2018 Space Symposium

METHODOLOGY AND RESULTS OF JWST THERMAL VACUUM OPTICAL SYSTEM ALIGNMENT TESTING AND ANALYSIS

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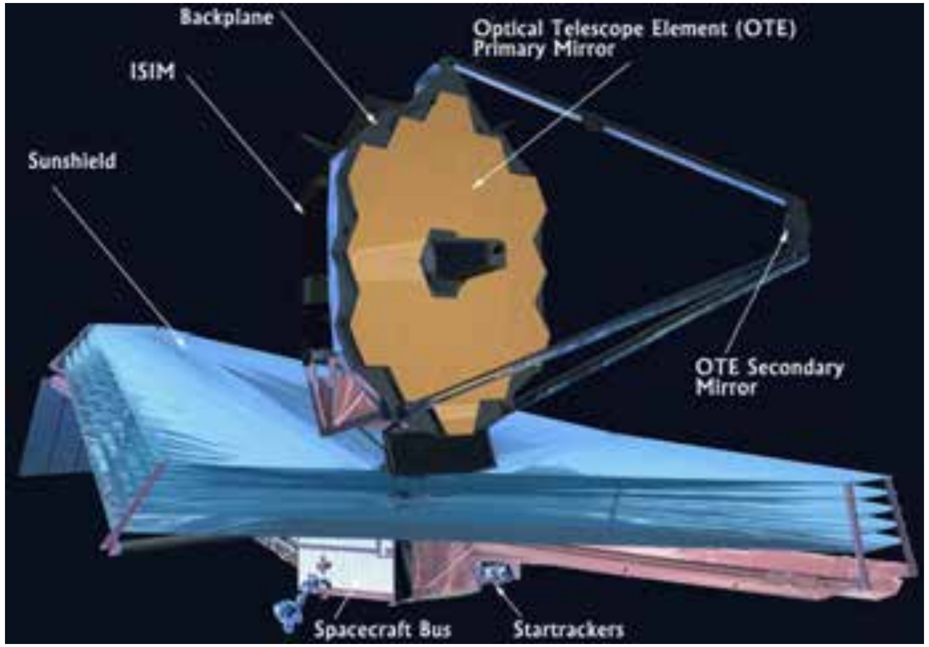
JWST Overview

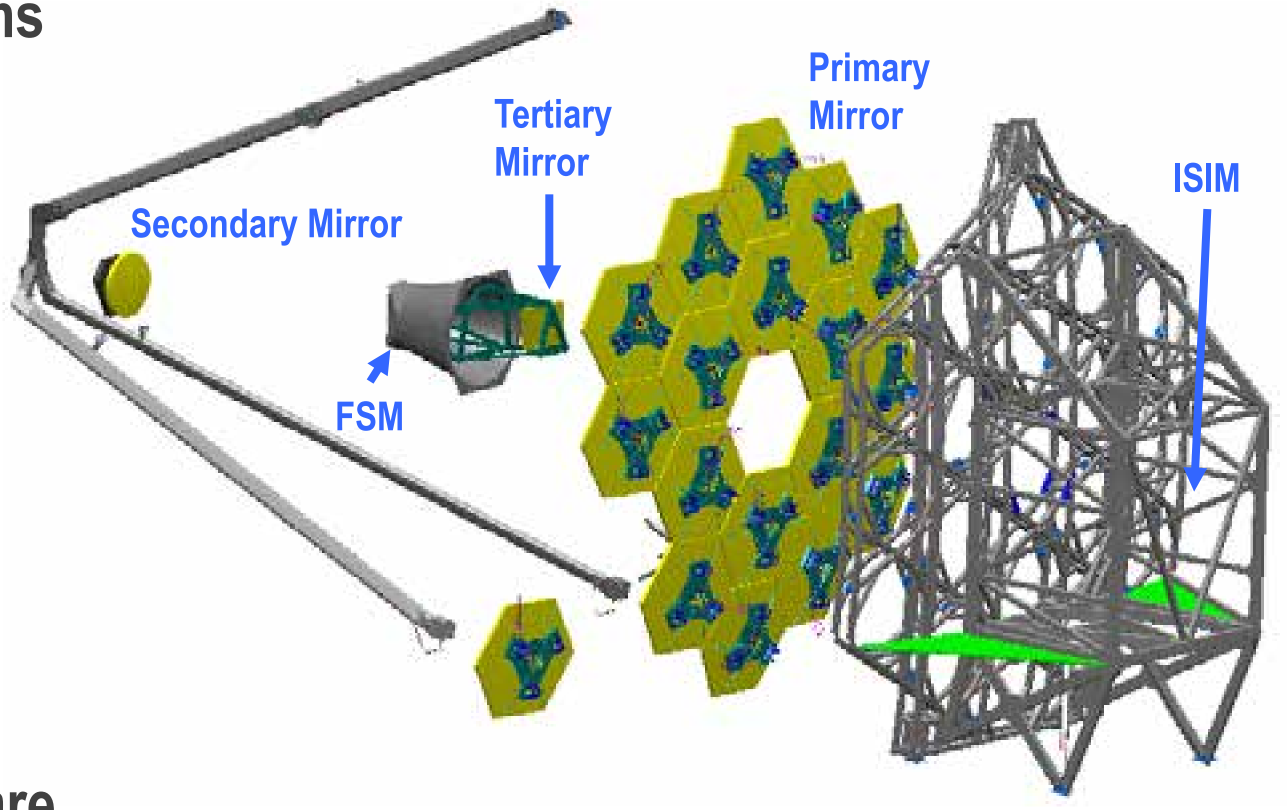
- James Webb Space Telescope (JWST) is a large infrared (0.6 to 29 microns wavelength) observing space telescope which is planned to launch in 2020.
- The observatory is comprised of 4 major subsystems
    1. Optical Telescope Element (OTE)
    2. Integrated Science Instrument Module (ISIM)
    3. Sunshield
    4. Spacecraft Bus



- The large size of Webb required that the entire observatory to be folded and stowed to fit within the fairing of an Ariane 5 launch vehicle.
- The observatory is then deployed en route to the second Lagrange point.

Webb Telescope Optical System Overview

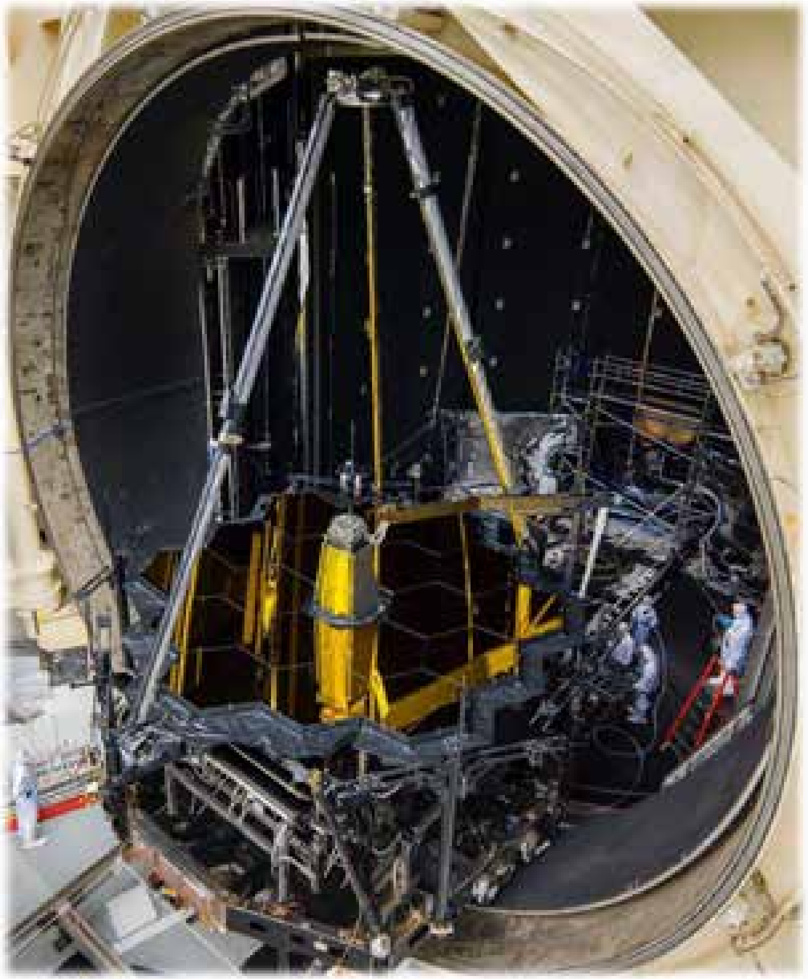
- **The telescope consists of 4 optical sub-systems**
  - Segmented Primary Mirror (6 DoF & RoC actuation)
  - Secondary Mirror (6 DoF actuation)
  - Aft-Optics Subsystem (AOS)
    - Tertiary Mirror (Fixed)
    - Fine Steering Mirror (flat mirror used for pointing stabilization and very small offset maneuvers)
  - Integrated Science Instrument Module (ISIM)



- **The AOS and ISIM are the "fixed" optical sub-systems. The primary and secondary mirrors are aligned to the AOS/ISIM on-orbit.**
- **This type of optical system architecture is a pragmatic approach to large, deployable, space telescope systems that are not serviceable by providing active alignment capability on-orbit to mitigate ground-alignment and deployment risks.**

Webb Telescope Cryogenic Test Overview

- As an infrared observatory, Webb's optical system will operate at approximately 45K.
- A full optical system verification test program for such a complex observatory would have been prohibitively expensive.
- Therefore, the cryogenic ground-test program for the assembled telescope was designed to focus on alignment vs total performance.
- Verify the fixed systems are aligned and that the active systems have the range of motion to be aligned on-orbit.

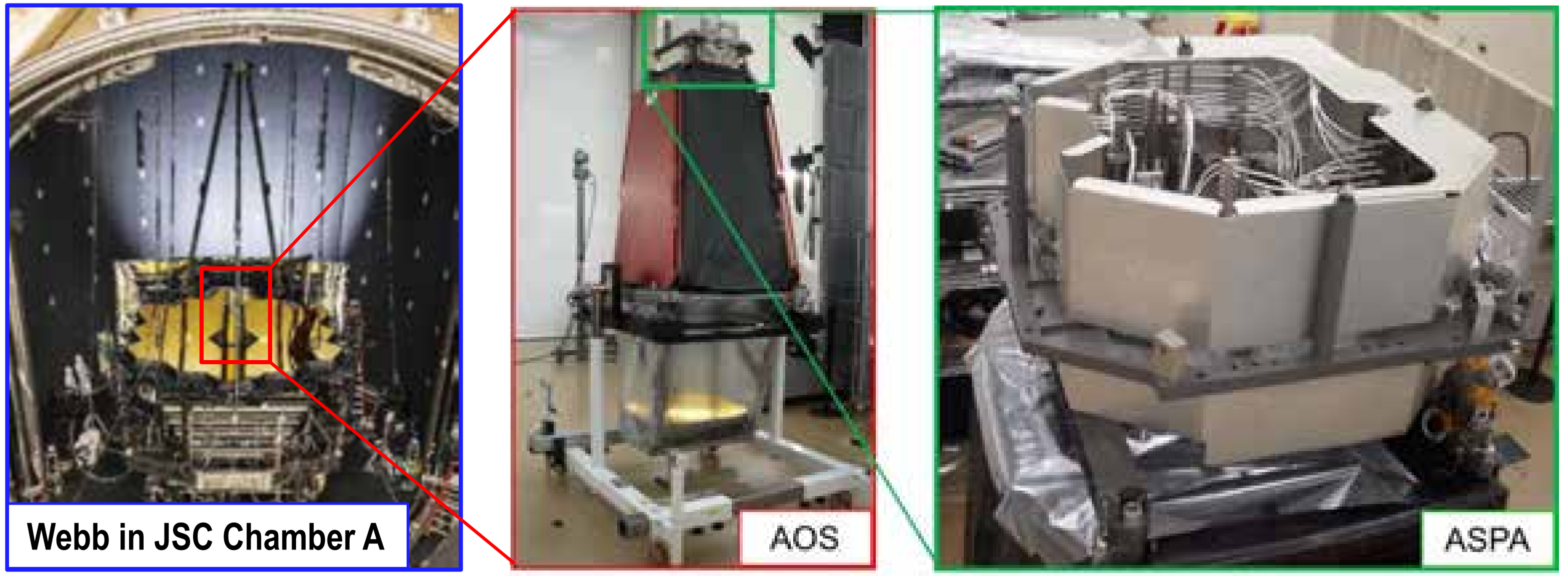


Webb Telescope Rolling into JSC Chamber A

<u>Main Test Goals:</u>

1. Verify the relative cryogenic alignment of the ISIM to the AOS.
2. Demonstrate that the quantity 18 primary mirror segments can be aligned and phased into a monolithic primary.
3. Verify expected ground alignment of the primary and secondary mirrors to the AOS.
4. Cross-check the wavefront of the entire optical system.
5. Demonstrate a subset of various flight-like wavefront sensing & control operations.

Webb Telescope Cryogenic Optical Test Sources

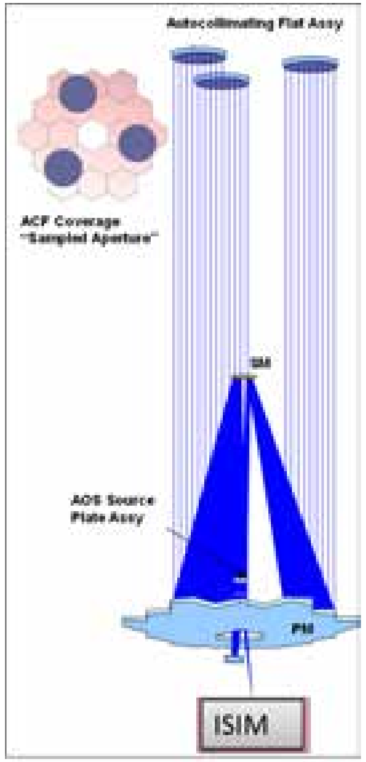


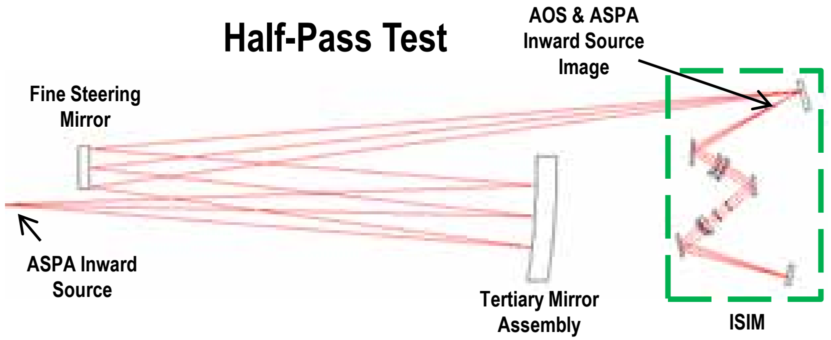
An array of fiber optic sources in a ground-test chassis were installed onto the top of the AOS, at the intermediate focus of the telescope. These fibers and chassis are collectively known as the AOS Source Plate Assembly (ASPA).

Within ASPA, there are sources that emit towards the tertiary mirror and others that emit towards the secondary mirror.

- The sources that emit towards the tertiary mirror are for assessing the AOS to ISIM alignment, which is called the Half-Pass test.
- The sources that emit towards the secondary mirror are for assessing the total optical system, which is called the Pass-and-a-Half test.

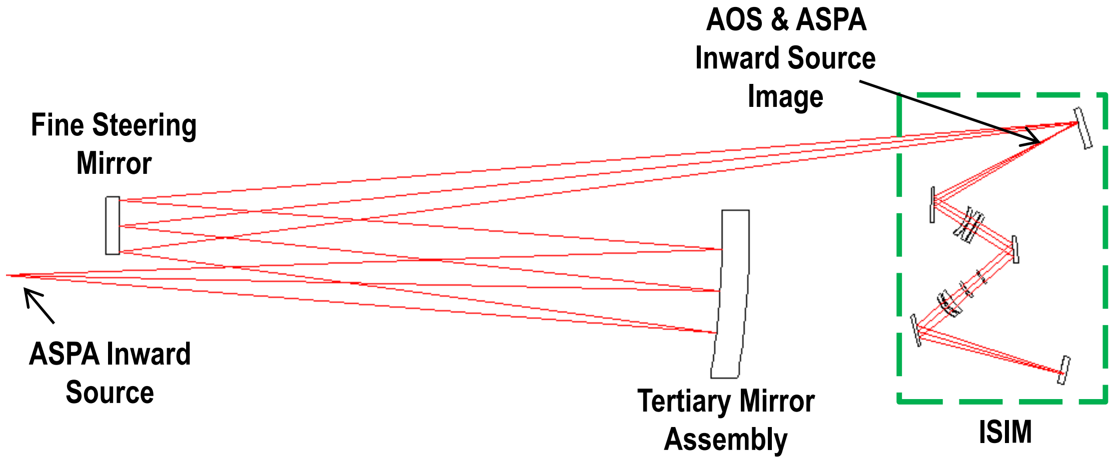
Pass-and-a-Half Test

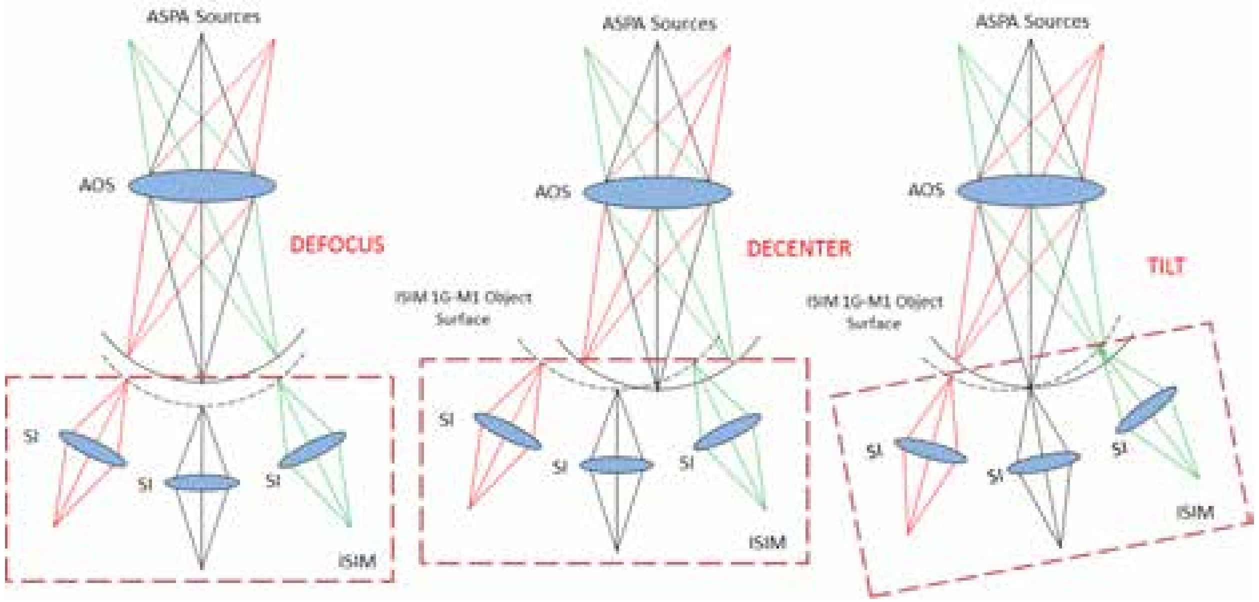


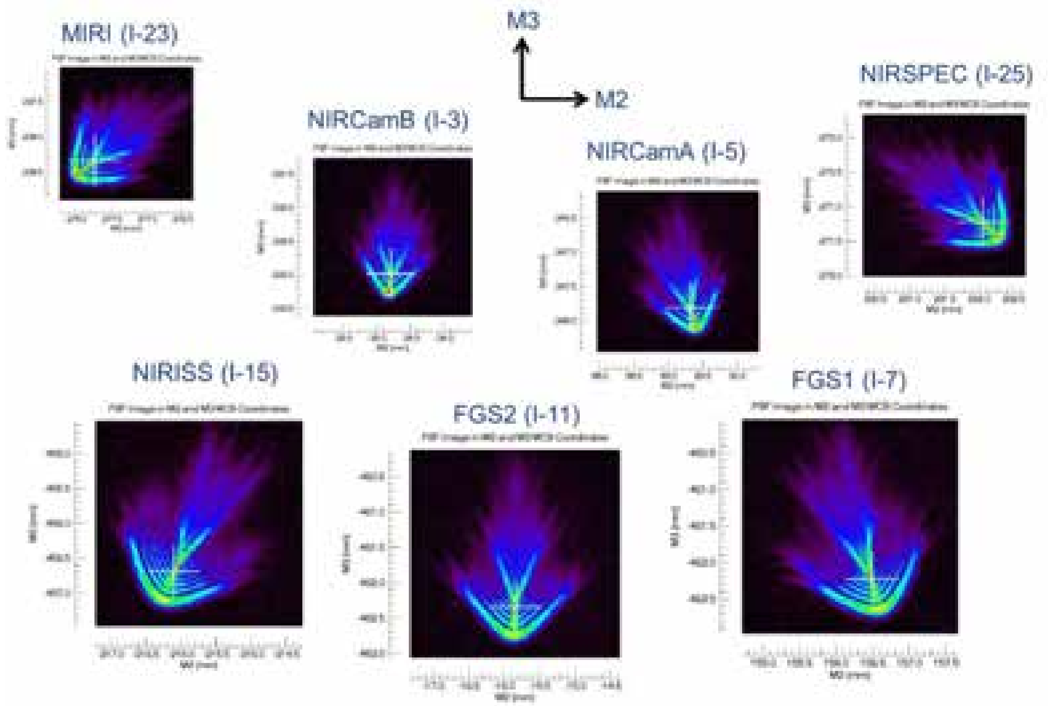


AOS TO ISIM ALIGNMENT

Methodology of Verifying AOS to ISIM Alignment





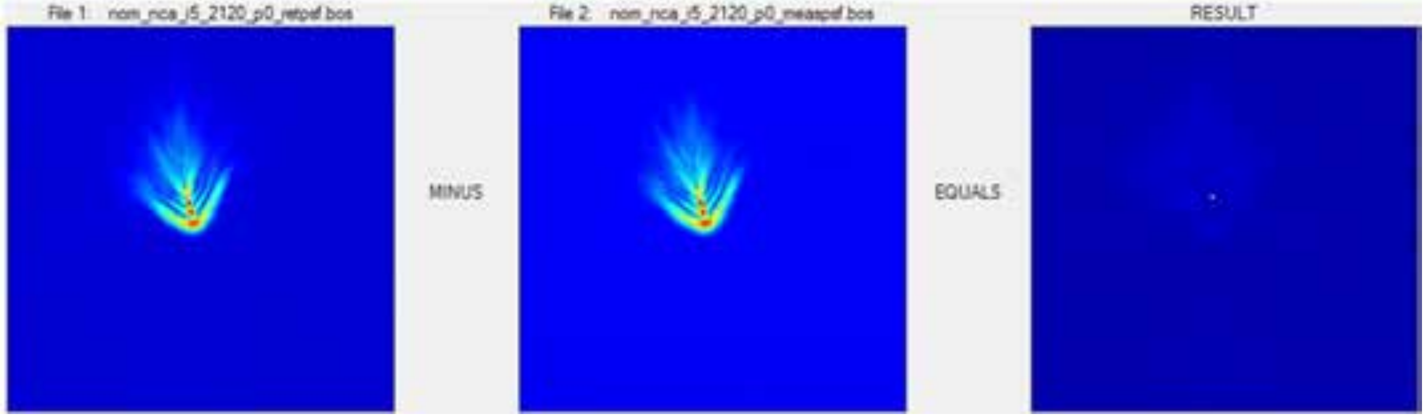


- Three-dimensional calibration of AOS & ASPA image locations for each science instrument field of view was completed.
- Calibration data was used to create correlated optical model to predict image location and wavefront at each science instrument.
- Differences in the measured and modeled image locations along with pupil images are used to assess rigid body alignment of ISIM to AOS.

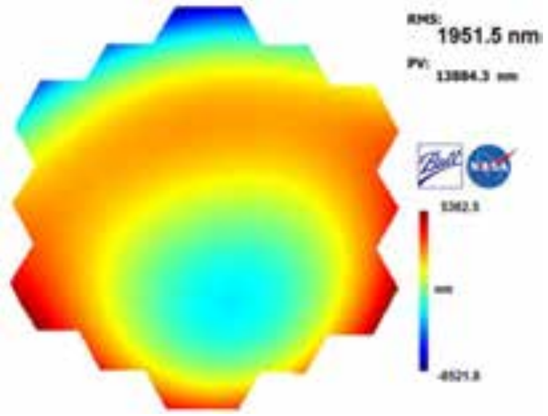
AOS to ISIM Alignment Data Processing

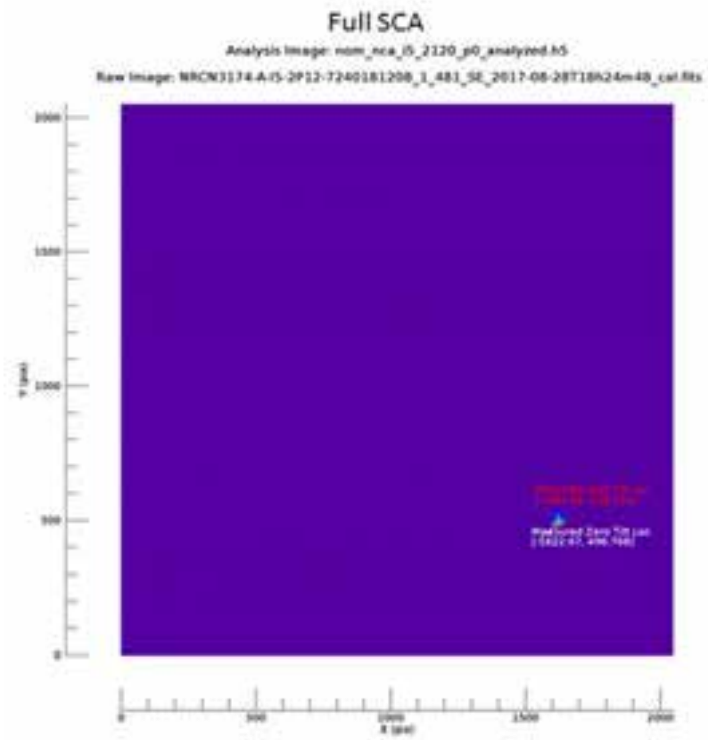
Phase Retrieval Results

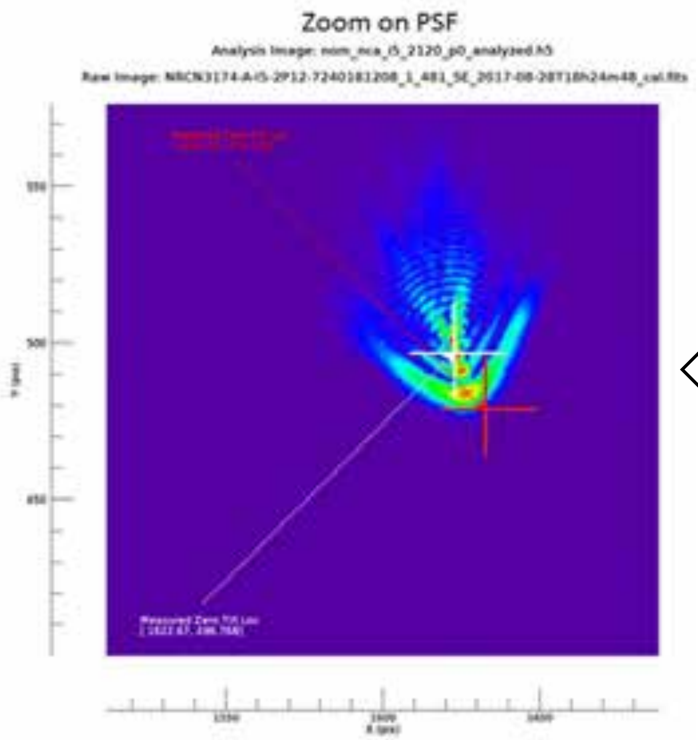
Retrieved PSF | **Measured PSF** | **Measured - Retrieved**



Retrieved Wavefront

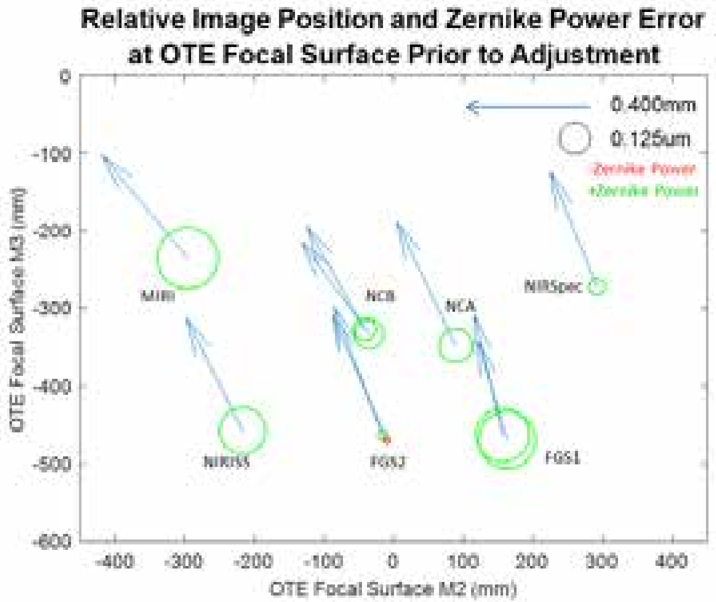


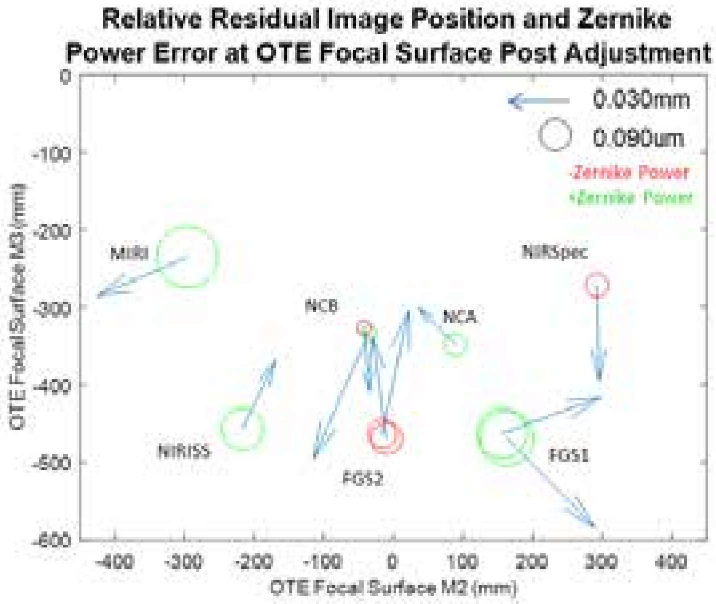




Measured and Predicted Image Position on SCA

AOS to ISIM Alignment Results





ISIM 6 Degree of Freedom Position Error

	6DOF	Optical	Yellow Flag Limit
Focus/M1 (mm)	-0.415	-0.415	±1.360
M2 Decenter (mm)	0.207	0.427	±0.605
M3 Decenter (mm)	-0.374		
RM1 Clocking (mrad)	-0.138	-0.138	±1.502
RM2 Tilt (mrad)	0.319	0.322	
RM3 Tilt (mrad)	0.045		

Residual Zero-Tilt Location Error Post ISIM Object Surface Alignment

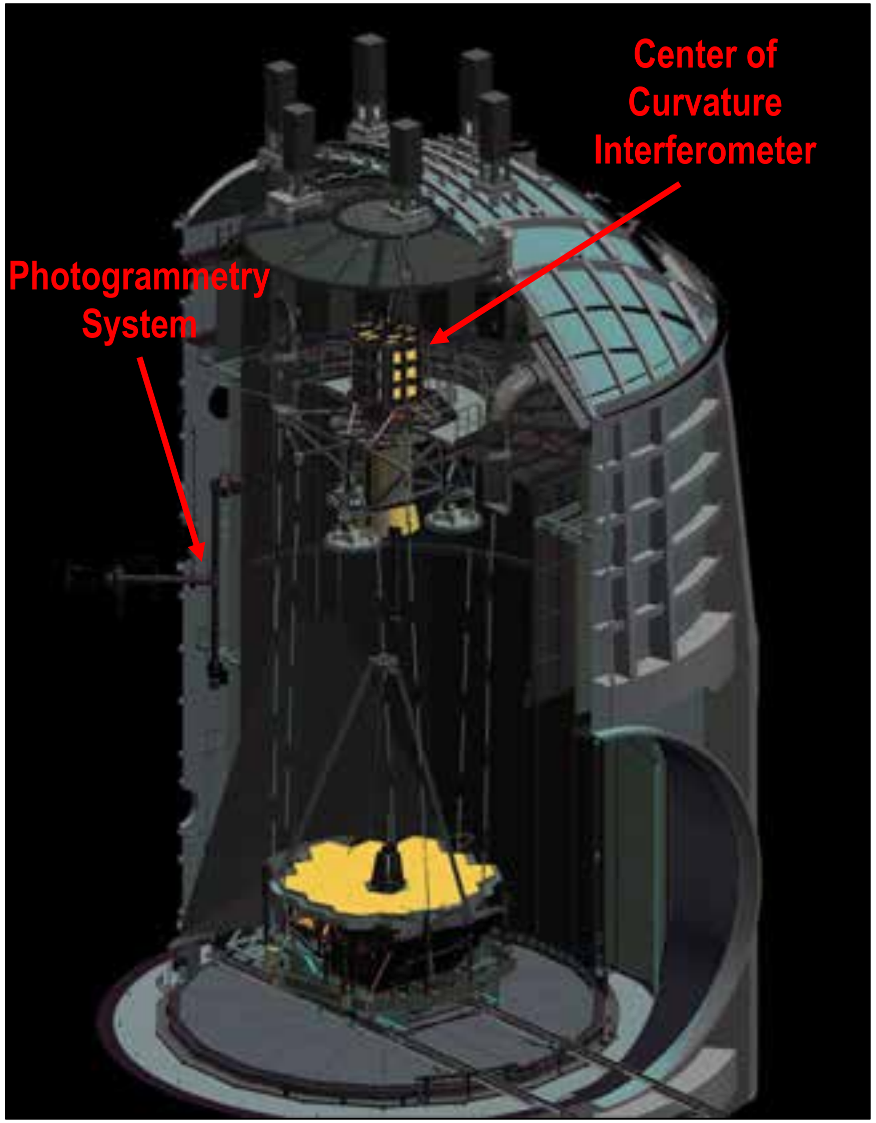
ASPA Source	Instrument	dX (pix)	dY (pix)	dZ4 (um)
I-1	NCB	0.2	-1.7	-0.019
I-3	NCB	-1.7	-3.4	0.020
I-5	NCA	-1.1	1.0	0.046
I-7	FGS1	-0.5	1.3	0.234
I-9	FGS1	1.1	1.2	0.277
I-11	FGS2	1.5	0.3	-0.076
I-13	FGS2	1.2	-0.2	-0.092
I-15	NIRISS	-0.9	0.5	0.161
I-19	MIRI	0.7	-0.4	0.348
I-25	NIRSpec	-0.6	0.5	-0.047

- **Data over the field of view indicates a cryogenic alignment error of the ISIM with respect to the AOS of less than 0.5mm in translation 0.4mrad in tilt.**
- **This level of misalignment was well within the expected level of disagreement between measured and predicted due to uncertainty.**
- **Nearly all residual image position errors are within 1 or 2-pixels indicating that the observed error is primarily rigid body motion of ISIM.**
- **These are excellent results for the cryogenic alignment of the fixed optical systems.**

CROSS-CHECK OF PRIMARY AND SECONDARY MIRROR ALIGNMENT TO AOS

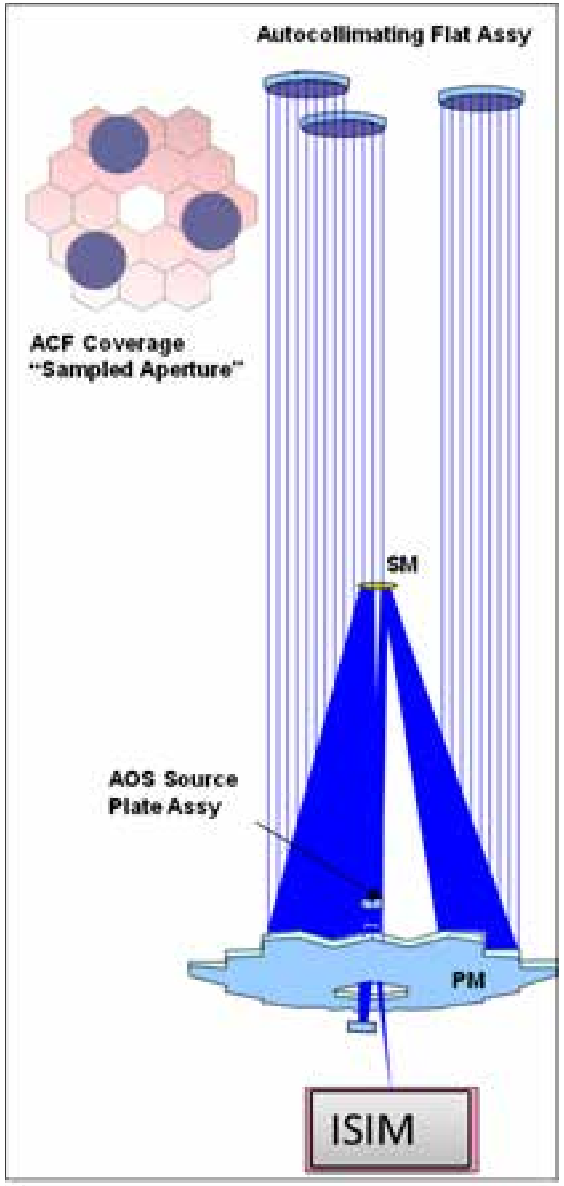
Alignment of Primary and Secondary Mirror

- All of the OTE optics have been measured and characterized individually at cryogenic temperatures.
- Based on those individual measurements, a combination of optical and structural modeling is used to establish the cryogenic target positions for the primary and secondary mirrors in the ground test.
- Fiducials attached to the edge of the mirrors are used in combination with a photogrammetry system to set the mirrors' positions at cryogenic temperatures.
- A center of curvature interferometer is then used to align and phase the entire primary mirror.
- A cross-check of the primary mirror and secondary mirror alignment was performed by examining the images from the total system.



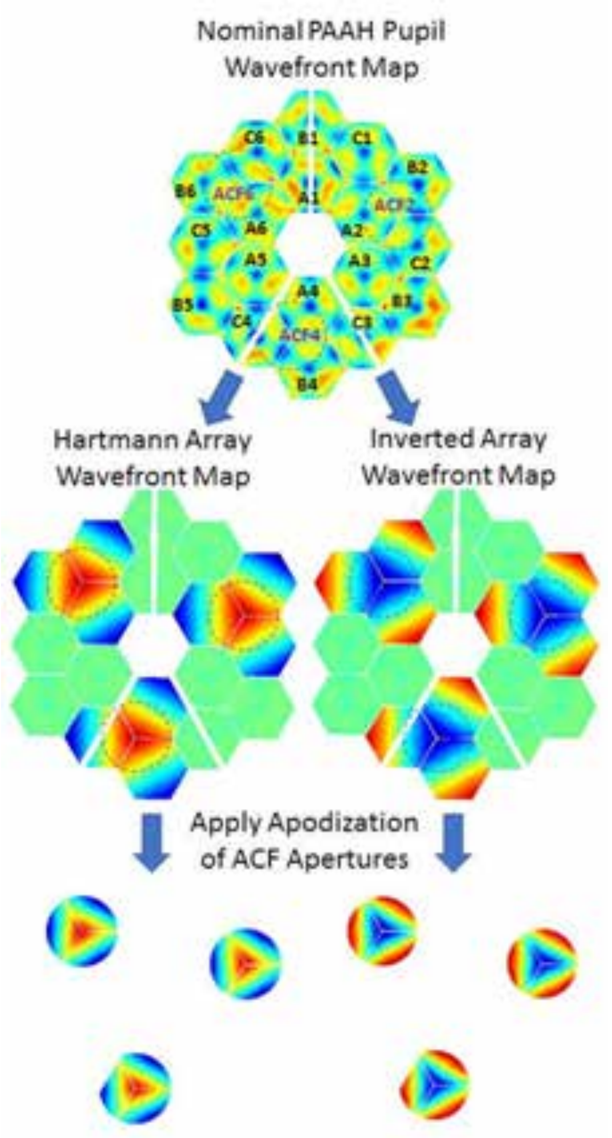
Webb Telescope Test in JSC Chamber A

Methodology to Cross-Check Alignment of PM & SM to AOS

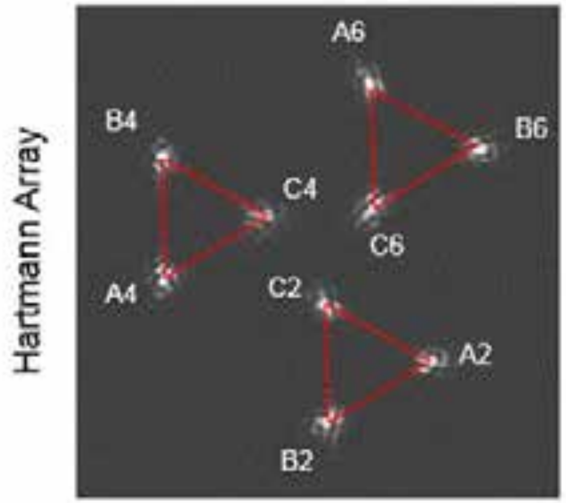


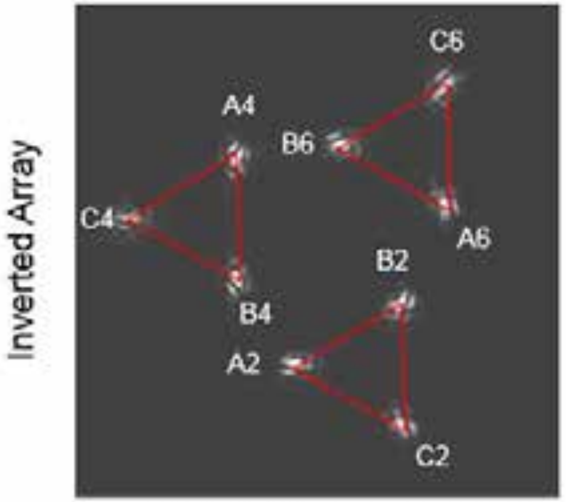
- The Pass-and-a-Half (PAAH) test utilized the ASPA sources that emitted towards the secondary.
- That light was collimated by the secondary and primary mirror of the telescope and was then incident upon quantity three 1.6m auto-collimating flats (ACF), after which the light passed back through the telescope optical train.
- The location of the auto-collimating flats was chosen such that each flat partially covered three adjacent primary mirror segments.
- This sparse-aperture test allowed for a sufficient sampling of the primary mirror and telescope pupil to assess the alignment state of the primary mirror and secondary mirror.

Webb Hartmann Test Approach



- A novel Hartmann-style test was developed for this crosscheck to be robust to the expected level of vibration in the test.
- In this Hartmann test, the primary mirror segments are tilted a known amount in a known direction along with the tilting the ACFs.
- This tilting process produces nine individual images on the detector, one for each primary mirror segment.
- The leg lengths between the images under an ACF, a triad, are examined.
- Differences between the measured and predicted leg lengths of each triad provide a metric to solve for secondary and primary mirror alignment errors.





(PMSA tilts are reversed)

SM and PM Alignment Cross-Check Results

SM Sensitivity Analysis Solution Check

SM Influence Pert	Commanded			Measured			Error		
	dM1	dM2	dM3	dM1	dM2	dM3	dM1	dM2	dM3
SM Focus (mm)	0.355	-	-	0.353	-	-	-0.002	-	-
SM Focus (mm)	-0.355	-	-	-0.357	-	-	-0.002	-	-
SM X Tilt (mrad)	-	0.200	-	-0.007	0.193	0.001	-0.007	-0.007	0.001
SM Y Tilt (mrad)	-	-	-0.070	-0.009	-0.011	-0.061	-0.009	-0.011	0.009
SM X Decenter (mm)	-	0.200	-	-0.005	0.204	0.003	-0.005	0.004	0.003
SM Y Decenter (mm)	-	-	-0.100	-0.008	-0.002	-0.096	-0.008	-0.002	0.004

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SM was moved in known amounts and solver was used to measure position change. This test verifies sensitivities are correct!

SM & PM Alignment Error Cross-Check

Degree of Freedom	Measured Value	Measured 2σ Uncertainty	2σ Uncertainty Requirement
SM Focus	+0.165 mm	±0.021 mm	±0.030 mm
SM Tilt (radial)	0.35 mrad	±0.14 mrad	±2.5 mrad
SM Decenter (radial)	0.29 mm	±0.12 mm	±2.1 mm
PM Tilt (radial)	0.036 mrad	±0.015 mrad	N/A
SI Relative Focus (OTE Field Tilt)	1.96 mm (max)	±1.09 mm (max)	±3 mm

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All measured position errors are within allowable differences and the measured uncertainties met test requirements! This assessment successfully cross-checks the modeled system performance and the ground placement of the optics by photogrammetry.

Conclusion

- **Summary**
  - The ground-testing of deployable, active, space telescopes can be a complicated and expensive endeavor.
  - The test approaches presented here show an alternative test philosophy and approach that focuses on the critical parameters for an active system; verification of the fixed optical systems and ensuring sufficient actuator range for the active systems.
  - Measurements indicate that the Webb Telescope's AOS to ISIM alignment and the primary mirror and secondary mirror alignments were well within expectations for the ground-test with high confidence.
  - The risk against successful on-orbit operations for these systems is mitigated.
- **Acknowledgements**

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