

Compact, lightweight, and athermalized mirror and mount for use on JWST's NIRCam instrument

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ABSTRACT

This paper describes the design of the compact, lightweight, and athermalized Pick Off Mirror and Mount. Structural and thermal analysis as well as actual prototype testing are also described.

Keywords: JWST, James Web Space Telescope, NIRCcam , Pick Off Mirror, POM, POMA, mirror, mount, athermal, cryogenic

1. INTRODUCTION

NIRCcam is an imaging instrument that will make up part of the science instrument complement of the James Webb Space Telescope. JWST will possess an aperture with ten times the collecting area of the Hubble Space Telescope. JWST will have a broadband IR capability that, from the vicinity of Lagrange 2 (nine hundred thousand km from earth), will allow a view into the distant history of galaxy formation. The instrument will be required to furnish high-quality infrared imaging performance while operating in a challenging cryogenic (37 Kelvin) space environment over a minimum 5-year mission.

Two optical modules, mounted back to back, make up the NIRCcam instrument. Each module (Figure 1) contains a short wavelength (SW) and long wavelength (LW) path. The instrument will be mounted to the Integrated Science Instrument Module (ISIM) of the spacecraft with kinematic mounts.

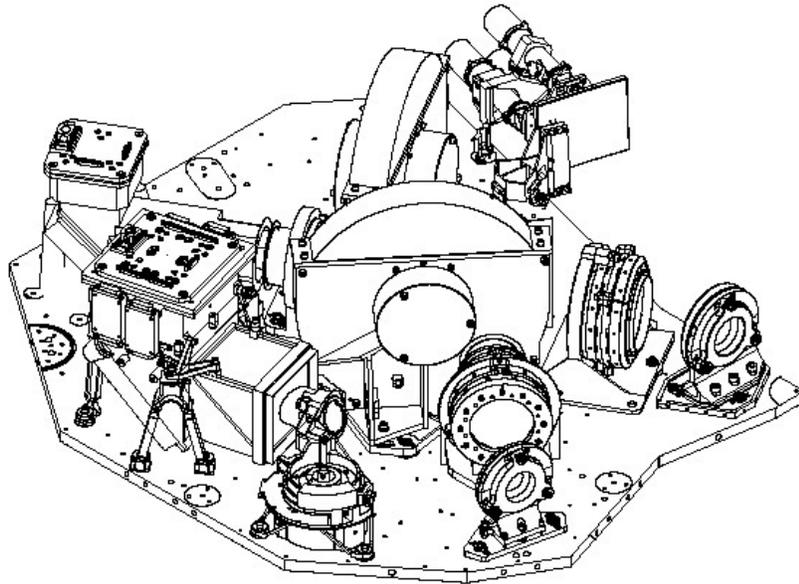


Figure 1. NIRCcam Module A (shown without baffles)

2. PICK OFF MIRROR ASSEMBLY DESIGN

Each module includes one Pick Off Mirror, which is mounted to the focus and alignment mechanism (FAM) as shown in Figure 2. The Pick-off Mirror (POM) is a mounted, spherically concave mirror that reflects the starlight from the JWST optical telescope element (OTE) into the NIRCam Instrument.

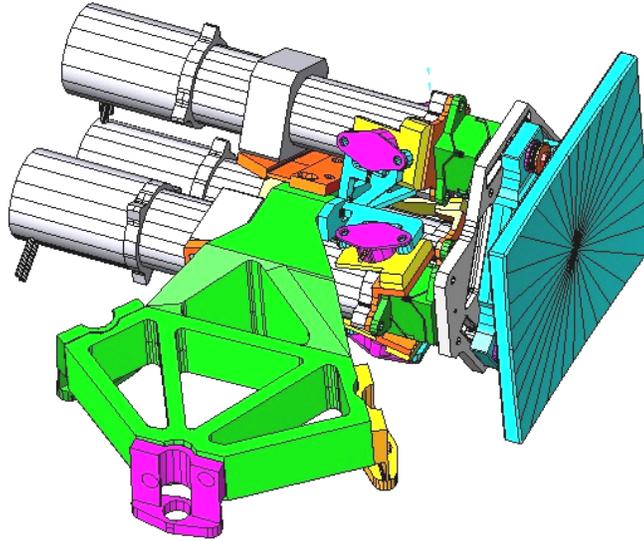


Figure 2. Focus and Alignment Mechanism

Table 1. Driving Requirements

Element	Title	Description	Requirement
POM	First-Mode Frequency	POM subassembly	> 150 Hz
	Wavefront Quality	POM subassembly WFE	<0.063λ rms
	Mass	POM subassembly mass	< 0.6 kg
	Clear Aperture	Central clear aperture	93.5 x 113.7 mm

The POM (Figure 3) is made from fused silica. It is a monolithic glass structure consisting of a nominal 6mm face sheet, a hub, three tabs, and a cutout in the central hub.

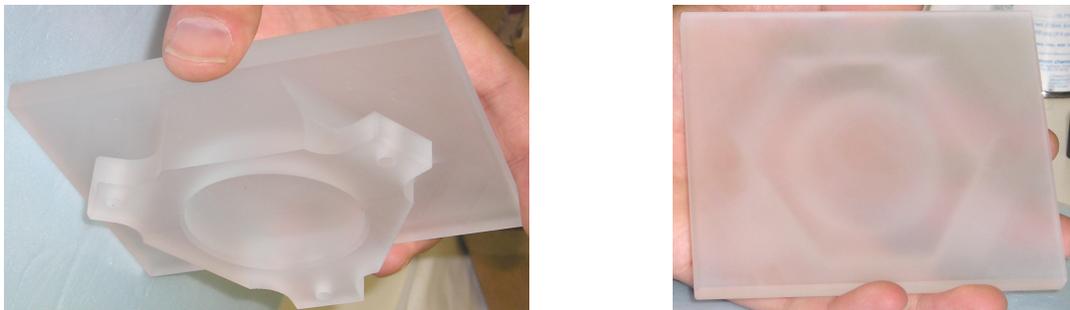


Figure 3. Pick Off Mirror (Uncoated)

A titanium delta plate (shown in Figure 4), containing integral flexures, interfaces between the mirror and the FAM. The flexures on the delta plate have one single degree of freedom, allowing relative radial expansion/contraction of the low dl/L fused silica mirror and the high dl/L titanium plate, while minimizing stresses in the two parts. As a secondary benefit, the flexures allow a pre-defined radial alignment adjustability between the mirror holes and the holes in the plate. In three places, titanium shoulder bolts (Figure 5) secure the delta plate to the mirror. A close fit diameter titanium sleeve fits over the shoulder of the bolt. The sleeve's length determines a specific preload using a stack of bellville washers. The bellville washers are confined between two flat washers, one titanium and the other PCTFE. Since its modulus is less than titanium, PCTFE is used to reduce contact stresses on the glass.

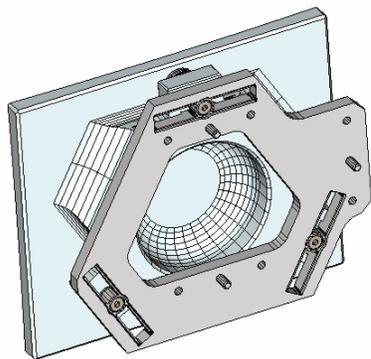


Figure 4. Pick Off Mirror Assembly (POMA)

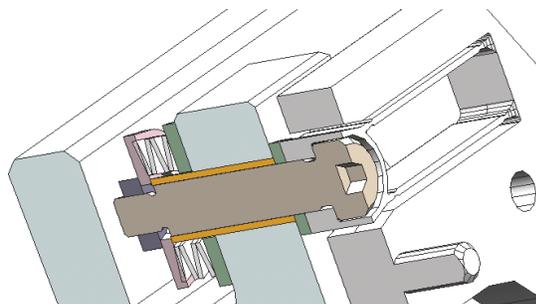


Figure 5. Cross Section of Clamp Mechanism

Besides designing for the cryogenic environment, mass and envelope size are limiting. The optic is lightweighted approximately 40%, while the mounted optic is only 30mm thick, from front to back. The lightweighted mirror has a central hub and a backside cutout to remove additional mass. This approach to optic and mount design results in a compact and nearly athermal mount design, allowing the mount surrounding the mirror to shrink while the low expansion material mirror changes dimension very little.

3. POMA STRUCTURAL ANALYSIS

The mirror and the delta plate were modeled with second order tetrahedrons as shown in Figure 6. The surface of the mirror is meshed with a thin layer of shell elements in order to extract 5 degree of freedom displacements for surface distortion analysis (solid elements have only 3 degrees of freedom). Interfaces were connected with rigid bar elements. Lastly, the flexures on the delta plate were modeled with shell elements. The delta plate attaches to the FAM at three locations with one pin and two fasteners at each location. The FAM has kinematic flexures in the linear actuators, which allow each FAM interface to take axial and tangential loads only. Bending, torsion, and radial degrees of freedom are free. Boundary conditions were applied to the interfaces such that the pins take tangential shear load and the fasteners take only axial load. All of the models presented in this paper were meshed in I-DEAS Master Series version 9 and exported through a translator for MSC/NASTRAN version 2001. Analysis runs and model checks were performed with NX/NASTRAN version 2.0.

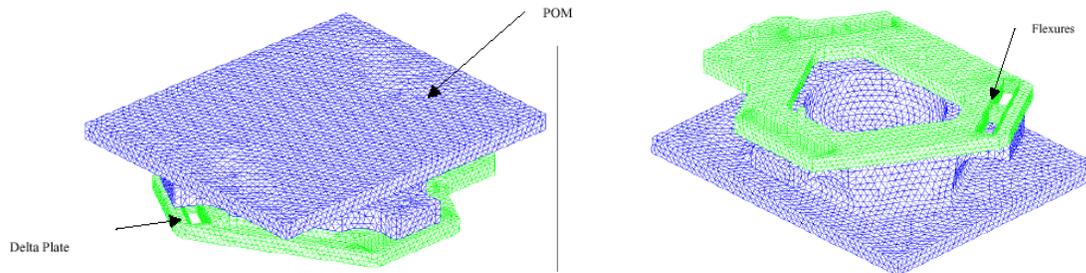


Figure 6. Finite Element Model

Distortion Load Cases:

The following load cases were evaluated for their affects on the mirror surface distortion:

- **Cool Down:** Cool down from room temperature (293K) to cryo (35K), which results in 1.4 Newton flexure force.
- **1g in X:** Lateral gravity sag.
- **1g in Y:** Lateral gravity sag.
- **1g in Z:** Axial gravity sag.
- **Fastener Preload:** 68 Newton preload in fasteners attaching mirror to delta plate flexures.
- **Flexure Preload:** 127 micron enforced displacement at flexures due for assembly tolerance that results in 4.6 Newton flexure force.
- **Side Thermal Gradient:** A side-to-side operational thermal gradient of 0.25K.
- **Top Thermal Gradient:** A top-to-bottom operational thermal gradient of 0.25K.
- **FAM Load (6 cases):** FAM flexure induced distortion on delta plate when FAM is driven to 1 degree tilt with 4.0 N-m/rad FAM flexure stiffness.

The modal analysis results in Table 2 show that the assembly is very stiff and the first mode frequency of 454 Hz is well above the 150 Hz goal.

Table 2. Modal Analysis Summary

Mode	Frequency (Hz)	Description	Modal Effective Mass					
			ux	uy	uz	rx	ry	rz
1	454	Shear	29%	11%	10%	3%	11%	0%
2	512	Shear	21%	57%	0%	0%	0%	8%
3	677	Despace	27%	7%	50%	2%	13%	1%
4	846	Tip/Tilt	6%	1%	6%	8%	36%	31%
5	891	Tip/Tilt	14%	1%	17%	22%	20%	18%
6	1032	Tip/Tilt	0%	20%	0%	43%	4%	40%

The following factors of safety were used in the analysis:

- 3.0 Glass Ultimate
- 10.0 Fatigue Fracture
- 1.4 Metallic Ultimate
- 1.25 Metallic Yield

Table 3 shows that all of the margins are positive and acceptable.

Table 3. Margins of Safety

Component	Load Case	Material	Failure Mode	Allowable	Working Load	Safety Factor	Margin of Safety
Flexure	Launch	6-AL-4V Titanium	Buckling	256 N	27 N	1.4	5.77
Flexure	Launch	6-AL-4V Titanium	Tension	827 MPa	182 MPa	1.25	2.64
Flexure	Cool Down	6-AL-4V Titanium	Tension	827 MPa	116 MPa	1.25	4.70
Flexure	Launch	6-AL-4V Titanium	Tension	827 MPa	103 MPa	1.25	5.42
FAM Interface Pin	Launch	6-AL-4V Titanium	Shear	572 MPa	20 MPa	1.4	19.43
FAM Pin Hole	Launch	6-AL-4V Titanium	Bearing	1220 MPa	9 MPa	1.25	102.83
Preload Bushing	Launch	6-AL-4V Titanium	Compression	827 MPa	19 MPa	1.25	33.82
Preload Bushing	Launch	6-AL-4V Titanium	Buckling	6046 MPa	19 MPa	1.4	226.29
POM Attachment Tabs	Launch	SiO2	Bearing	1140 MPa	3 MPa	3	125.67
POM Attachment Tabs	Launch	SiO2	Tension	54 MPa	3 MPa	10	0.80
POM Facesheet	Launch	SiO2	Tension	54 MPa	1 MPa	10	4.40
POM Facesheet	Cool Down	SiO2	Tension	54 MPa	0.3 MPa	11	15.36

4. POMA THERMAL ANALYSIS

Thermal analysis was performed on the POMA to determine the maximum thermal gradients (Figure 7) for thermal stress calculations during cooldown and at operating temperature. In addition, thermal gradients were determined between the POMA and OBA for contamination prevention reasons. For accurate results, the POMA model was integrated with the FAM model. Radiative properties of the mirror and delta plate were also inputted into the model.

The maximum gradient during NIRCcam operation is very small, 0.25 K

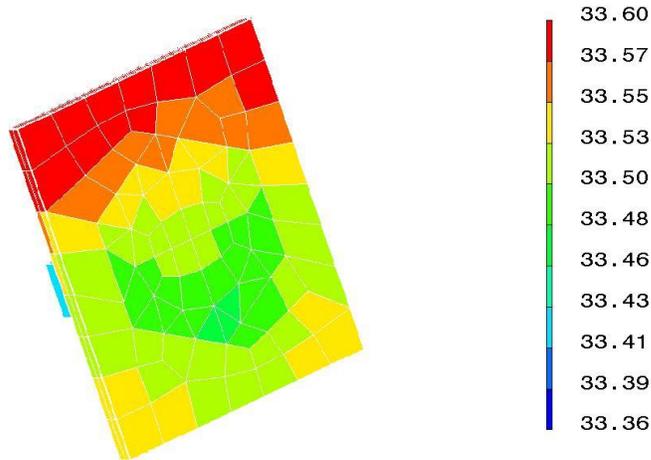


Figure 7. POMA gradient during NIRCcam operation

During cooldown (Figure 8) the front of the mirror could remain much colder than the rest of the NIRCcam instrument. The result would be that the mirror surface could act as a cold trap, collecting ice from the rest of the instrument. To combat this effect, a heater is placed on the supporting delta plate. The heater is powered on during cooldown. The delta plate responds to the heater and effectively turns into a radiative surface. The plate radiates to the back of the mirror, heating up the mirror and keeping the mirror surface temperature at or above the bench temperature. This eliminates the potential contamination issues.

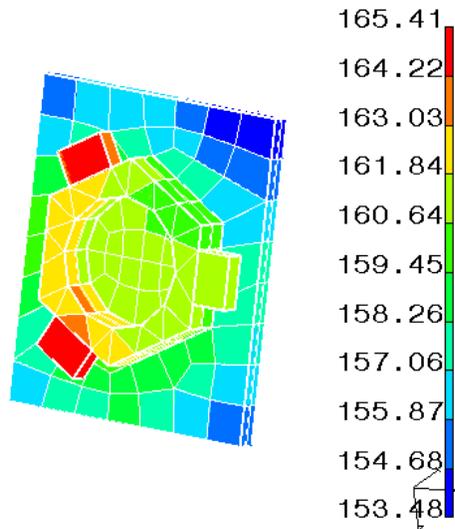


Figure 8. POMA (with heater) gradient during NIRCcam cooldown

5. POMA OPTICAL/THERMAL/MECHANICAL ANALYSIS

The mesh containing the thermal gradient, and is mapped onto the structural model. The combined model is used to determine the total cooldown distortion as well as the distortion caused by thermal gradients at operating temperature. The following surface distortion summary in Table 4 shows how nearly athermally the assembly behaves. Figures 9 and 10 show the associated distortion and loads. All of the predicted errors (with the exception of gravity, non-operational) are on the single digit nanometer rms level.

Table 4. Surface Distortion Summary

Source	Predicted Error (nm RMS)	Allocation (nm RMS)
Cool Down (1.35 N Flexure Force)	2	17
1g Sag in X	20	22
1g Sag in Y	16	22
1g Sag in Z	15	22
Mechanical Preload (68 N Fastener Force)	2	20
Mechanical Preload (127 micron Flexure Displacement)	7	20
0.25K Side to Side Thermal Gradient	0	5
0.25K Top to Bottom Thermal Gradient	4	5
FAM Flexure Load at Flexure 1 (.1 N-m)	3	TBD
FAM Flexure Load at Flexure 2 (.1 N-m)	3	TBD
FAM Flexure Load at Flexure 3 (.1 N-m)	0	TBD
FAM Flexure Load at Flexure 1 (.1 N-m)	1	TBD
FAM Flexure Load at Flexure 2 (.1 N-m)	1	TBD
FAM Flexure Load at Flexure 3 (.1 N-m)	0	TBD

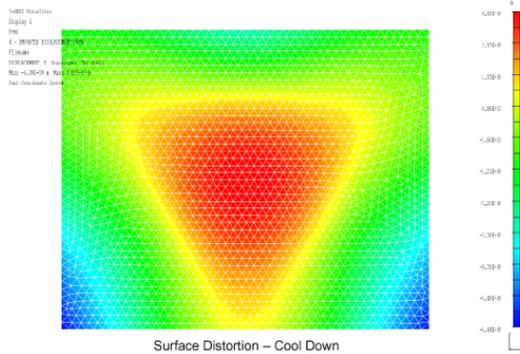


Figure 9. Cool Down Distortion

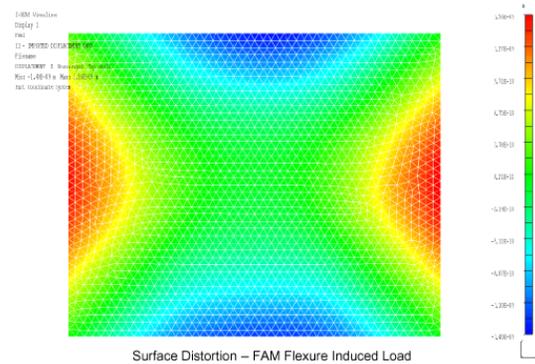


Figure 10. FAM Flexure Induced Load

6. PROTOTYPE

A POMA prototype (Figure 11) was manufactured, assembled, and tested in order to reduce risks and to build confidence in the areas of manufacturing, launch environment performance, and thermal environment performance. The prototype POM was manufactured by Nu-Tek Precision. The prototype assembly underwent a random vibration to proto-flight level (14grms for one minute per axis). The assembly was then placed in a cryogenic vacuum chamber and the wavefront was measured near operating temperature. The assembly was thermally cycled three times and the wavefront was measured after each cycle.

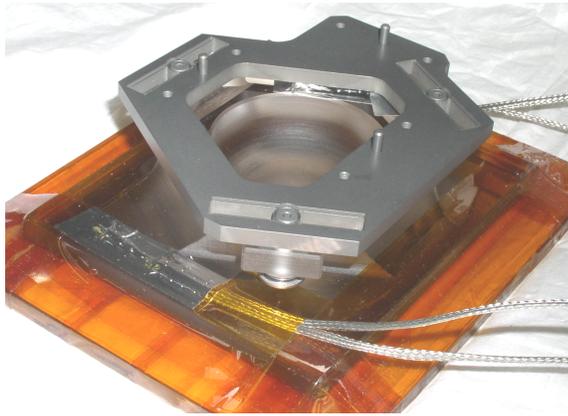


Figure 11. Prototype POMA (shown with protective cover)

7. LESSONS LEARNED

An early design of the POMA included bipod flexures that were to be bonded to the mirror's back hub. High stresses would have developed at the bonded interface after cool down, due to drastically different dL/Ls . These predicted stresses would lead to significant mirror surface deformation. A different iteration used ball bearings in vee grooves to account for small motions during cool down. For small motions, ball bearings tend to have hysteresis and as a result this configuration was shown to be unpredictable by analysis. Finally, clamped flexures were chosen and through analysis they were shown to be repeatable causing minimal surface distortion.

In analysis, small changes to the FEM mesh, boundary conditions, loads, and material properties sometimes have a large effect on the outcome. In this case, the sensitivity of the friction factor between PCTFE and fused silica has a significant impact on the results. Knowledge of these friction factors can be tricky, but should be measured.

8. SUMMARY

The POMA uses geometric features, flexures, materials, and careful consideration of preloading and mount points in order to perform at or better than the required level after severe launch loading and then a dramatic cooldown from room temperature to 35K.

Manufacturing considerations and a combined optical/thermal/mechanical model all contributed to a good design that meets requirements. The design of the mirror and mount are proven through correlation between the predicted performance, through analysis, and the tested performance with the prototype.

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