# NIRCam Instrument Optics

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## ABSTRACT

The Near Infrared Camera (NIRCam) 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 32 to 37 K to produce high resolution images in two wave bands encompassing the range from $\lambda = 0.6$ to 5.0 microns. In addition NIRCam is used as a metrology instrument for the JWST observatory, providing critical data for alignment 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 hardware and performance. Detailed discussions of specific subassemblies will be presented in other papers in the same conference.

**Keywords:** NIRCam, James Webb, JWST, ISIM

## 1. INTRODUCTION

### 1.1 Instrument Overview

NIRCam is located near the focus of the JWST Optical Telescope Element (OTE), and consists of two autonomous and nearly identical Modules. The top-level optical requirement for the OTE / NIRCam system is to provide diffraction-limited images at $\lambda = 2.0$ microns.
Each Module images a (2.2 arcmin)$^2$ star field onto two HeCdTe detector arrays, one of which is optimized for the 0.6 to 2.3 micron spectral band (the Shortwave channel), and the other for the 2.4 to 5.0 micron spectral band (the Longwave channel). The Pickoff Mirror for each Module is equipped with a three degree-of-freedom Focus and Alignment Mechanism that allows for fine focus and pointing. Figure 1 shows the optical layout of a Module.

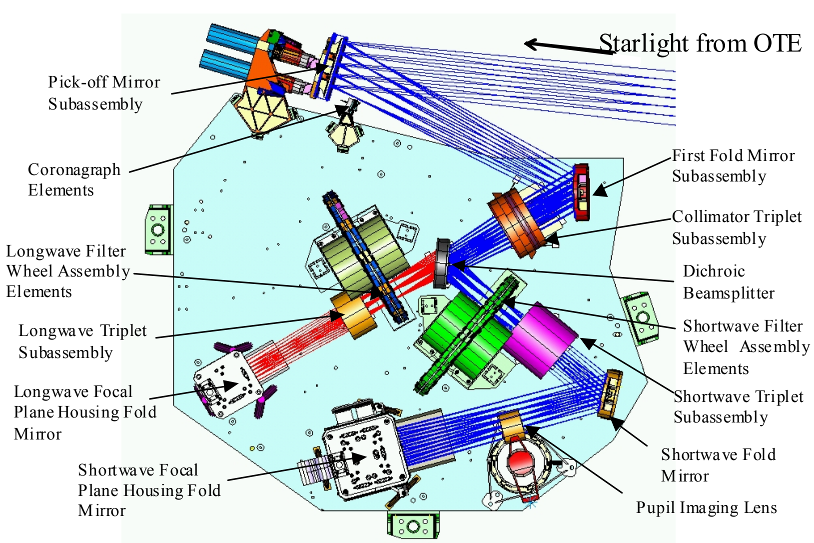



Figure 1: NIRCam Instrument Optical Overview

A predominantly refractive design was chosen for NIRCam in order to meet tight packaging requirements. Because NIRCam also provides Wavefront Sensing and Control (WFS&C) data for the OTE, wavefront error (WFE) within the NIRCam instrument must be controlled and characterized so as to limit the amount of NIRCam's internal WFE that gets imprinted on the other science instruments.

### 1.2 Imaging Mode

The primary purpose of the NIRCam instrument is to relay images of celestial objects from the focal plane of the OTE onto NIRCam's Focal Plane Arrays (FPAs). Each NIRCam Module has a square Field of View (FOV) approximately 8° on a side which, given the plate scale of the OTE, amounts to 2.2 arcmin on a side in object space. Both SW and LW channels are furnished with a Filter Wheel that allows for observations through more than 12 different spectral bands.

### 1.3 Coronagraphic Mode

NIRCam is also equipped to make Coronagraphic measurements. A Coronagraphic Occulting Mask (COM), consisting of four or five patterned masks deposited on a polished Silicon substrate, is located on each Module at the OTE focus, and Lyot Stops are located in the Pupil Wheels. The COM masks will be chosen from a selection of sinc$^2$, top-hat, and Gaussian designs, optimized for light at either 2.0 or 4.6 microns; (the exact design of the Lyot Stops and COM masks is, as of this writing, still being worked). During normal Imaging Mode, light from the Coronagraph falls off to the side of the FPAs; the Lyot Stop substrates have wedge in them that optically shifts the COM masks onto the FPAs.

### 1.4 Other Modes

NIRCam also serves as the WFS&C camera for the JWST Observatory. As such, there are diagnostic elements within the NIRCam instrument that provide the information necessary to support fine phasing of the Telescope's mirrors. These elements fall into three categories:

#### 1.4.1 Diffractive Hartmann Sensor (DHS)

The DHS is a WFS&C element, located in the NIRCam Pupil Wheel, that provides information on segment-to-segment position and orientation. There are two DHS's in each SW Pupil Wheel.

#### 1.4.2 Phase Diversity Lenses (aka "Weak Lenses")

The Weak Lenses provide phase diversity information for the Telescope. There are two Weak Lenses in each SW Pupil Wheel and one in each SW Filter Wheel.

#### 1.4.3 Pupil Imaging Lens (PIL)

The PIL images the Telescope's Primary Mirror onto the NIRCam focal plane, thereby providing instantaneous information about the relative alignment of the OTE Primary Mirror segments. The PIL is typically stowed to the side of the beam path; a mechanism brings the PIL into the beam path when it is needed.

## 2. OPTICAL COMPONENTS

### 2.1 Overview

Referring to Figure 1, in normal imaging mode, each NIRCam Pickoff Mirror (POM) directs starlight from the OTE focal plane up to the First Fold Mirror and then into the NIRCam Collimating Lens Triplet. The collimated starlight is then split into shortwave ($\lambda$ = 0.6 to 2.3 microns) and longwave ($\lambda$ = 2.4 to 5.0 microns) paths by the Dichroic Beamsplitter (DBS). Once split, the light in each path passes through a Pupil Wheel and a Filter Wheel, each of which can be moved independently. Each Wheel has 12 positions for the required scientific and diagnostic hardware.

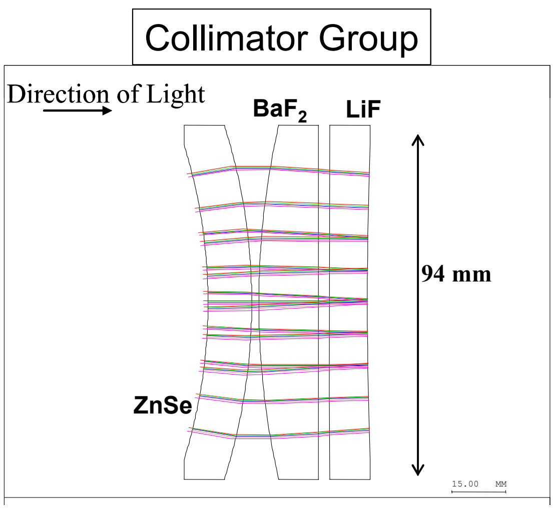
The light then enters a Camera Triplet, which focuses it onto an FPA. The SW Camera Triplet creates the f/18 cone that fills the SW FPA (4096 x 4096 pixels); the LW FPA is ¼ the area of the SW FPA, and is filled with an f/9 cone from the LW Camera Triplet. The SW Fold Mirror is required for packaging purposes. The SW & LW FPA Mirrors provide radiation protection for the FPAs. Short descriptions of these subassemblies follow. More detailed discussions of their design, performance, and peculiarities may be found in other papers being presented at the conference.

### 2.2 Pickoff Mirror

The Pickoff Mirror is a rectangular, concave spherical mirror -- approximately f/12 -- that reflects the starlight into the rest of the NIRCam instrument. The POMs have a lightweighted Fused Silica substrate, a field stop, and a Silver coating (with protective overcoat). Each POM is actuated by a three degree-of-freedom focus and alignment (FAM) mechanism that provides fine positioning in tip, tilt, and piston, allowing NIRCam to accommodate small pointing and focus changes that may manifest themselves once the Observatory is on-orbit. The spherical figure of the POM relays the image of the OTE exit pupil to the NIRCam Pupil Wheels, where the various diagnostic hardware associated with the WFS&C operations is located.

### 2.3 Lens Triplets

The design of the Lens Triplets is based on designs developed by Mr Thomas Jamieson (Lockheed Martin ATC) in 2001 to advance large spectral band imaging systems.
The three Lens Triplets are shown in Figure 2.

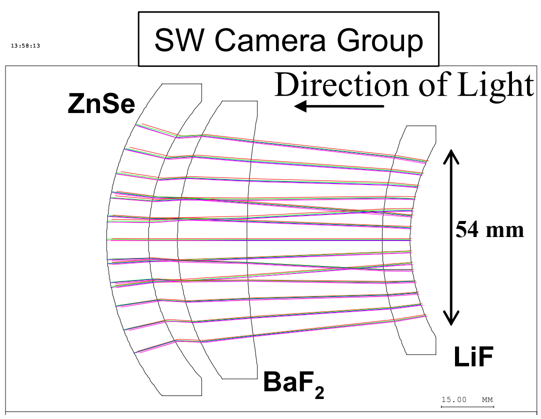



| Element | Material | R1 | R2 | Thickness |
|---|---|---|---|---|
| COL1 | ZnSe | 122.9 | 136.6 | 12.8 |
| COL2 | BaF2 | 184.2 | ∞ | 17.5 |
| COL3 | LiF | ∞ | 1096.2 | 11.1 |

| Element | Material | R1 | R2 | Thickness |
|---|---|---|---|---|
| SW1 | LiF | 64.98 | 93.47 | 8.0 |
| SW2 | BaF2 | 311.3 | 80.79 | 19.9 |
| SW3 | ZnSe | 69.22 | 107.85 | 12.0 |

| Element | Material | R1 | R2 | Thickness |
|---|---|---|---|---|
| LW1 | LiF | 42.33 | 57.07 | 7.5 |
| LW2 | BaF2 | 453.3 | 60.0 | 17.65 |
| LW3 | ZnSe | 56.68 | 65.76 | 9.8 |

All dimensions in mm



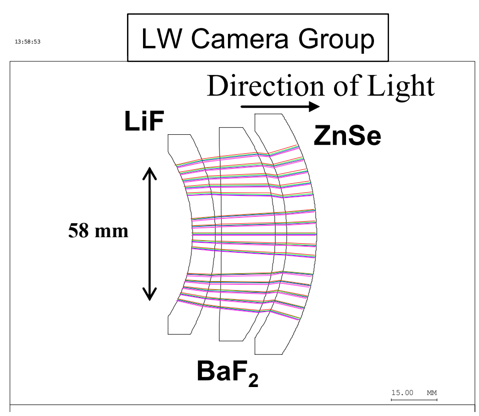




Figure 2: NIRCam Lens Triplets

Each Triplet is composed of elements of Lithium Fluoride (LiF), Barium Fluoride ($BaF_2$), and Zinc Selenide (ZnSe). The elements in the Collimating Triplet are all 94 mm in diameter; in the other Triplets, they range from about 55 mm to about 82 mm in diameter. The concave surface of the Zinc Selenide elements in the Camera Groups are slightly aspheric -- otherwise, all optical surfaces are spheres. We have set a requirement for the diameter to thickness aspect ratio of the elements to be < 8:1. The fabrication and mounting of the LiF elements, in particular, present significant technical challenges. The material is relatively soft (meaning it is prone to structural deformation, and is extraordinarily difficult to polish), is slightly hygroscopic, has a high CTE, and is susceptible to thermal shock. A great deal of effort has been devoted to understanding its behavior and to developing appropriate mount designs. The NIRCam team, in collaboration with Optical Solutions Inc of Charlestown, New Hampshire, has successfully fabricated flight-like prototypes of LiF elements; these have been mounted, shaken, and cryo-cycled, and we have confidence that the current approach is viable.

## 2.4 Dichroic Beamsplitter

The Dichroic Beamsplitter is an 85 mm diameter x 15 mm thick Silicon substrate with multi-layer thin films stacks on both sides. It reflects light at $\lambda = 0.6$ to 2.3 microns and transmits at $\lambda = 2.4$ to 5.0 microns, allowing for a 100 nm transition zone from 2.3 to 2.4 microns. Because of its location (near the system pupil), orientation (35° angle of incidence) and nature (reflective in the SW band), it is a major contributor to the overall WFE in the SW channel. As such, meeting its spectral and flatness requirements poses a significant thin films design challenge. JDSU, Inc. (formerly OCLI) of Santa Rosa, California, has been chosen to fabricate this optic, and their team has developed a design that supports all of the requirements.

## 2.5 Pupil & Filter Elements

The optical elements that are located in the Pupil and Filter Wheels can be divided into three categories: Bandpass Filters, Lyot Stops, and Diagnostic elements. See Figure 3.

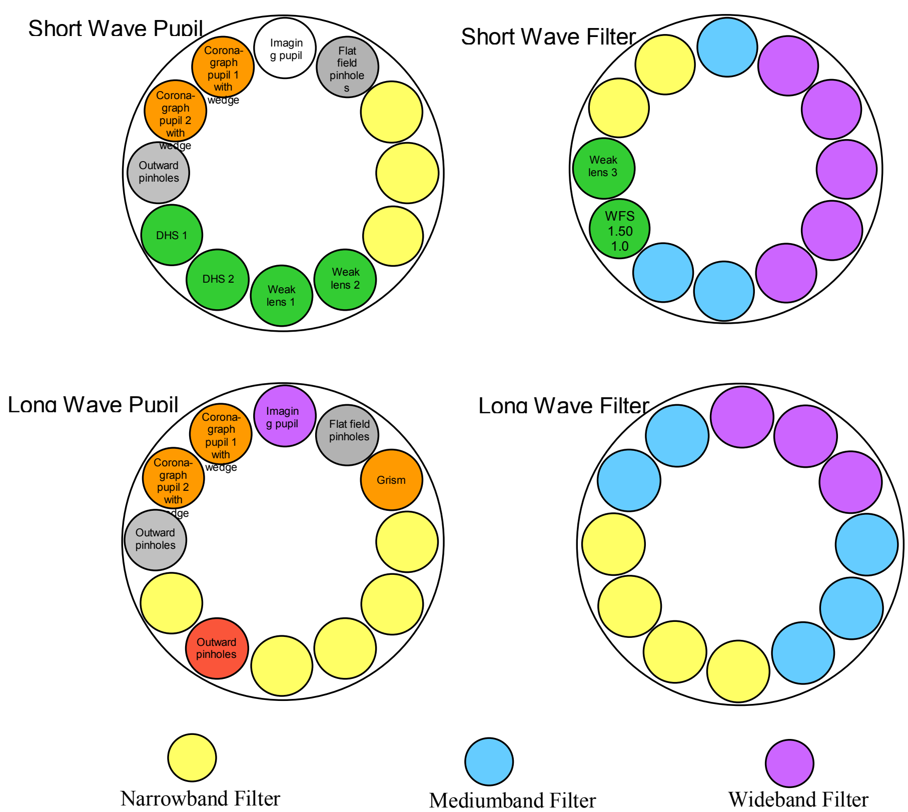



Figure 3: Pupil & Filter Wheel Populations

### 2.5.1 Bandpass Filters

There are three categories of Bandpass Filters: wideband (R = 4), medium band (R = 10 to 20), and narrowband (R = 100), "R" being defined as the ratio of the center wavelength to the bandwidth. A list of the NIRCam Bandpass Filters is given in Table 1.

| NIRCam Filter List (v.13) | | |
|---|---|---|
| **Filter** | Center (microns) | FWHM (microns) |
| F070W | 0.71 | 0.175 |
| F090W | 0.90 | 0.200 |
| F108N | 1.08 | 0.011 |
| F110W | 1.10 | 0.275 |
| F140M | 1.40 | 0.200 |
| F150W | 1.50 | 0.375 |
| F150W2 | 1.50 | 1.000 |
| F162M | 1.62 | 0.150 |
| F164N | 1.64 | 0.016 |
| F182M | 1.82 | 0.250 |
| F187N | 1.87 | 0.019 |
| F200W | 2.00 | 0.500 |
| F210M | 2.10 | 0.250 |
| F212N | 2.12 | 0.021 |
| F225M | 2.25 | 0.200 |
| F270W | 2.70 | 0.680 |
| F300M | 3.00 | 0.400 |
| F325N | 3.25 | 0.033 |
| F335M | 3.35 | 0.300 |
| F356W | 3.56 | 0.890 |
| F360M | 3.60 | 0.200 |
| F390M | 3.90 | 0.200 |
| F405N | 4.05 | 0.041 |
| F418N | 4.18 | 0.042 |
| F430M | 4.30 | 0.200 |
| F444W | 4.44 | 1.110 |
| F460M | 4.60 | 0.200 |
| F460N | 4.60 | 0.046 |
| F470N | 4.69 | 0.047 |
| F480M | 4.80 | 0.200 |

Table 1: Bandpass Filters

### 2.5.2 Lyot Stops

There are two Lyot Stops in each Pupil Wheel, consisting of a patterned mask deposited on a wedged Silicon substrate. The purpose of these Stops is to 1) optically move the COM images onto the FPAs, and 2) suppress diffraction from the COMs so as to allow for precision coronagraphy of various celestial objects. As of this writing, the exact nature of the patterned masks on the Stops is still being studied.

#### 2.5.3 Diagnostic Elements

Each Pupil Wheel contains a Flat Field Pinhole Source (also known as the "Inward Pinholes") and an Outward Pinhole, used primarily for Integration & Test.
Two Diffractive Hartmann Sensors (DHS's), which provide information on the relative phasing and orientation of the OTE Primary Mirror segments, are located in each SW Pupil Wheel. Additionally, a number of Weak Lenses are located in the SW Pupil and Filter Wheels to permit phase diversity analysis of the OTE's optical alignment.

### 2.6 Calibration Sources

The NIRCam Optical Subsystem includes two internal light sources, the Flat Field Sources and the Coronagraphic Sources, to aid with on-orbit calibration and characterization. The Sources are also used in the Instrument Integration & Test process.

#### 2.6.1 Flat Field Sources

The Flat Field Sources are located at the Pupil Wheels. A broadband light source, consisting of a stationary Tungsten lamp assembly that projects light into a pinhole source in the Pupil Wheel, will periodically (on a monthly basis) illuminate the FPAs with uniform-intensity, broadband light to allow the Observatory to perform in-situ pixel-to-pixel calibration of the FPAs.

#### 2.6.2 Coronagraphic Sources

The Coronagraphic Sources are located at the OTE focal plane, in the mounting hardware of the COMs. LED sources will project light through pinholes to simulate star images. The Coronagraphic Sources will allow for health and status checks of NIRCam during the Observatory commissioning phase.

### 2.7 Pupil Imaging Lens

The Pupil Imaging Lens (PIL) is a lens triplet designed to project an image of the OTE Primary Mirror onto one of the SW FPA quadrants. The PIL will be used during the commissioning phase (and occasionally throughout the life of the Mission) to provide feedback on the orientation of the OTE Primary Mirror Segments. Under normal operations, the PIL is stowed out of the beam path; a mechanized arm inserts the PIL into the beam path when it is required.

## 4. REQUIREMENTS AND PERFORMANCE

### 3.1 Physical Requirements

The physical requirements of the NIRCam optical system are shown in **Table 2**

| Parameter | Requirement | Predicted Performance |
|---|---|---|
| Mass | < 40 Kg | 37 Kg |
| Operating Temp | 32 - 37 K | √ |
| Survival Temp | 20 - 330 K | √ |
| Atmospheric pressure | Vacuum | √ |
| Random Vibe | 13 g rms | √ |
| Mission Life | 5 years | √ |
| Contamination | < Level 550 (EOL) | √ |

Table 2: NIRCam Optics: Physical Requirements

### 3.2 Optical Requirements

The optical requirements of the NIRCam optical system are shown in Table 3.

| Parameter | Requirement | Predicted Performance |
|---|---|---|
| | | |
| Spectral Band | 0.6 - 5.0 microns | √ |
| Field of View | 2.2 x 2.2 arcmin | √ |
| WFE ($\lambda$ = 0.6 - 2.3 microns) | < 70 nm rms | 66.7 nm rms |
| WFE ($\lambda$ = 2.7 microns) | < 120 nm rms | 99.0 nm rms |
| WFE ($\lambda$ = 3.57 microns) | < 155 nm rms | 117.7 nm rms |
| WFE ($\lambda$ = 4.44 microns) | < 180 nm rms | 113.4 nm rms |
| Transmission | > 66% | √ |
| Internal Pupil Diameter | 31 ± 1 mm | 31.14 mm |
| Vignetting | None | √ |

Table 3: NIRCam Optical Requirements

### 3.3 General Fabrication Specifications

Starlight passing through the NIRCam system encounters approximately 20 optical surfaces, and the optical requirements for those surfaces must perforce be kept fairly tight. Table **4** describes the general fabrication requirements. All specifications need to be met at the Instrument's operating temperature of 32 - 37 K. Small variations in the specifications are allowed to accommodate different materials, thin films, etc.

| Parameter | Specification |
|---|---|
| | |
| Surface Figure | < $\lambda$/10 P-V (0.022 $\lambda$ rms) @ $\lambda$ = 633 nm |
| Scratch Dig | 40 / 20 |
| Surface Roughness | < 20 Å rms |
| Dimensional Tolerance | ± 0.05 mm |
| Radius of Curvature Tolerance | ± 0.1 % |
| Mechanical Wedge | < 1 arcmin |
| Edges and chamfers | Polished or acid-etched |

Table 4: General Fabrication Requirements

### 3.4 Wavefront Error Budget

A separate Wavefront Error budget is kept for each of NIRCam's 30 or so spectral bands (as defined by the various Bandpass Filters). Because most of the optical requirements are evaluated through the $\lambda$ = 2.0 micron Filter (known as the F200W filter), this is the one for which we typically present results. The WFE budget for the F200W Filter is shown in Figure 4.

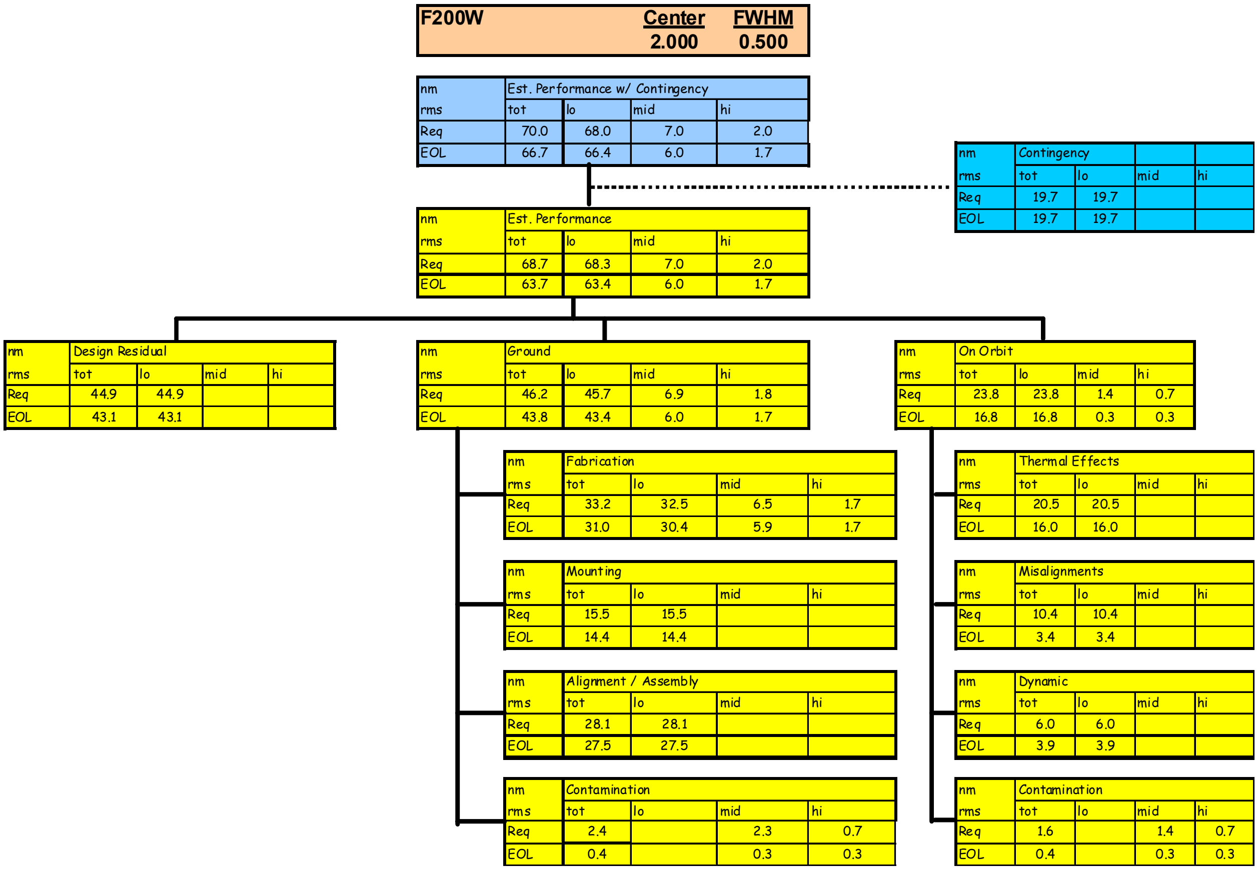



Figure 4: NIRCam Wavefront Error Budget

## 4. SUMMARY

Work on the NIRCam Optical Subsystem has been ongoing for over three years; as of this writing, the design has been thoroughly reviewed and vetted and is considered mature enough to begin fabrication of the hardware. The NIRCam optics team is confident that the design will be compliant with all requirements and will furnish excellent astronomical data over the entire life of the Mission.