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Numerical Simulation of the VLT/MUSE Instrument

A. Jarno, R. Bacon, P. Ferruit, A. Pécontal-Rousset

Centre de Recherche Astrophysique de Lyon (CRAL), 69561
Saint-Genis-Laval Cedex, France

Abstract. The MUSE (Multi Unit Spectroscopic Explorer) instrument is a second-generation integral-field spectrograph in development for the VLT, operating in the visible and near IR wavelength range (465–930 nm). It is combining a large 1'×1' field of view with a spectral resolution of 3000 and a spatial resolution of 0.2"×0.2" coupled to a sophisticated ground-layer Adaptive Optics (AO) system. Given the complexity of the MUSE instrument we are developing a numerical model of the instrument based on Fourier optics formalism, taking into account both optical aberrations and diffraction effects. It will serve as a basis for early performance verification purposes, provide inputs and support for the testing phases, as well as for the development of the instrument calibration and data reduction procedures. In this paper we present the end-to-end simulator software that has been written to accurately model this complex instrument in all its modes and up to the detector readouts.

1. Introduction

The Multi-Unit Spectrograph Explorer[1] (MUSE) is a panoramic Integral Field Spectrograph (IFS) in development for ESO's second-generation VLT instrumentation and that will be coupled with a new adaptive optic system of the VLT (Bacon et al. 2006). This spectrograph, built by a consortium led by CRAL of six major European institutes and the Optical Detector team of the ESO instrument division, is designed for deep spectrographic exposures and will be uniquely suited for the study of the formation and evolution of galaxies.

In its usual operating mode, MUSE will, in a single observation, produce a 3-dimensional data cube consisting of 90,000 R≃3000 spectra, each covering a full spectral octave (465–930 nm), and fully sampling a contiguous 1'×1' field of view with 0.2"×0.2" apertures. A high spatial resolution mode with a 7.5"×7.5" field of view will allow refining the spatial sampling down to 0.025"×0.025" per spaxel. MUSE is built around an arrangement of 24 identical spectrographs, which are fed by a set of 24 advanced image slicers.

2. The Need of an End to End Instrument Simulator

Given the complexity of the MUSE instrument (24 IFS, adaptive optics, high volume of data, etc.), it was found necessary to develop an instrument numerical model. This simulator will, serve as a basis for early performance verification

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[1] http://muse.univ-lyon1.fr/

purposes, generate synthetic detector readouts for the development of the data reduction software, provide inputs for the test campaign and for the calibration procedures.

Although some specific commercial software (mainly the ZEMAX and ASAP softwares) are now able to simulate complex instruments taking into account both optical aberrations and diffraction effects, they are mainly lacking the flexibility we need for these simulations and quite often do not provide the level of control on the computations that we need. Moreover they are difficult to integrate in an overall simulation software that will be used by a wide range of different users involved in the MUSE consortium (from engineers to astronomers).

This has led us to decide to develop our own software (although we still use some of the ZEMAX capabilities at one stage in our modeling).

3. Main Capabilities

In order to fullfill these needs, the MUSE instrument simulator must have the following capabilities (we only list the main ones):

- take into account both optical aberrations and diffraction effects;
- take into account the effects of the atmosphere and of the adaptive optics;
- include a simulation of the complete optical train for all the modes of the instrument (both science and calibration related);
- include a simulation of the CCD properties and of the impact of cosmic rays.

In turn, these capabilities can be translated in software functionalities and modules:

- model the instrument optical performances using the Fourier optics formalism combined to phase masks for the optical aberrations: synthetic PSF computations between key image planes;
- model the distortion: maps between various stages of the instrument;
- model the radiometric response of the instrument: throughput of the optical elements, the amount of light lost at aperture level and in pupil planes;
- simulate calibration, scientific and tests exposures: detector outputs.

4. How does it work?

4.1. Zemax macros

The main input of the simulator is the optical design of the instrument, given as a Zemax file. We use the Zemax software to get all the data we need, that is coordinate transform maps between key optical planes, wavefront error maps and focal lengths. All those data are extracted using Zemax macros.

4.2. Coordinate Transforms Parametrization

One of the Zemax macros scans the field of view and the range of the MUSE wavelenghts (the instrument is chromatic due to the use of lenses) and use raytracing to create coordinate transform maps between key optical planes. Coordinate transforms at a given wavelength is then parametrized using a tenth degree 2D polynomial. The coefficients of this 2D polynomial are then linearly fitted as a function of the wavelength.

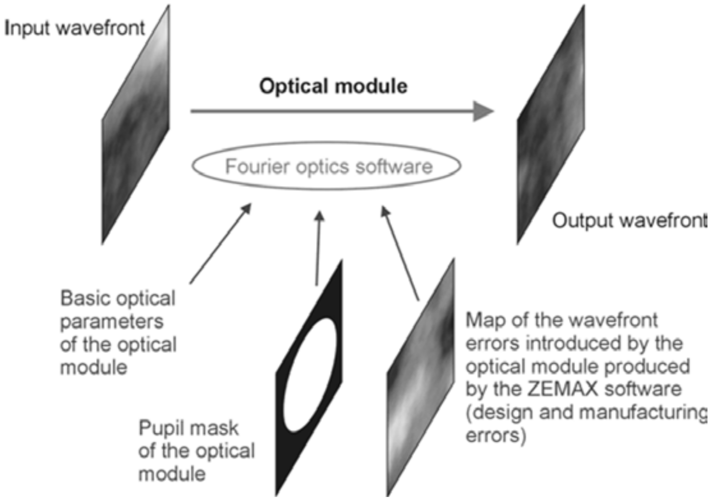

Figure 1. Concept of the Fourier optics computation of the output wavefront of an optical module.

The parametrization of the coordinate transforms allow us to compute very quickly (i.e. using a few multiplications and additions) the chief ray through the whole instrument for a given input point in the field of view.

4.3. Fourier optics module

The wavefront error maps and the focal lengths are used by the Fourier optics software component (Goodman 1996; Gnata et al. 2004). We assume that we are in a far-field Fraunhofer diffraction regime and we use the Fourier transform approach to compute the transformation of the complex amplitude between the conjugate planes of a given optical module (e.g. between the exit pupil plane and the exit image plane of an optical sub-system, see Figure 1). Alternatively we use Fresnel propagation when a plane is not a pupil or an image plane (e.g. spectrograph slit plane). To obtain good sampling of both the pupils and PSF we use zero padding which involves performing FFT on a quite large matrix (above 6000×6000). We use the FFTW library to compute Fourier transforms.

The Fourier optics software component is used to compute standalone PSF (see Figure 2), and to compute a library of PSF. PSF are function both of wavelength and position within the field of view.

4.4. Exposure simulator

The exposure simulator uses the coordinate transform parametrization and the PSF library to compute the image in the plane of the CCD for a given input, by convolving the PSF with the input points.

Unfortunately using brute force, that is to say propagating each of the input points with spatial and spectral oversampling, is not possible as it would take too much time (weeks or months). This has lead us to find an alternative strategy. The input objects are separated in three different spectral types: point sources, extended sources, and diffuse sources with little spatial structure. The

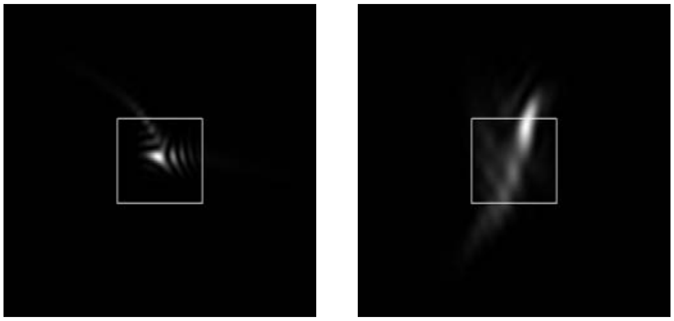

Figure 2. PSF of the instrument on the CCD in WFM mode for slice n°12 at 465 nm (left) and 930 nm (right). The white square represents the size of a CCD pixel (15μm).

same way they are separated in three different spatial types: spectrally unresolved absorption and emission-line features, spectrally resolved features, and continuum features with little spectral structure. That is in total nine different types of objects.

With this approach, we take into account the type of object when computing an image. For instance a diffuse source with little spatial structure does not need to be convolved with the PSF of the instrument, as the PSF is small enough compared to the structure in the source.

Finally, the CCD simulator adds the effects of the detector: noises, non-linearity, charge diffusion, hot and dark, hot and dark columns, cosmic rays.

4.5. Conclusion and Future Work

This simulator is now able to simulate the MUSE instrument including the effects of diffraction and optical aberrations, and its outputs will be used to develop the data reduction software. Future work includes the introduction of the effects of the atmosphere and adaptive optics in a correct way.

References

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