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End to End Simulation of the JWST/NIRSpec Instrument

X. Gnata, P. Ferruit, A. Pécontal-Rousset,

CRAL Observatoire de Lyon 9, avenue Charles André 69561 Saint-Genis-Laval cedex, Email: gnata@obs.univ-lyon1.fr

Abstract. The near-infrared multi-object spectrograph NIRSpec is one of the three science instruments onboard the future James Webb Space Telescope. NIRSpec will cover the 0.6 to 5.0 μm wavelength range and will be able to obtain simultaneous spectra of more than 100 objects in a 9 square arcminute field of view, thanks to an array of micro-shutters. It has been realized that accurate modelling of the instrument was needed: to obtain realistic estimates of its expected performance and to check that the science goals could be achieved; to define and validate the operation and calibration scenarios; and, on the long run, to develop and test the data reduction software. In this context and as part of the EADS NIRSpec study funded by ESA, we have developed an end-to-end Fourier-optics model of the instrument, which takes into account both geometrical aberrations and diffraction. In this paper, we will first describe the model, its objectives and its implementation. We will then show some results and how they are used to estimate the instrument performance. We will conclude by stressing that this kind of modelling is now becoming a standard task in the studies of some major astronomical instruments.

1. James Webb Space Telescope (JWST) and NIRSpec

The JWST is known as the successor of the Hubble Space Telescope. It is an infrared telescope operating from 0.6 to 28μm; diffraction limited at 2μm. JWST will be constructed using deployed structures since the maximum size of the rocket shrouds will not accommodate the full mirror or sunshade diameter. That is why the primary mirror is not a circular one but a 6.5m-segmented hexagonal mirror. JWST launch is planed for late 2011.

NIRSpec (Near Infrared Spectrograph) is one of the 3 instruments onboard JWST. This instrument will be the multi-object spectrograph of JWST and is under ESA responsibility. NIRSpec will be able to observe simultaneous spectra of more than 100 objects in a 9 square arcminute field of view in the 0.6 to 5μm band, thanks to an array of micro-shutters (MSA). Users will be able to select the objects of which they want to get spectra by closing or opening each micro-shutter.

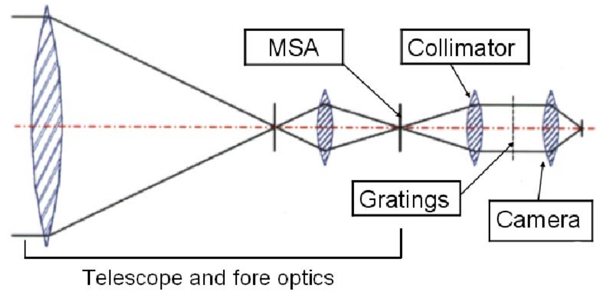

Figure 1. Simplified view of NIRSpec optical design.

2. Why do we need an End to End Simulation of NIRSpec?

We first need to assess the combined impact of diffraction and aberrations on the instrument performance. That is why we need to compute the PSFs (point spread functions) on the micro-shutters array and on the detector, and the image on the grating. In order to be able to use NIRSpec as a photometric instrument, we also have to assess the diffraction losses at the level of both the micro-shutters and the gratings. Simulated NIRSpec science and calibration exposures will also be very useful to validate calibration and operation procedures and to develop the data reduction software.

3. Modeling Input Parameters

Fourier optics and more especially Fresnel Approximation is used to model diffraction effects. Fast Fourier transformations (FFTs) are used to progress from the telescope pupil plane through the MSA plane, the gratings plane and the detector image plane (See Figure 1).

Apertures are simulated using binary matrices called intensity masks (1 when the point is in the aperture, 0 otherwise). In our model, we do not have to assume that we have perfect optics because we take geometrical aberrations effects into account by introducing phase masks before computing FFTs. These phase masks correspond to the wavefront errors produced by the real instrument. Low frequency wavefront errors due to optical aberrations are described using Zernike polynomials. Roughness of the optics introduces high frequency wavefront errors, which are described by a random phase mask (Born and Wolf 1989). To obtain good sampling of both the pupils and PSFs we use zero padding which involves performing FFTs on a quite large matrix (above 6000*6000).

4. Calculation Scheme and Implementation

We have used Zemax (a commercial program that can model and analyze optical systems) to extract all the optical parameters (e.g. focals, aperture or diameters) and Zernike coefficients needed to simulate NIRSpec. We have written some user-friendly macros in the Zemax Programming Language in order to put all

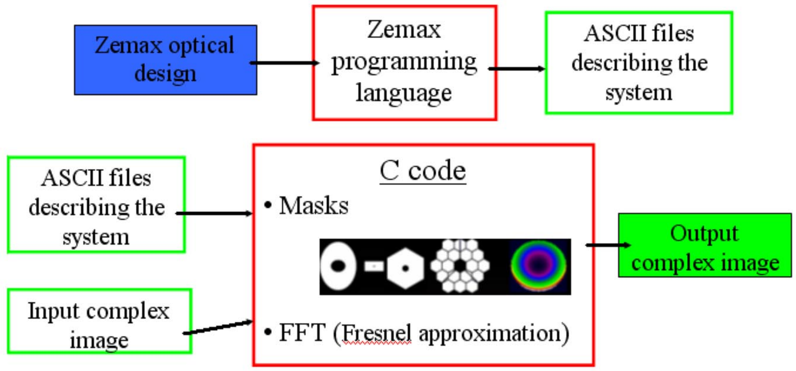

Figure 2. Calculation scheme.

these parameters into a formatted ASCII file in a very simple way. By running these macros, one gets an ASCII file describing the system per wavelength and per point in the field. Only the format of these files really matters and they could have been obtained another way.

Zemax only supports some diffraction calculations and is not usable alone to assess the impact of diffraction in NIRSpec. To simulate propagation from pupil to image plane our code running under GNU/Linux takes ASCII files computed by Zemax as input and performs masks and FFT calculations (see figure 2). This code has been designed with a modular approach: It is a Fourier Optics library easy to reuse as a black box in other simulation software because there no hardcoded parameters describing the optical system and because one can simulate all of the most common shapes of optical apertures. Complex FITS images store the amplitude and phase repartition. Our simulation code is written in C and makes use of the Euro3D development environment and I/O libraries developed by Arlette Pécontal-Rousset (Pécontal-Rousset 2004). To compile and use it you only need the standard GNU tools and two libraries. The first one is called GSL (GNU Scientific Library) which is a numerical library written in ANSI C. The other one is FFTW which is a very efficient C library for computing the Discrete Fourier Transform (DFT) in one or more dimensions (and more especially in two dimensions in our simulation code), of arbitrary input size, and of both real and complex data.

5. From Raw Results to Instrument Performance

Using this simulation C code, we have computed PSFs on the MSA, images on the gratings plane and PSFs at the detector level. PSFs are, however, only raw results and that is why we have developed tools to assess the instrument optical performances. These “slit tools” are written in C. Given an output FITS image computed by the simulator, it is for example straightforward to plot the encircled (or ensquared) energy using slit tools. If we assume we have a random distribution of point sources whose PSFs centers are in a given rectangular area inside an open micro-shutter (180μm in spatial direction times 80μm in spectral

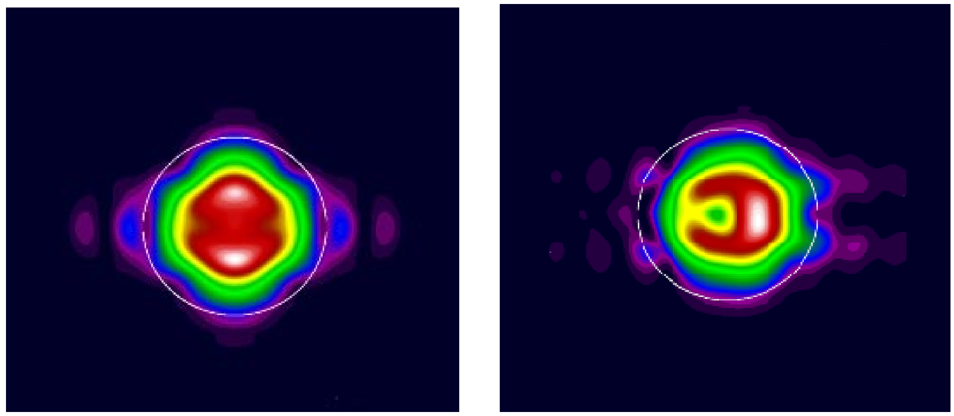

Figure 3. Effect of a 20μm decenter of the PSF at the level of the MSA on the image at the level of the gratings. The white circle represents the gratings aperture. (Log scaled image)

one), the slits tools are able compute the average slit losses at this level. This study led us to define an available micro-shutter area inside which the losses are not too great. This area will play a leading role in defining the operation scenarios.

We have also proven that the diffraction losses at the plane of the gratings slightly depend on the way the PSFs are centered in the open micro-shutter (See Figure 3). This fact proves that we do need an accurate model of NIRSpec to be able to extract photometric well calibrated data from the exposures.

Simulated PSFs at the detector level have enabled us to compute the spectral and spatial resolution of NIRSpec assuming for now that the detector is perfect.

6. Conclusion and Future Work

Using this model we have assessed the effect of diffraction and optical aberrations on NIRSpec's optical performance. We now have to use more detailed wavefront errors maps and to model real detector effects. Thanks to the modular approach we have taken, this code is going to be reused in other projects.

References

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