TECHNICAL REPORT

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Title: NIRISS AMI target scene simulations	Doc #: JWST-STScI-004484, SM-12 Date: 30 June 2015 Rev: -
Authors: D. Thatte, A. Sivaramakrishnan — Phone: 410 – 338 - 4462	Release Date: 28 April 2016

1 Abstract

We describe a simulation framework that takes two-dimensional (polychromatic in a filter bandpass) or three dimensional (hyperspectral or multiple wavelength cube) input sky scenes from the user and generates simulated observations with the non-redundant mask (NRM) on JWST's NIRISS (Near-InfraRed Imager and Slitless Spectrograph). Starting from our Python simulation of binary point source data (Thatte D., Sivaramakrishnan A. and Lafrenière, D., JWST-STScI-004255, 2015, and the ami_sim package on GitHub at https://github.com/agreenbaum/ami_sim, which also includes 2D target scene simulator based on the code discussed here) we generalized the code to accept input arbitrary count rate images.

2 Introduction

The Aperture Masking Interferometry (AMI) mode of JWST's NIRISS instrument uses a non-redundant aperture mask (NRM) in the pupil wheel with one of three medium-band filters (F380M, F430M, and F480M) or a wide-band filter (F277W) in the filter wheel. In effect, the 7-hole mask turns the full aperture of the telescope into an interferometric array, that generates an interferogram in the image plane. This mode is capable of detecting planets that are very close (70-500 mas[1]) to their parent star. It enables high resolution imaging of extended sources (e.g. AGNs, QSOs, solar system satellites), and is also targeted at exoplanet characterization.

Our Python code generates simulated data for this mode at four pre-defined dither positions on an 80×80 pixel subarray using an input target scene provided by a user. The dithers are separated by a 40 detector pixel step —about 2.6" with a pixel scale of 0.065"—with the exception of the last dither step, which is 36 pixels. The dithering mitigates against persistence and reduces the effect of flat field errors (which we simulate with uncorrelated 0.1% standard deviation pixel-to-pixel flat field error). Each dither step is modeled with a 15 mas (rms[2], single-axis) Gaussian-distributed error. We do not model

[1] milliarcsecond
[2] root mean square

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the pixel response function that is described by Hardy et al., 2014, or inter-pixel capacitance (IPC) effects. We may implement IPC in a future release.

Before discussing the observations in detail we review common terminologies that are applied to JWST observations (JWST MOCD, 2014, JWST-STScI-002018).

READ:	To clock and digitize pixels in an SCA. Note that 'READ' is a verb but has been used interchangeably with FRAME.
FRAME:	The result of sequentially clocking and digitizing all pixels in a rectangular area or subarray of an SCA
TFRAME:	The time to sample a frame
GROUP:	One or more consecutively read frames. There are no intervening resets. Frames are averaged to form a group in case where multiple frames are used.
NFRAMES:	The number of frames per GROUP.
GROUP_GAP:	The number of frames that are not averaged between successive GROUPS.
INTEGRATION:	The end result of resetting the detector and then non-destructively sampling it one or more times (consisting of one or more GROUPS) over a finite period of time before resetting the detector again.
NGROUPS:	The number of GROUPS in an INTEGRATION.
GROUP_GAP:	The number for FRAMES between GROUPS that aren't
EXPOSURE:	The end result of one or more INTEGRATIONS over a finite period of time. EXPOSURE defines the contents of a single FITS file produced by the data handling system.
NINT:	The number of INTEGRATIONS in an EXPOSURE.

NIRISS observations with the NRM typically use the NISRAPID readout pattern, which is characterized by one frame per group (NFRAME=1) and no gaps between groups (GROUP_GAP=0).

An ***exposure*** at each dither position consists of NINT integrations that are placed in a FITS data cube with dimensions FOV × FOV × NINT, where FOV is the size of the input target scene from the user, in detector pixels. Each ***integration*** is made up NGROUPS up-the-ramp frames, each of TFRAME=0.0745 seconds duration that is the frame read time for SUB80 array. A pointing jitter of 7 mas rms (one-axis) is introduced between each integration.

We start with a noiseless count rate image provided by the user and convolve it with the appropriate NRM PSF. We create an 11 times oversampled two dimensional array filled with ones. This is used to create NINT sections depending upon the total positional error due to the combination of dither and jitter. These sections are multiplied by the input image to create NINT realizations of the input sky scene. We expect an 11 times oversampled input image from the user or treat the image from the user as an oversampled image and adjust the simulation parameters accordingly. The size of the oversampled images is (FOV × 11) × (FOV × 11) pixels. Thus we can center our images at 121 different locations (1 pixel/(11×11)) within a detector pixel. For each of these NINT realizations we create a simulated ramp with non-destructively read frames, and add cumulative Poisson noise, read noise, dark current, and background. We then fit a slope to the simulated ramp for each individual pixel using a linear least-squares regression and create a ***slope image***. This slope image is divided by a flat field error array to introduce a 0.1% flat field error, and then divided by TFRAME to convert the slope image from counts per frame to counts per second.

3 Details of the simulation steps.

1. Read the image or stack of images provided by the user. Our requirements for the input image are as follows: -
    a. Field of view (FOV): The user can provide an 11 times oversampled image that has FOV ≤ 80 detector pixels. Alternatively we can treat the image from the user as an oversampled image that we will bin by a factor of 11.
    b. Units: photoelectrons/sec when observed with one of F277W, F380M, F430M or F480M, (without the NRM).
    NIRISS throughput values are in the filter files in the WebbPSF's supporting data at https://pythonhosted.org/webbpsf/installation.html#data-install and can be used to create the count rate images that are required as input. Please note that at the time of writing this document the throughput values have been superseded and they will be updated by STScI in near future.
    c. If a stack of monochromatic images is provided, the wavelength of each slice must be specified in meters with primary header keywords WAVEnn (e.g. WAVE0, WAVE1, …WAVe10, in the somewhat extreme case of 11 wavelengths across the bandpass). The range of monochromatic wavelengths in the stack should be within the passbands of the above-mentioned filters used by the AMI mode. We remove hyperspectral cube slices outside the filter's passband.
    A sky brightness image stack as a function of wavelength can be converted to counts/second/micron/pixel at each wavelength by (1) multiplying by the NIRISS pixel size, and (2) multiplying by the system throughput at the corresponding wavelength, (3) converting the sky brightness units to W/m^2/micron/steradian if required, (4) multiplying by the JWST primary mirror area, and (5) dividing by the photon energy. This gives values in units of photon/s/pixel/micron at the detector. Total count rate per NIRISS pixel in electrons/second can be obtained by integrating over the wavelength interval for a slice in the 3D stack.
    Similar method can be used for a 2D input scene by integrating over the wavelength interval for the entire bandpass.

2. Create the noiseless oversampled ***base NRM PSF*** of a single star using WebbPSF[3]. The PSF is normalized to represent a 2-dimensional probability distribution of a photon entering JWST. For most applications it is normalized to sum to unity. For the NIRISS AMI mode it sums to the relative throughput of the NRM as compared with the full JWST pupil (about 15%, or 0.15). We expect count rate image in full aperture and the filter selected by the user since we account for the NRM throughput. If the input scene is a hypercube (i.e. stack of monochromatic images at specified wavelengths), we create a stack of base PSFs at the corresponding wavelengths.
3. Convolve the input target scene with the base PSF (for each slice if we are processing a hypercube). For three-dimensional input scene we co-add the slices together after the convolution.
4. Create an oversized, 11-fold oversampled array filled with ones.

   The 4 dithers, each contained in 80×80 subarrays, are located in this array. The size of the array—256x256—is chosen to accommodate all 4 dithers and also to make sure that the exposures remain inside the detector boundary after introducing dither positional error and jitter.
5. Calculate the exposure parameters NGROUPS, NINT. The user can provide an initial estimate of exposure time, but this might need to be refined to accommodate the count rate in the brightest pixel after convolution by the NRM PSF (see example of simulation of Io in section 4).
6. Apply dither and jitter to integrations.

   Each integration is shifted from the ideal dither location by a positional error that is the sum of independent dither positional error and jitter. The dither positional error gets accumulated when going from one dither position to the next. The dither and jitter errors give unique (x, y) coordinates of the center of the array for each integration. For each dither, create NINT sections of the array created in step 4 , centered at these (x, y) locations, and multiply the convolved image created in step 3 by the corresponding section. At this point we have NINT realizations of the input target scene that take into account the dither and jitter. Align these realizations about the actual dither location and rebin each section to FOV × FOV detector pixels.
7. For each reliazation first create a noiseless ramp with NGROUPS non-destructive frames (in NISRAPID mode each group has one frame). Add Poisson noise by first creating independent realizations of signal plus Poisson noise and then accumulating those realizations up-the-ramp. Then add read noise, dark current and background to each frame of the ramp. The read noise for correlated double

[3] A JWST PSF simulator that uses Optical Telescope Element (OTE) wavefront error models, instrument properties such as detector pixel scales, rotations, filter profiles, and input point source spectra). It transforms optical path difference (OPD) maps and input pupil geometries into simulated PSFs

sampling (CDS) is assumed to be 21 electrons, so we used $21/\sqrt{2}$ as an approximation to the read noise per frame. We used a dark current of 0.04 electrons/sec and a background of 0.121 electrons/seconds (provided by Kevin Volk) respectively. Fit a slope to the ramp using linear regression and create a *slope image*. Multiply the slope image by a pixel-to-pixel flat field error array to introduce a 0.1% flat field error.

8. Put the integrations at each dither location in a FOV × FOV × NINT FITS data cube, and repeat steps 1 through 7 for each dither position. Update the headers of the FITS files with information about the as-designed geometry of the mask (Sivaramakrishnan, A. and Beaulieu, M. JWST-STScI-002326, 2011).

4 Example 1: simulating NIRISS observations of volcanoes on Io.

We used a count rate image of Jupiter's innermost Gallilean satellite Io, along with Loki (Io's largest volcanic depression) as a two-dimensional input target scene. We estimated the count rate of the disk of Io observed with filter F430M to be 25000 photons/sec per detector pixel through NIRISS' NRM. We calculated the count rate of Loki and placed all its flux in one sub-pixel of the 11 times oversampled image. Loki's net count rate is 5.4×10^5 photons/second in this instrument mode. Figure 1 shows the input target scene (Panel (a)), NRM PSF for F430M (Panel (b)), convolution of input target scene with NRM PSF (Panel (c)), and one integration of the simulated data (Panel (d)).

The uniform brightness Io disc yields a spatially varying count rate when it is convolved with the NRM PSF. The expected count rate from the disc of Io in one 0.0745 second frame is 25000 photons/second/detector pixel × 0.0745 second, or 1862 counts/pixel. However we get a count rate of about 800 counts/pixel in the central region of binned convolved image. This is because the diameter of Io disc is 15 detector pixels, which is somewhat smaller than the "size" of the NRM PSF that has significant amount of signal. If Io's disc was much larger than the extent of the NRM PSF then in the interior of Io's detector image the count rate would match the "predicted" count rate, since the convolution with the NRM PSF would only dilute flux at the edge of Io's image.

The dilution introduced by convolving a sky scene with the NRM PSF influences the value of NGROUPS, since it changes how many non-destructive frames can occur before the brightest pixel reaches our pre-defined saturation limit of 35000 electrons. We treat Loki as a point source. The expected count rate in the peak pixel of a Loki image in a single read's frame time (TFRAME) of 0.0745 seconds is obtained by multiplying Loki's count rate, the central pixel fraction of the NRM PSF (~0.02) (fraction of signal contained in the peak pixel of the NRM PSF as compared to the signal in the entire PSF) and TFRAME. This gives 800 counts per frame in the peak pixel of Loki, assuming Loki is centered on a detector pixel. Adding these to the ~800 counts per frame from the disc of Io we expect about 1600 counts per frame in the peak pixel. NIRISS' detector saturates at 35000 electrons (in order to stay below potentially troublesome non-linear detector response). Therefore Loki would saturate in 35000/1600 ~ 22 frames. We therefore choose NGROUPS=22. At each of the four dither positions we simulated an exposure with NGROUPS=22 and NINT=18 giving a total exposure time of 22 × 18 × 0.0745 sec × 4 = 118 seconds. The simulated image is shown in panel (d) of Figure 1.

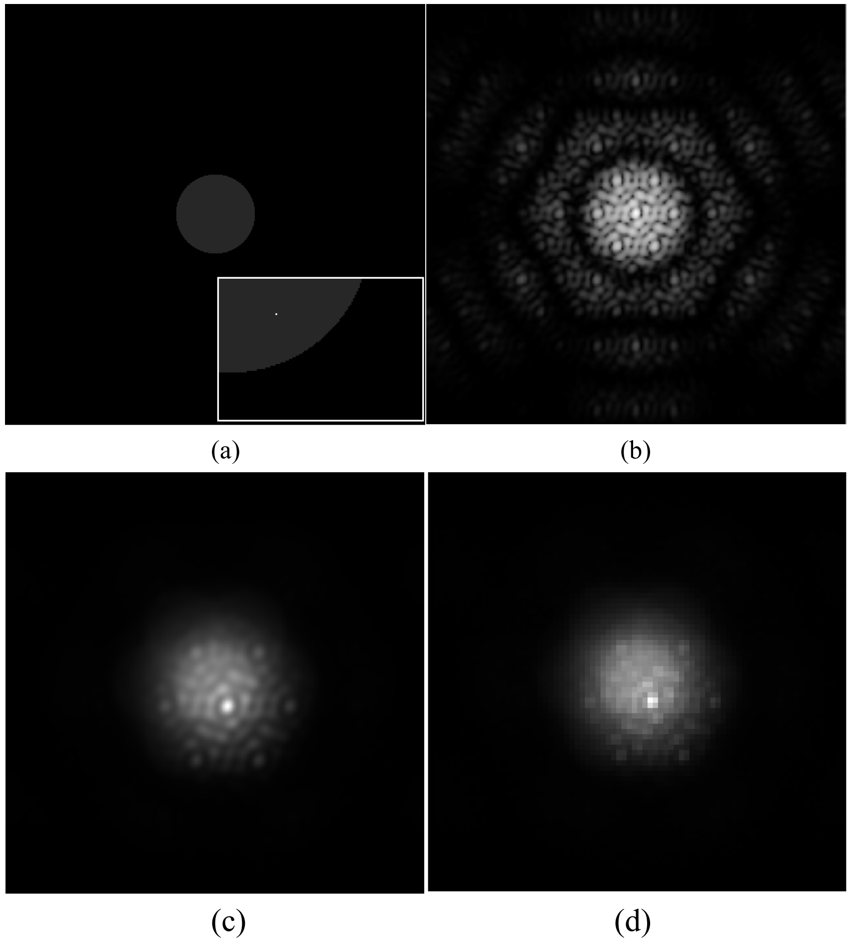

Figure 1. Panel (a) shows count rate image of Io with Loki that is used as an input target scene with the insert showing zoomed up region around Loki panel (b) is the PSF of NRM created using WebbPSF for F430M filter. Panel (c) shows the convolution of input target image with NRM PSF and panel (d) is the simulated data (one integration). The dimensions of panels (a), (b) and (c) are in oversampled pixel units (880 × 880) while panel (d) is binned to the 80 × 80 detector subarray. A linear stretch greyscale is used to display these images.

Example 2: Comparison of observations of equal and unequal binaries with NRM and FULL aperture.

We used our binary point source simulation code that is very similar to the target scene simulation code to demonstrate the unique high resolution imaging ability of the aperture masking interferometry mode. Comparison of panels (a) and (e), (b) and (f), (c) and (g) shows that the sources are well resolved when observed with NRM.

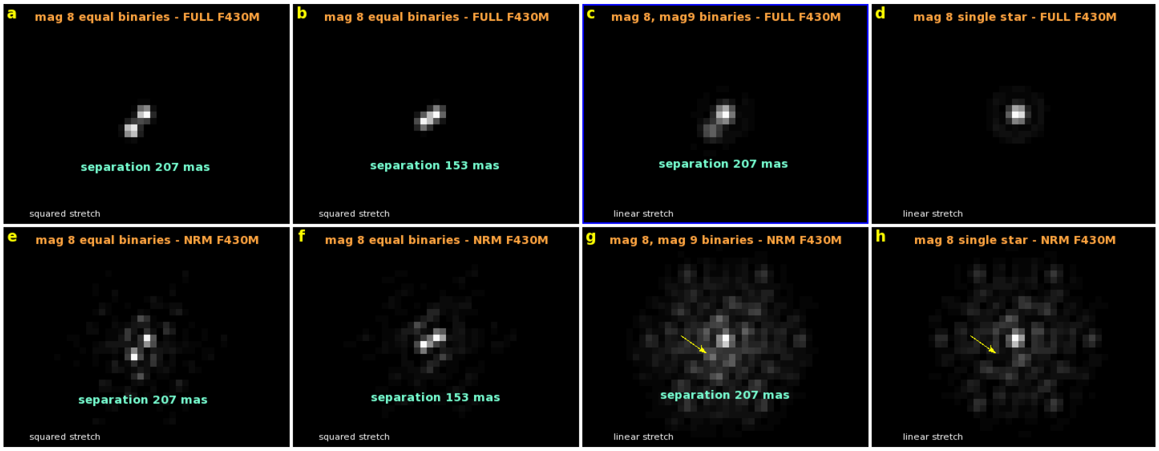

Figure 2. Panels (a) and (b) show simulated observations of equal magnitude binaries observed with full aperture and F430M at two different separations. Panels (e) and (f) show observations with NRM and F430M at the same separations. Observations of unequal binaries are shown in panels (c) (full aperture and F430M) and (g) (NRM and F430M). Panels (d) and (h) show single star observations that can be used to easily locate the fainter companion.

5 Acknowledgements

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6 References

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