

Lens Design for the Near Infrared Camera for the James Webb Space Telescope

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ABSTRACT

The Near InfraRed Camera (NIRCam) for the James Webb Space Telescope (JWST) is a refracting camera system. Its unique performance derives from the Lithium Fluoride, Barium Fluoride and Zinc Selenide lenses that provide aberration and color correction over the large operating wavelength. This paper describes the optical prescription, lens materials and prototype characterization for the camera lenses.

Keywords: lenses, Lithium Fluoride, Barium Fluoride, Zinc Selenide

1. INTRODUCTION

NIRCam is a refracting camera that images from 0.6 – 5 microns. The imaging path is split into two segments, a shortwave and a longwave path. The shortwave path images from 0.6 to 2.3 microns and the longwave path images from 2.4 to 5 microns. The instrument consists of two identical cameras that are mounted back to back. Each camera consists of three lens triplets, a collimating triplet, a shortwave path triplet and a longwave path triplet. All triplets are comprised of a Lithium Fluoride (LiF), Barium Fluoride (BaF₂) and Zinc Selenide (ZnSe) lens. The NIRCam lenses are made from materials that allow for the large color spectrum required for operation. The layout of the lens triplet path is illustrated in figure 1. As in any refracting system the lenses are critical performance elements. The alignment and manufacturing tolerances are strict to produce the high optical quality required for the instrument.

An extensive study has been performed by the NIRCam team to test and characterize the lens mechanical and optical properties. LiF and BaF₂ are single crystal materials. ZnSe is a deposition crystal material. ZnSe is a well understood material that is routinely grown and manufactured for lenses. A major design challenge of this material is the absorption cut-off around 0.55 microns that significantly affects lens anti-reflection coating design. Special care is required to meet the NIRCam transmission requirements. The LiF and BaF₂ are both challenging lenses to manufacture. The crystals are grown by few suppliers and most optical manufacturing houses have little experience working with these delicate materials. LiF has no space flight heritage but has been used in the FLITECAM instrument build by UCLA for SOPHIAⁱ. Optical Solutions Inc. is making the NIRCam lenses and also made the FLITECAM lenses which were of comparable size and manufacturing difficulty. The delicate nature of LiF makes mounting the optics without inducing stress or damage a challenge. The prototype studies done to date conclude that a successful mount design has been achievedⁱⁱ and all of the lenses can be satisfactorily manufactured to meet NIRCam performance requirements.

Lens Design Summary

- All lenses have less than 1/10 Peak-to-Valley surface errors at 633 nm.
- All performance parameters are evaluated at the NIRCam operating temperature of 35K. The prescription was designed for this temperature and then modeled for room temperature performance during the alignment phase. Each lens triplet will be tested as a group at the cold operating temperature prior to system integration.
- Each lens is designed to have 3 to 5 mm at the extreme radius allocated for roll-off for ease of mounting.
- Optical Substrate Materials are LiF, BaF₂, and ZnSe.
- The lenses vary in size from 58mm to 94mm diameter. Each lens maintains a minimum diameter to thickness aspect ratio of 8:1.
- Alignment Tolerances for each lens in a group are typically ± 50 micron decenter / defocus; ± 1 arcmin tip / tilt
- Surface Roughness requirements are $< 20 \text{ \AA}$ rms with a Scratch / Dig of 40 – 20.

- The ZnSe lenses in the shortwave and longwave camera groups each have mild aspheric surfaces on the concave side of the elements. The aspheric departure is relatively mild < 3 waves peak-to-valley.
- Extensive effort has been put into determining the index of refraction for each lens material. Index knowledge at operating temperature is accurate to less than 0.001.

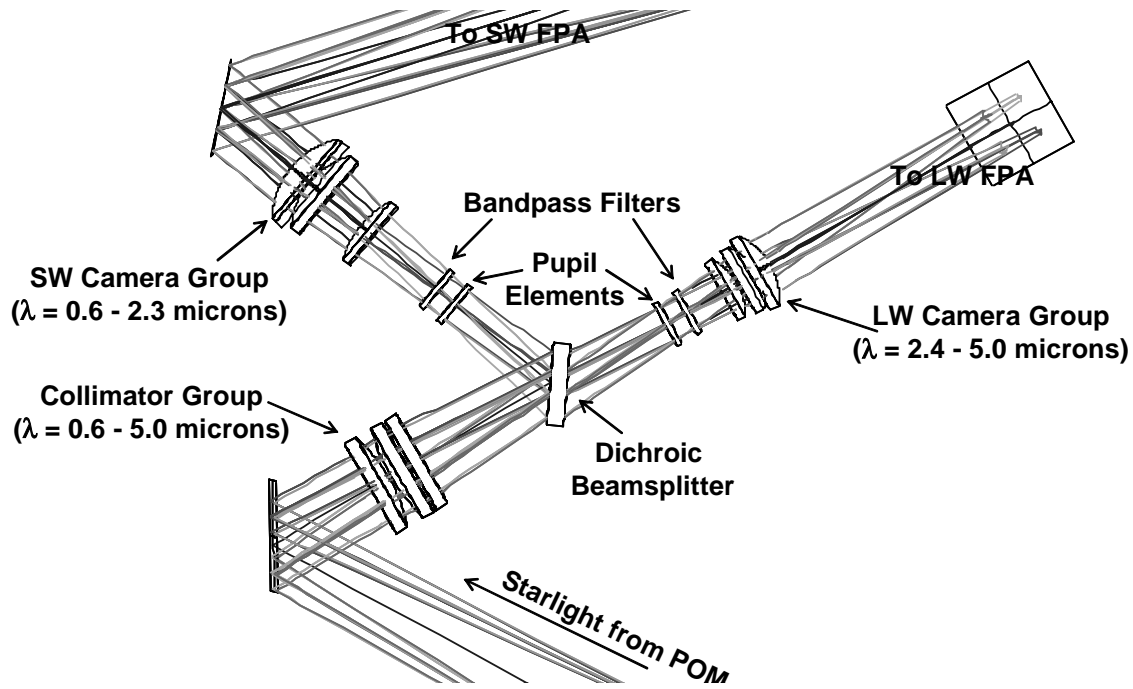
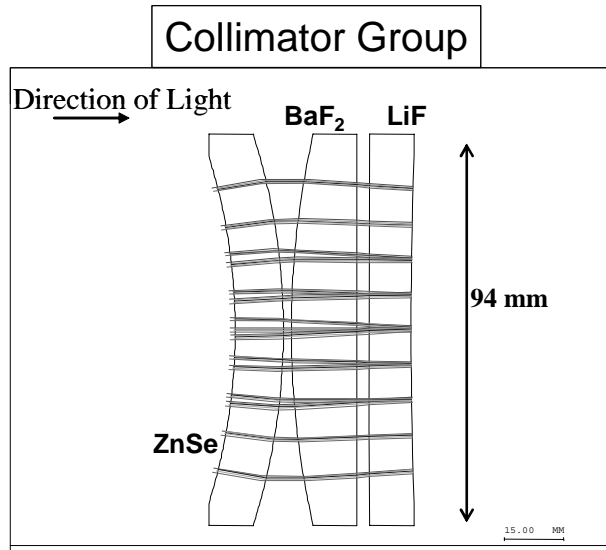


Figure 1: NIRCcam optical path

2. LENS DESIGN

Each NIRCcam bench consists of three lens triplets (see fig 1) 1) a collimator triplet, 2) a shortwave camera triplet and 3) a longwave camera triplet. All of the lenses are anti-reflection coated to improve performance and to protect the lens substrates. The collimator group is the largest of the lens triplets. It has nearly a 90 mm clear aperture and precise lens spacing which makes the mounts for this group particularly challenging. The high power of the BaF₂ element makes the ZnSe to BaF₂ spacing the most sensitive set to misalignment. The BaF₂ lens and the ZnSe lens are fast; refer to figure 2b for the lens prescription. Higher powered lenses have more inherent sensitivity to positioning errors. Therefore two high power elements next to each other must be carefully aligned so as not to induce aberrations beyond acceptable optical tolerances. The LiF is a weakly powered lens on the concave surface and is planar on the other side. The LiF element induces lesser aberration to the wavefront than the ZnSe or BaF₂ elements so the alignment of the LiF element is looser than that of the other lens elements. The collimator group has the tightest requirements for lens to lens alignment, 50 microns, and the tightest group position alignment of all the NIRCcam triplets. These positioning requirements are stringent because the collimator triplet is that part of the camera around which all other optical elements are referenced.

The shortwave and longwave camera triplets are similar in design. Each camera group has the LiF as the smallest element. The LiF and ZnSe elements are relatively fast lenses. The longwave triplets, with a 60mm clear aperture, are smaller in diameter than the shortwave triplets. Both camera triplets allow slightly looser lens to lens alignment requirements than the collimator triplet. Each camera triplet has of a mild aspheric surface on the ZnSe lens singlet. The ZnSe element is diamond turned to precisely match the lens specifications.



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

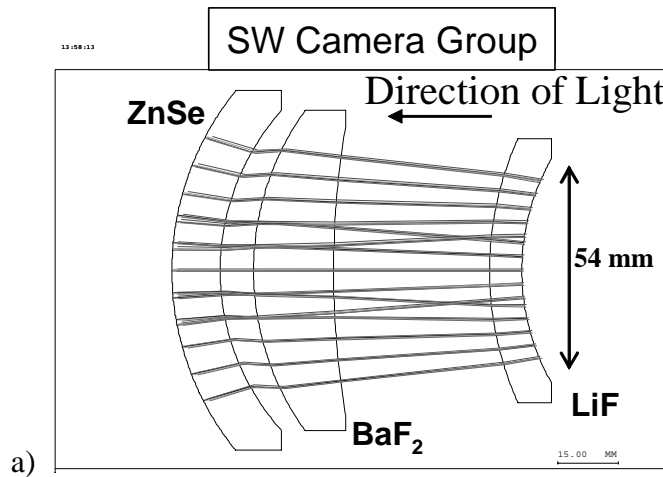
Element	Material	R1	R2	Thickness
SW1	LiF	64.98	93.47	8.0
SW2	BaF2	311.3	80.79	19.9
SW3	ZnSe	69.22	107.85	12.0

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

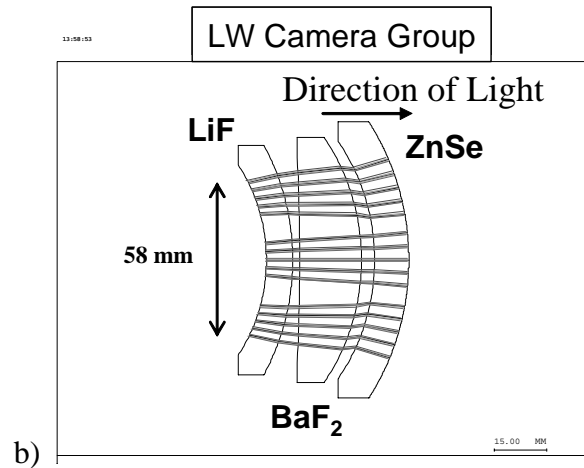
All dimensions in mm

Figure 2: a) Collimator lens triplet

b) lens prescription



a)



b)

Figure 3: a) Shortwave camera lens triplet

b) Longwave camera lens triplets

2.1 Aberrations

The NIRCams lenses have been designed to minimize optical aberrations over the JSWT field of view. The system is designed to be optimized at 2 microns. For peak-to-valley measurements a half a wave is the diffraction limit for the system. The optical path difference (OPD) is analyzed at each wavelength. The refractive optics for a broadband design forces some spread in the OPD. Except for the 600 nm wavelength the correction is within the diffraction limit. The OPD is on the order of a quarter-wave peak-to-valley for most wavelengths. The OPD shows that chromatic aberration is larger at the edge of the pupil and is well corrected at the center. The longwave path is better corrected than the shortwave path. Figures 4 and 5 show the OPD for the different colors of interest.

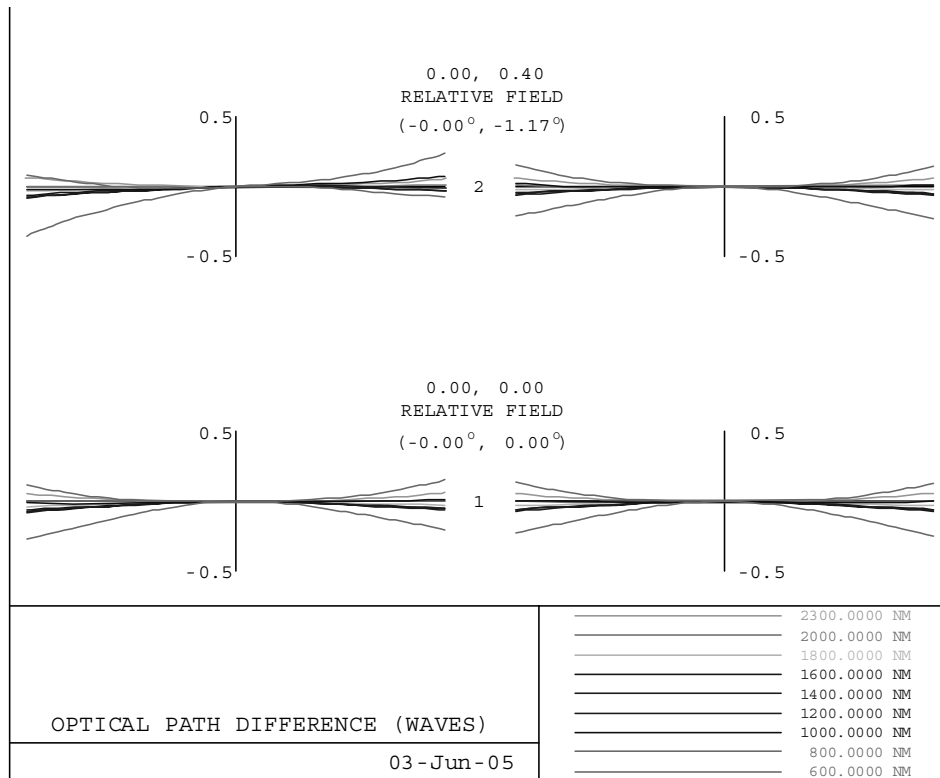


Figure 4: Shortwave path (collimator and shortwave triplet groups) optical path difference. Note that the largest OPD is at the shortest wavelength. Performance is optimized to meet the 2 micron design wavelength.

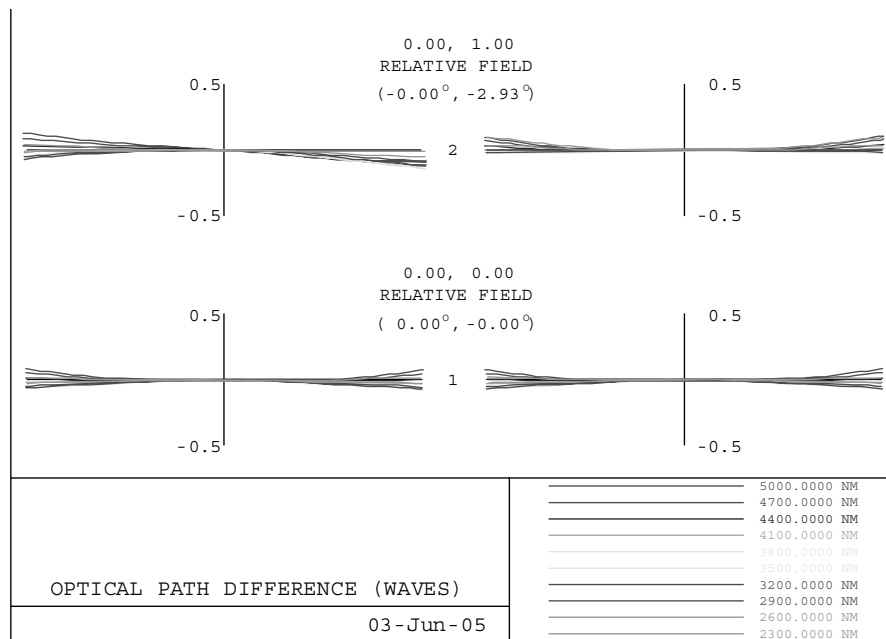


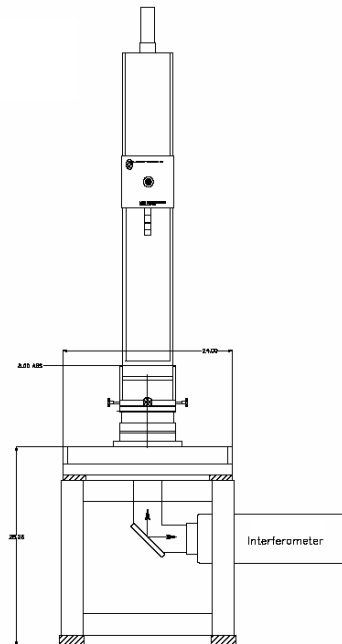
Figure 5: Longwave path (collimator and longwave triplets) optical path difference. Note OPD spread increases the at 5 micron edge of the wavelength band and decreases near the 2 micron design wavelength.

3. ASSEMBLY AND TEST PLANS

An engineering test unit (ETU) optical system, identical to the shortwave leg of the flight NIRC*am* imager, will be implemented. The ETU will be used to demonstrate the alignment and assembly process as well as the wavefront sensing capability of the JWST as a whole. Three sets of lenses will be made for the ETU for the shortwave and collimator group. This allows for 1 set of each lens for the ETU with 2 spare sets. For each lens in the collimator, shortwave and longwave triplets, 7 flight quality lenses will be manufactured resulting in 5 spare lenses per lens type.

Lens separation is a critical element in setting the power of the triplets. Separation is determined by the lens center thickness and the spacing between the singlets. Lens thickness may vary within the mechanical tolerance but the final thickness must be precisely known to accurately determine the air spacing between the lenses which sets the correct power for each lens. The lenses will be measured in thickness during manufacturing. The lens mounts will be lapped to meet the spacing requirement based upon final center thicknesses of the lens. This combined technique will set the lens spacing accurately. Spacing will be verified by measuring the power of the triplet interferometrically. To reduce the effect of gradual surface transmission losses all lens alignment, assembly and testing will occur within Class 1000 (or better) environments. Tests on prototype mounts determined that the lenses will retain centration with respect to the lens mount during cryogenic cycling and shake tests. This centration is best maintained by environmentally seating each lens into the mount prior to aligning the lens triplet. Each lens will be seated in the mount by being vibrated and cryo-cycled so the lens will settle into the mount

Figure 6: Laser Alignment Station. Key features are the laser and CDD reference, the rotary table to establish centration of the lens, and the interferometer that can take in-situ measurements during triplet alignment.



A precision lens alignment station made by Opto-Alignment Technology Inc will be used to align each lens in centration (fig 6). The station will consist of an air-bearing rotary table with a laser and CCD above the table. The reflection of the laser from the lens surface is used to align each lens to the laser input. When each lens is centered and flat relative to the input laser the beam will reflect back into the laser cavity. The lens triplets will not have tip or tilt adjustment capability. Tip/tilt requirements are met by requiring tight mechanical tolerances on the lenses and mounts. Room temperature wavefront tests will be required to verify alignment. Since the triplets are designed to correct for aberrations at an operating temperature of 35K, at room temperature the triplet WFE will be too great to be measured interferometrically. The aberrations will have to be corrected to test the lenses at room temperature. Triplets will use test (null) lenses to correct for these aberrations. When the aberrations are corrected the triplets with null lenses will be measured interferometrically to verify alignment. Figure 7 shows a null lens concept design paired with the collimating triplet. Lens triplet alignment is an iterative process with a goal to minimize required iterations. The NIRC*am* specification is written in terms of nm rms error thus it is desirable to measure the lenses interferometrically. The rotary table is made with a hole cut through the center through which wavefront measurements can be taken of the triplet in-situ with the laser alignment of the triplets. This allows the triplets to remain on the alignment station while they are measured interferometrically so as not to misalign

the triplets during the verification process. After each lens is aligned into a triplet the baseline plan is to deliver lenses to the next-level-of-integration for assembly into the ETU or flight base plate with performance verified after cryo-cycling and vibration testing. Calibration will be done using NIST traceable and commercial tools. The lens triplets will be tested at operating temperature for wavefront performance with the collimator and camera triplets as a pair. Testing the triplets in pairs simulates system level performance. The lenses and test mirrors will be positioned into the test set-up by referencing their position with a coordinate measuring machine (CMM) arm. Reference cubes on the lens cells will set the tip and tilt of each lens into the test configuration. The lenses are then placed into the cryogenic chamber and their positions are finely adjusted based upon interferometric and autocollimator results. During the cryo-cycle the optical wavefront of the lens groups will be measured interferometrically at multiple field points to verify performance. The

resulting interferograms will be compared to calculated interferograms from optical models of the test set-up to confirm that the correct alignment has been achieved.

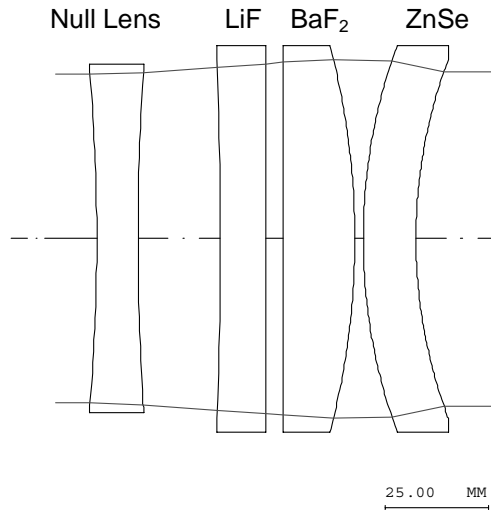


Figure 7: Example of null lens for the collimator triplet. A full aperture collimated beam from the interferometer fills the full aperture of all the lens elements and is an afocal beam out. The result is an rms=0.23 nm.

4. PROTOTYPE LENSES

In early 2004 multiple optical shops were contracted to make prototype evaluation lenses for NIRCcam. Since the lenses are critical to the success of NIRCcam and the desired materials have not been widely used it was considered essential to verify that the lenses could be manufactured within required tolerances. The requirements on the evaluation lenses in terms of size, radius, surface quality etc. are as rigorous as the flight designs. The key capabilities compared among the products from the various shops were: wavefront quality, radius of curvature, surface quality and roughness. The surface qualities are critical since these features have large impacts upon system scattered light. Several shops had difficulty making compliant lenses out of LiF and BaF₂. However one vendor was found to meet all requirements thus the lenses were deemed manufacturable. The successful manufacture of the prototype lenses validated the selection of these exotic substrate materials. Figure 8 shows the results for the surface quality for the evaluation lenses made by Optical Solutions Incorporated. Figure 9 shows a prototype LiF lens and a prototype triplet assembled in an early candidate mount design. Figures 10 and 11 show that good wavefront performance is maintained for a LiF element after vibration testing.

Material	Parameter	Requirement	Achieved
LiF	Surface Quality	$< 0.022 \lambda$ rms	0.016λ rms
	Roughness	$< 20 \text{ \AA}$ rms	15.7 \AA rms
BaF ₂	Surface Quality	$< 0.022 \lambda$ rms	0.017λ rms
	Roughness	$< 20 \text{ \AA}$ rms	8.0 \AA rms
ZnSe	Surface Quality	$< 0.022 \lambda$ rms	0.015λ rms
	Roughness	$< 20 \text{ \AA}$ rms	14.5 \AA rms

Figure 8: NIRCcam prototype lenses critical manufacture results. These lenses all met the manufacturing requirements.

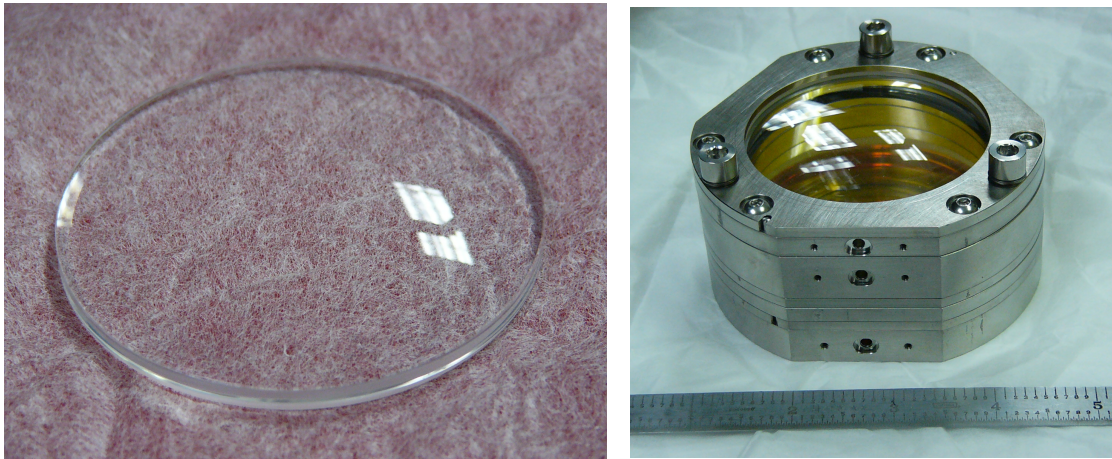


Figure 9: a) Photograph of 70 mm diameter prototype LiF lens b) assembled prototype evaluation lens triplet. The soft LiF lenses were particularly challenging to build mount.

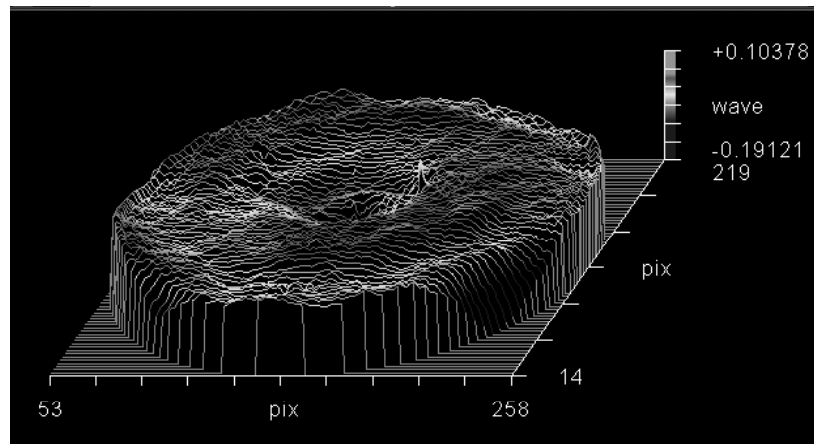


Figure 10: Oblique plot for unmounted prototype LiF lenses after vibration test. Lens diameter is 70 mm with a 65 mm clear aperture. This is tested at 633 nm wavelength.

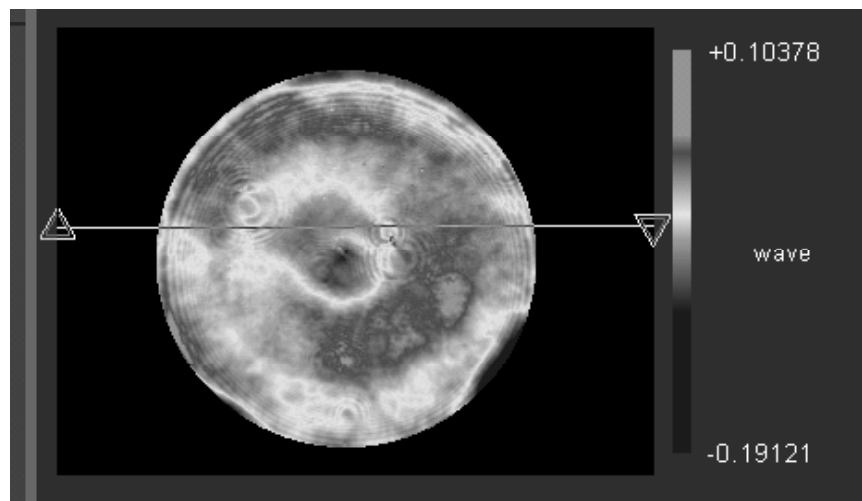


Figure 11: Wavefront measurement for unmounted prototype LiF lenses after vibration test. Clear aperture WFE meets specified requirements.

5. CONCLUSION

The design of the NIRCam optical system demands lenses that push the limits of fabrication to manufacture them. The selected materials are challenging to work with but extensive analytical results show they are the best combination of materials for chromatic correction over the long wavelength requirements on NIRCam. The results from the fabrication of the evaluation lenses clearly illustrate that lenses of the required quality can be manufactured. All of this information has led to the conclusion that the lens design path has been optimized for the NIRCam instrument.

6. REFERENCES

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