky brightness:
- a reference exposure is taken, and the average ADU level is estimated.
- Depending on this level, we estimate the integration time for the next exposure required in order to maintain a constant (and high) ADU level.
- This sequence is continued until the conditions are no longer appropriate for twilight exposures or the maximum number of exposures to be taken is reached (whichever comes from)

6.1.4 Geometrical (spatial) calibration

Geometrical calibration is performed monthly. The instrument is set up in WFM with a multi-pinhole mask (WFM_SMP) covering the entire FOV (more details on this mask are given for reference in Section 6.7). The mask is translated vertically by 0.034" between each exposure, and a total of 80 exposures is taken to fully cover all slices by the pinholes.
These exposures are analysed by the DRS to derive the relative location and orientation of each slice in each channel. Already processed geometry tables will be provided in the instrument package.

6.1.5 Spectro-photometric calibration

The spectro-photometric calibration is performed daily, whenever possible, using observations of a field containing a spectrophotometric standard star. Several high SNR exposures (~ 20 000 ADU at peak) of the star are used to derive the flux calibration curve. The stars used for this calibration are taken from the reference list of standard stars:

https://www.eso.org/sci/observing/tools/standards/spectra.html

6.2   MUSE data reduction

The output of an exposure with the instrument is a raw frame, which has the following multi-extension FITS format:

- **Primary extension (Extension 0, header only):** contains the keywords specific to the exposure and common to all channels, such as information about the observing program, telescope, overall instrument and weather conditions, etc.

- **Extensions 1 to 24:** contains for each channel a short header (with information specific to the detector) and the image frame corresponding to this particular channel. The order of the extensions in the FITS file does not follow the order of the channel numbers so they should be addressed with their **extension name** CHAN01, CHAN02, CHAN03 …. CHAN22, CHAN23, CHAN24 corresponding to the channel number. The size of the image frame, in the absence of binning, is 4224 x 4240 (including the overscan regions, see Section 2.2.4.3).

- **Extension 25 to 27** (for science exposures) contain information from the SGS taken in parallel to the science exposures, when SGS is activated. The SGS will record images with the TCCD and produce stack median images every ~ 2 min. These median images can be average over the entire science exposure to give a deeper image of the region surrounding the MUSE FOV.

    - **Extension 25 (SGS_IMG):** an image of size 1024x1024 contains the average of all the stacked median images taken during the science exposure.
    - **Extension 26 (SGS_CUBE):** a cube of 1024x1024xN pixels, containing all N stacked median images taken during the science exposures.
    - **Extension 27 (SGS_DATA):** a FITS table containing information from the SGS system in the form of (4+NSTARSx10)xN entries, for the N measurements done using NSTARS (NSTARS<10) stars detected in the SGS. For each measurement, the 4 first columns give general information about the time and the offsets sent to the telescope, while the last 10 x NSTARS entries give information on each star.

The MUSE Data Reduction Software (DRS) has been developed to fully reduce MUSE raw science observations using the associated calibrations. Data reduction is performed following a number of calibration recipes. The final output of the DRS is a FITS datacube (with RA, DEC and wavelength as the three axes), as well as a number of quality control (QC) parameters for each recipe. Full details on installing and using the MUSE DRS will be provided in the User Manual.

Note that given the data volume and complexity of MUSE exposures, data reduction can be extremely resource intensive on computer architecture, especially on memory. It is not recommended that data be reduced on personal computer, rather a multi-core workstation with at the very least 32 GB RAM is recommended. However, for the end-cube production and combination of multiple datacubes a machine with at least 150 GB RAM is needed.

7 Templates

We describe in this section the parameters for each of MUSE templates. The descriptions in this section will be superseded by the final list of templates to be released with the first instrument package for Phase2.

7.1 MUSE acquisition templates

Full details on acquisition are provided in Section 5.3, including the parameters to define in P2PP. The main parameters of the acquisition are the instrument mode (WFM-NOAO-N or WFM-NOAO-E), position angle, exposure time for the acquisition, use of SGS, and (optionally) definition of telescope guide star and/or blind offsets.

7.1.1 MUSE_wfm-noao_acqfast template signature file

MUSE_wfm-noao_acqfast.tsf		
KEYWORD	**Range (Default)**	**Label in P2PP**
To be specified		
DET.UIT1	0..120 (0)	Integration Time (seconds)
SEQ.SGS	T F (T)	Start slow-guiding?
TEL.TARG.OFFSETALPHA	-999..999 (0.0)	Alpha offset for the reference star (arcsec)
TEL.TARG.OFFSETDELTA	-999..999 (0.0)	Delta offset for the reference star (arcsec)
TEL.AG.GUIDESTAR	CATALOGUE/SETUPFILE/NONE (CATALOGUE)	Get Guide Star from
TEL.GS1.ALPHA	0….240000 (000000.000)	RA of guide star (as HHMMSS.TTT)
TEL.GS1.DELTA	-900000…..900000(000000.000)	DEC of guide star (as +-DDMMSS.TTT)
INS.DROT.POSANG	-180….180 (0)	Position Angle on Sky (deg)
INS.MODE	WFM-NOAO-E WFM-NOAO-N	Instrument Mode

7.2   Observation Templates Tables

Full details on observing templates are provided in Section 5.4, including the main parameters to define in P2PP, in particular the definitions and conventions for offsets.

7.2.1   MUSE_wfm-noao_obs_offset template signature file

MUSE_wfm-noao_obs_offset.tsf		
KEYWORD	**Range (Default)**	**Label in P2PP**
To be specified		
SEQ.NEXPO	1..1000 (NODEFAULT)	Total number of exposures
SEQ.OBSTYPE.LIST	O S (NODEFAULT)	Observation type list, O/S
SEQ.OFFSET.COORDS	SKY DETECTOR (SKY)	Offset coordinate type selection
SEQ.OFFSET.POSANG.LIST	-360..+360 (0)	List of relative offsets in position angle (deg)
SEQ.OFFSET1.LIST	-600..600 (NODEFAULT)	List of relative offsets in RA or X (arcsec)
SEQ.OFFSET2.LIST	-600..600 (NODEFAULT)	List of relative offsets in DEC or Y (arcsec)
SEQ.RETURN	T F (T)	Return to origin?
SEQ.UIT.LIST	1 (1)	List of UITs

7.2.2   MUSE_wfm-noao_obs_stare template signature file

MUSE_wfm-noao_obs_stare.tsf		
KEYWORD	**Range (Default)**	**Label in P2PP**
To be specified		
SEQ.UIT.LIST	1 (1)	List of UITs
SEQ.NEXPO	1..1000 (NODEFAULT)	Total number of exposures

7.3   Calibration Templates Tables

7.3.1   Templates specifically written for night astronomers

These templates perform wavelength and internal flat calibration directly following a science exposures, at the same telescope and derotator position. These calibrations are useful when a very accurate wavelength or flat-field correction is necessary for the science observations, and they are charged to the User Program.

7.3.1.1 MUSE_wfm_cal_waveatt

This template is the equivalent of MUSE_wfm_cal_wave in case of attached calibration.

MUSE_wfm_cal_waveatt.tsf		
KEYWORD	**Range (Default)**	**Label in P2PP**
To be specified		
SEQ.LAMP3.UIT	0..3600 (0.7)	Integration time on Neon penray lamp (s)
SEQ.LAMP4.UIT	0..3600 (19)	Integration time on Xenon penray lamp (s)
SEQ.LAMP5.UIT	0..3600 (1)	Integration time on HgCd High Power lamp (s)
SEQ.LAMP6.UIT	0..3600 (0)	Integration time on Neon High Power lamp (s)
SEQ.NEXPO	1..1000 (3)	Total number of exposures

7.3.1.2 MUSE_wfm_cal_specflatatt

This template is the equivalent of MUSE_wfm_cal_specflat in case of attached calibration.

MUSE_wfm_cal_specflatatt.tsf		
KEYWORD	**Range (Default)**	**Label in P2PP**
To be specified		
DET.UIT1	0..3600 (0.4)	Integration Time (seconds)
SEQ.NEXPO	1..1000 (5)	Total number of exposures

7.3.2   Other calibration templates

7.3.2.1 MUSE_cal_bias template signature file

Parameters for bias exposures include: number of biases to be taken and the binning factor (always 1 for science exposure).

MUSE_cal_bias.tsf		
KEYWORD	**Range (Default)**	**Label in P2PP**
To be specified		
DET.BINY	1 4 (1)	Binning factor along Y
SEQ.NEXPO	1..1000 (11)	Total number of exposures

7.3.2.2 MUSE_cal_dark template signature file

This template is used to perform dark calibrations.

MUSE_cal_dark.tsf		
KEYWORD	**Range (Default)**	**Label in P2PP**
To be specified		
DET.UIT1	0..3600 (3600)	Integration time (seconds)
SEQ.NEXPO	1..1000 (3)	Total number of exposures

7.3.2.3 MUSE_wfm_cal_geometry template signature file

This template is used to perform the geometrical calibration, as described in Section 6.1

MUSE_wfm_cal_geometry		
KEYWORD	**Range (Default)**	**Label in P2PP**
To be specified		
SEQ.NEXPO	1..1000 (3)	Total number of exposures
SEQ.ONTIME.LIST	"" (60 60 60 60)	List of lamp on time (s)
SEQ.YSHIFT	0..40.767 (0.069)	Y offset applied on the mask (arcsecs)
INS.MODE	WFM-NOAO-E WFM-NOAO-N (NODEFAULT)	Instrument Mode

7.3.2.4 MUSE_wfm_cal_specflat template signature file

This template is used to perform the daily flat-field calibration, as described in Section 6.1

MUSE_wfm_cal_specflat.tsf		
KEYWORD	**Range (Default)**	**Label in P2PP**
To be specified		
DET.BINY	1 4 (1)	Binning factor along Y
DET.UIT1	0..3600 (0.5)	Integration time in seconds
SEQ.NEXPO	1..1000 (5)	Total number of exposures
INS.MODE	WFM-NOAO-E WFM-NOAO-N (NODEFAULT)	Instrument Mode

7.3.2.5 MUSE_wfm_cal_wave template signature file

This template is used to perform the daily wavelength calibration, as described in Section 6.1

MUSE_wfm_cal_wave.tsf		
KEYWORD	**Range (Default)**	**Label in P2PP**
To be specified		

SEQ.LAMP3.UIT	0..3600 (0.7)	Integration time on Neon penray lamp (s)
SEQ.LAMP4.UIT	0..3600 (19)	Integration time on Xenon penray lamp (s)
SEQ.LAMP5.UIT	0..3600 (1)	Integration time on HgCd High Power lamp (s)
SEQ.LAMP6.UIT	0..3600 (0)	Integration time on Neon High Power lamp (s)
SEQ.NEXPO	1..1000 (3)	Total number of exposures
INS.MODE	WFM-NOAO-N WFM-NOAO-E (NODEFAULT)	Instrument Mode

7.3.2.6 MUSE_wfm_cal_twilight template signature file

This template is used to perform the twilight flat calibration.

MUSE_wfm_cal_twilight.tsf		
KEYWORD	**Range (Default)**	**Label in P2PP**
To be specified		
SEQ.ADU.TARGET	1..60000 (21000)	Target number of counts
SEQ.UIT.START.DAWN	0.1..600 (30)	Start integration time at dawn time (s)
SEQ.UIT.START.TWILIGHT	0.1..600 (1.0)	Start integration times at twilight time (s)
SEQ.NEXPO	1..1000 (10)	Maximum number of exposures
INS.MODE	WFM-NOAO-E WFM-NOAO-N (NODEFAULT)	Instrument Mode

7.3.2.7 MUSE_wfm_cal_std template signature file

This template is used to perform a spectrophotometric standard star calibration.

MUSE_wfm_cal_std.tsf		
KEYWORD	**Range (Default)**	**Label in P2PP**
To be specified		
DET.UIT1	0..3600 (NODEFAULT)	Integration Time (seconds)
SEQ.NEXPO	1..1000 (1)	Total number of exposures
SEQ.OBSTYPE.LIST	O S (O)	Observation type list, O/S
SEQ.OFFSET.COORDS	SKY DETECTOR (SKY)	Offset coordinate type selection
SEQ.OFFSET.POSANG.LIST	-360..360 (0)	List of relative offsets in Position Angle (deg)
SEQ.OFFSET1.LIST	-600..600 (0)	List of relative offsets in RA or X (arcsec)

SEQ.OFFSET2.LIST	-600..600 (0)	List of relative offsets in DEC or Y (arcsec)
SEQ.RETURN	T F (T)	Return to origin?

7.3.2.8 MUSE_wfm_cal_telstd template signature file

This template is used to perform a telluric standard star calibration.

MUSE_wfm_cal_telstd.tsf		
KEYWORD	**Range (Default)**	**Label in P2PP**
To be specified		
DET.UIT1	0..3600 (NODEFAULT)	Integration Time (seconds)
SEQ.NEXPO	1..1000 (1)	Total number of exposures
SEQ.OBSTYPE.LIST	O S (O)	Observation type list, O/S
SEQ.OFFSET.COORDS	SKY DETECTOR (SKY)	Offset coordinate type selection
SEQ.OFFSET.POSANG.LIST	-360..360 (0)	List of relative offsets in Position Angle (deg)
SEQ.OFFSET1.LIST	-600..600 (0)	List of relative offsets in RA or X (arcsec)
SEQ.OFFSET2.LIST	-600..600 (0)	List of relative offsets in DEC or Y (arcsec)
SEQ.RETURN	T F (T)	Return to origin?

7.3.2.9 MUSE_wfm_cal_astrom template signature file

This template is used to perform the astrometric calibration, on a regular basis.

MUSE_wfm_cal_astrom.tsf		
KEYWORD	**Range (Default)**	**Label in P2PP**
To be specified		
SEQ.UIT.LIST	(NODEFAULT)	List of UITs
SEQ.NEXPO	1..1000 (1)	Total number of exposures
SEQ.OBSTYPE.LIST	O S (O)	Observation type list, O/S
SEQ.OFFSET.COORDS	SKY DETECTOR (SKY)	Offset coordinate type selection
SEQ.OFFSET.POSANG.LIST	-360..360 (0)	List of relative offsets in Position Angle (deg)
SEQ.OFFSET1.LIST	-600..600 (0)	List of relative offsets in RA or X (arcsec)
SEQ.OFFSET2.LIST	-600..600 (0)	List of relative offsets in DEC or Y (arcsec)
SEQ.RETURN	T F (T)	Return to origin?

8 Reference material

8.1 Detector cosmetics

We provide in Table 11 for reference the detectors showing 1 or several bad columns, with the corresponding region affected on the detector.

Table 11: List of defects identified for each detector (arranged by channel) by the MUSE pipeline as a DQ issue. Each detector is identified by its name (DET_ID) and associated IFU number. The last columns gives (when relevant) the number of bad columns (bc), bad pixels (bp), and the rectangular region showing defects marked as [x1:x2,y1:y2] in pixel positions on the raw data frames.

CHANNEL	IFU	DET_ID	DET_INDEX	DQ Cosmetics
1	24	psyche	6	None
2	1	victoria	6	None
3	10	flora	6	2055bp(1bc) [1828,2058:4112]
4	4	juno	6	None
5	15	vesta	5	None
6	2	hebe	5	None
7	12	circe	5	6025bp(3bcs) [2800:2802,2057:4068]
8	3	massalia	5	None
9	18	thalia	4	None
10	20	lutetia	4	4111bp(2bcs) [2156,2057:4112]
11	21	parthenope	4	None
12	11	hygiea	4	2034bp(1bc) [1567,23:2056]
13	17	harmonia	3	2056bp(1bc) [1101,1:2056]
14	19	irene	3	None
15	15	astraea	3	None
16	8	pallas	3	None
17	7	thetis	2	None
18	16	iris	2	None
19	9	kalliope	2	None
20	6	fortuna	2	None
21	13	proserpina	1	2054bp(1bc) [1411,1:2054]
22	5	eunomia	1	2051bp(1bc) [2673,6:2056]
23	23	metis	1	None
24	22	melpomene	1	None

8.2 Arc lamps list

We provide in Table 12, Table 13 and Table 14 the list of lines identified in the arc lamps used for wavelength calibration.

8.2.1 HgCd arc lamp

Table 12: list of wavelengths and relative fluxes for the HgCd arc lamp.

Wavelength (Angstroms)	Relative Flux
4339.2232	30
4347.4945	80
4358.335	5500
4412.9894	2
4662.352	25
4678.1493	1200
4799.9123	3800
4916.068	85
4960.1	3
4980.64	0.5
5025.6	3
5045.8	0.5
5085.8217	7150
5120.637	0.5
5154.6605	32
5290.74	0.5
5316.776	1
5354.034	10
5365.5	0.5
5460.75	35000
5549.634	1
5675.81	8
5769.61	7000
5790.67	6600
5803.782	8
5859.254	4
5871.975	0.5

5890.2	1
6072.64	6
6099.1421	4
6111.495	2
6123.27	5
6234.36	18
6325.1661	11
6330.0133	2
6438.4695	2800
6716.34	15
6778.1157	1
6888.564	0.5
6907.46	160
6965	6
7067	8
7081.901	40
7091.86	13
7177.8	0.5
7269.9	2
7345.6704	25
7367.3	0.5
7372.5	1
7383.2	18
7397	4
7504.1	6
7514.8	8
7552.1	0.5
7603	2
7635.2	30
7675.2	2
7724.2	12
7728.825	22
7821.2	1

7948.2	10
8005	30
8006.1	2
8014.8	8
8067	3
8070.7	2
8013.8	10
8115.4	42
8163.4	1
8195.6	2
8200.3089	4
8264.2	8
8408.3	14
8424.5	13
8521.4	3
8625	140
8652.7	1
8758.1	6
8763	1
8773.1	0.5
8783.7	0.5
8887.5	0.5
8988.9	1
9039.2	1
9067.2	0.5
9123.1	10
9138	2
9243.1	5
9253.9	1
9255	15
9499	35

8.2.2 Xe arc lamp

Table 13: list of wavelengths and relative fluxes for the Xe arc lamp

Wavelength (Angstroms)	Relative Flux
4500.978	9
4524.6805	7
4582.7472	3
4603.03	1
4624.2756	33
4671.2258	70
4690.97	2
4697.0208	11
4734.1518	20
4792.619	4
4807.019	24
4829.708	15
4843.2934	13
4916.507	16
4923.152	21
4972.71	1
5028.2794	4
5044.92	0.5
5261.95	1
5292.22	2
5337.89	2
5392.795	1
5394.738	1
5418.02	2
5439.923	1
5440.39	1
5532.78	6
5552.385	1
5566.615	2
5567.77	2
5570.91	3
5697	3
5716	2
5824	7
5875.018	6
5889.12	1
5894.988	6
5934	7
5974.152	0.5
5978.29	0.5
5998.115	0.5
6030	4
6111.8	5
6163.8	6
6178.303	3
6179.665	10
6182.42	14
6198.26	5
6200.892	3
6201.49	2
6224.168	0.5
6261.212	1
6265.302	1
6273.23	0.5
6286.011	2
6293	3
6318.062	19
6333.97	0.5
6344.98	0.5
6355.77	0.5
6419	1
6469.705	12
6472.841	6
6487.765	7
6498.717	5
6504.2	7
6521.508	1
6533.159	3
6543.36	1
6554.196	4
6595.561	11
6608.87	0.5
6632.464	6
6668.4	20
6679.8	2
6728.008	30
6767.12	1
6778	6
6827.315	25
6846.8	8
6860.19	1
6866.838	6
6872.107	18
6882.155	50
6910.82	1
6925.53	7
6935.8	4
6976.182	12
6982.05	2
6991.65	0.5
7019.02	4
7035.53	1
7048	5
7078.46	0.5
7119.598	110
7136.57	0.5
7200.79	1
7244.94	4
7257.94	10
7262.54	3
7266.49	7
7284.7	38
7316.272	27
7321.452	22
7336.48	15
7355.58	8
7386.003	29
7393.793	36
7400.41	8
7424.05	3
7441.94	4
7451	5
7473	15
7492.23	3
7501.13	3

Wavelength	Flux
7514.7	1
7559.79	9
7584.68	80
7600.77	2
7642.024	290
7664.3	12
7740.31	6
7783.66	5
7790	1
7802.651	30
7881.32	8
7887.393	96
7937.41	6
7967.342	125
8003.26	1
8029.67	13
8057.258	48
8061.339	45
8101.98	8
8109.46	1
8118.29	0.5
8171.02	6
8206.336	215
8231.6336	20000
8266.52	120
8280.1162	8500

Wavelength	Flux
8297.71	2
8324.58	3
8346.8217	795
8372	2
8392.37	2
8409.1894	1370
8437.55	1
8522.55	7
8530.1	9
8576.01	30
8624.24	17
8648.54	56
8692.2	24
8696.86	23
8709.7	11
8739.37	180
8758.2	34
8819.4106	37800
8851.44	3
8862.32	240
8885.71	3
8908.73	125
8930.83	170
8952.3	6800
8981.05	45
8987.57	90

Wavelength	Flux
9025.98	17
9032.18	23
9045.4466	8888
9096.13	25
9112.24	5
9131.59	4
9152.12	10
9162.652	10800
9167.52	70
9203.2	45
9211.38	27
9222.39	6
9245.18	2
9301.95	33
9306.64	36
9334.08	1
9374.76	250
9412.01	65
9441.46	5
9442.68	30
9445.34	100
9488	4
9497.07	27
9505.78	3
9513.377	450
9585.14	6

8.2.3 Ne arc lamp

Table 14: list of wavelengths and relative fluxes for the Ne arc lamps

Wavelength (Angstroms)	Relative Flux
4704.3949	0.5
4708.8594	0.5
5031.3484	0.5
5037.7512	5
5080.383	3
5154.4271	0.5
5188.6122	0.5
5193.1251	0.5
5193.224	0.5

Wavelength	Relative Flux
5203.8962	0.5
5210.5672	0.5
5222.3517	0.5
5234.0271	0.5
5298.1891	0.5
5330.7775	18
5341.0938	15
5400.5616	38
5433.6513	0.5
5562.691	7
5656.6588	8
5662.5489	0.5
5689.8163	5
5719.185	4

Wavelength	Relative Flux
5748.2985	16
5760.5885	0.5
5764.4188	90
5804.4496	20
5811.4066	0.5
5820.1558	50
5852.4878	3250
5872.8275	40
5881.895	2700
5901.409	40
5906.4294	18
5913.633	6
5918.9068	2
5919.029	2

5934.4522	3	6717.043	9200	8571.3535	35
5944.834	4400	6738.032	1	8582.9031	19
5961.6228	3	6929.4672	12450	8591.2583	550
5965.471	25	7024.05	1300	8634.6472	630
5975.122	1250	7032.4128	34000	8647.0412	64
5987.9074	16	7051.2922	47	8654.3828	1050
5991.6477	3	7059.1079	205	8680.794	215
6000.9275	4	7112.3075	1	8681.9216	215
6029.9968	1500	7173.938	2650	8704.1122	45
6064.5359	5	7245.1665	17000	8771.6575	100
6074.3376	3800	7304.8422	1	8781.969	1000
6096.163	4800	7438.8981	5200	8792.5056	5
6118.0187	1	7472.4383	80	8830.9067	6
6128.4498	270	7488.8712	1000	8853.8669	450
6143.0627	10000	7535.7739	920	8865.701	240
6163.5937	3700	7544.0439	370	8919.5007	102
6174.802	12	7833.0281	0.5	8988.5564	25
6182.146	20	7839.052	5	9148.672	130
6189.0649	2	7927.1172	7	9201.7588	95
6205.7775	6	7936.9957	20	9220.468	72
6217.2812	3500	7943.1805	120	9226.691	17
6246.7294	5	8082.4576	210	9275.5191	8
6266.4952	7000	8118.5495	50	9300.8532	70
6293.7447	4	8128.911	20	9310.5833	8
6304.7893	2600	8136.4061	250	9313.9731	25
6313.6855	6	8248.6826	5	9326.5072	55
6332.766	9600	8259.3795	45	9373.3079	15
6382.9914	11500	8266.0769	97	9425.3797	40
6402.248	21000	8300.3248	620	9459.211	18
6421.7044	2	8365.7464	85	9486.6825	18
6444.7118	7	8377.507	2900	9534.164	45
6506.5277	12000	8418.4265	470	9547.4052	20
6532.8824	5500	8463.3569	52	9665.42	45
6598.9528	7100	8484.4424	22		
6652.0925	48	8495.3591	1650		
6678.2766	12000	8544.6952	30		

8.3 Description of the WFM_SMP mask

The geometrical calibration is performed by translating a multipinhole mask covering most of the WFM FOV of the instrument (Figure 17). It is composed of 12 vertical lines of 57 pinholes covering a rectangular region of 55.6 x 58.5 arcsecs on each side with a regular grid. By translating the mask vertically we are able to have pinholes entering and exiting each slice of the instrument during the geometrical calibration.
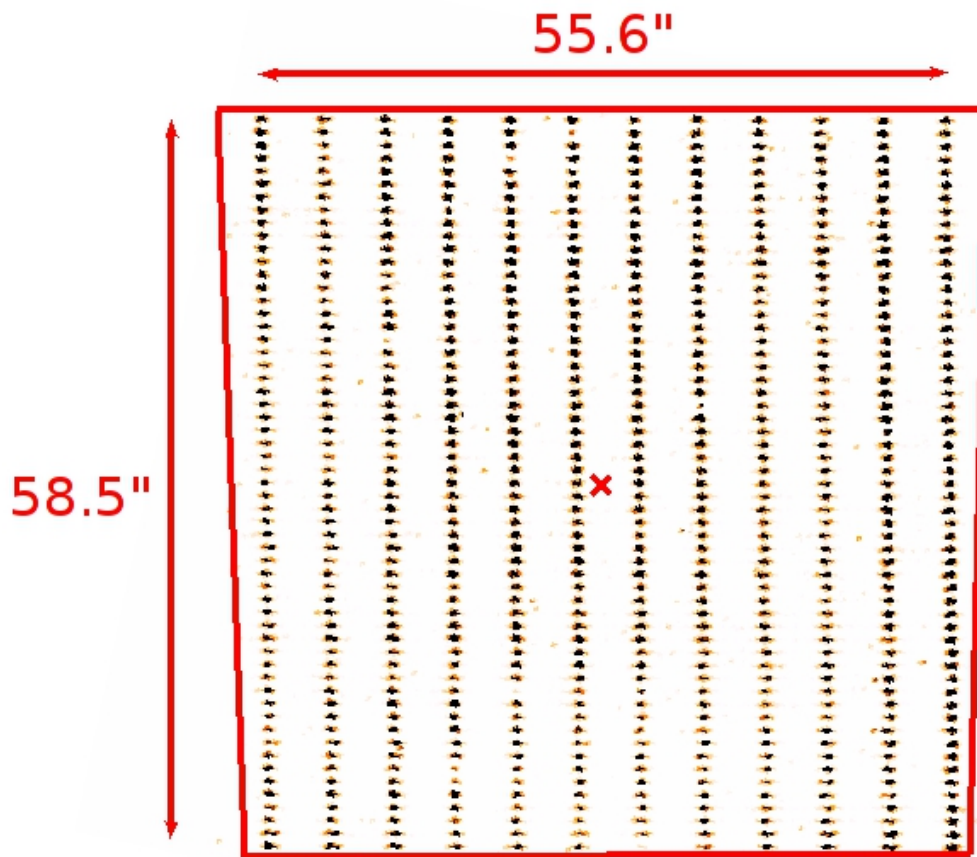

Figure 17: arrangement of the WFM_SMP mask used for geometrical calibration, as viewed on a reconstructed image when illuminated with internal lamps. We overlay the trapezoidal shape of the FOV in red.

8.4 ds9 template

We provide below the code used to create a ds9 template showing the trapezoidal FOV of MUSE in WFM mode, together with the SGS metrology field regions surrounding it.

One can simply copy/paste the code below in a MUSE.tpl file and use it as a ds9 region template.

```
global color=green dashlist=8 3 width=1 font="helvetica 10 normal roman" select=1 highlite=1 dash=0
fixed=0 edit=1 move=1 delete=1 include=1 source=1
wcs0;fk5
# composite(0,0,359.99998) || composite=1 color=red
point(0,0) || # point=x
polygon(0.0086683878,0.0084439565,359.99128,0.008499508,359.99172,-0.0082782215,0.0080579666,-
0.0083893106) ||
polygon(0.012835385,0.0085544861,0.0085551081,0.012277302,0.00027758977,0.012,359.99189,0.012277352,3
59.98778,0.0091101444,359.98739,-0.0091121412,359.98955,-0.010111818,359.99417,-
0.01050022,359.99422,-0.011722438,359.99611,-0.01172232,359.99622,-0.012166759,0.004002035,-
0.012222326,0.0040555527,-0.011777885,0.0060549064,-0.011833571,0.0060015071,-
0.010611345,0.0090006082,-0.010444971,0.012444522,-0.0095565611)
```