Astrometry and Photometry Extraction Tool for Directly Imaging Exoplanets using James Webb Space Telescope NIRCam

Trinity Chung

Pasadena City College

Astrophysics and Space Sciences, NASA Jet Propulsion Laboratory

Dr. Marie Ygouf

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Abstract

One of the capabilities of the newly launched James Webb Space Telescope (JWST) is to image exoplanets. In preparation to analyze the data JWST will send, this project aims to simulate coronagraphic data, develop a script for extracting astrometry (location) and photometry (brightness) of planets from the data, and analyze the accuracy of this tool. Simulated images were generated using software packages WebbPSF and PyNRC. The algorithm for extracting astrometry involves iteratively using the location of the maximum value of the image cross-correlated with a point spread function (PSF). Photometry is calculated using the sum of values in a circular area around the center of the planet in proportion to the expected amount of flux as determined by the normalized PSF at that location. Finally, the accuracy of the tool is calculated using a Monte-Carlo simulation.

Overview

Background

In the spirit of JPL's mission of "exploring where humans cannot reach" (JPL), this project is about discovering distant exoplanets using direct imaging techniques with the James Webb Space Telescope (JWST) (Green et al.). The technique is called high contrast imaging (HCI) because of the extreme difference in light between the star and the planets. The Near Infrared Camera (NIRCam) on JWST is equipped with a coronagraph (Fig. 1, 2), a specialized attachment which blocks light from the star making the area around the sun (the corona) and the objects around it (including planets, our objective) visible. Directly imaging planets is challenging because they are millions of times less bright than stars, but recent developments in technology for coronagraphs and image processing have resulted in more planets being discovered through imaging (Beichman et al., 2010). The image post-processing part includes methods to remove residual starlight and identify the faint planets. Then, additional analysis is required to estimate the astrometry (location) and photometry (brightness) of those planets.

Fig. 1. A test sample for the NIRCam coronagraphs (Krist et al., 2006).

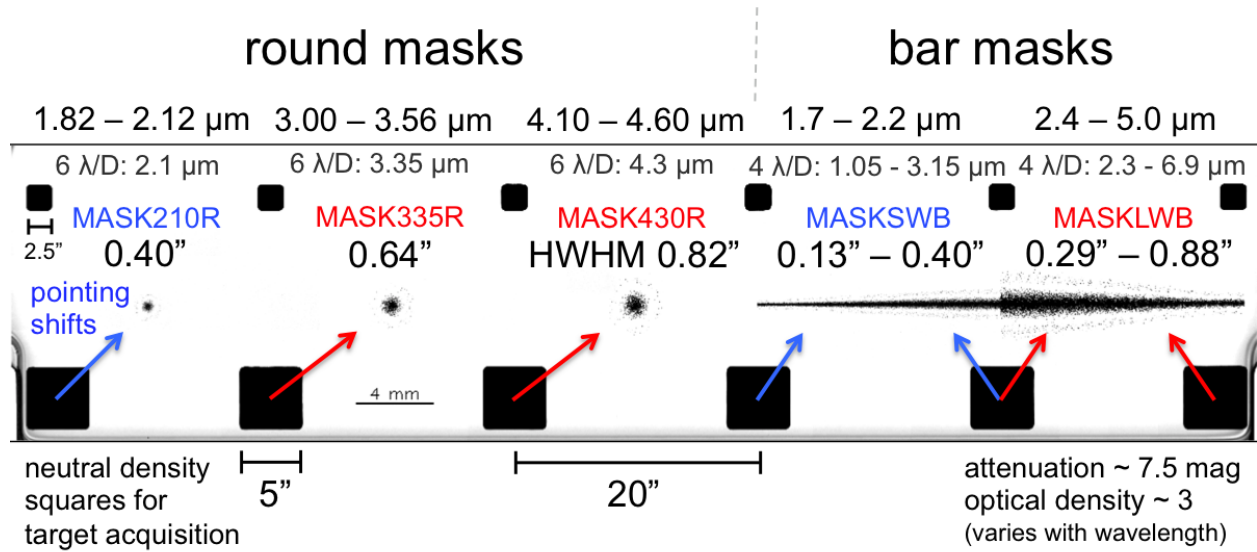*The black round/bar shapes are the 5 occulting masks .*

round masks   bar masks

1.82 – 2.12 µm   3.00 – 3.56 µm   4.10 – 4.60 µm   1.7 – 2.2 µm   2.4 – 5.0 µm

6 λ/D: 2.1 µm   6 λ/D: 3.35 µm   6 λ/D: 4.3 µm   4 λ/D: 1.05 - 3.15 µm   4 λ/D: 2.3 - 6.9 µm

MASK210R   MASK335R   MASK430R   MASKSWB   MASKLWB
2.5"   0.40"   0.64"   HWHM 0.82"   0.13" – 0.40"   0.29" – 0.88"

pointing shifts

neutral density squares for target acquisition

5"

20"

attenuation ~ 7.5 mag
optical density ~ 3
(varies with wavelength)

4 mm

Fig. 2. Detailed information about the NIRCam coronagraphs, including the names (beginning with MASK) and wavelengths. (Krist et al., 2010)

The planets and other objects like background stars appear as bright spots in the coronagraphic data with a hexagonal snowflake-like pattern caused by spreading of light in the telescope. This spreading of light is called diffraction and the pattern created by it is referred to as a point spread function (PSF). WebbPSF (Perrin et al., 2012) is a Python software package capable of generating detailed PSFs (Fig. 3) simulating different instruments on JWST. Using WebbPSF and other available software, this project aims to simulate basic coronagraphic data, develop a script for extracting astrometry and photometry of planets from the data, analyze the accuracy of this tool, and improve the accuracy of the tool as much as possible. My work would directly benefit the Guaranteed Time Observations (GTO) program led by Dr. Charles Beichman to detect and characterize exoplanets using high contrast imaging with NIRCam. Additionally, although this work will specifically focus on JWST NIRCam, the developed post-processing method could be applied to other instruments as well.
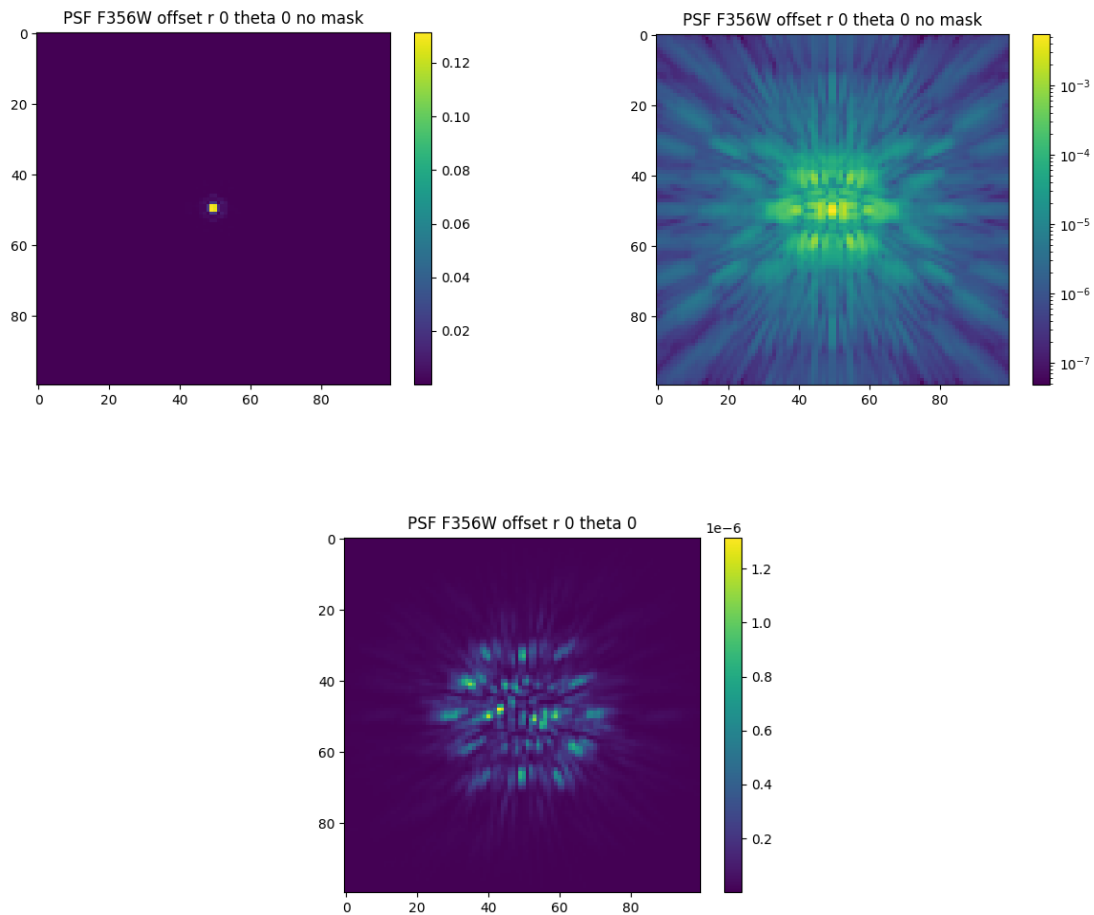
Fig. 3. Simulated NIRCam PSF generated by WebbPSF using the F356W filter.

Units are in normalized flux per pixel.

Top left: without mask. The point (at r=0, theta=0 which is the origin) is clearly visible.

Top right: without mask, logarithmic scale. With the log scale, the light diffraction pattern

becomes visible.

Bottom: using MASK430R. The bright point at the center is removed due to the mask, and we are

left with residual light in the form of these speckles. The scale is in 1e-6 which is significantly

less bright than the top right image with no mask.

Results

I built a script to extract astrometry and photometry from an image (see Methods section for the applied techniques), as well as an infrastructure to perform a Monte-Carlo simulation to test the accuracy of the algorithm. However, I was unable to determine the accuracy of the tool yet due to a gap in knowledge in converting the extracted output values to values comparable to the expected input values.
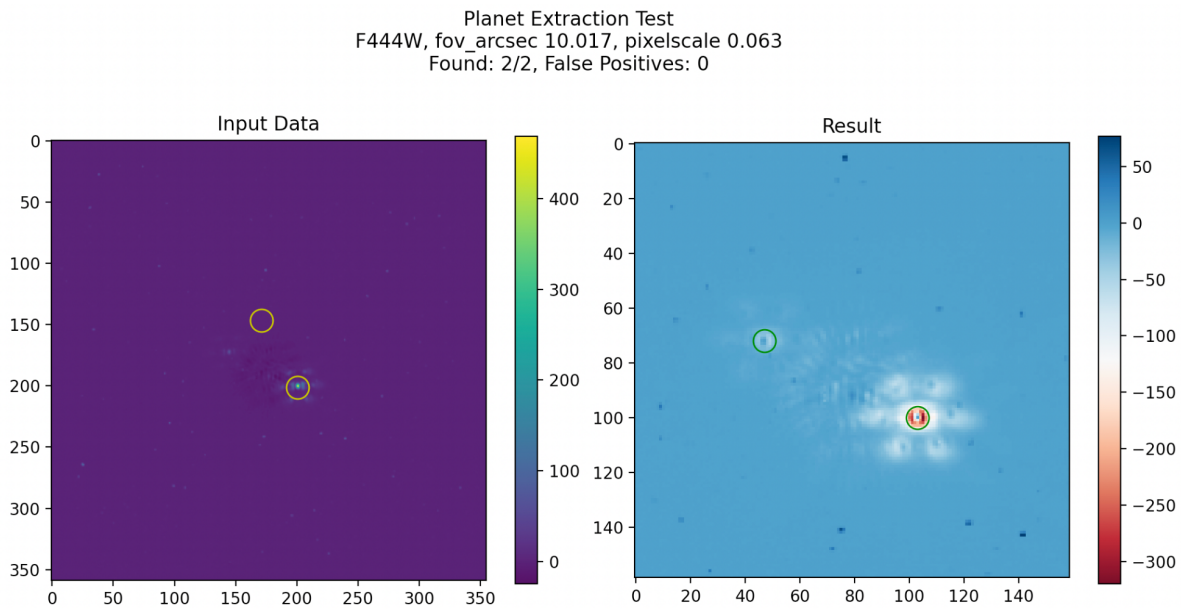
Fig. 4. Example output image file for testing planet extraction on one simulated image.

Left (Input Data): The PSF of two planets were generated using WebbPSF and pyNRC by Dr. Geoffrey Bryden based on NIRCam with a F444W filter and field of view of 10.017 arcsec, corresponding to 0.063 arcsec per pixel.

Right (Result): The two planets were identified.

*The other speckles in the image are background stars.*

Conclusions

Although the work completed so far is not immediately applicable for real data, it provides the foundation for a more robust astrometry and photometry extraction method. Future work includes determining the sources of error, reducing execution time by using PSF grids instead of generating new PSFs every iteration, and making improvements to the current extraction algorithm.

Methods

Extraction Technique

To find the astrometry and photometry of an unknown amount of objects in the image, I use a subtraction method of finding the brightest objects, simulating a PSF at the found location with the same brightness, and then subtracting the PSF from the data. A Gaussian blur is also applied to the subtrahend in order to account for local imperfections. This repeats until a specified threshold is reached.
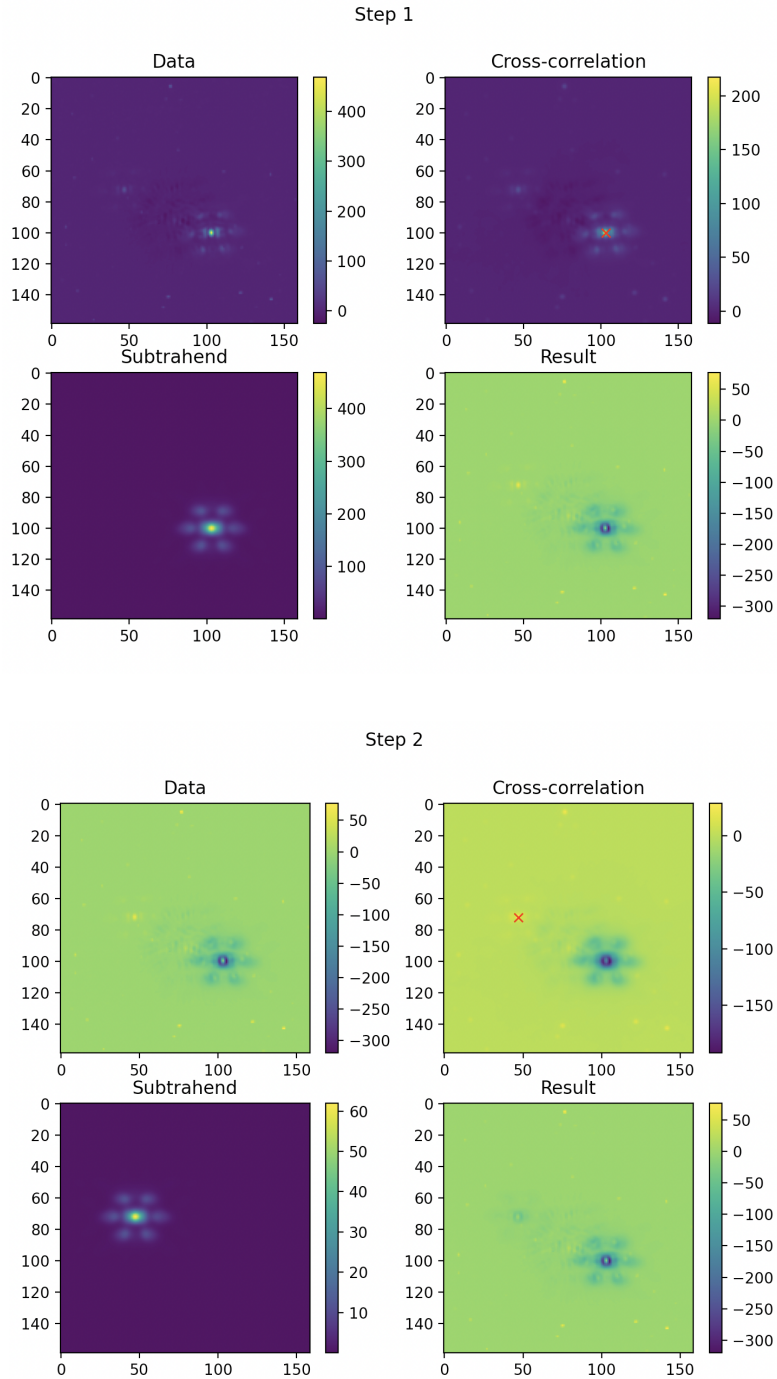
Fig. 5. Two steps of the PSF subtraction algorithm. From the data, a cross-correlation is applied with a template PSF. Then, a PSF is simulated, blurred, and subtracted to obtain an intermediate result which is carried to the next step.

Astrometry

The astrometry is found by first applying a cross-correlation to the image with a PSF as a template. Cross-correlation is used in signal processing and measures how similar two data are by calculating how closely they are aligned. The cross-correlation results in a new image where the highest value corresponds to the location where the image matches with the template PSF the most. Then, a quadratic fit is locally applied to the direction of both axes to obtain a subpixel estimate of the true location of the star.

Photometry

Then, the photometry is estimated by summing of values in the local area, divided by the expected flux for one PSF in that area. The simulated data is in mega-jansky per steradian, a unit of spectral radiance, and the PSF generated by WebbPSF is in normalized flux per pixel. Conversions are applied to obtain a measurement of flux for the planet.
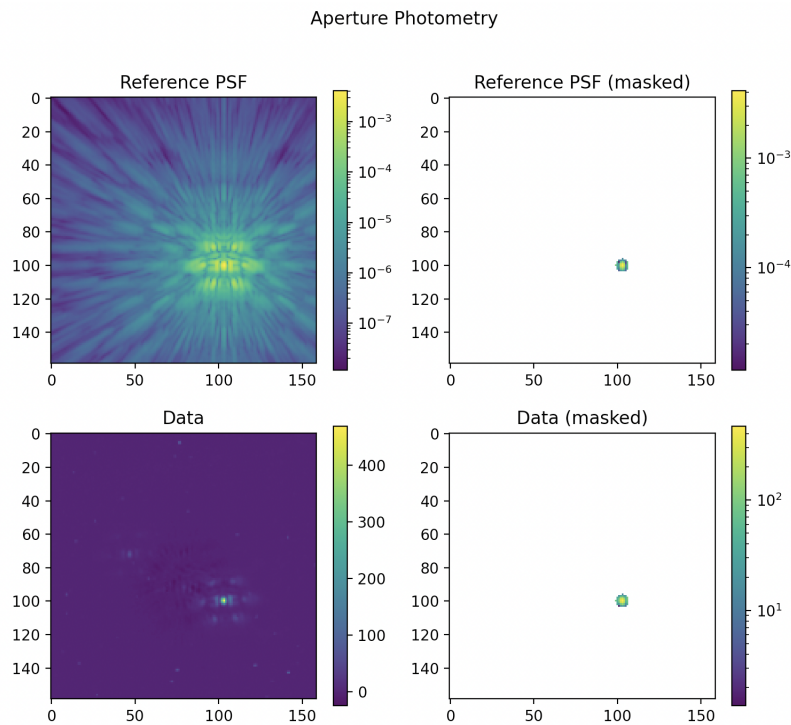
Fig. 6.

Monte-Carlo Simulation

At first, I was using a sample image of HR 8799 (Fig. 7) and simple simulated data I generated by summing PSFs from WebbPSF (Fig. 8). In order to apply my planet extraction and MC test script to the more realistic images which would be generated by Dr. Geoff Bryden, I created a JavaScript Object Notation (JSON) file containing the astrometry and photometry information for 50 random planets (Fig. 9). Associated with each planet is an identifier indicating which "star" or simulated image the planet is in as well as the planet number. This is so that any specific planet or outliers can be identified. Then, Dr. Bryden generated realistic images based on the JSON file.
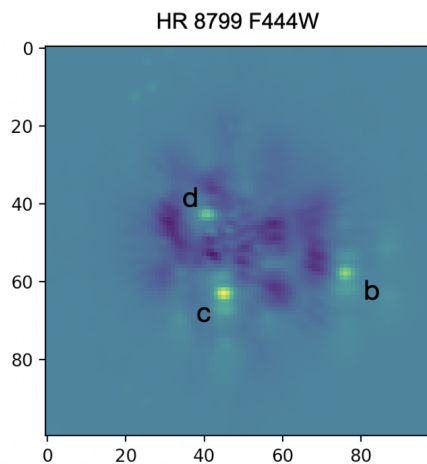
Fig. 7. Simulated NIRCam coronagraphic image for the star HR 8799 provided by Dr. Marie Ygouf using pyNRC and filter F444W. The three bright spots labeled b, c, *and* d *are the three planets of HR 8799 which were among the first exoplanets to be confirmed through the direct imaging technique (Marois et al., 2008).*
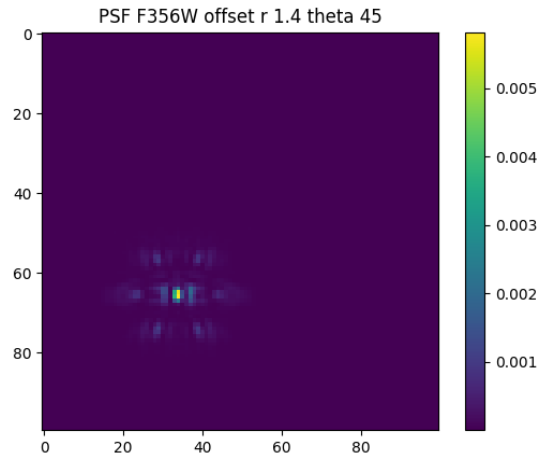
Fig. 8. Simple test data generated by WebbPSF using the F356W filter.

One simulated planet at r=1.4, theta=45

Fig. 9. JSON data file containing astrometry and photometry information for each planet.

*Brightness represents the flux contrast between the star and planet.*

The positions delta_X/Y *and* r/theta *are positions relative to the star in arcseconds*

(theta is in degrees).

To perform the MC simulation, I integrated the scripts I was using to simulate and extract planets. The MC test script reads from the input data file (json), then for every "star" in the input data, creates a simulated image and then runs the planet extraction. The results are then compiled and a summary containing the number of found planets, false positives, and error means/standard deviations for location and brightness. The complete output containing the found vs. expected location and brightness for every planet is saved to an Excel spreadsheet (.xlsx) format.

Future Work

I later received the more sophisticated simulated data to test with (Fig. 10) from Dr. Bryden. This posed a challenge for me since the data was not in the format I expected.
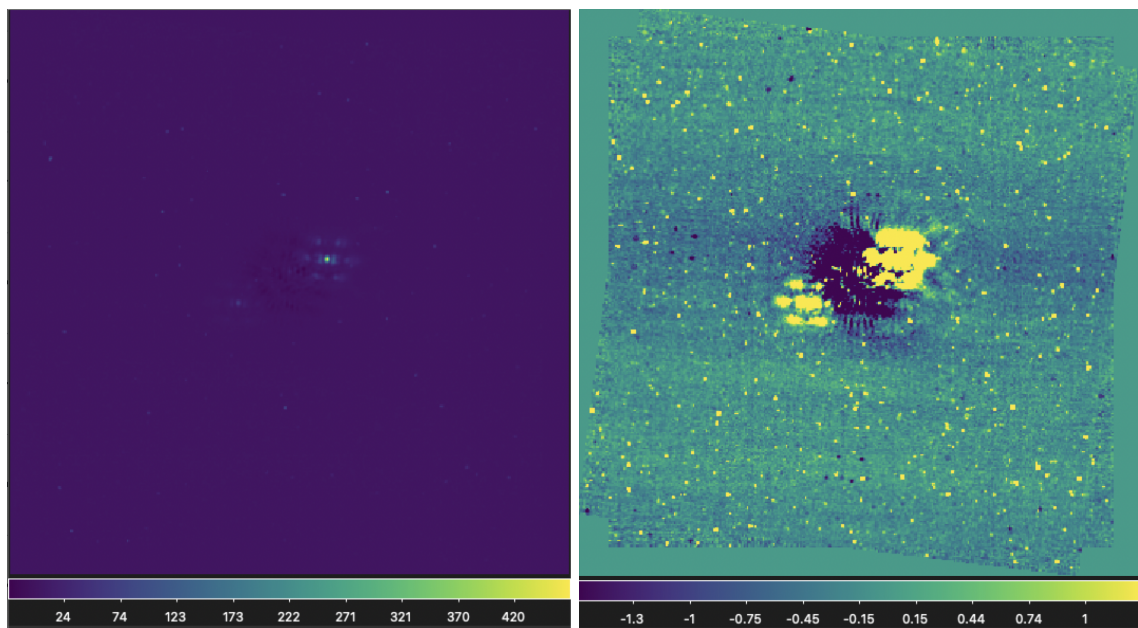
Fig. 10. Simulated calibrated data generated using WebbPSF and pyNRC.

Left: Linear scale. Right: Z-scale. Both represent the same data. Two images taken at an offset roll angle are aligned with each other to filter background stars.

Currently, the photometry and astrometry error calculations are off by a significant factor (Fig. 11), and further work is needed to determine the cause.

	distance	found planet flux	brightness % error	expected brightness contrast	found brightness contrast	expected delta x	...
0	0.082223	0.000310	31.380467	0.000082	0.000107	−1.319655	...
1	0.192016	0.002339	32.644903	0.000610	0.000810	0.533820	...

Fig 11. Truncated output from planet extraction script.

Target distance error is <0.0005 arcsec (5 ma) and brightness error <5%.

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