NIRCam optical calibration sources

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ABSTRACT

The Near Infrared Camera (NIRCam) instrument for NASA's James Webb Space Telescope (JWST) is one of the four science instruments installed into the Integrated Science Instrument Module (ISIM) on JWST intended to conduct scientific observations over a five-year mission lifetime. NIRCam's requirements include operation at 37 kelvins to produce high resolution images in two wave bands encompassing the range from 0.6 microns to 5 microns. In addition NIRCam is used as a metrology instrument during the JWST observatory commissioning on orbit, during the initial and subsequent precision alignments of the observatory's multiple-segment 6.3 meter primary mirror. JWST is scheduled for launch and deployment in 2012.

This paper is an overview of the NIRCam instrument's Optical Calibration Sources (Flat Field and Point Source). It will discuss the source requirements and will explain the optical and electronic technology developed to fulfill their mission requirements.

Keywords: NIRCam, James Webb, JWST, ISIM, calibration sources, flatfield, point source

1.0 INTRODUCTION

NIRCam will employ two in-flight calibration illuminators (Flat Field and Point Source) to measure respectively, the camera focal plane uniformity and the end-to-end optical train performances.

1.1 Flat Field Source Overview

The two NIRCam Flat Field Sources (short wavelength and long wavelength) are intended to provide a uniformly flat irradiance flux across the complete areas of the respective short wavelength (0.6 microns to 2.3 microns) and long wavelength (2.4 microns to 5 microns) cameras. Each broadband source will permit measurement of the overall variations in pixel-to-pixel sensitivity of the focal planes. In addition, it will provide an internal health check for verifying the overall functionality of the short wavelength and long wavelength focal plane filters.

1.2 Point Source Overview

The NIRCam Point Sources are intended to provide a diffraction-limited point emission at a selected wavelength to monitor the optical performance of the NIRCam end-to-end optical train. The point sources, either short wavelength (SW) or long wavelength (LW), are located at the input focus of NIRCam, and their respective projections pass through the complete optical trains of either the SW or LW cameras. Measurement of the deviation from the ideal diffraction-limit of the point-spread-function of the point image on each camera is a direct indicator of the health and status of each optical ensemble.

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2.0 FLAT FIELD SOURCE

2.1 Flat Field Source Architecture

The Flat Field Projection Source is located in pupil space, roughly midway between the NIRCam entrance focus and the camera focal plane focus, see Figure 1 below. The beam projector is located at a position on the Pupil Wheel which will be rotated to align the projector entrance aperture with a broadband tungsten source located adjacent to, but fixed to the optical bench, see Figure 2. The Projector consists of a Lambertian integrating cavity with a pinhole exit aperture. The pinhole aperture is boresighted to the center of the pupil so that the exiting beam will be centered upon, and expand through the camera optics, and continue to expand until it overfills and irradiates the camera focal plane.

For each bandwidth of the particular filter rotated into position to be placed between the source and the camera, a lamp intensity is set so that the operating camera integration times do not cause the camera pixel well to overfill its full well requirement.

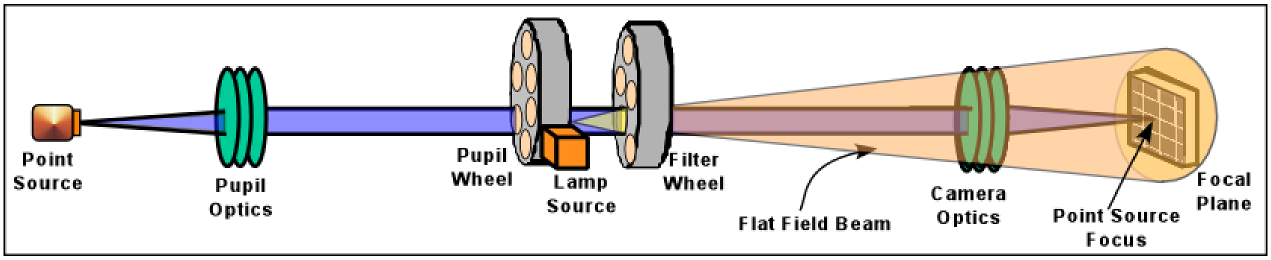

Figure 1. Location of NIRCam Calibration Sources

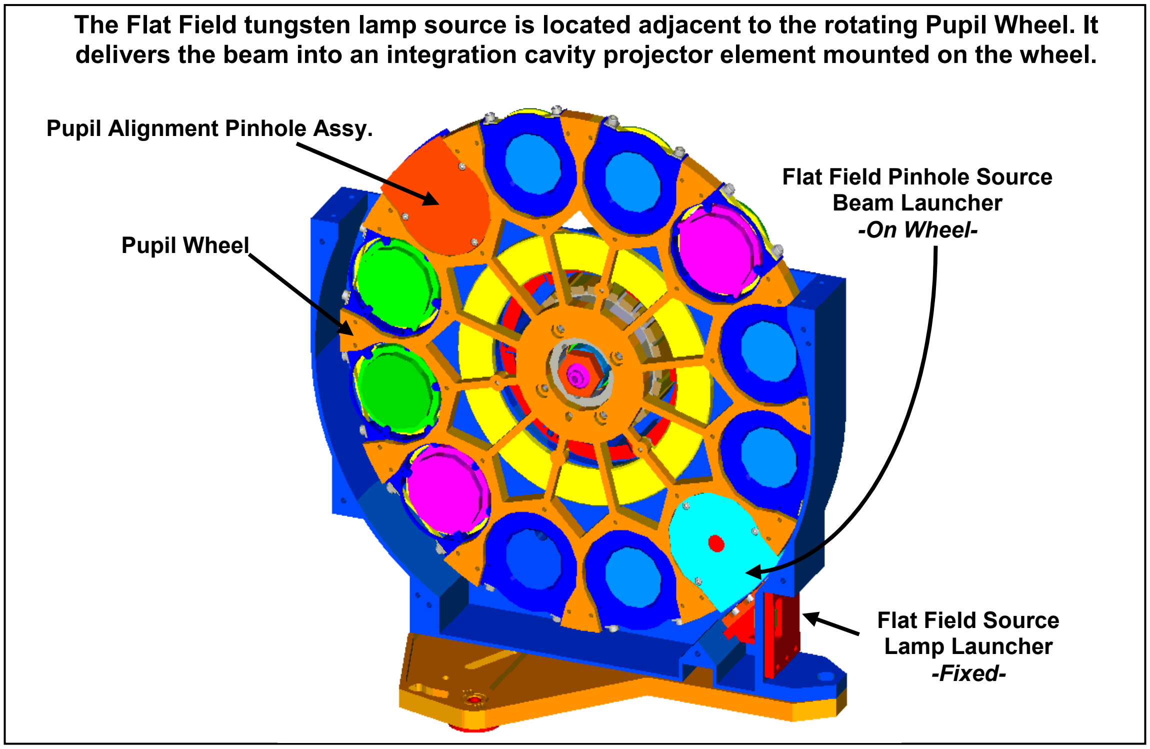

Figure 2. Flat Field Projector mounted on rotating Pupil Wheel. Adjacent source on fixed bench.

The lamp source is a tungsten filament lamp, which emits a classical broadband black body spectrum (tempered by the emissivity of tungsten and the transmission of the glass envelope), with a color temperature of roughly 2100 K. The lamp is mounted within an elliptical mirror reflector with the first focus located at the filament, and the second focus within the entrance to the projector integrating cavity on the Pupil Wheel. The Projector integrating cavity has a high reflectance gold coating on a diffuse Lambertian surface.

The design of the cavity, the quality of the Lambertian surface, and the reflectivity of the gold are the major contributing elements for ensuring that the projected beam is spatially uniform over the desired solid angle covering the camera detector focal plane. A high diffuse reflectance is critical to ensuring maximum spatial intensity uniformity of the diffused radiance projected through the exit aperture. A test fixture was fabricated for evaluating the performance of the projector, as well as validating the mathematical modeling of the optical throughput, see Figure 3.

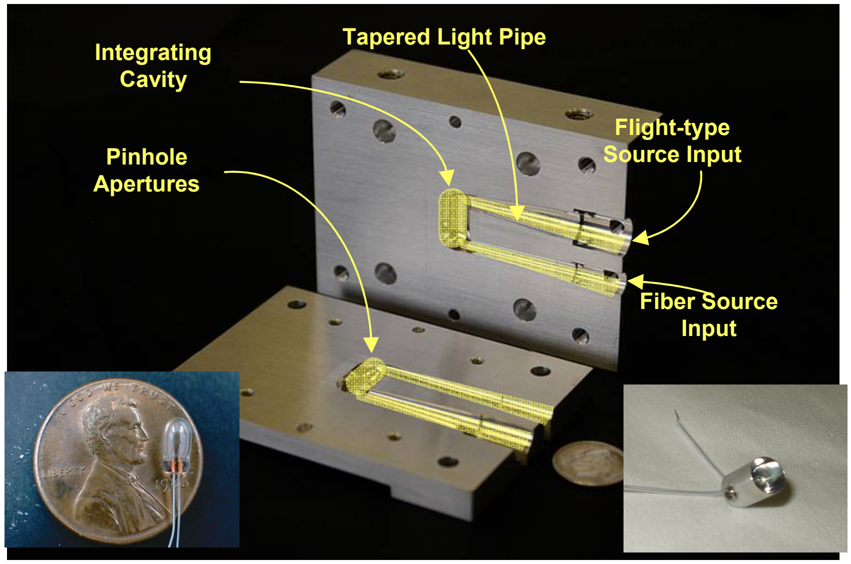

Figure 3. Gold coated integrating projection cavity. Test version.
Inset left, lamp source; *Inset right,* Elliptical mirror+lamp

2.2 Flat Field Source Performance (Spatial)

In order to validate the integrating cavity concept design a spatial uniformity measurement was made of the projection through a 400 micron aperture mounted on an integrating cavity with similar Lambertian properties to the gold coated cavity. To ensure that the measurement will employ a similar optical train arrangement as used in NIRCam, the projector was placed at a similar Pupil Wheel to lens and lens to camera distance. The projection was made through a surrogate optic of 500 mm focal length. See Figure 4.

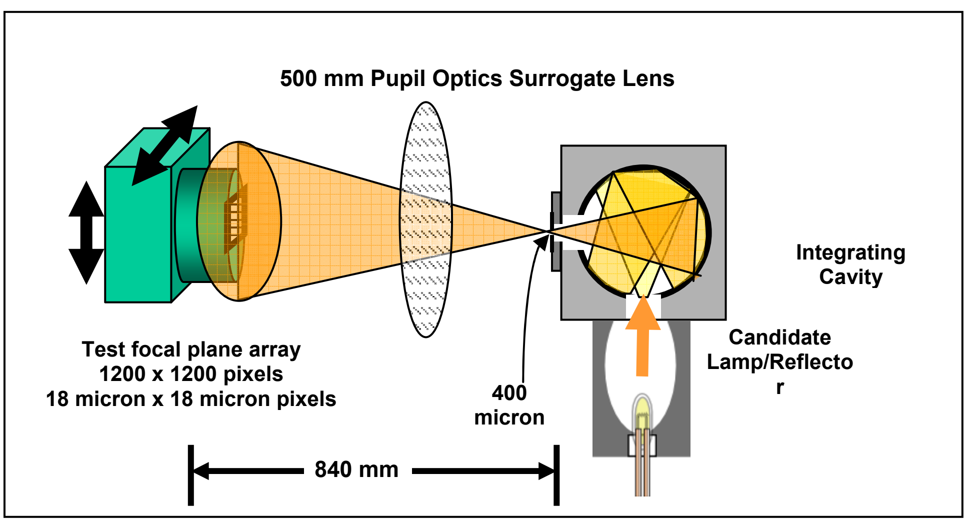

Figure 4. Flat field spatial distribution measured with integrating cavity and camera

It should be understood that the flatness of the internal cavity radiance need only be uniform over the surface opposite the exit aperture which subtends a solid angle equal to that of the camera focal plane as seen by the Flat field Projector exit aperture. In this case, the flight short wavelength focal plane array dimensions are 75 mm x 75 mm, with a distance of 840 mm from the Flat field Projector to the camera detector. This yields a 1mm diameter circle on the surface of the integrating cavity that must be spatially uniform.

The performance of the prototype Flat Field source gave extremely promising results, bettering the performance requirements of ±5% over the specified NIRCam focal plane range of 200 pixels. As is shown in Figure 5, below, the actual histogram variation was measured to be ±1% over the 200 pixel range. The distribution over the full test detector range of 1200 pixels was ±5%.

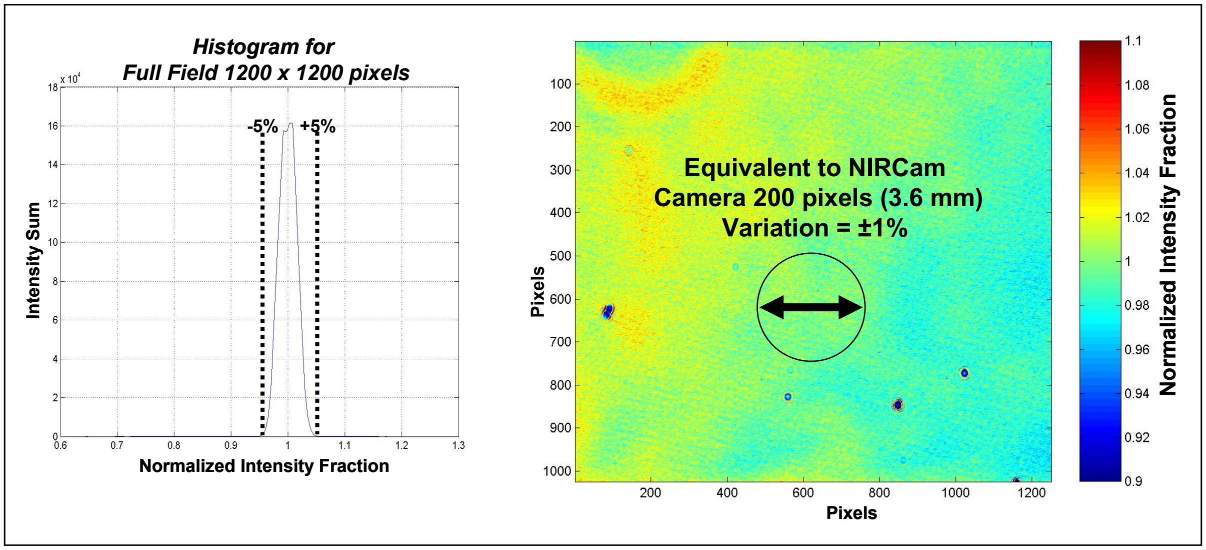

Figure 5. Results of flat field spatial distribution measurements

2.3 Flat Field Source Performance (Spectral)
In addition to spatial uniformity measurement, the NIRCam requirements also include providing sufficient optical intensity for the uniformity measurement over the complete spectral range of both the SW and LW ranges, which together spans from 0.6 to 5.0 microns. The projected beam's spectral bandwidth is determined by the convolution of the lamp spectral radiant intensity with the spectral reflectivity of the gold coating on the internal cavity projector.

Though the gold coating's spectral reflectance is an essential element in determining for a given wavelength band the ultimate number of photons onto the camera detector, the primary is the tungsten light source. Functionally, the total flux is determined by convolving the heated tungsten's spectral radiance, the spectral emissivity of the tungsten, and the transmission of the enclosing soda-lime glass envelope. The lamp chosen was a "commercial off-the-shelf" source type 715, with maximum operating power specification of 0.115 mA at 5 volts.

It was necessary to determine if the thermal conductivity and the radiative qualities of the lamp changed under different environmental conditions. The total integrated optical output power of the lamp at ambient conditions (295 K in air) was compared with measurements with the lamp in vacuum, and additionally at 34 K. A widely varying range of electrical input powers yielded virtually identical output optical powers when measured under the three environmental conditions. See Figure 6, below. These results gave strong evidence that the Flat Field Projector performance would be independent whether operated at ambient or cryogenic temperatures.

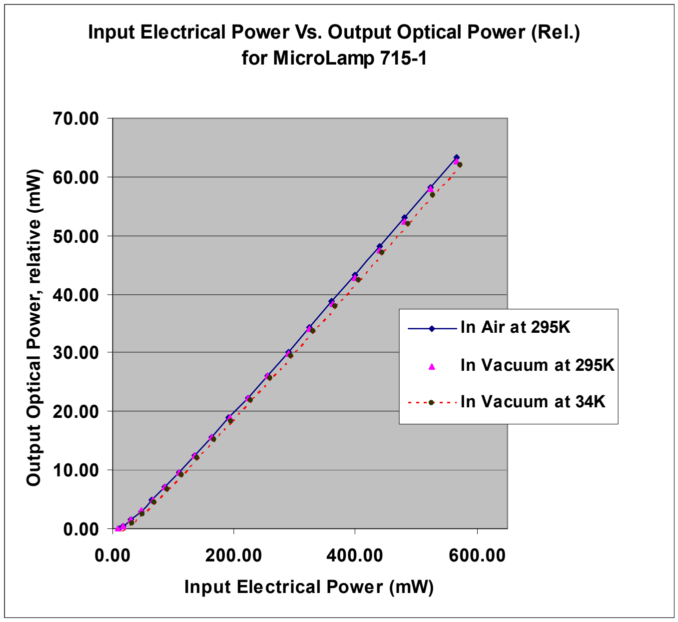

Figure 6. Input electrical power versus output optical power for air at 295 K, vacuum at 295 K, and vacuum at 34 K.

RADIOMETRIC SPECTRUM: The absolute spectral radiant intensity output of the lamp was tested over the spectral range of interest (0.6-5.0 microns) by Optronic Laboratories, in order to ensure that there was sufficient radiant emission over the instrument operational band. The radiometric calibration of the lamp was made by comparing it spectrally with an absolute blackbody standard. The results are given in Figure 7 below is superimposed upon the bandpasses of the individual SW and LW filters.

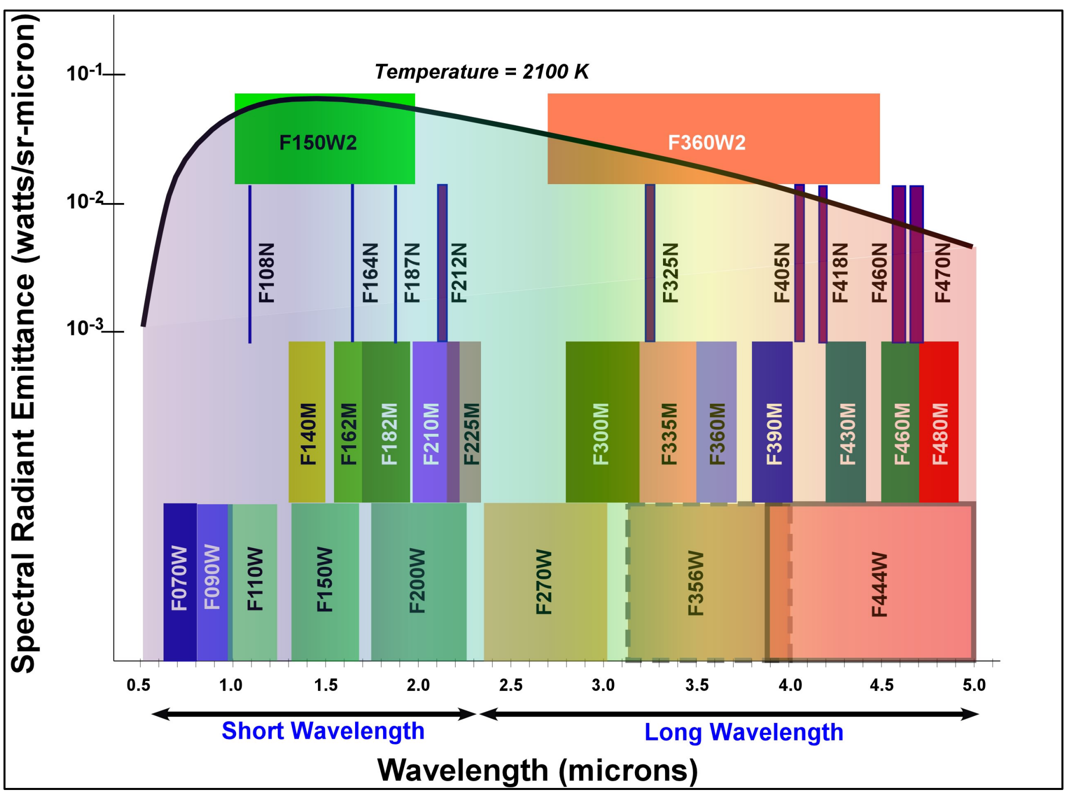

Figure 7. Absolute spectral radiance (Watts/sr-micron) for type 715 tungsten lamp, superimposed on NIRCam filters

A convolution of this radiant intensity curve, with the end-to-end modeled spectrally dependent optical throughput of the Flat Field Source projector within the NIRCam optical train, and the radiant sensitivity of the focal plane detector, shows that there is sufficient radiance across the entire spectral range to obtain measurable data with each filter. Acceptable camera integration times are predicted, on the order of ten to several hundred seconds.

Temperature = 2,100 K			
NIRCam Filter Name	**Central Wavelength (μm)**	**Focal Plane Integ. Time (sec)**	**Energy (Watt-sec)**
Broadband Filters			
F070W	0.708	107	32.1
F200W	2.0	10.6*	0.6
Intermediate Band Filters			
F210M	2.1	10.6*	1.6
F460M	4.6	62.2	18.7
Narrow Band Filters			
F212N	2.12	68.8	20.6
F470N	4.7	480	138

Figure 8. Typical focal plane integration times for wide, medium and narrow band filters.
*The lamp power is lowered to prevent pixel well overfill

FLAT FIELD CONCLUSION: The required performance and mathematical modeling of the prototype flat field source has been proven to meet NIRCam instrument requirements, both spatially and spectrally. The next step is the fabrication of a flight-type engineering test unit to be evaluated with NIRCam flight optics and focal plane detector.

3.0 POINT SOURCE

3.1 Point Source Architecture

The Point Source is intended to provide information on the health, status and focal quality of the NIRCam optical channels projecting onto the short (SW) and long wavelength (LW) focal planes during integration and testing and flight operation. Each source will emit a diffraction-limited point image at a selected narrow-band wavelength (SW or LW) to allow monitoring and analysis of the projected beam on to either of the two respective camera focal planes.

The Point Source is a relatively narrow (150 nm) spectral band light emitting diode (LED) source located on the outer rim of the Coronagraph Occulting Mask fixture at the input focus plane to the NIRCam optical train, see Figure 9. It projects a point image through the Pupil Optics, which relays the beam within pupil space, through the Pupil Wheel optics (contains an optical wedge which tilts the beam to place it within the field of the focal plane). The beam exiting the Pupil Wheel wedge optics passes through an adjacent filter (filter chosen to simply pass the beam without attenuation), then passes through the Camera Optics, which focuses the beam on to the Camera detector focal plane.

In order for the LED to project a diffraction-limited point source a 50 micron aperture is mounted in front of the normally Lambertian LED exit aperture to define the projecting beam width, see Figure 10. Surmounting the aperture is a neutral density filter, employed to keep the intensity low enough so as to maintain the source driving electrical pulse at longer than 0.1 millisecond. This pulse limit is controlled by the frequency bandwidth of the moderately resistive, low thermally conducting electrical wires passing through the cryogenic region of the NIRCam instrument.

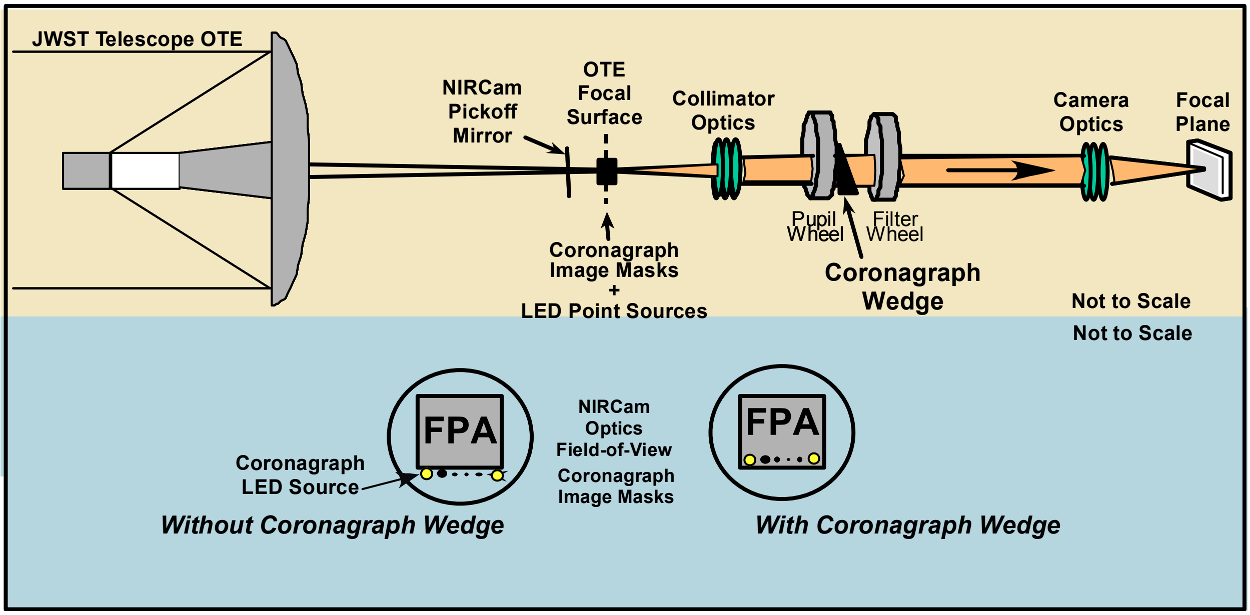

Figure 9. Relative locations of LED Point sources with respect to NIRCam optical train.

The LED pinhole aperture projectors are placed on the mounting fixture of the Coronagraph Occulting Mask substrate, as seen in Figure 10 below. The LEDs are arranged in pairs on either side of the fixture. Each pair consists of one short wavelength (1.8 microns) and one long wavelength LED (3.8 microns).

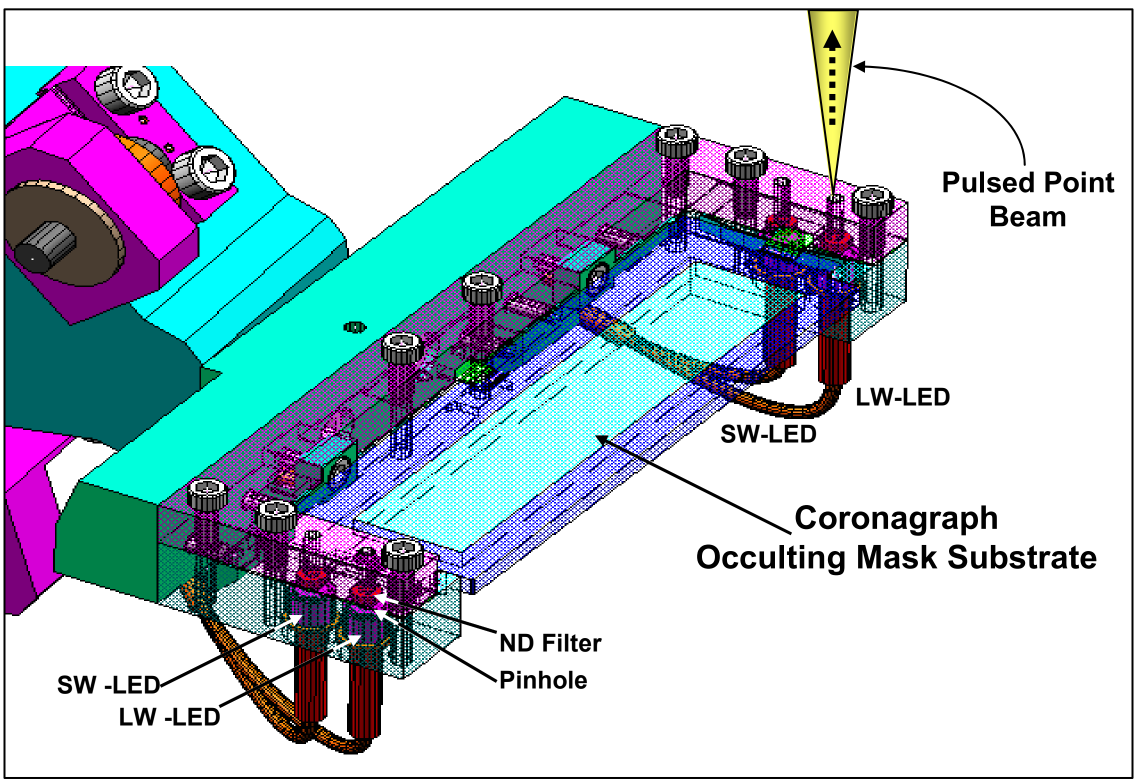

Figure 10. Coronagraph Occulting Image Mask mounting fixture with LED point source projectors

One of the pair on one side is the backup for the other. Each LED emitter is contained in a windowless TO-18 can enclosure; see Figure 11a and b, which is mounted on the edge of the Coronagraph Occulting Mask fixture. The active emission area is a square 300 microns on the side. Side electrode contacts are employed to provide a clear and uniform emission area.

Figure 11a (left), magnified view of the 300 micron square emission surface
Figure 11b (right) shows the TO-18 size LED package

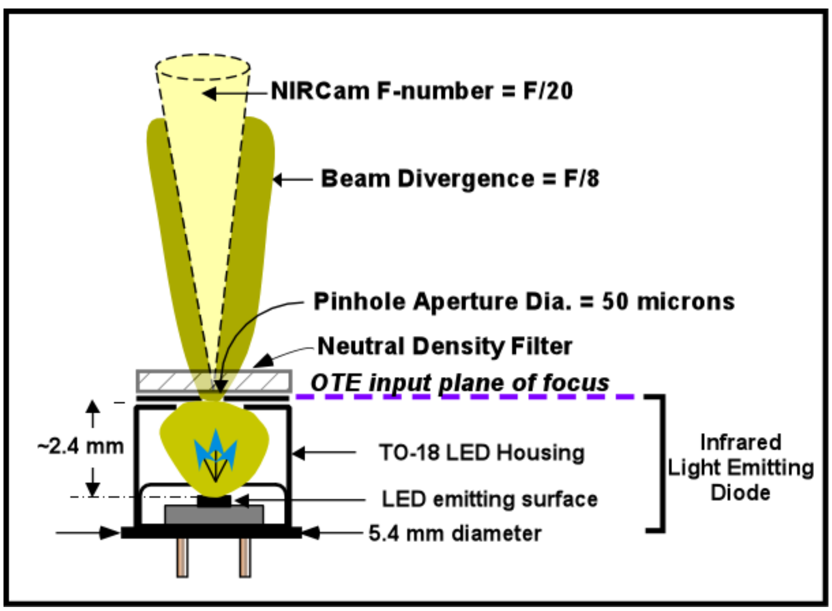

Figure 12. Point source design with pinhole aperture and neutral density filter

DIFFRACTION-LIMITED APERTURE: It is essential that the respective beams projected onto each SW and LW focal plane detector be diffraction-limited. A 1.8 micron wavelength LED was selected for the short wavelength focal plane and a 3.8 micron LED for the f/20 long wavelength camera. The diffraction-limit at 1.8 microns has an Airy diameter of 88 microns. Similarly, the diffraction limit for the f/9 long wavelength camera is 83 microns. In both cases, the 50-micron projection aperture diameter is well below either limit.

RADIOMETRY (See Figure 12): An end-to-end radiometric model was formulated to determine what the ultimate neutral density filter and LED pulse width settings to ensure that the peak focal plane pixel well depths are not saturated. The model took into account:

- The power of the initial Lambertian-emitted optical power, $\sim P_{0)}$
- The fraction of Lambertian power passing through the 50 micron aperture,
  $\sim (P_0/\pi) \times (\pi/4) \times (50 \text{ microns})^2/(2.4 \times 10^{-3})^2$
- The solid angle of the projected beam through the 50 micron aperture, roughly f/8 cone
- The solid angle will overfill the NIRCam input acceptance angle of f/20. This reduces the effective power transmitted through the optics by $(8/20)^2$
- NIRCam transmission, T
- Number of pixels under the Airy disk
- Number of photoelectrons for well fill

It is essential that the number of photons per pixel of the projected spot image do not saturate the focal plane detector. This requires that a means be available for regulating the LED flux over several orders of magnitude. The shortest integration time for both camera focal planes is 10.6 seconds. If the LED source were run in CW mode this would make intensity regulation adjustable solely by introduction of a neutral density filter. This would be a cumbersome arrangement. Consequently, the intensity is regulated by pulsing the LEDs with short (~1 millisecond) 0.25 ampere adjustable pulse widths. An ND filter will be employed to reach the range of refined attenuation, where the pulse width will be regulated to home in on an optimal signal level. Laboratory measurements of the output of the LED with the 50-micron aperture show a 95% correspondence to mathematical modeling.

RESULTS: Calculations show that for the 1.8 micron wavelength LED a range of ~1-10 milliseconds pulse width, along with an ND = 3 filter will permit regulating the focal plane detector to a 50% well fill. The calculations for the 3.8 micron LED require an ND = 2 filter, along with a ~1-10 milliseconds pulse width range. All these values are readily achievable with available technology.