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pyNRC: A NIRCam ETC and Simulation Toolset

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ABSTRACT

With the approaching launch of the James Webb Space Telescope (JWST), the astronomical community requires easily accessible software tools to assist in the development of observing proposals. Each science instrument aboard JWST offers a variety of observing modes with a range of flexibility and complexity often confusing to an uninitiated user. As the observatory's primary near-IR imager, NIRCam is no exception, offering simultaneous wide-field imaging of two wavelength channels, coronagraphic imaging over small fields of view, wide-field slitless spectroscopy at two perpendicular orientations, and time-series observations in both imaging and spectroscopic modes. We present the open-source Python package `pyNRC`, a NIRCam-specific exposure time calculator (ETC) and simulator to help choose optimal instrument settings for specific science cases. At its core, `pyNRC` uses point-spread-function (PSF) information generated by WebbPSF to create two-dimensional signal and noise images. The package incorporates realistic filter bandpasses, detector effects, and MULTI-ACCUM ramp sampling schemes with results verified and validated by the NIRCam science instrument team. Building off of this framework, `pyNRC` also provides capabilities to generate realistic simulations of complex astronomical scenes, enabling end-to-end testing of the JWST data management system, reduction pipelines, and analysis techniques.

Keywords: Coronagraphy, Detectors, JWST, NIRCam, Python Simulations

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1. INTRODUCTION

NIRCam acts as the primary near-infrared (NIR) camera for the James Webb Space Telescope (JWST). With wavelength coverage from $\lambda = 0.6$ to $5.0\ \mu$m, NIRCam offers multiple observing modes such as wide-field imaging, coronagraphic imaging ($20'' \times 20''$), and slitless spectroscopy spanning $\lambda = 2.4$ to $5.0\ \mu$m (Beichman et al. 2012; Krist et al. 2007; Rieke et al. 2005; Greene et al. 2007, 2017). In addition, future proposal cycles may expand the allowed science modes, presenting users the opportunity to observe with NIRCam's dispersed Hartmann sensors (DHSs), which provides spectral coverage at $\lambda = 1$ to $2\ \mu$m with $R \equiv \lambda/\delta\lambda \simeq 300$ (Schlawin et al. 2017).

As the main instrument responsible for wavefront sensing and primary segment phasing, NIRCam was constructed with multiple redundant systems to minimize risk of critical failures. Specifically, the instrument consists of two identical modules (A and B), each with an independent $2\rlap{.}'2 \times 2\rlap{.}'2$ field of view (FOV) adjacently aligned. Each module further houses two wavelength channels separated by a dichroic beam-splitter and occupying the same FOV. The short-wavelength (SW) channel images $\lambda < 2.4\ \mu$m light onto a grid of four HAWAII-2RG (H2RG; Beletic et al. 2008) detectors (32 mas/pixel), whereas the long-wavelength (LW) channel utilizes a single H2RG with approximately twice the pixel scale (65 mas/pixel). This allows simultaneous observations with the SW and LW channels of the same NIRCam field in each module.

While a boon for observers, the expanded instrument modes and built-in flexibility also burdens users with added complexity and potential confusion. For instance, it may not be obvious which observational mode and detector readout setting will optimize the scientific return, especially when taking into account instrument and observatory overheads and efficiency. Initially devised as a guide for Guaranteed Time Observations (GTO) science program, the NIRCam instrument team developed an exposure time calculator (ETC) to better understand the relative instrument performance and trade-off between different operating modes. This software evolved into `pyNRC`, a Python-based toolset that includes a simple ETC for quick calculations, a rudimentary slope image generator, and a full-featured simulator to produce realistic raw data for testing data reduction pipelines and analysis software. Simulation components, such as instrument throughputs and detector characteristics, are based on as-built performance tests wherever possible and observatory design parameters otherwise. All PSFs are generated via WebbPSF[1] (Perrin et al. 2012, 2014) to reproduce realistic NIRCam images and spectra.

2. PROGRAM STRUCTURE

3. EXPOSURE TIME CALCULATOR

[1] https://webbpsf.readthedocs.io

4. GENERATING REALISTIC PSFS

While `pyNRC` is meant as a multipurpose tool for the general astronomical community, we placed significant effort on development of coronagraphic imaging in order to better represent the instrument's contrast performance. This was driven in part during the planning stage of the NIRCam GTO exoplanet and disk programs to investigate trade-offs between different operational modes, such as direct imaging compared to the various coronagraphic occulters.

Detection of faint objects in high contrast observations is generally limited by our ability to optimally remove the PSF of the host star and minimize residual speckle noise within the subtracted stellar halo. A number of physical factors can affect the contrast performance of segmented, diffraction-limited telescopes (Perrin et al. 2018). For instance, in the regime of a static telescope (i.e., constant wavefront error), we must consider the impact on contrast of spectral type mismatches between science and reference observations, target acquisition uncertainties, field-dependent WFE differences, and fundamental noise limits (e.g., photon and detector read noise). Further dynamic, time-variable factors include pointing jitter, thermal distortions of the OTE, and fast pseudo-random oscillations of the OTE wavefront due to state changes in onboard electronics. Generating realistic simulations therefore requires high-fidelity PSFs that encode range of variations to the optical state of the instrument.

WebbPSF offers the capabilities to input arbitrary OPD maps where each mirror segment consists of a unique set of WFE Zernike coefficients. During ISIM CV3 at GSFC, prior to integration with the telescope OTE, we derived the NIRCam WFE for a number of positions across the instrument FoV. These low-order Zernike components of the measured field points match particularly well to the finalized optical model as represented in CODEV and Zemax. Because the wavefront retrieval optics our housed in the same wheel as the Lyot stops, we were measure the WFE maps for NIRCam's coronagraphic mode; WFE measurements from Zemax are used instead. The NIRCam optical model as implemented in `pyNRC` assumes the science instrument Zernike components for each field point stays constant while varying the overall telescope OPD map with time. A series of nominal OTE OPD maps have been built based on ground-based OTIS cryo testing at JSC, allowing segment-level manipulation of the anticipated OTE state over time.

Add references.

Major Zernike and WFE RMS differences between coronagraphy and imaging.

Add image of OTE OPD.

Rather than hosting a library of oversampled monochromatic PSFs that vary with time and field position, `pyNRC` takes a different tack of fitting and saving a set of polynomial coefficients to quickly generate an arbitrary number of monochromatic PSFs (limited by the host machine's memory).

High fidelity PSFs that take into account the as-built telescope OPD map and science instrument WFE figures, which vary over the field of view and can change over time due to differential thermal load.

We also wanted the process of generating, storing, and loading PSFs to be expedient and efficient.

5. EXAMPLE SIMULATIONS

5.1. *LMC Astrometric Field*

5.2. *HR8799 Coronagraphy*

5.3. *Debris Disk Coronagraphy*

6. SUMMARY

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