The Center of Curvature Optical Assembly for the James Webb Space Telescope Primary Mirror Cryogenic Optical Test

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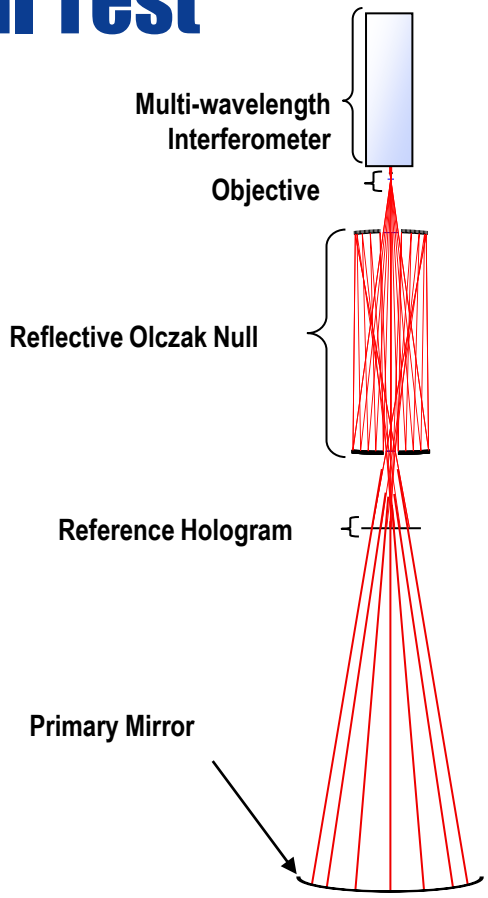

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Acknowledgements

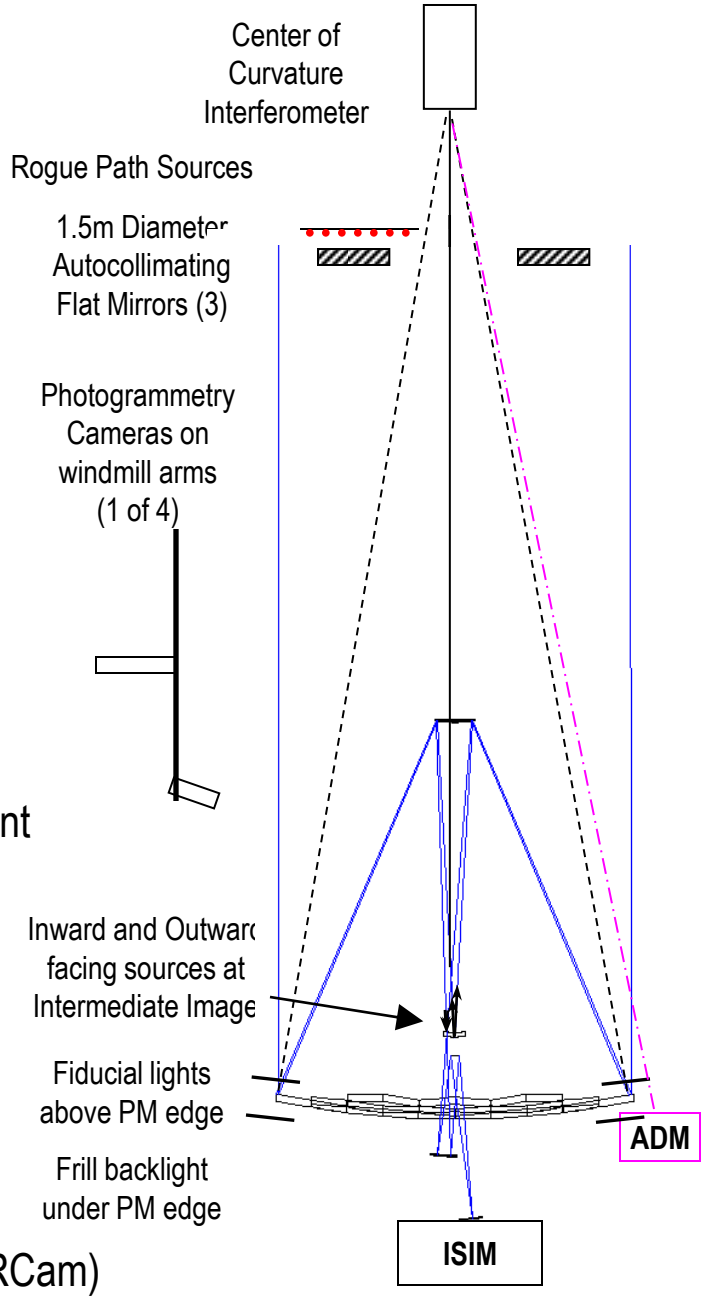
- Gene Olczak – Lead Optical Designer
- Cormic Merle, Tom Dey, John Hannon, Art Jensen - Optical Design, analysis and configuration.
- Tony Whitman, Mark Waldman, Aaron Peer- Other contributors

Agenda

- **Review of JWST cryo-optical tests at Johnson Space Center**
- **Center of Curvature Optical Assembly Introduction and Subsystems**
  - Multi-Wave Interferometer
  - Coarse and Fine Alignment Systems
  - Null design and assembly
  - Calibration hologram
- **JWST Primary Mirror Testing**
- **Conclusion**

Key Measurements

- **Center of Curvature interferometry**
  - Demonstrate PM phasing
  - Measure PM WFE
  - Read actuator positions when aligned
- **Photogrammetry**
  - Positional measurement of PM-SM-AOS alignment (independent of optical path)
    - » Aligns SM
- **Half Pass Imaging (all SI's)**
  - Imaging on all SI's provides AOS-ISIM interface alignment
    - » Phase retrieval WFE and image centroid positions
- **Pass and a Half Imaging (all SI's)**
  - Demonstrates and crosschecks end-to-end optical path (phase retrieval WFE on all SI's)
- **Pupil Imaging (NIRCam-PIL)**
  - Measures coalignment of 3 pupils (OTE, FSM Mask, NIRCam)



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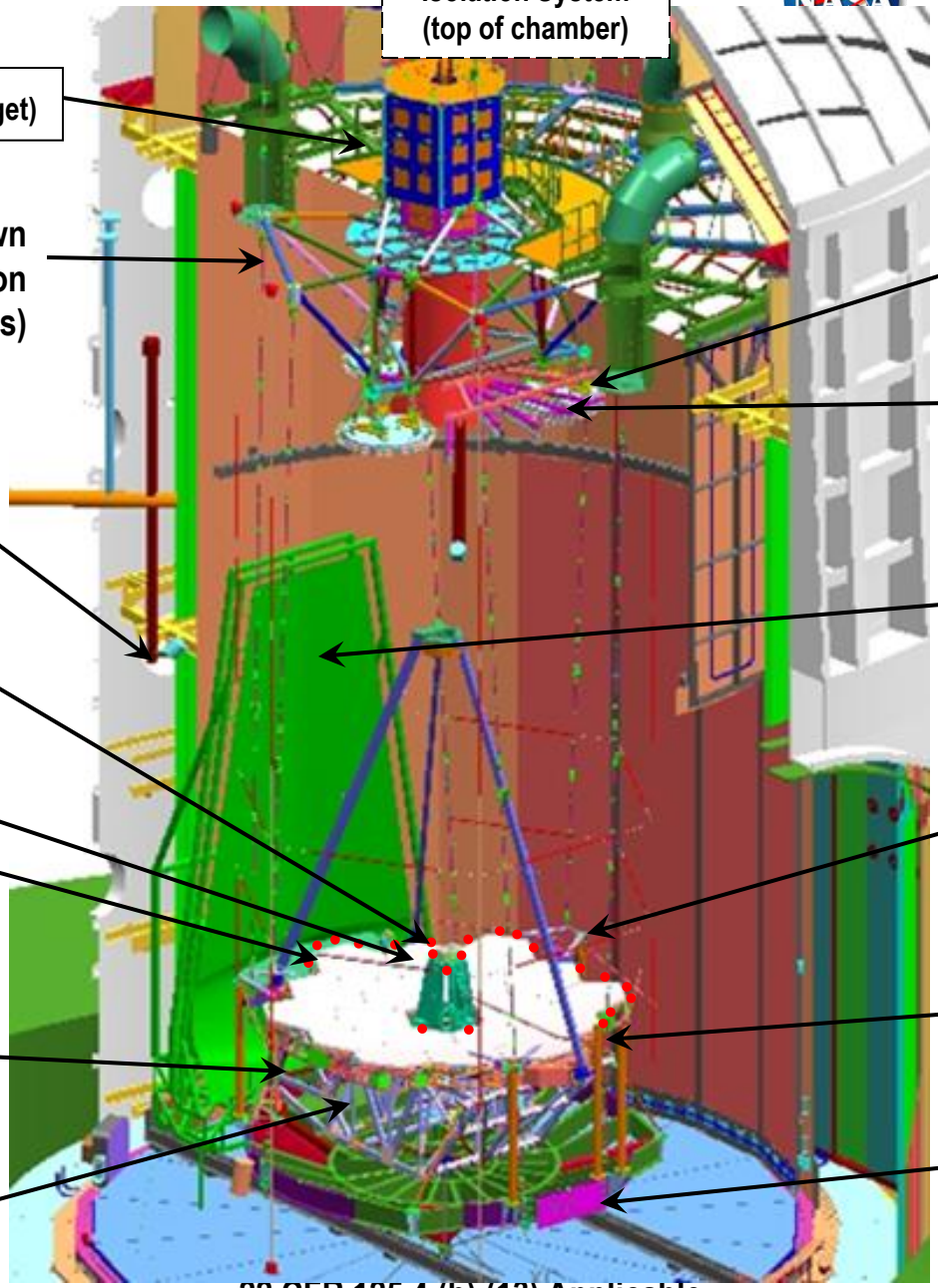
JSC Optical Test GSE



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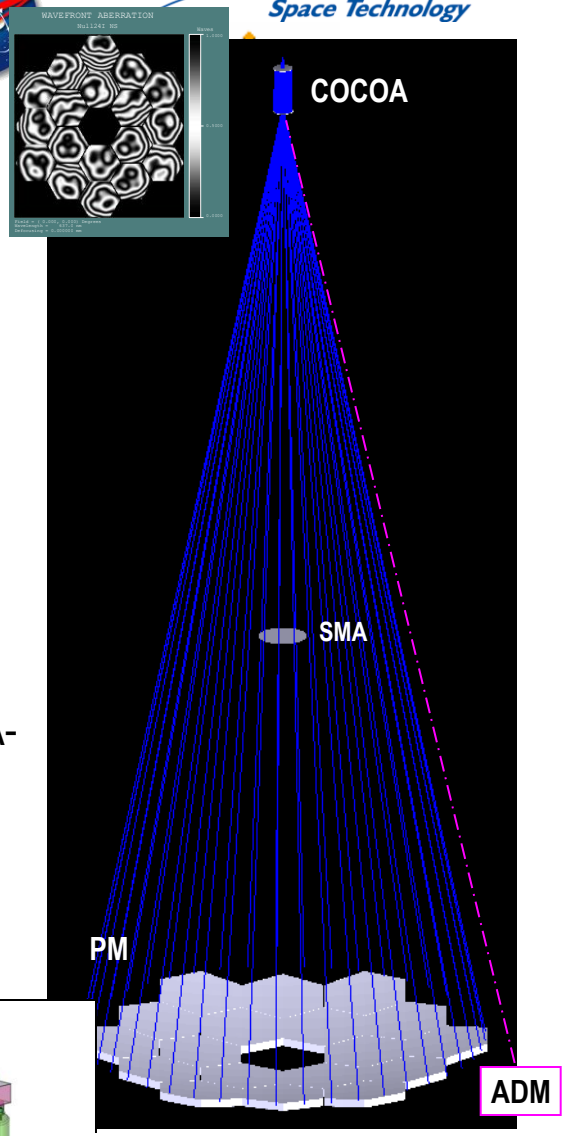
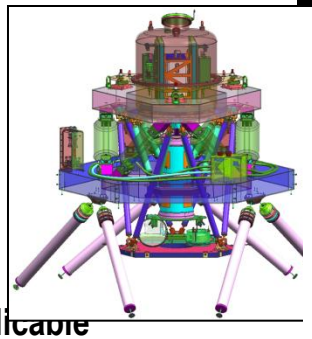
PM Center of Curvature Interferometry

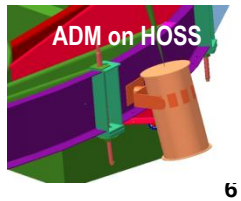
- **Full aperture COC interferometric test with null lens**
  - PMSAs are aligned and phased based on this test
  - Final PM WFE measured by this test
  - Test monitors PM figure change during temperature change (Thermal Distortion Test)

- **COCOA features provide alignment and test capabilities**
  - Alignment cameras provide capture of PMSA images ("alignment mode")
  - Multi-wavelength interferometer (2λ, variable separation) measures PMSA-PMSA piston up to 1 mm and high accuracy WFE of phased PM
    - » Many interferograms averaged for accuracy with dynamic variation
  - In-situ WFE calibration provided by on-board hologram
  - Includes achromatic all-reflective null
  - COCOA always at room temperature
    - » Shutter to 20K region
  - Separate Absolute Distance Meter (ADM) measures 16m distance for proper RoC





Center of Curvature Optical Assembly



CoCOA System Introduction

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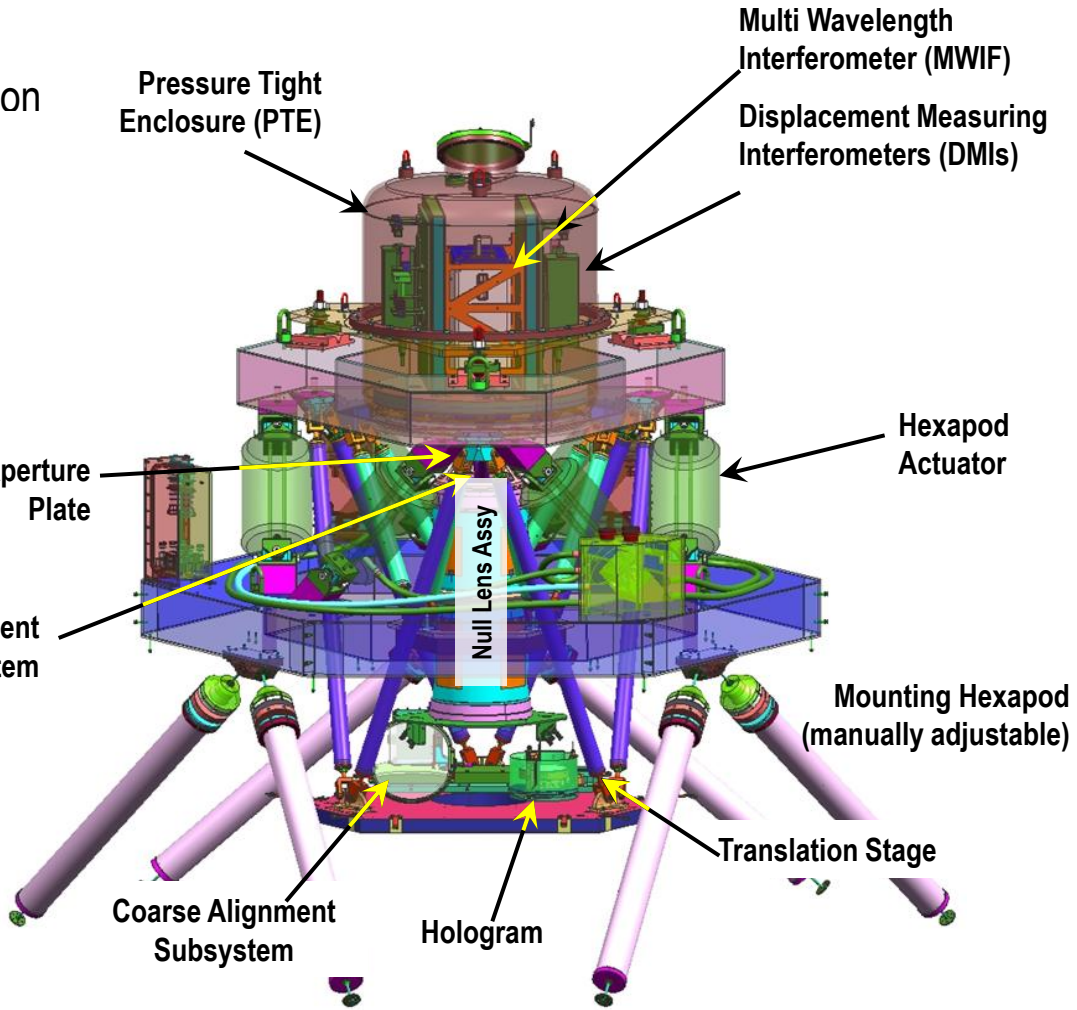
COCOA Subsystems

PMSA capture and "stacking"

- **Coarse Alignment Camera**
  - Includes incoherent PM illumination
- **Fine Alignment Camera**
- **Multi Wavelength Interferometer**
- **Reflective Null Lens Assembly**
- **Calibration CGH**
- **6DOF Hexapod position adjustment**
  - Ability to pivot about COC and PMV
- **Distance Measuring Interferometers (DMIs)**
  - Monitor axial distance change during thermal distortion testing



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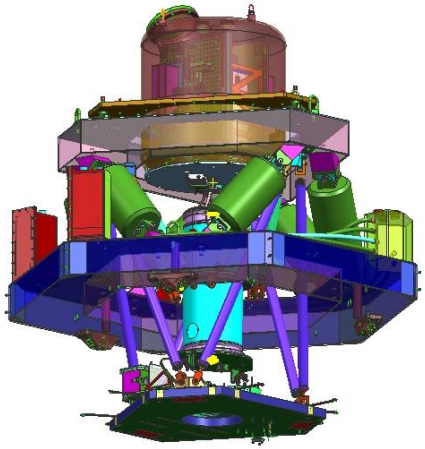
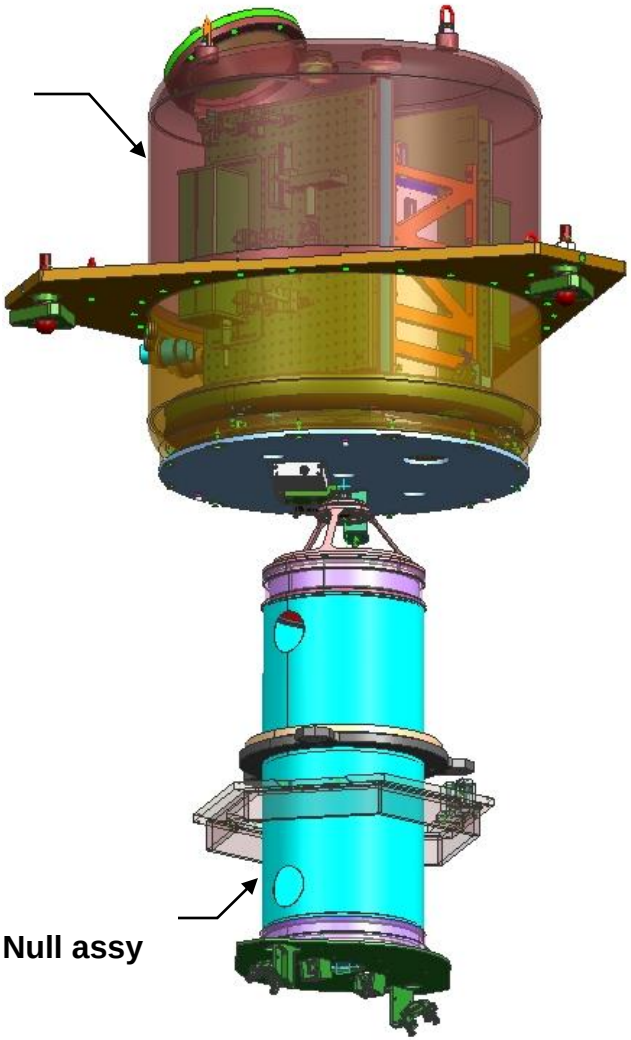
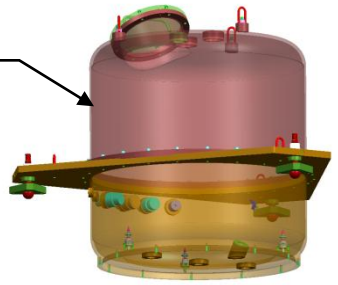
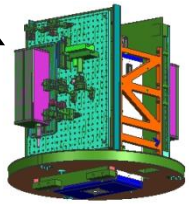
Components

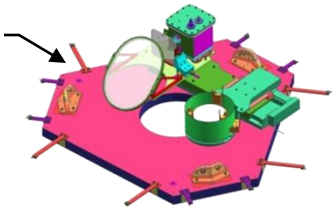


COCOA without thermal panels and main mount struts









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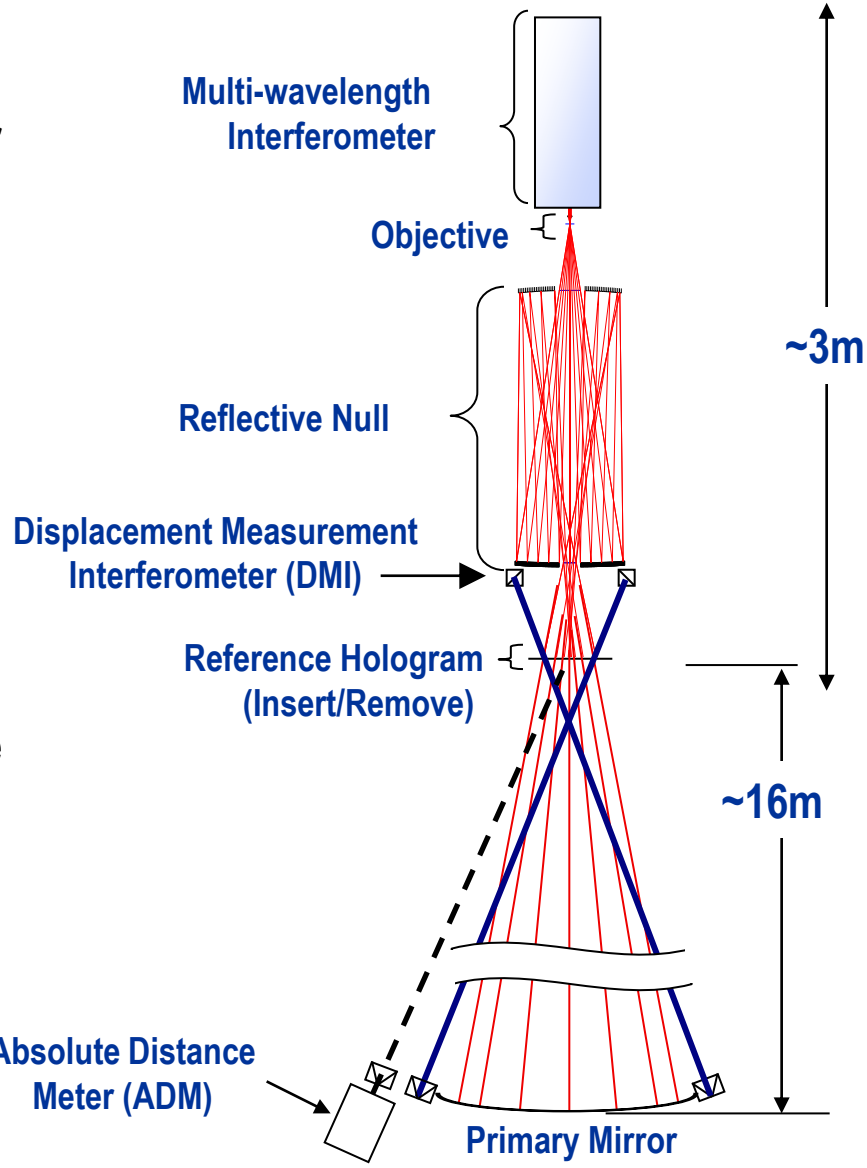
COCOA Optical Schematic

- **COCOA Objective: Measure 6.6 m segmented near-parabolic PM (RoC = 15.880m) from center of curvature (R/2.4 test)**
- **Multiwavelength interferometer provides capability to measure the relative piston between segments**
- **All-reflective Olczak Catoptric Null selected as optimum solution over interferometer spectral range**
  - The refractive objective is designed to be achromatic over the operating wavelength of the MWIF (660-687 nm)
  - Null design: US Patent 7,336,370 (objective patent pending)
- **Interferometer wavefront is calibrated at its fundamental wavelength (687 nm) via reflective Computer Generated Hologram**
  - CGH slides into beam for calibration and out of beam for PM testing



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Multi-Wave Interferometer

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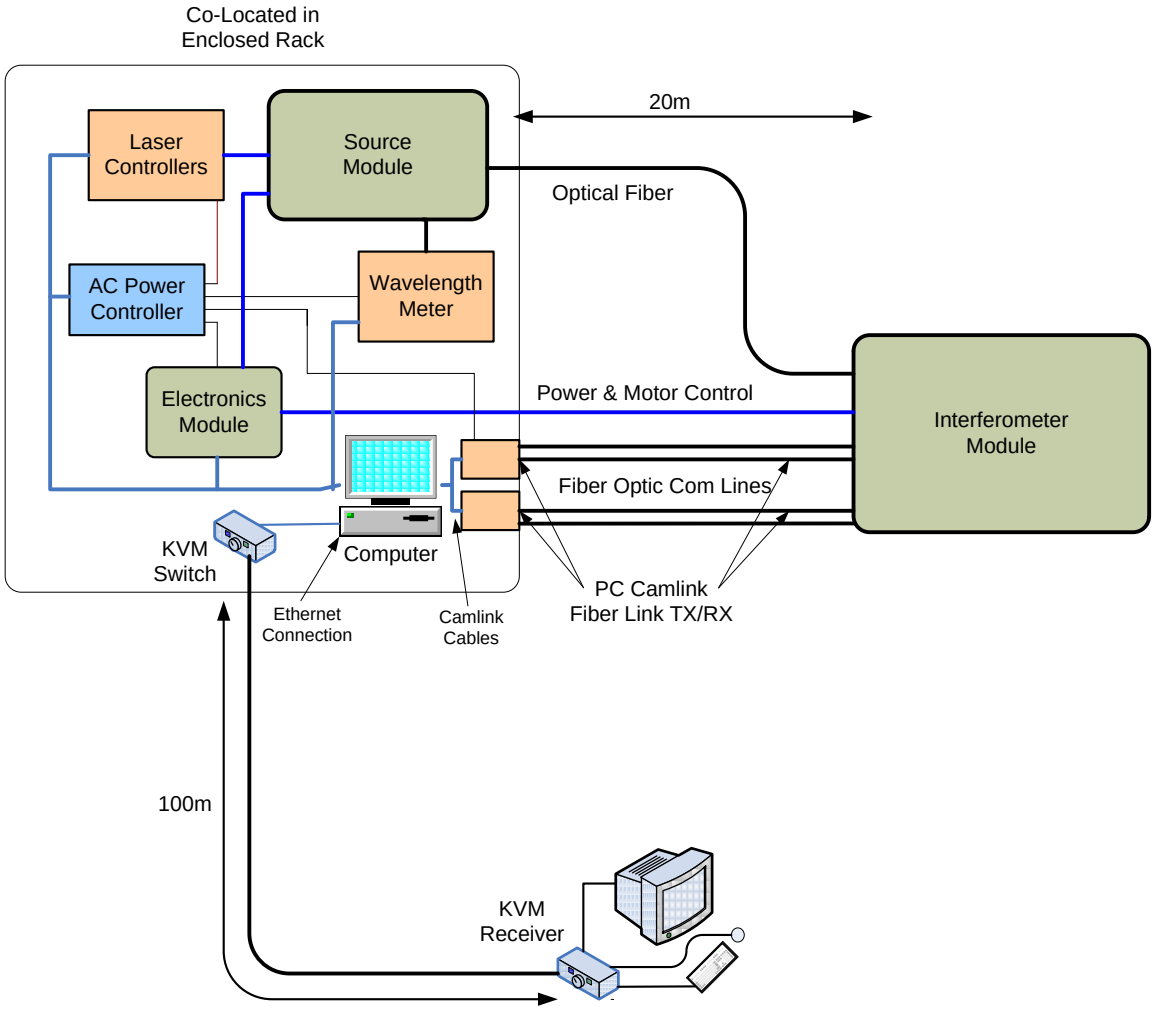
MWIF Architecture



- Modular Fiber Fed Source Module
- Redundant Conductors in Cables Connecting the Electronics Module to the Interferometer Module.
- Fiber Optic Extension of Frame-grabber Communication
- KVM Switch for Remote Operation from 100m
- Support Electronics Co-located in an Enclosed Rack

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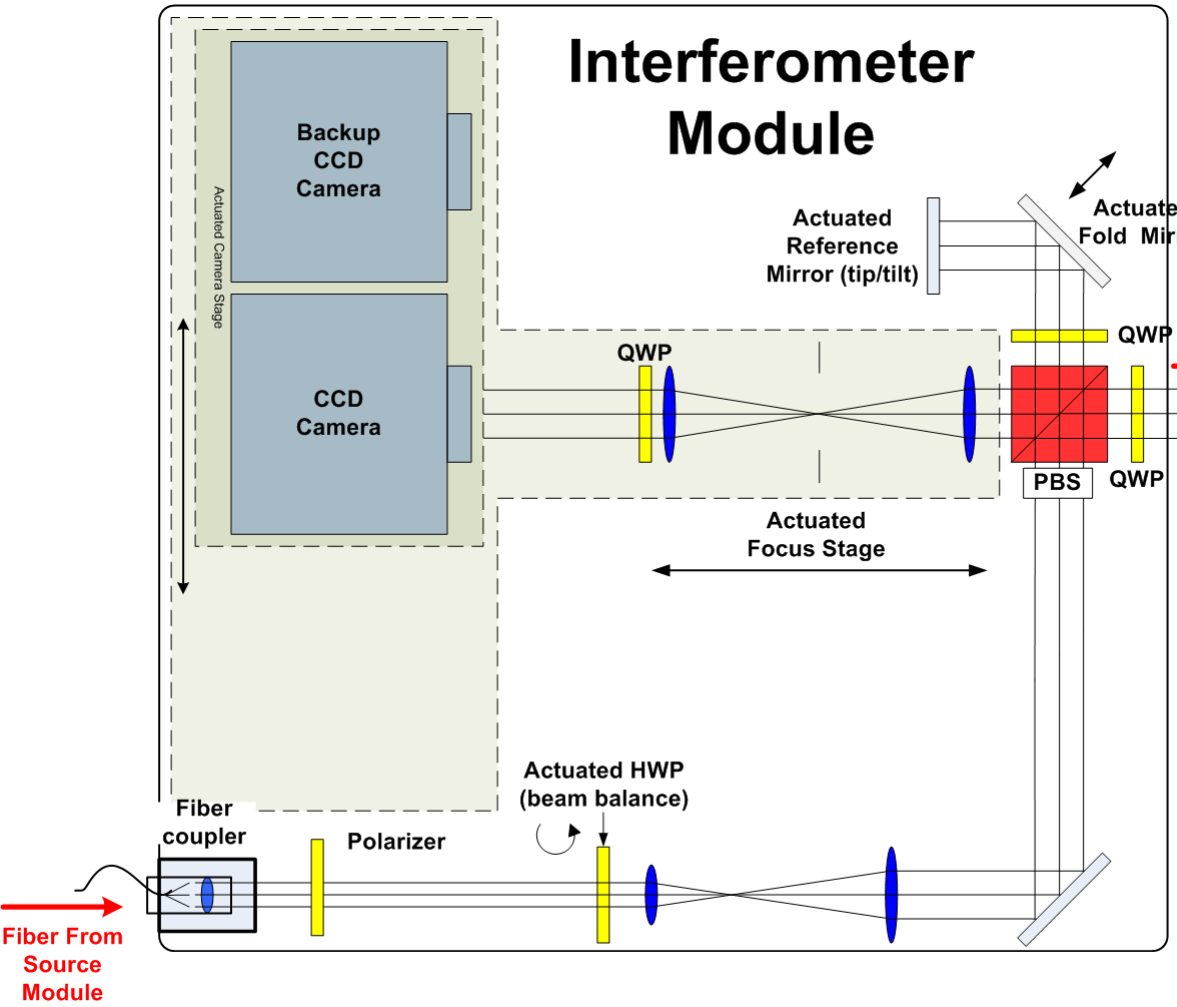
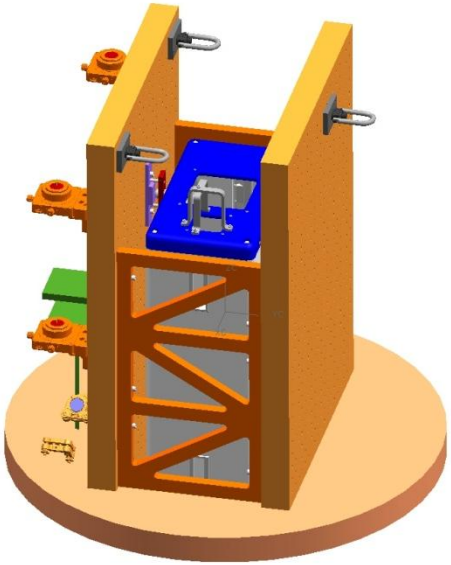
MWIF Architecture



- Redundant Camera and PZT on Actuated Fold Mirror for Improved Reliability



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Coarse and Fine Alignment Systems

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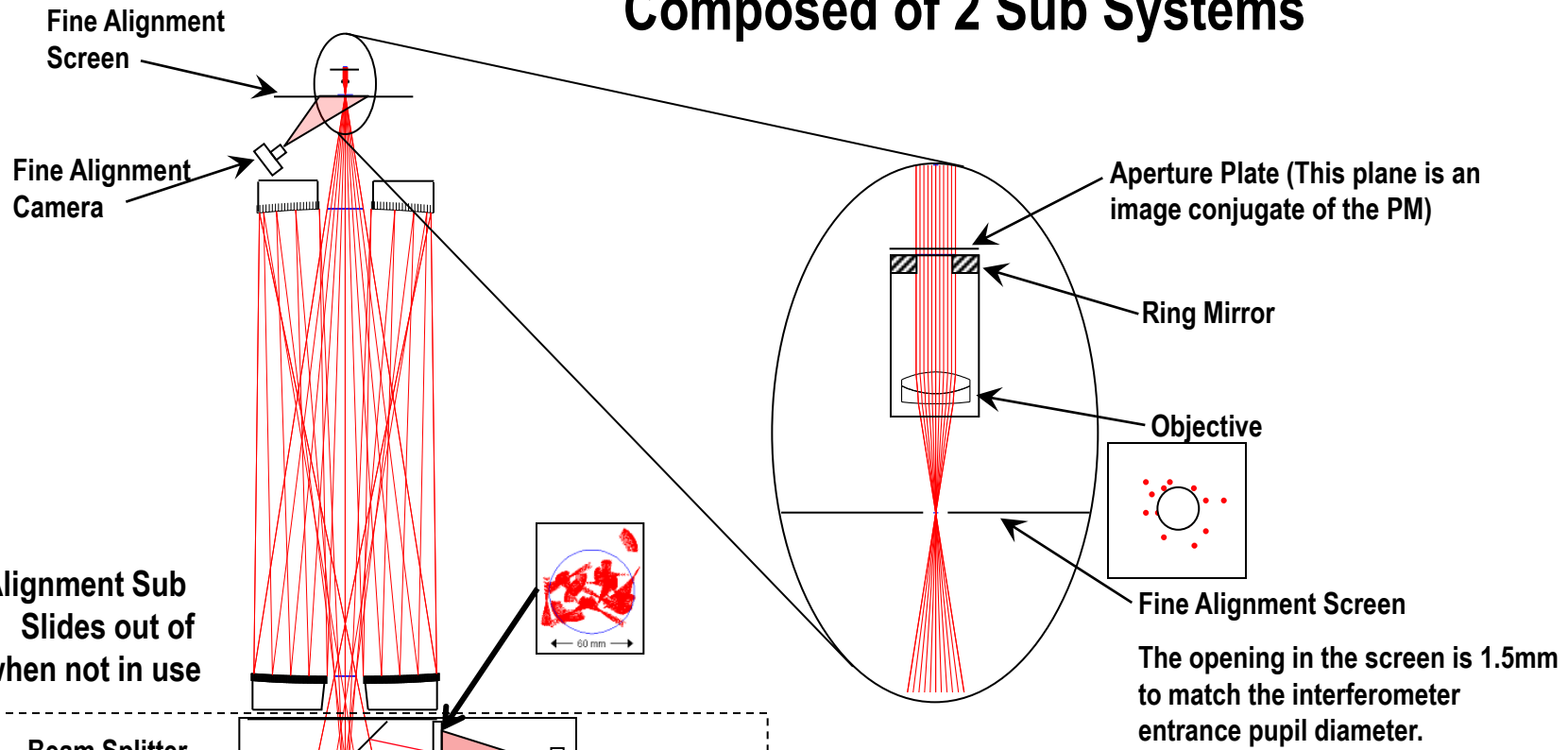
COCOA Alignment Systems

The alignment system is composed of simple screens and cameras

Composed of 2 Sub Systems



Coarse and Fine Alignment Cameras cover the PMSA deployment uncertainty range

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Null Design & Assembly

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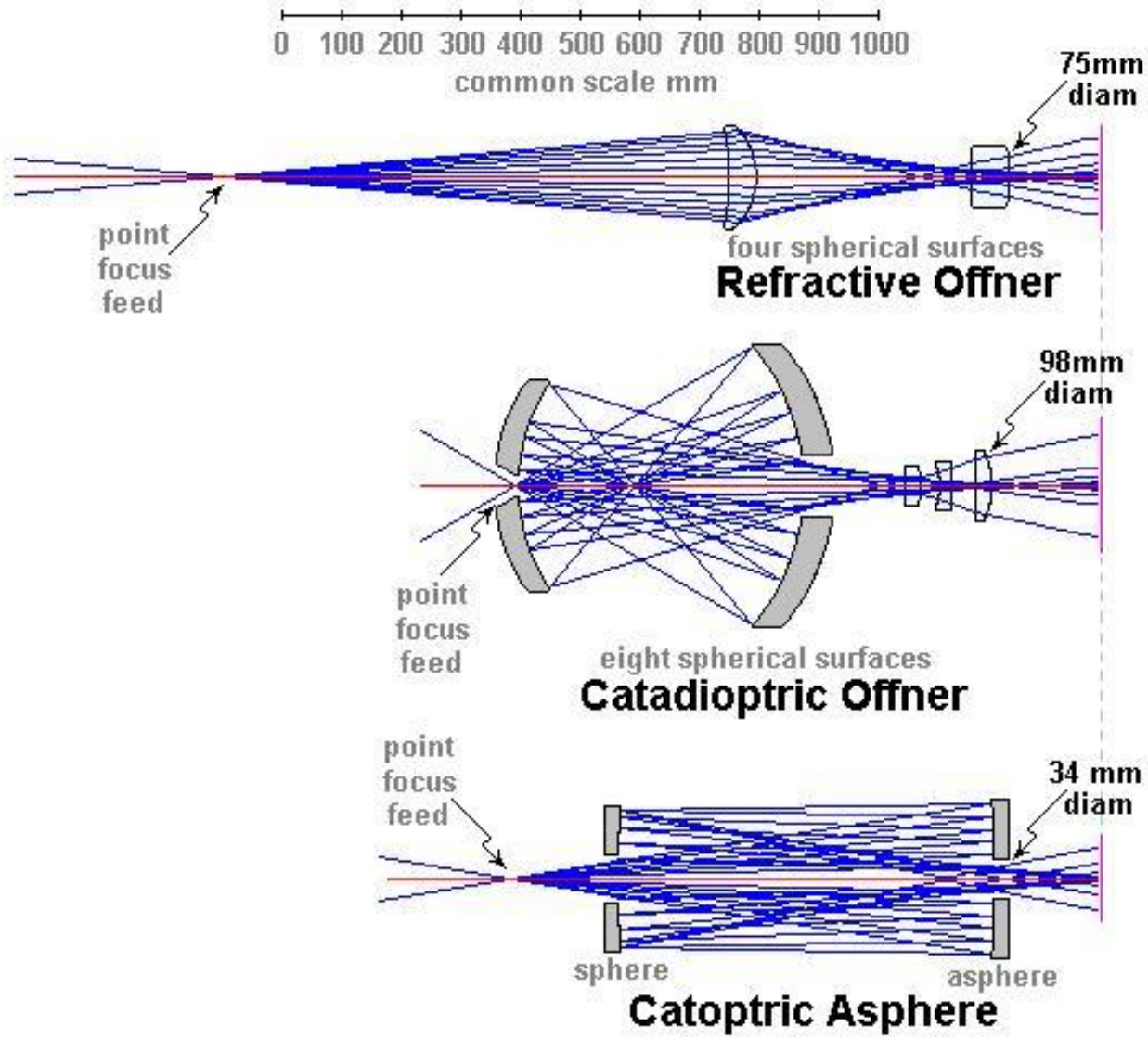
Design Types Optimized and Compared



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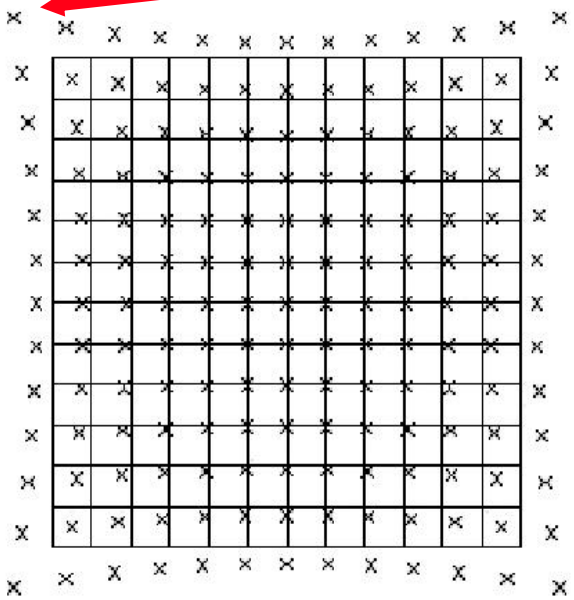
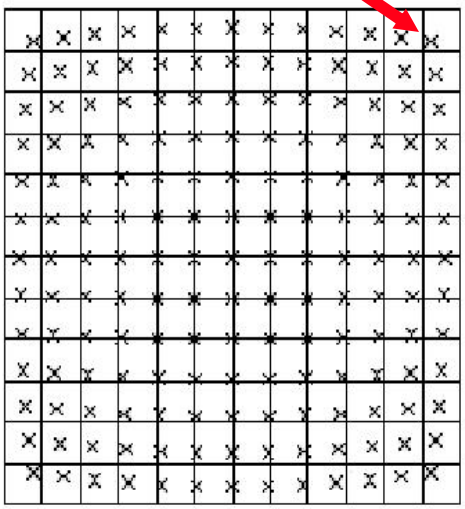
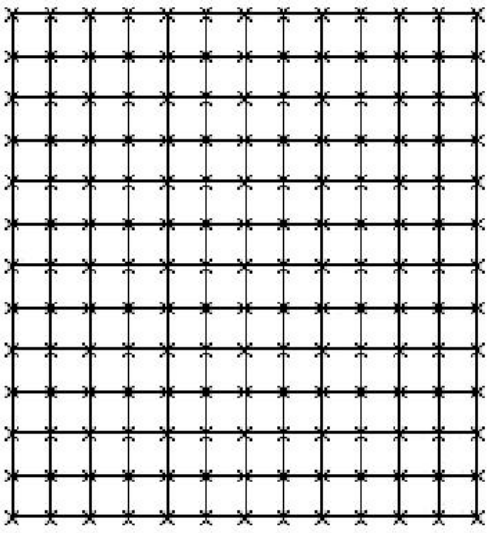
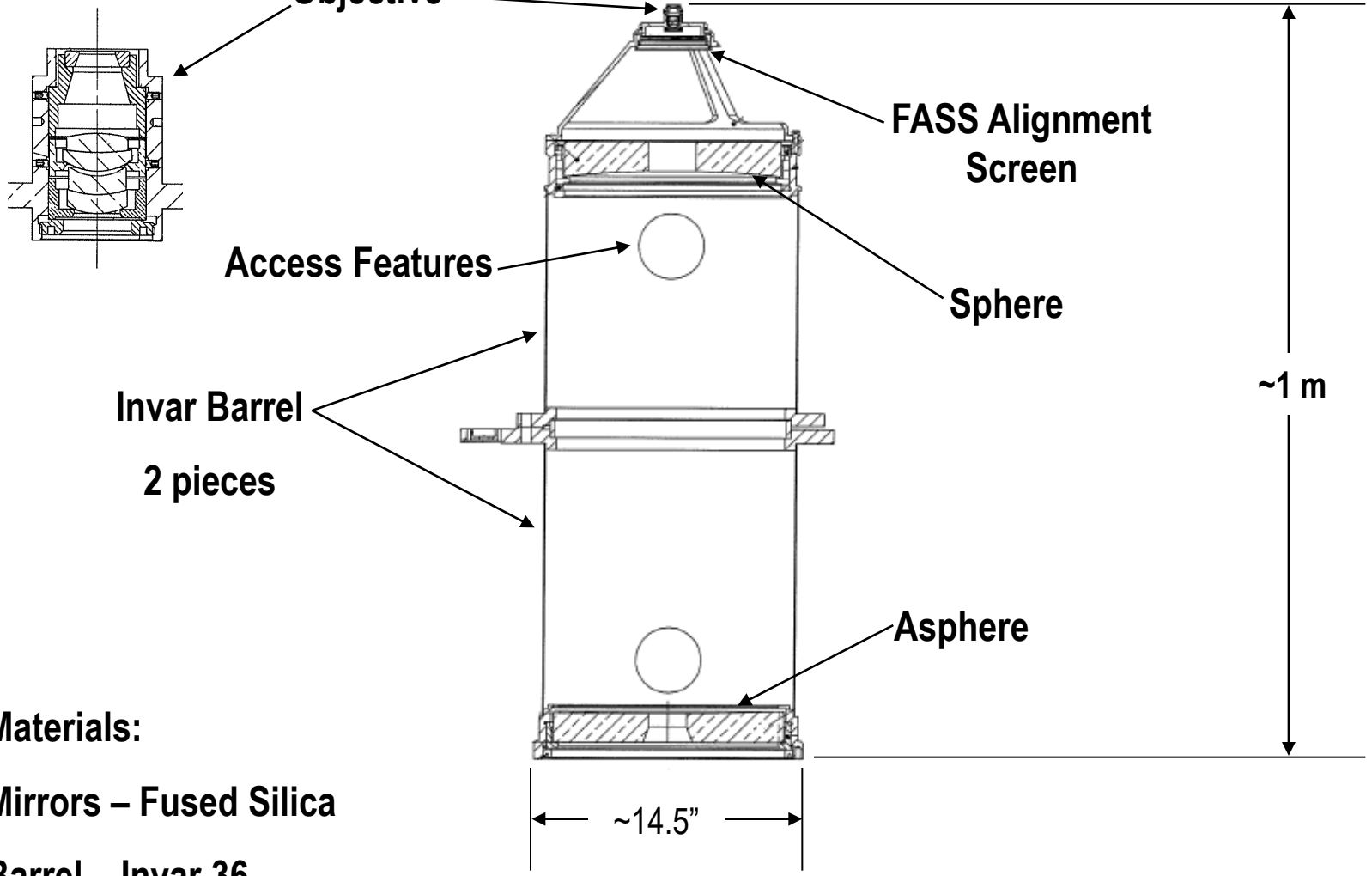
Pupil Distortion Comparison

Pincushion	Barrel	Negligible
Need to map and backout		No backout required
		
Refractive Offner	Catadioprtic offner	Catoptric Asphere

- The Refractive Offner suffers significant “pincushion” distortion
- The Catadioptric Offner suffers significant “barrel” distortion
- The Catoptric Asphere enjoys negligible distortion. This greatly relaxes or eliminates the fiducialization and backout needs.

Null Design and Assembly

This is NOT Small!



Materials:

Mirrors – Fused Silica

Barrel – Invar 36

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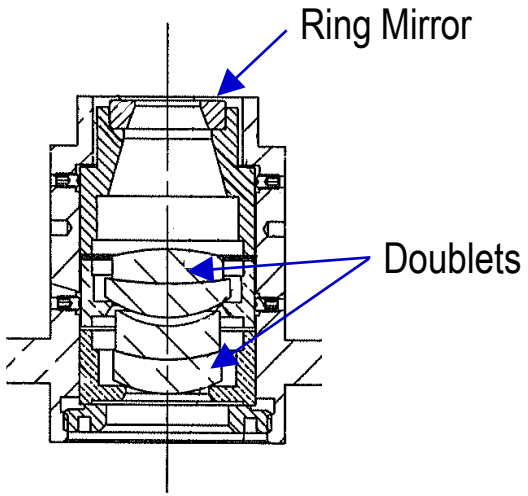
Null Design and Assembly

Tolerances are Very forgiving

- **Alignment Plan (simplified / over simplified)**
  - Manufacture components to tolerance
  - Measure components to verify tolerances have been met
  - Assemble parts
  - Ready for test



- **Assembly Tolerances (T0600-0540)**
  - Spherical Mirror
    - » Tilt – 1.2 arcmin (0.02 deg, 349 uRad)
    - » XY Decenter – 200 um (~8 mil)
    - » Spacing – 75 um (~3 mil)
  - Aspheric Mirror
    - » Same as Sphere
  - Objective elements
    - » Tilt – 6.9 arcmin (0.12 deg, 2000 uRad)
    - » XY Decenter – 20 um (~8 10^{ths})
    - » Spacing 100 um (~4 mil)

- **Single pass Wavefront error due to assembly tolerances**
  - 51.08 nm rms

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CoCOA System Wave Front Calibration

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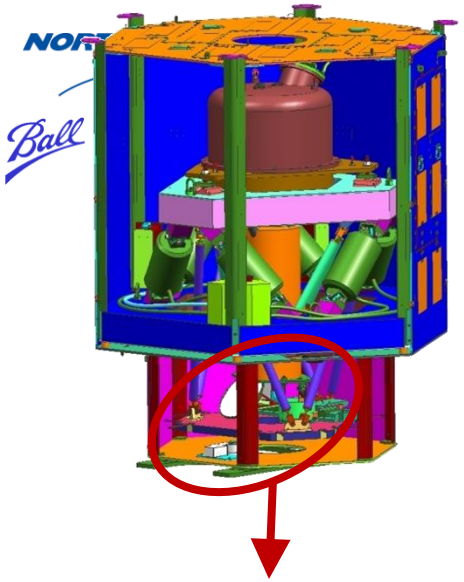
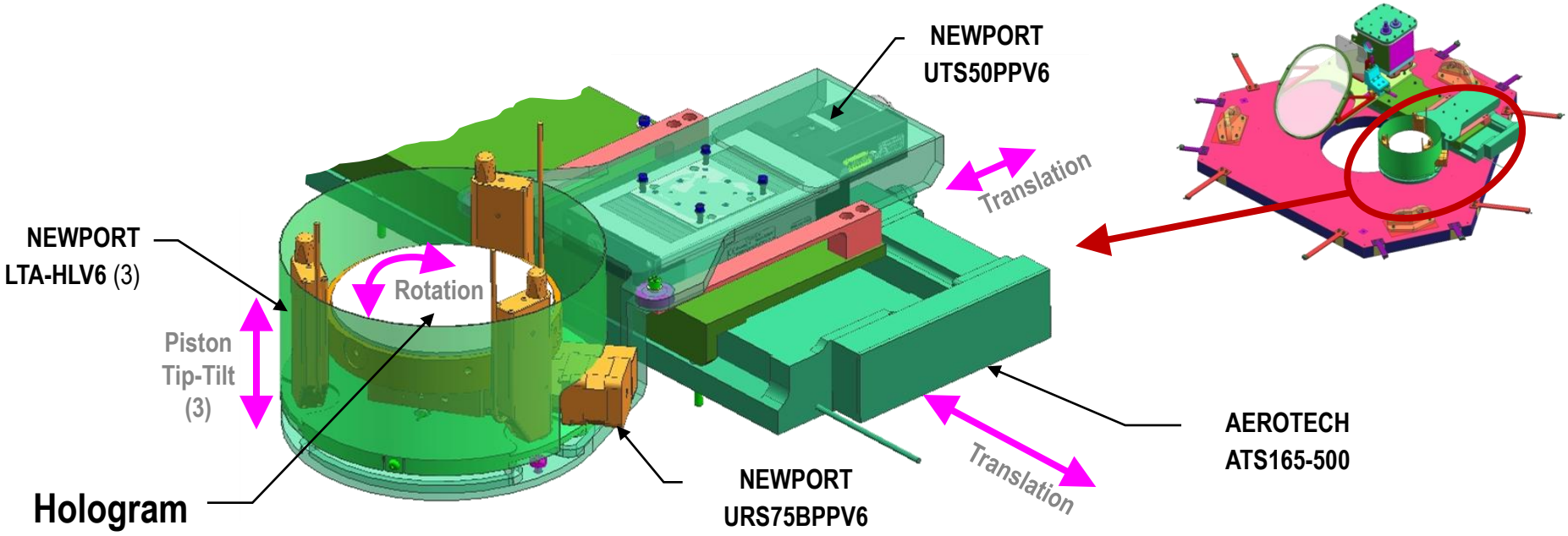
In-Situ CGH Calibration

- The CoCOA system wave front is calibrated in situ by a computer generated hologram on the lower optical bench





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JWST PM System Testing

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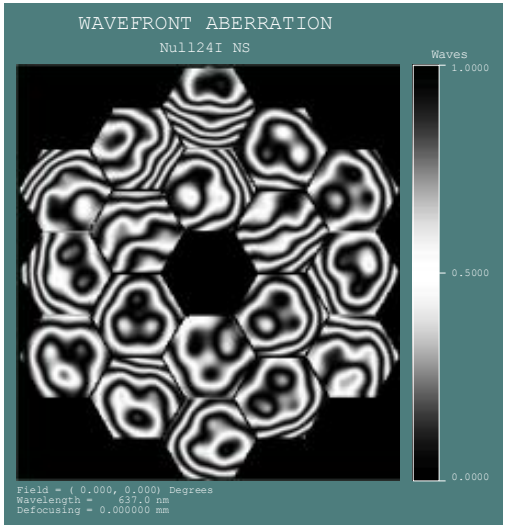
Ground Effects – Gravity

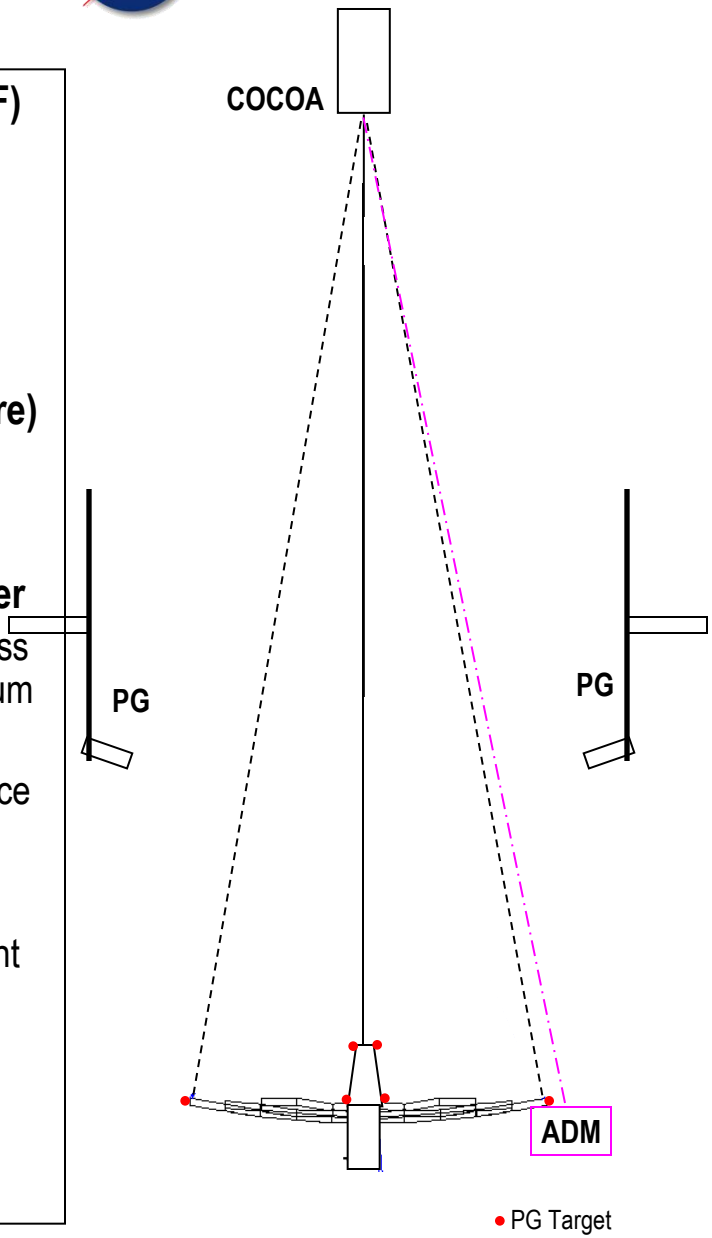
- **Figure deformation**
  - PMSA 1g figure deformation ~90 nm rms surface
    - » With RoC correction from flight actuator
  - Deformation backed out of test result to predict 0g WFE
    - » Figure map registered to PMSA separately
      - Baseline approach: Autocorrelation of the figure deformation



Sample interferogram of almost-aligned PMSAs in 1g

Primary Mirror Alignment Process

1. **Deploy PMSAs to best starting point per previous I&T (SSDIF)**
2. **Align outer PMSAs (B&C) to AOS per photogrammetry**
   - Only outer PMSAs are equipped with PG targets
3. **Align COCOA to Outer PMSAs (initial)**
   - Set axial position per ADM
4. **Tilt all PMSAs per COCOA Coarse Alignment Camera (capture)**
5. **Tilt all PMSAs per COCOA Fine Alignment Camera (into interferometer test range)**
6. **Phase all PMSAs per COCOA Multi Wavelength Interferometer**
   - Correct PMSA piston errors progressively via step-down process through incremental "synthetic wavelengths" from 4 mm to 17 um
   - Final alignment per 670 nm single wavelength interferometry
   - Maintain COCOA pointing to avoid coma. Maintain axial distance per ADM.
7. **Align phased PM to AOS per photogrammetry**
   - Ensemble of PMSAs provides large base for accurate alignment
   - COCOA follows PM
8. **"Tweak" PMSA phasing as required**



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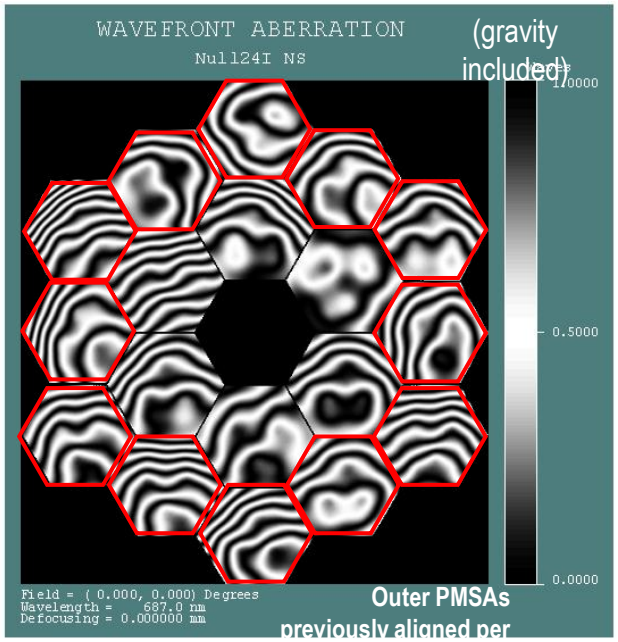
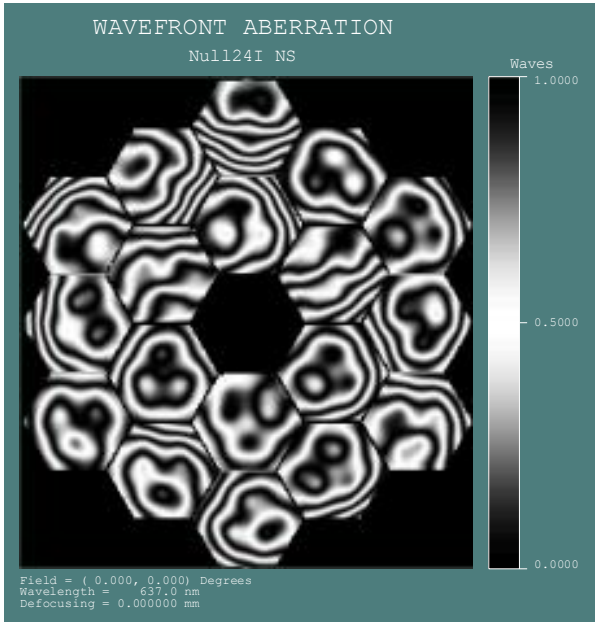
COCOA Tilt Alignment (Global Coma)

- **Two methods provide feedback for COCOA tilt**
  - COCOA optical axis must be aimed at PM center to eliminate coma

Astigmatism over outer PMSAs





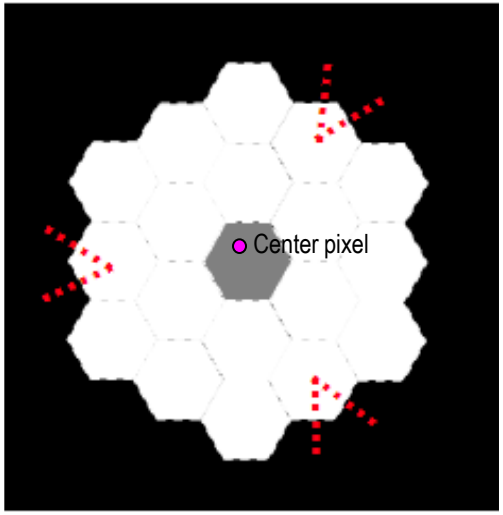
Outer PMSAs positioned per PG

Local astigmatism over outer PMSAs indicates decenter

COCOA tilted about COC to remove average outer PMSA astigmatism (i.e. remove global coma)

Should match tilt that centers PM image on center pixel.

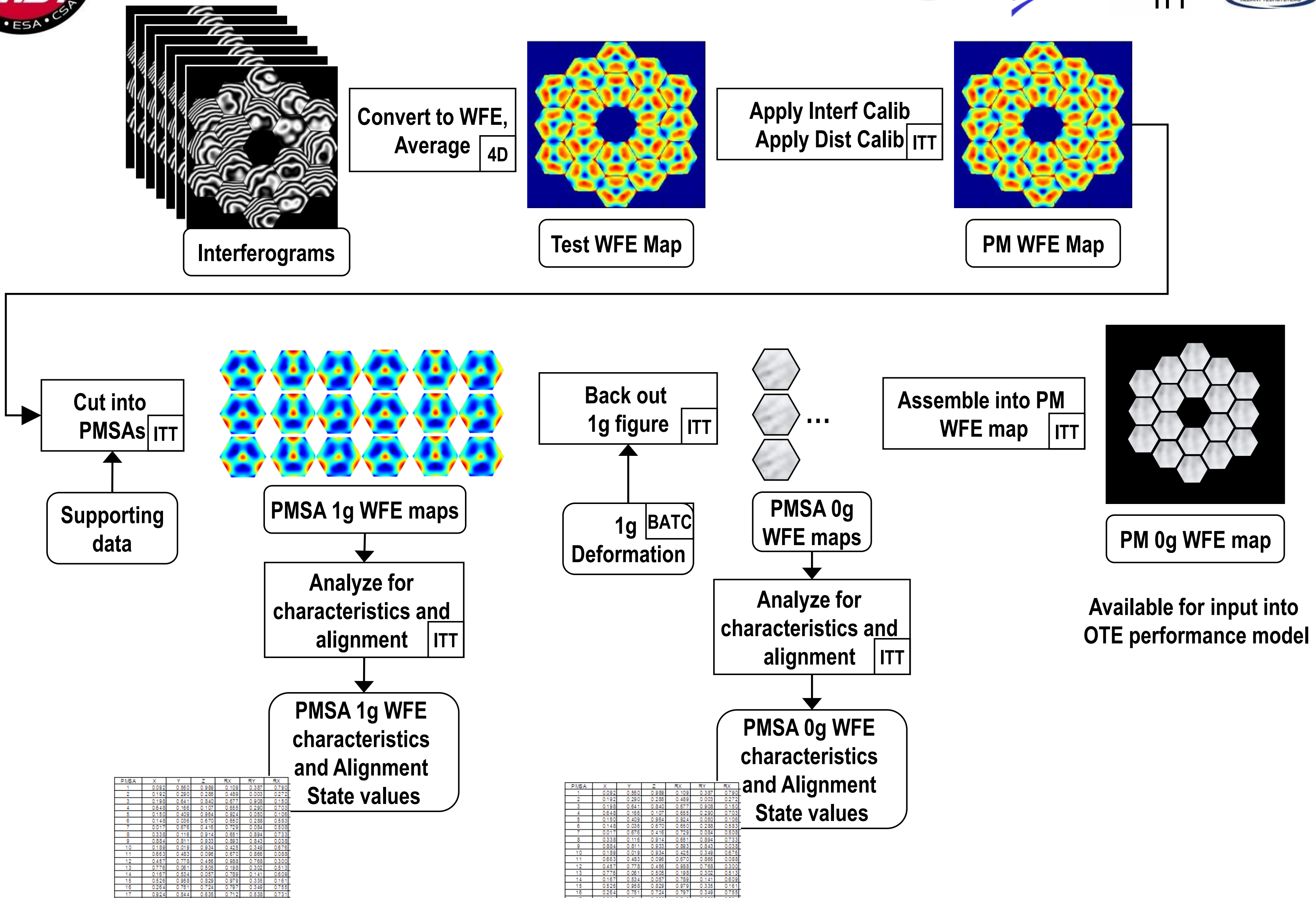
Image centering on COCI camera



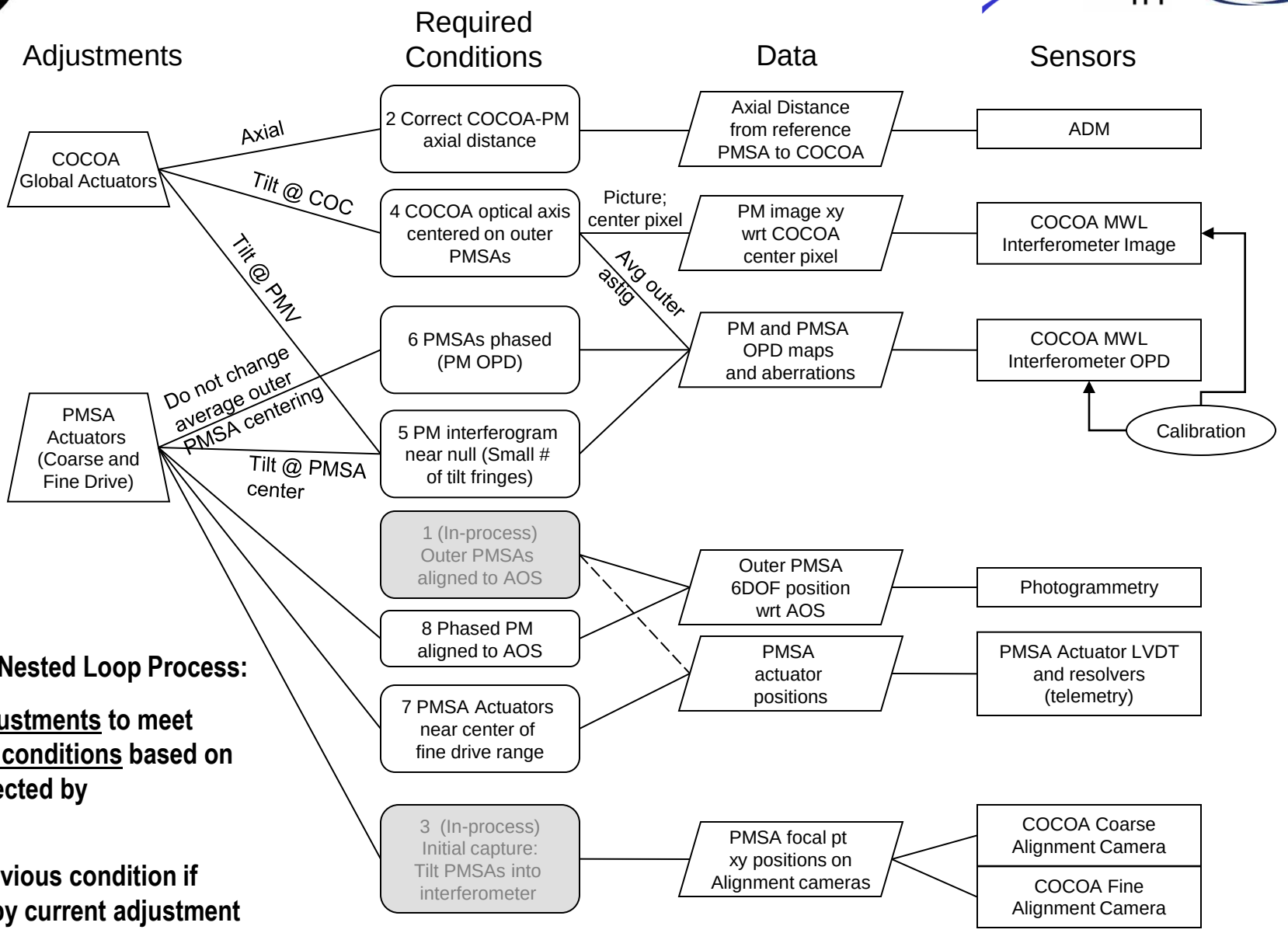
Second measurement: Location of PM image on interferometer camera vs. Center Pixel*

*COCOA optical axis intersection with camera detector

PM WFE Data Reduction Flow Chart:



PM Alignment Process Matrix



Iterative/ Nested Loop Process:

Make <u>Adjustments</u> to meet <u>Required conditions</u> based on <u>Data</u> collected by <u>Sensors</u>

Reset previous condition if affected by current adjustment

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Conclusion

- **CoCOA system is used for cryogenic testing of the JWST Primary Mirror.**
  - The design has completed a Critical Design Audit and manufacturing is underway.
- **Multi-wave interferometer enables piston measurements for segment phasing.**
- **Coarse and fine alignment systems enable PMSA alignment .**
- **Unique reflective Olczak Catoptric null is achromatic and low distortion.**
- **System is calibrated in situ.**