Performance of the primary mirror center-of-curvature optical metrology system during cryogenic testing of the JWST Pathfinder telescope

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ABSTRACT

The James Webb Space Telescope (JWST) primary mirror (PM) is 6.6 m in diameter and consists of 18 hexagonal segments, each 1.5 m point-to-point. Each segment has a six degree-of-freedom hexapod actuation system and a radius-of-curvature (RoC) actuation system. The full telescope will be tested at its cryogenic operating temperature at Johnson Space Center. This testing will include center-of-curvature measurements of the PM, using the Center-of-Curvature Optical Assembly (COCOA) and the Absolute Distance Meter Assembly (ADMA). The COCOA includes an interferometer, a reflective null, an interferometer-null calibration system, coarse & fine alignment systems, and two displacement measuring interferometer systems. A multiple-wavelength interferometer (MWIF) is used for alignment & phasing of the PM segments. The ADMA is used to measure, and set, the spacing between the PM and the focus of the COCOA null (i.e. the PM center-of-curvature) for determination of the ROC. The performance of these metrology systems was assessed during two cryogenic tests at JSC. This testing was performed using the JWST Pathfinder telescope, consisting mostly of engineering development & spare hardware. The Pathfinder PM consists of two spare segments. These tests provided the opportunity to assess how well the center-of-curvature optical metrology hardware, along with the software & procedures, performed using real JWST telescope hardware. This paper will describe the test setup, the testing performed, and the resulting metrology system performance. The knowledge gained and the lessons learned during this testing will be of great benefit to the accurate & efficient cryogenic testing of the JWST flight telescope.

Keywords: James Webb Space Telescope, JWST, primary mirror, multiple-wavelength interferometer, interferometry, cryogenic, optical testing, optical metrology.

1. INTRODUCTION

The James Webb Space Telescope (JWST), shown in Figure 1 below, will operate in the near to mid-infrared to observe the formation of the earliest stars and galaxies.[1] The primary mirror (PM) is 6.6 m in diameter and consists of 18 hexagonal mirror segments, each approximately 1.5 m point-to-point. The observatory will orbit the L2 point 1.5 million kilometers from Earth, away from the sun. A large sunshade will keep the telescope cold, with the primary mirror at approximately 45 K. The segments are coated with gold for high infrared reflectance. Each primary mirror segment assembly (PMSA) is constructed from a lightweight beryllium substrate with both a radius-of-curvature (ROC) actuation system and a six degree-of-freedom hexapod actuation system. The actuation systems will allow the 18 segments to be precisely aligned and adjusted in ROC once at L2 to form a phased primary mirror with the appropriate optical quality for diffraction-limited imaging at a wavelength of 2 um.

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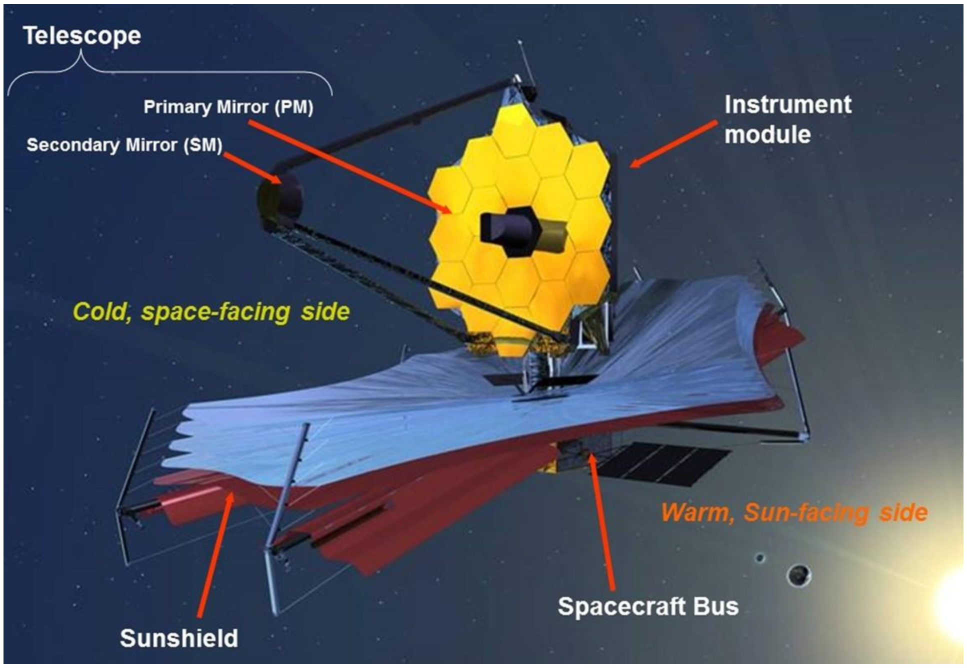


Figure 1. The James Webb Space Telescope.

The JWST Optical Telescope Element (OTE) and the Integrated Science Instrument Module (ISIM), together known as the OTIS, will be tested at the cryogenic operating temperature at Johnson Space Center. The testing will include center-of-curvature measurements of the PM, using the Center-of-Curvature Optical Assembly (COCOA) and the Absolute Distance Meter Assembly (ADMA). The performance of these metrology systems, including hardware, software, & procedures, was assessed during two cryogenic tests at JSC, using the JWST Pathfinder telescope. This paper describes the test setup, the testing performed, and the resulting metrology system performance.

2. CRYOGENIC TESTING OF THE TELESCOPE

The top-level goals of the OTIS cryogenic testing will be to check the OTE & OTE-to-ISIM alignment and to assess the optical performance.[2,3] One of the main components of the testing is the PM center-of-curvature metrology system. This system will be used to accomplish the following.

- Align the 18 PMSA's into a phased PM, with the proper ROC & conic constant.
- Align the phased PM globally to the Aft Optical Subsystem (AOS).
- Measure the phased PM wavefront error (WFE), ROC, and conic constant.

The measurement results will then be used for the following.

- Compare the measured 1g PM WFE, ROC, & conic constant to predictions.
- Estimate the 0g PM WFE.
- Determine the PM collecting area.
- Compare the global location & local pose of each PMSA to predictions, as well as to the actuator range budget.

In addition to the basic demonstration that the PMSA's can be aligned into a phased PM, which is globally aligned to the AOS, the center-of-curvature optical metrology system will also be used to check & adjust the PMSA/PM alignment, as necessary, in support of other OTIS testing, such as the pass-and-a-half testing.

The chamber configuration and the optical layout of the PM center-of-curvature testing is illustrated in Figure 2 below.

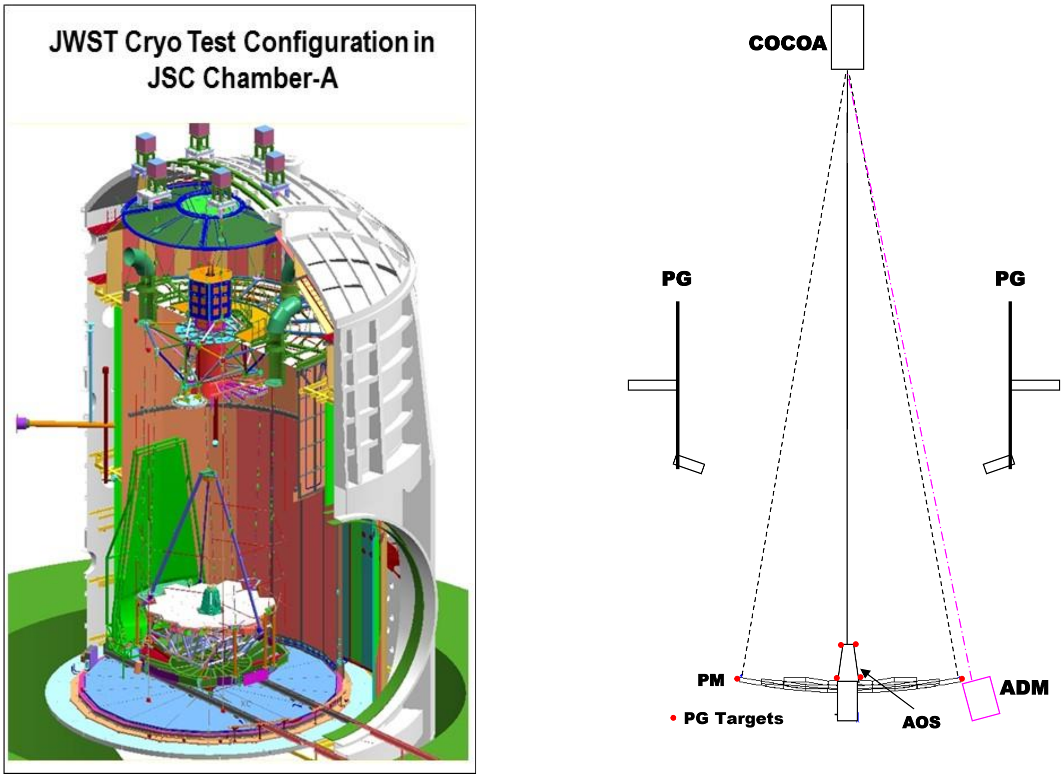


Figure 2. Chamber configuration and optical layout of the PM center-of-curvature testing.

The process for aligning & measuring the PM is as follows.

- Use the PG system to globally align the outer 12 PMSA's (only ones with PG targets) to the AOS.
- Use the COCOA coarse & fine alignment subsystems (CASS & FASS), the fiducial light bars, and the ADMA to initially align the COCOA to the PM.
- Use the FASS to initially align the PMSA's in tilt.
- Use the COCOA multi-wavelength interferometer (MWIF) to fine align the COCOA to the PM and to align & phase the PMSA's.

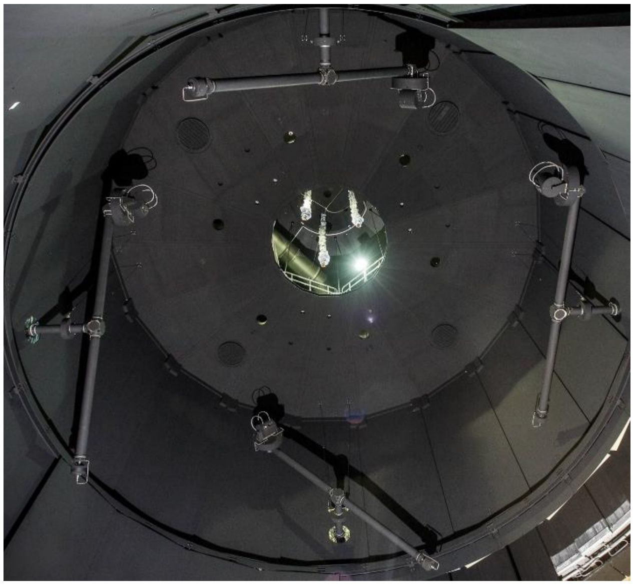
The various optical metrology subsystems mentioned will be described in the following section.

3. THE PM CENTER-OF-CURVATURE OPTICAL METROLOGY SYSTEM

The major components of the center-of-curvature optical metrology system include the PG system, the COCOA, and the ADMA.

3.1 The Photogrammetry (PG) System

The PG system, as shown in Figure 3 below, consists of a set of four cameras on rotating windmill booms at 90° intervals around the chamber. PG targets are attached to all of the major telescope & metrology components. The cameras collect hundreds of images as the windmills rotate. The images are then used to determine the global positions of the outer PMSA's, among other things, with respect to the AOS (the reference) to an uncertainty of <0.1 mm. The PG system was found to meet all of its measurement requirements during the Pathfinder testing. Further details on the PG system, and its performance, are provided in a separate paper in these proceedings.[4]



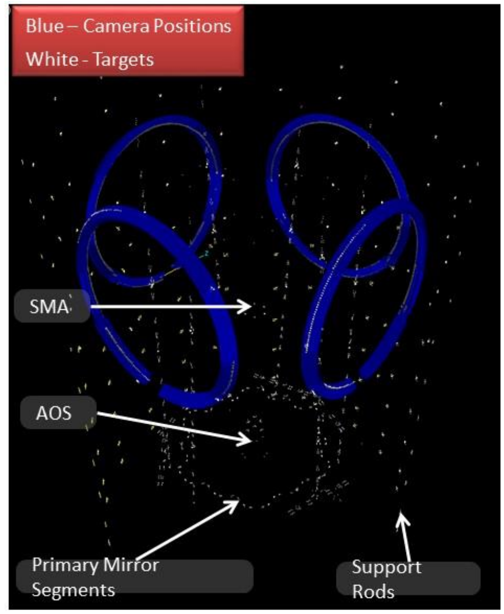


Figure 3. PG system arrangement inside vacuum chamber (left) and simulation of camera movement & PG targets (right).

3.2 The Center-of-Curvature Optical Assembly (COCOA)

The COCOA, illustrated in Figure 4, consists of a multi-wavelength interferometer (MWIF), a reflective null, a MWIF-null calibration subsystem, coarse & fine alignment subsystems (CASS & FASS), and a displacement measuring interferometer (DMI) subsystem.[5,6,7] The MWIF & DMI's are housed in a pressure tight enclosure (PTE) since they are not vacuum compatible. A hexapod motion subsystem provides the capability to position the COCOA in six degrees-of-freedom. And a thermal control subsystem, consisting of multi-layer insulation, heater panels, and a thermal shutter, is used to maintain the internal COCOA temperature at 291 K while in the cryogenic environment. The COCOA is located in an LN_2 environment above the gaseous helium shroud.

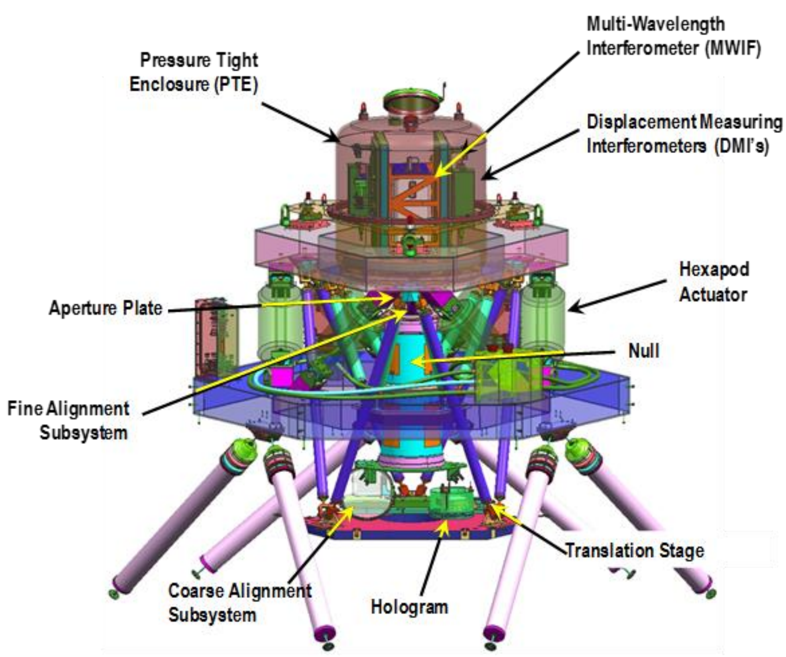


Figure 4. The COCOA (thermal shutter and external heater panels & shrouds not shown).

The MWIF is an instantaneous phase-shifting interferometer with multi-wavelength capability, designed for segmented mirror measurements. It has two single-wavelength lasers (687 nm & 660 nm) and one tunable wavelength laser (680-690 nm). Measurements can be made at the fundamental laser wavelength of 687 nm and at synthetic wavelengths from 16.8 um to 15 mm, produced by combining two measurements made at separate laser wavelengths. This range of wavelengths allows phasing of the PMSA's in piston from several mm down to the nm level. The use of polarized light and a polarizing mask bonded to the interferometer CCD enable phase-shifted data to be captured during a single camera exposure for each wavelength, with only 10 usec between the two exposures. This minimizes the impact of vibration between the COCOA and the PM on the measured WFE.

Alignment & phasing of the PMSA's with the COCOA occurs in stages, beginning with the Coarse Alignment Subsystem (CASS), proceeding to the Fine Alignment Subsystem (FASS), and ending with final alignment using the MWIF. A computer-generated hologram (CGH) is periodically inserted at the paraxial focus of the null to measure, or calibrate, the MWIF/null WFE for removal from the PM WFE measurements. Lastly, the DMI's are used to monitor the COCOA-to-PM axial spacing during certain phases of the test.

3.3 The Absolute Distance Meter Assembly (ADMA)

As indicated in Figure 2 above, the ADMA is positioned just beneath the PM, and faces upward. A drawing of the ADMA is given on the right in Figure 5. It is used, along with the PG system, to set the PM-to-COCOA axial distance. It does this by measuring the distance to a corner cube mounted to the edge of one of the PMSA's and to a cube mounted inside the COCOA, with a known offset from the COCOA paraxial focus. Photogrammetry supports the process by measuring the global locations of the ADMA & the PM. Risley prisms inside the ADMA are used to steer the measurement beam to each corner cube. The geometry of the measurements is shown on the left in Figure 5.

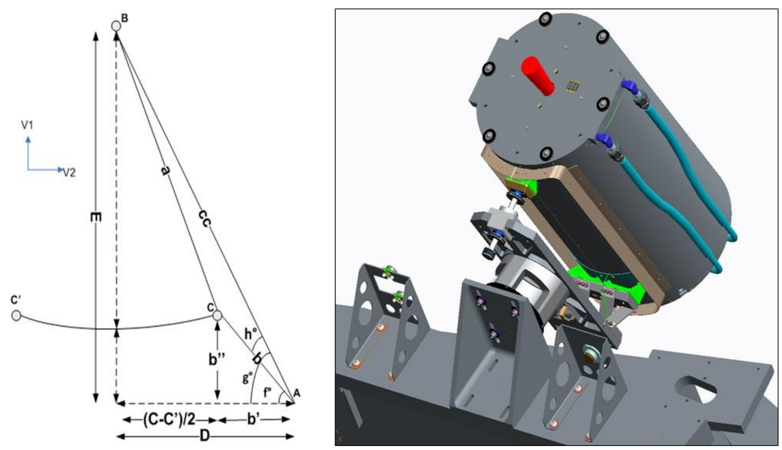


Figure 5. The PM-to-COCOA axial distance geometry (left) & the ADMA (right).

4. JWST PATHFINDER TELESCOPE TESTING OVERVIEW

To prepare for the flight JWST test, two optical GSE (OGSE) tests were performed in 2015. The test article was the Pathfinder OTE, consisting of a non-flight primary mirror backplane center section & secondary mirror support structure, two spare PMSA's, the spare secondary mirror assembly, and either the AOS simulator (first test) or the flight AOS (second test). Testing of the Pathfinder was carried out using the same GSE to be used for the flight telescope test, with the exception of the ADMA, which was only included in the second test. The two OGSE tests were designed to prove out the OGSE systems operating together in a cryo-vac environment, verify the software & analyses used to process the test data, and provide experience in operating the systems.

A photograph of the Pathfinder inside the chamber, with the flight AOS installed, and the layout of the PM for this testing are shown in Figure 6 below. For both tests, PG targets were attached to both PMSA's. And since there was not a PMSA in the B3 location for the mounting of the ADMA retro target, the target was mounted to a post to position it at approximately the correct location.

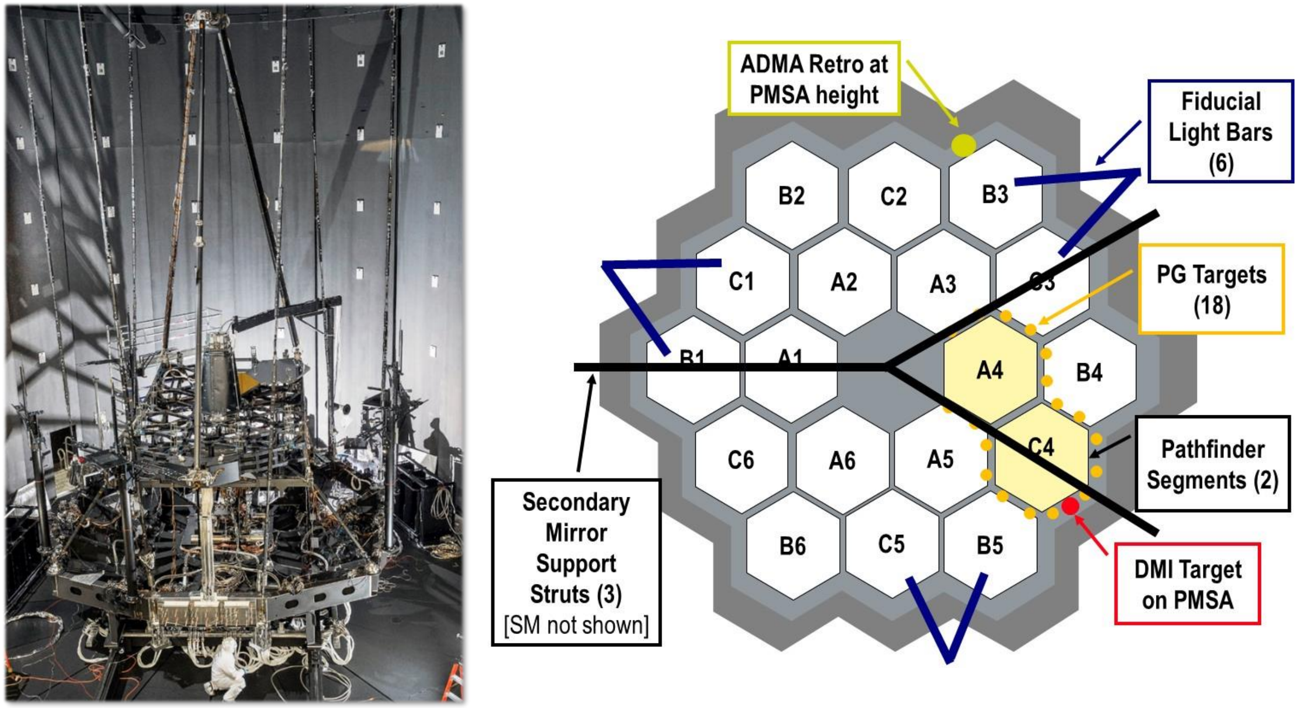


Figure 6. The Pathfinder telescope in the vacuum chamber (left) & the PM layout (right).

The primary OGSE test goals for the PM center-of-curvature optical metrology system consisted of the following.

- Operate the PM center-of-curvature optical metrology system in the flight telescope test environment.
- Complete commissioning, characterization, & stress testing of the PG system, the COCOA, & the ADMA.
- Demonstrate the ability of the PG system to globally align the PM.
- Demonstrate the ability of the COCOA & ADMA to align & phase the PMSA's and to measure the PM WFE.
- Quantify the performance of the optical metrology system.
- Confirm/update the procedures, software, & analyses.
- Increase test team experience.

5. PM CENTER-OF-CURVATURE METROLOGY SYSTEM PERFORMANCE

The full PM alignment & phasing process was performed, multiple times during the two tests, using the PG system, the COCOA (CASS, FASS, & MWIF), and the ADMA. A top level summary of the Pathfinder testing is provided in a separate paper in these proceedings.[8] A review of the most critical performance results for the PM center-of-curvature optical metrology system will be presented in the following subsections (PG results provided in reference 4).

5.1 Alignment & Phasing of the PMSA's

The initial alignment with the CASS, FASS, & fiducial light bars was straightforward, although some software deficiencies were identified, and eventually resolved.

The final COCOA & PMSA alignments were performed using the MWIF. The COCOA was aligned in translation to null global PM tilt, and in rotation to null global PM coma. Since the PM retro for the ADMA could not actually be mounted to a PMSA with the Pathfinder telescope, the ADMA could not be used to set the axial distance. The distance was, instead, set by nulling the global power over the PM. Nevertheless, ADMA measurements were performed, using the surrogate PM retro, to evaluate the system and to gain experience. Section 5.4 below gives the ADMA performance results.

Software developed by Harris for the processing of the MWIF interferograms was used to calculate the PMSA adjustments required for alignment & phasing, and for the adjustment of their ROC's. As above, many software improvements & upgrades were identified, and implemented, during this testing. As a result, the alignment & phasing of the PMSA's was successfully demonstrated during the second test. For the best alignment at cryo, the PMSA's were aligned and phased in piston to 32 nm-PV. A fringe image after one alignment & phasing run is shown in Figure 7. Note that the PMSA's were partially obscured by the secondary mirror support struts, the secondary mirror mount, and a cable tray arm. The WFE of the best-phased PM is shown in Figure 8. Note that the total PM WFE of 415.8 nm-rms is mostly due to the figure error of the PMSA in position C4 (the lower one in the figures) since, as a spare, it was not polished to meet the flight requirements.

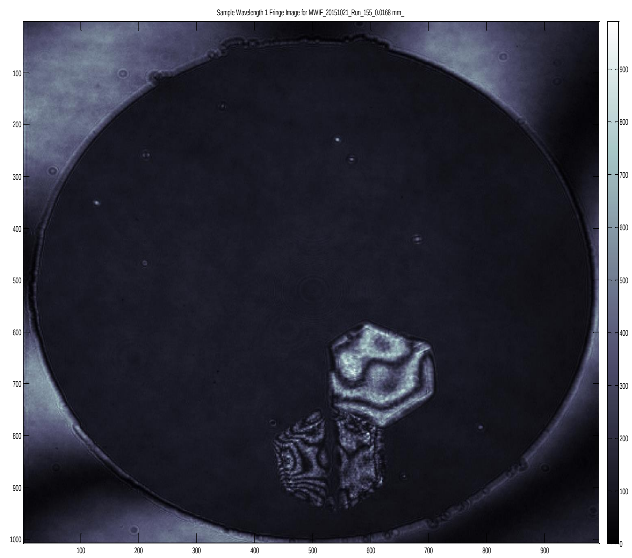


Figure 7. Fringe image of aligned & phased PMSA's.

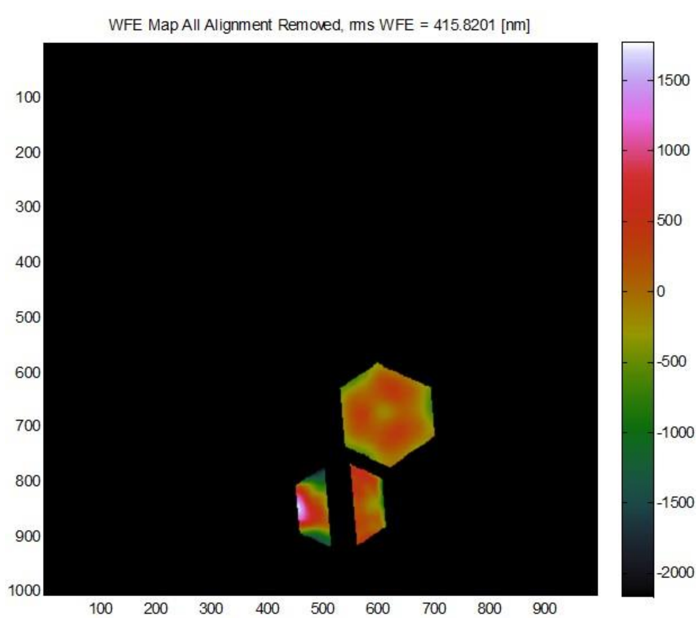


Figure 8. WFE map of phased PM.

Another challenge encountered during the Pathfinder testing was higher-than-expected vibration. Further details on the vibration, and how the MWIF was able to overcome it, are provided in a separate paper in these proceedings.[9]

5.2 PM WFE Measurement Repeatability

The repeatability of the COCOA PM WFE measurements was evaluated using five back-to-back measurements, each an average of 100. The differences in the RMS WFE of each measurement from the average of the five measurements are plotted in Figure 9. The RMS precision of the PM WFE measurements was 10.8 nm-rms, well within the allotted uncertainty.

687 nm (avg of 100 frames in each meas)		
Meas #	RMS (nm)	Delta RMS (nm)
AVG	585.0	NA
1	586.1	9.9
2	579.6	20.9
3	585.6	8.3
4	588.6	10.2
5	585.6	4.8
Mean	585.1	10.8
Std Dev	3.0	5.4
Parameter	Definition	Value
RMS Repeat	Std Dev of RMS values	3.0
RMS Precision	Mean of Delta RMS values	10.8

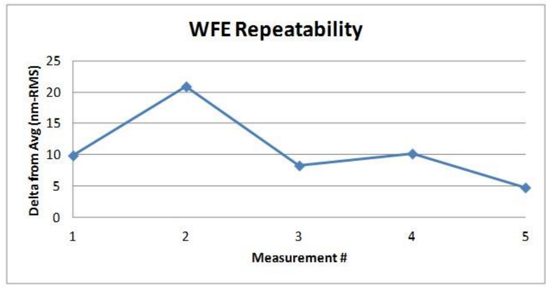


Figure 9. PM WFE measurement repeatability.

The variation of the PMSA piston, calculated from the measured PM WFE, is plotted on the left side of Figure 10. The repeatability of the piston was 7 nm-rms. An example of the segment tilt variation is shown on the right side of the figure. The repeatability of the tilt was 7 nrad-rms. These results are also excellent and consistent with expectations.

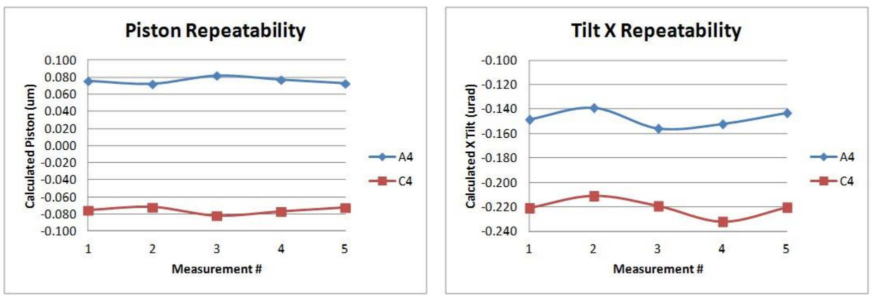


Figure 10. PMSA piston & tilt measurement repeatability.

5.3 Measured versus Predicted WFE

An assessment of the absolute uncertainty was performed by comparing the measured WFE of PMSA A4 to that predicted. The prediction was generated by combining the 0g WFE measured previously during PMSA final acceptance testing (PMSA mounted horizontally) with the vertical gravity deformation predicted via a structural model. The results are shown in Figure 11. Alignment aberrations (tilt, power, & astigmatism) have been removed, the fit of the maps has been optimized for lateral alignment & scale, and a 136-term Zernike fit has been applied to reduce high-frequency noise. The resulting difference of 31 nm-rms is consistent with the estimated combined measurement/predict uncertainty of 30 nm-rms.

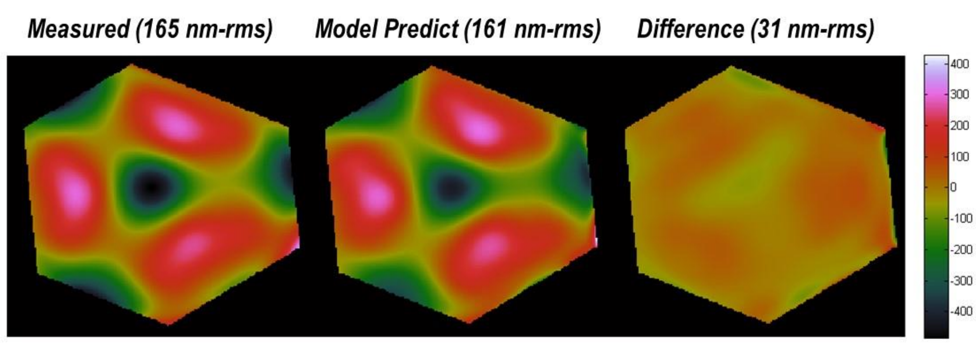


Figure 11. Measured WFE of PMSA A4 compared to that predicted.

5.4 Performance of the ADMA

Functionality of the ADMA was successfully demonstrated at vacuum & cryo.

The absolute uncertainty in the ADMA measurements was assessed by comparing distances measured with the ADMA to the same distances measured with a laser tracker, in an atmospheric pressure environment. The ADMA & laser tracker measurements agreed to 96 um, against a requirement of 120 um.

The system was evaluated for repeatability by making five measurements of each retro cube in the vacuum environment. The repeatability to the closer surrogate PMSA retro was 2 um, and that to the distant COCOA target was 23 um, both well within expectations.

6. SUMMARY & CONCLUSIONS

All of the goals for the PM center-of-curvature optical metrology system were met during the Pathfinder testing, as presented in the following list of accomplishments.

- Verified proper functionality of the PG system, COCOA, & ADMA in a cryo-vac environment.
- More fully established the performance envelope of the system components with the successful completion of characterization & stress measurements.
- Successfully aligned & phased the PMSA's to 32 nm-PV in piston, with a piston measurement repeatability of 7 nm-rms and a PM WFE measurement repeatability of 10.8 nm-rms.
- Greatly improved the test procedures, software, & analyses.
- Gained invaluable experience for the test team.

The knowledge gained and the lessons learned so far during these Pathfinder tests will be of great benefit to the accurate & efficient cryogenic testing of the JWST flight telescope. And one further Pathfinder test, the Thermal Pathfinder Test, will provide an opportunity for a final check of the hardware, procedures, and data analysis tools prior to the flight telescope test.

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