JWST Optical Telescope Element Center of Curvature Test

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ABSTRACT

The James Webb Space Telescope (JWST) Optical Telescope Element (OTE) and Integrated Science Instrument Module (ISIM) completed element level integration and test programs and were integrated to the next level of assembly called OTE/ISIM (OTIS) at Goddard Space Flight Center (GSFC) in Greenbelt, Maryland in 2016. Before shipping the OTIS to Johnson Space Center (JSC) for optical test at cryogenic temperature a series of vibration and acoustic tests were performed. To help ensure that the OTIS was ready to be shipped to JSC an optical center of curvature (CoC) test was performed to measure changes in the mirror's optical performance to verify that the telescope's primary mirror was not adversely impacted by the environmental testing and help us in understanding potential anomalies identified during the JSC tests. The primary is a 6.5 meter diameter mirror consisting of 18 individual hexagonal segments. Each segment is an off-axis asphere. There are a total of three prescriptions repeated six times each. As part of the CoC test each segment was individually measured using a high-speed interferometer (HSI) designed and built specifically for this test. This interferometer is capable of characterizing both static and dynamic characteristics of the mirrors. The latter capability was used, with the aid of a vibration stinger applying a low-level input force, to measure the dynamic characteristic changes of the PM backplane structure. This paper describes the CoC test setup and both static and dynamic test results.

Keywords: JWST, interferometer, optical testing

1. INTRODUCTION

The JWST observatory is the next generation space telescope designed to study the formation of the earliest stars and galaxies. To meet its science objectives JWST will operate at cryogenic temperatures and provide a large collecting area, over seven times that of the Hubble Space Telescope. The observatory consists of 4 major subsystems. The Optical Telescope Element (OTE), the Integrated Science Instrument Module (ISIM), the sun shield, and the spacecraft bus. The integration of two of the modules, the OTE and the ISIM, was completed at GSFC in 2016 resulting in the OTIS assembly[1].

The JWST telescope is a three mirror anastigmat comprised of a segmented primary mirror, a position adjustable convex secondary mirror, and a fixed tertiary mirror. Additionally, there is a flat fine steering mirror used to maintain alignment of the telescope relative to the observatory's instrument module. Figure 1 shows an overview diagram of the JWST observatory. In order to fit within the rocket fairing the entire assembly will be folded up and then deployed while in route to its L2 orbital position. For this reason, the primary mirror is segmented, consisting of 18 hexagonal mirrors each approximately 1.5 meters point to point. Each mirror segment is constructed from a lightweight beryllium substrate with a protected gold coating. Two actuation systems are mounted to the back of the mirror. One to adjust the segment's radius-of-curvature and the other to allow for six degree-of-freedom motion. The eighteen Primary Mirror Segment Assemblies (PMSA) are mounted to a graphite/epoxy backplane support structure.

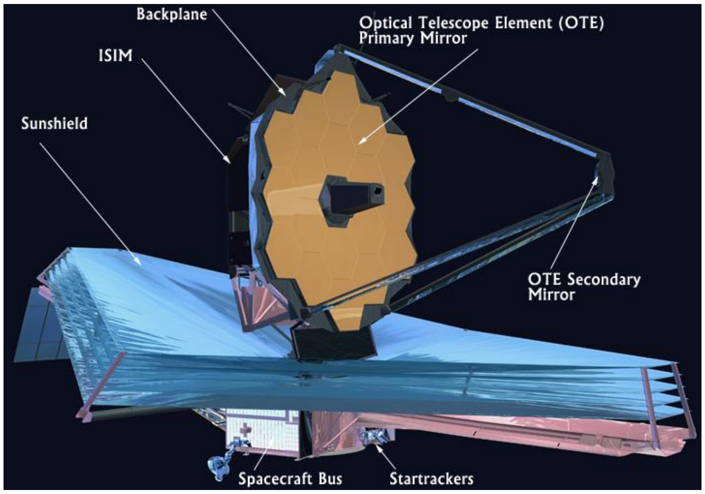


Figure 1: JWST observatory overview diagram.

The telescope was assembled and instruments installed at NASA Goddard Space Flight Center clean room facility. The Integrated Science Instrument Module (ISIM) consists of four science instruments in its instrument housing which is attached to the backplane of the primary mirror. Before shipping the OTIS to Johnson Space Center (JSC) for optical testing at cryogenic temperature a series of vibration and acoustic tests were performed to simulate the launch conditions for the telescope assembly. As part of this environmental testing several methods were employed to look for changes which may have occurred to the telescope or flight instruments. This included accelerometers placed on the OTIS and observed before, during, and after the environmental tests. Additionally, functional testing of all the electronic and motorized components were performed. Finally, as part of the overall test plan a center of curvature (CoC) optical test was performed to look for changes in the primary mirror shape to the nanometer level[2] to help assure the telescope's primary mirror was not adversely impacted by this environmental testing. This is important since the primary mirror must meet its 25nm rms surface figure specification on-orbit if the observatory's science objectives are to be met.

The primary mirror was measured before and after environmental exposure statically by measuring the surface figure of each segment. The standard center of curvature test method was expanded upon by the development of a high-speed interferometer (HSI) to allow testing of the primary mirror segments dynamically to gain additional insight into the state of the telescope. This interferometer was designed and built specifically for this test by 4D Technology[3]. HSI allows thousands of surface figure measurements to be taken every second and then pieced together temporally to determine mode frequencies and shapes of each mirror. When this is combined with a low level vibrational stimulus to the composite backplane structure a series of transfer functions can be generated and used to look for changes in their gain and phase properties.

2. TEST OVERVIEW

The optical layout of the primary mirror testing was the classical interferometric center of curvature test[6]. The primary mirror segments were tested statically and dynamically by measuring the surface of each segment using a CGH at Center of Curvature (CoC) of the primary mirror.

As previously discussed each primary mirror segment has a 6-DOF hexapod actuation system that will be used during on-orbit phasing of the primary mirror. This allows us to consider changes to the alignment correctable errors, predominantly astigmatism separate from changes to the surface figure. This is also important since astigmatism is the first bending mode of the mirror and is therefore the most likely shape to be observed from an actual deformation of the mirror. Additionally, astigmatism is harder to measure since it is introduced into the measured wavefront from several metrology based sources including alignment and will need to be allotted additional measurement uncertainty. For these reasons the static portion of the center of curvature testing was broken up into changes in surface figure and astigmatism for each mirror.

A high-speed interferometer capable of taking surface figure measurements at a rate of 5.9 kHz allowed dynamic testing. The high-speed interferometer (HSI) was designed and built by 4D Technology in collaboration with Space Flight Center. The HSI obtains simultaneous measurements at 4 separate phases. Therefore, it can obtain relative spatial phase differences in one exposure. This allows for a reduction in the sensitivity to background vibrations. This technique along with the use of a high frame rate camera and other improvements is what allows for the increased measurement speed[4].

The six degree of freedom alignment of the CGH to the mirror segment is critical. This alignment is set using several metrology methods including using features built into the CGH design, and use of an alignment CGH. The metrology system consisting of the interferometer, CGH and the alignment camera system is mounted on an optical table which rests on top of a six degree of freedom hexapod stage called Rotopod built by Mikrolar Inc[5]. Rotopod provides a good range of motion with a high load capacity. The stage was also designed to give micron and sub arcsecond level motion resolution. As shown in Figure 2 the entire metrology system is placed on top of an 18-foot-tall tower used to elevate the test setup to the same height as the primary mirror optical axis. This stand was designed and manufactured to reduce vibrational effects within the optical test. The stand is positioned in its proper test location using a Leica Laser Tracker. The environment within the SSDIF (Spacecraft Systems Development and Integration Facility) cleanroom, where testing occurred was optimized to minimize the effects of air turbulence and air stratification along the approximately 16 m optical path distance in the test setup. Specifically, the temperature fluctuations within the cleanroom were kept to less than 0.1˚C/10 min with a rate much less than this for the majority of time. A detailed description of the alignment process can be found in Ref. 6

The CoC test is a differential test. The post-environmental test results are differenced from the pre-environmental measurements. Therefore the post-environmental alignment state must match the pre-environmental alignment to within the budgeted tolerances. To achieve the decenter and clocking portion of the alignment of the mirror relative to the CGH a new method was developed. This method did not require the attachment of any fiducials onto the primary mirror, as this would have been problematic given the approximate 6 mm gap between segments. Instead this new method used an alignment camera system to image the mirror under two conditions. From these two images the alignment of the mirror relative to the CGH was ascertained. The first image was that of the mirror illuminated with a source near the center of curvature point. The second image captured was also of the mirror with the interferometer laser light passing through the CGH. The CGH is designed with four features that act as lenses to focus light spots onto the mirror surface. The first image was analyzed for edge finding to locate the position of the mirror on the CCD image. The second image was processed with centroiding analysis to locate the four spots on the CCD image. Using the two images the mirror location relative to the spot location could be determined. This same method is used on the post-environmental CoC test but this time the two new images are compared to the baseline images to match the relative alignment. This assures the mirror-to-CGH alignment matches for the pre and post environmental CoC tests. Custom software written by Space Telescope Science Institute (STScI) was used to analyzed the images and provide for rapid alignment of the mirror.

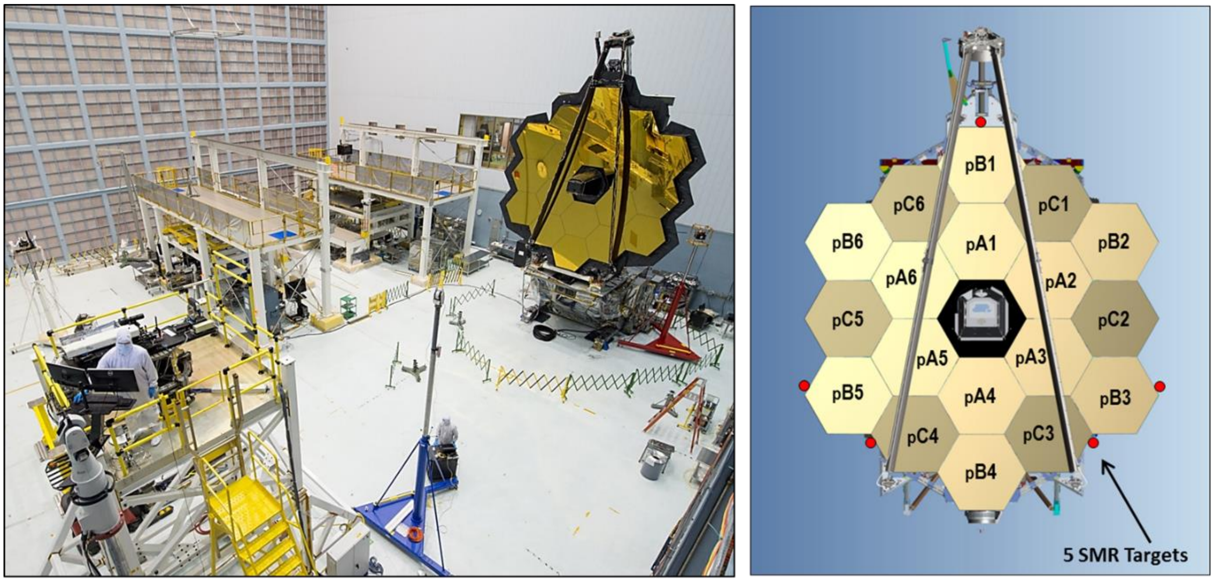


Figure 2. Center of Curvature Testing at GSFC.

Additional metrology equipment was needed for the dynamic portion of the test. One metrology instrument specific to the dynamic testing is the OTIS vibration stinger. Dynamic data analysis relies on the use of transfer functions to determine changes to the OTIS vibrational characteristics. This is accomplished using a low-level force applied to the OTIS composite support structure location to create a known input. This force only needs to be large enough to assure the signal is above the background vibration but low enough to assure the mirror velocity requirements are maintained. The vibration input force is measured using a force gauge at the input stinger location. This measured force is synced to the HSI data using a trigger signal. Figure 3 shows the shaker/stinger setup. The shaker was held approximately six feet from the OTIS contact point. The stinger rod was made of graphite epoxy so that it was very light weight but very stiff.

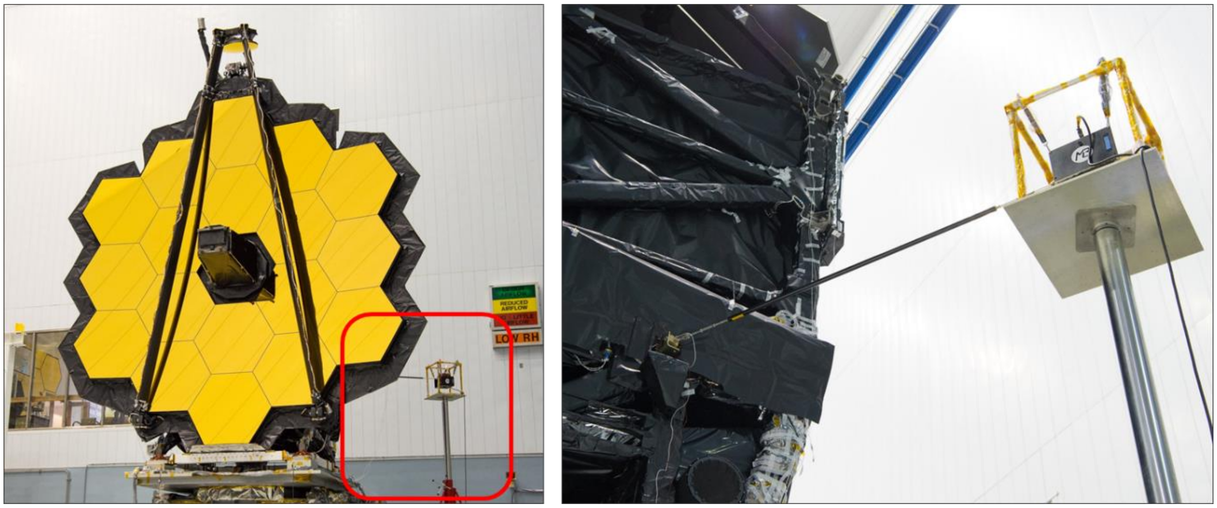


Figure 3. Vibration Stinger System.

Additionally, a DMI (Distance Measuring Interferometer) system was developed for dynamic measurements. The DMI system was developed to measure the motion of the entire telescope at a higher speed, 20 kHz. This would allow the global rigid body motion to be backed out of the HSI data to aid in the determination of the local vibration of a single segment. In the end it was not needed for the HSI data analysis since the velocities of the mirrors during CoC testing were within the required limits.

The dynamic test generated large amounts of data requiring high speed fiber optic data lines and a high-powered computer server to process the large amount of data in a timely fashion Figure 4 shows a block diagram of the high speed interferometric test layout[7].

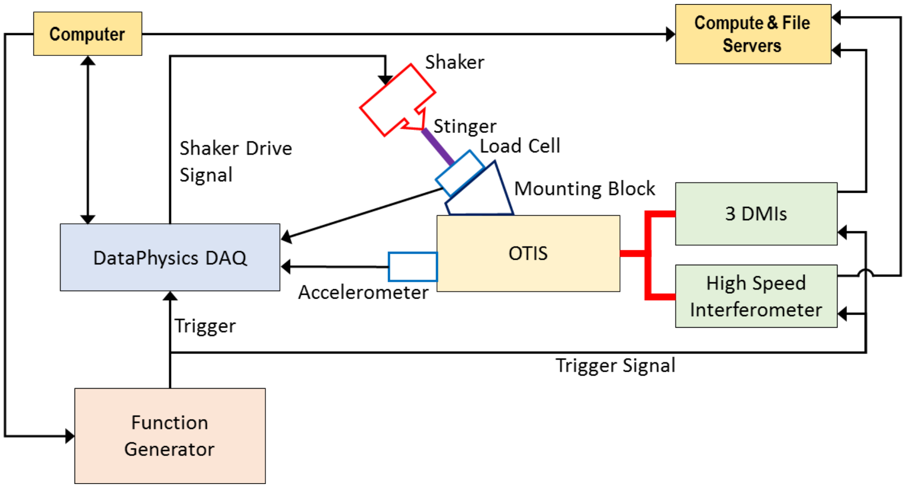


Figure 4. Dynamic Measurement System Block Diagram.

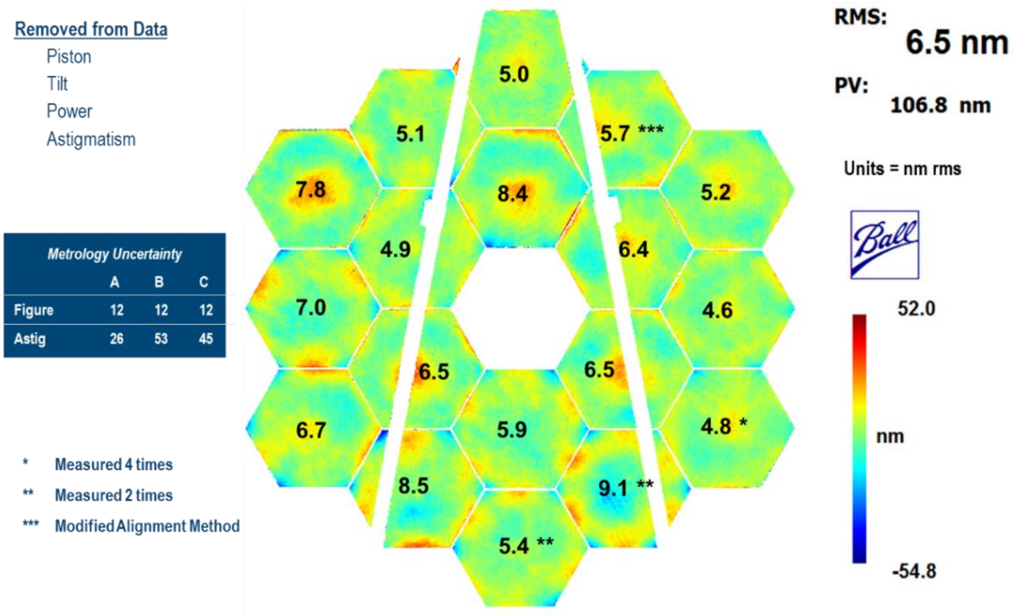
TEST RESULTS

2.1 Static Measurement Results

Static measurements for the center of curvature test refer to the primary mirror segment surface figure measurements using standard interferometric techniques. The static measurements are analyzed for a time average shape of the mirror surface. The same high-speed interferometer is used but at a typical rate of speed. For static measurements 1500 individual phase maps are collected and averaged using 4D Technology's 4Sight software. This process takes approximately 20 minutes. Therefore, environmental effects such as background vibration and air turbulence are averaged over this 20 minute time period. This helps reduce specific errors that contribute to the wavefront measurement.

Each segment was measured individually (i.e., no full aperture measurement of the entire primary mirror) before and after the environmental testing. The delta measurement was analyzed for surface figure and astigmatism changes to the mirror shape. The data collected was post processed to separate the astigmatism change from the surface figure change. Measurement uncertainty error budget was developed for the delta of the pre and post environmental measurements of the static portion of the CoC test. It includes measurement repeatability, alignment, temperature, gravity and data processing terms. Each prescription type (A, B, & C) has its own uncertainty due to its specific alignment sensitivities. The error budget was developed based on test mirror measurements in the SSDIF cleanroom, analysis of 1500 measurements taken during the CoC test, thermal control in the cleanroom, 20 min averaging of the effect of the temperature gradients within the mirror assembly and matching the environmental conditions and test hardware parameters as close as possible before and after vibro-acoustic testing including room lighting, camera settings, LED illumination source settings, and software setting. Additionally, to determine the magnitude of these effects a separate but limited test was performed during the post-environmental CoC test to determine the impact on alignment when setup variables were altered.

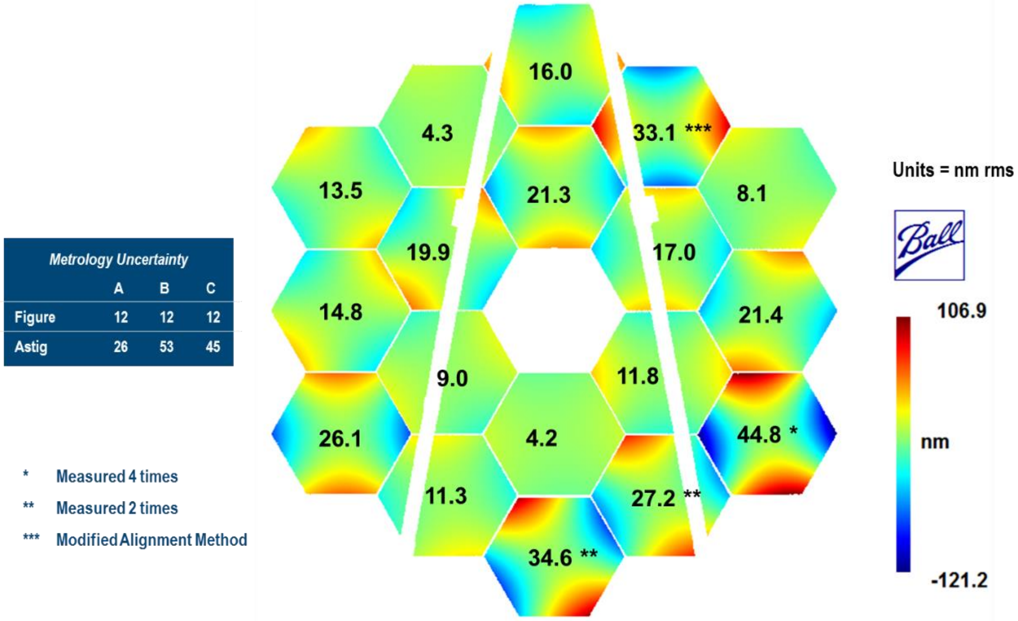
The measured results for the static portion of the CoC test are shown in Figures 5 and 6. These figures show a composite image generated from the 18 individual mirror measurements.



Metrology Uncertainty

	A	B	C
Figure	12	12	12
Astig	26	53	45

Figure 5. Static Surface Figure Changes.



Metrology Uncertainty

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Figure	12	12	12
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Figure 6. Static Measurement Astigmatism Changes.

The results for both figure and astigmatism show all measured delta values within uncertainty budget. Therefore, we can conclude that no significant changes occurred to any of the primary mirror segments. The surface figure deltas show four primary contributions; random noise, trefoil, hexafoil, and coma. The trefoil and hexafoil are common signatures of temperature effects while coma is most likely due to an alignment error between the two datasets. All of these contributions are small, expected, and allotted for within the budgeted uncertainty. Astigmatism changes, while also small does show two areas which require a more in-depth analysis. First the pC1 mirror has a larger change than the mirrors around it. This is most assuredly due to the fact that the alignment method for this mirror had to be altered slightly. The alignment camera system directs four laser spots onto the mirror surface. However, the secondary mirror support struts will occasionally block one of the spots from getting to the mirror. In the case of the pC1 mirror two spots were blocked. This was the only mirror which had this condition. Since the use of only two projected spots will lead to a very large alignment uncertainty an alternate method was employed. The CGH was rotated 180 degrees in its mount to place four spots on the mirror. The alignment camera images were taken with the CGH in this orientation and after the alignment process was complete the CGH was flipped back to its nominal orientation prior to performing the interferometric measurements. This process works in part thanks to the very repeatable CGH mechanical interfaces as provided by Diffraction International. While this alternate alignment method works better than using only two spots, it does potentially add some additional alignment error which in turn led to the larger astigmatism value. Therefore, the pC1 mirror shows no errors of concern.

The other region of interest is the three mirrors on the bottom lower right. This is the pB3, pC3, and pB4 mirror segments. Additional testing showed that alignment errors can be introduced by variation from a number of factors including room lighting. While we can’t say for certain why these three segments had a slightly larger astigmatism change the deltas are within our measurement uncertainty after accounting for these potential errors in the alignment camera system. A visual inspection of the pB3 mirror after completion of the CoC test did not reveal any issues with the mirror segment.

2.2 Dynamic Measurement Results

The main goal of the dynamics portion of the CoC test is to acquire diagnostic survey data of the OTIS vibrational characteristics at low input levels. The CoC dynamics test uses low level of forcing functions on order of 10 N or less. This force was a dynamic load applied to the OTIS composite structure while the HSI observed a PMSA. The loading condition was repeated for each PMSA and the full primary mirror (PM) correlated response was generated by applying transfer functions as described later in this writing. Using these low-level inputs as references, the dynamic response of the OTIS is measured before and then again after the environmental testing and analyzed for changes in the observed response.

The OTIS was subjected to a number of mechanical operations and environmental tests between the two CoC tests. This includes stowing and deploying the primary mirror wings, stowing and deploying the primary mirror segments, the vibration and acoustic testing, and the transfer of the OTIS assembly on and off several handling fixtures. Despite these events no significant changes were observed in the dynamic CoC data. Although statistical differences in response functions were observed, they were not considered significant in magnitude.

The data is processed in two steps. The first step is the individual test data processing. The second step combines the data sets and tests for statistically significant changes. Figure 8 shows the general data processing flow for a single data set. The raw data consists of time series of images. Each image contains spatially interleaved intensities of the observed fringes at 4 different phases of the interfering reference beam[8]. From these images it is possible to derive a wrapped phase cube and then unwrap this cube using both temporal and spatial techniques. The result is a time series displacement cube of data. Each frame of data is then undistorted to eliminate the large amount of pupil distortion and mapped into the OTIS Mirror Master Reference (MMR) coordinate system. At this point the data can be processed in a variety of ways depending on what additional analysis is desired.

In the Zernike analysis Zernike coefficients are fit to each image to create a time series coefficient dataset. A Fourier transform is applied to the coefficient data to generate a spectrum of Zernike content versus frequency. From here we create transfer functions for each Zernike response in reference to the input forcing function. This is accomplished by dividing the complex Zernike frequency response by the complex stimulus frequency distribution. This allows comparisons to be made of datasets with different stimulus levels and taken at different times.

The CoC test was performed in an open integration bay and had noticeable background noise. The effects of the noise level were addressed in two manners. First, the test input load attempted to drive the response above the noise without exceeding the HSI velocity constraints so that temporal unwrapping could still be accomplished. Additionally, multiple measurements were taken and resulting transfer function response coefficients of phase and gain were averaged. Signal to Noise Ratio (SNR) and coherence functions were generated for the averaged datasets to be certain the data used for determining an actual change to the flight hardware was of high quality.

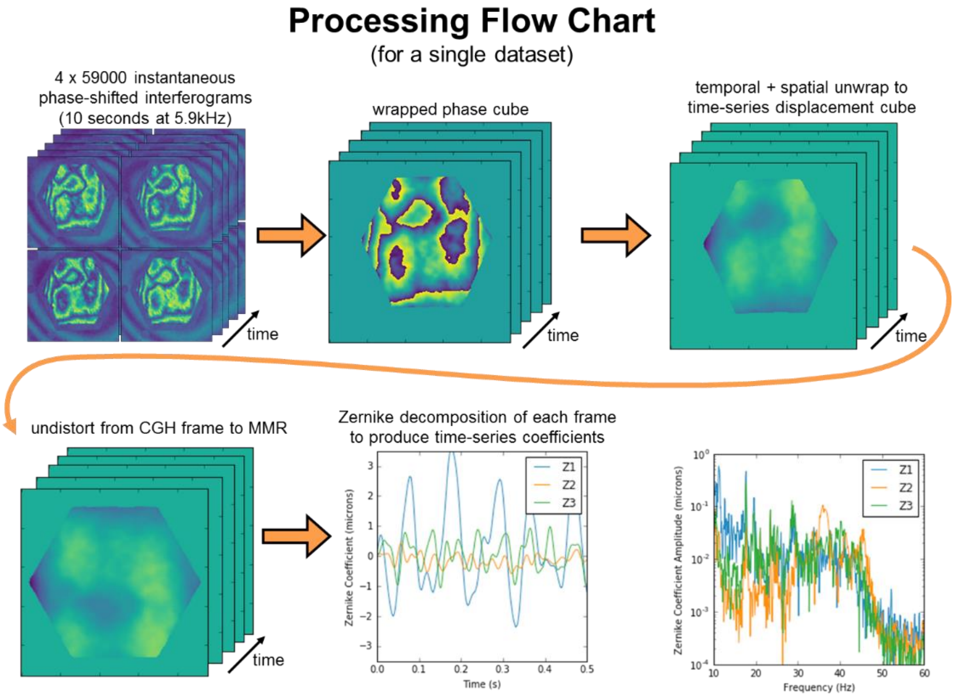

Figure 7. Data Processing for Dynamic Results.

Dynamics testing generally took place in the evenings to exploit the lower background vibrations. Each PMSA segment was aligned sufficiently to reduce the fringe density and assure quality data. Absolute alignment was not necessary for the dynamics measurements since the first frame of 59000 total frames per test is used as a reference for temporal changes to the mirror position or shape. Once aligned a series of 10 second measurements are taken with a frame rate of 5.9 kHz. While the interferometer is capable of spatial resolutions up to approximately 2K x 2K the dynamics data was collected at 240x240 to enable maximum camera speed. The high speed was essential for balancing velocity limits and background noise level limits. Measurements are taken under various input stimulus conditions including: Background with no input stimulus, Sine Sweep over 25-50 Hz or 10-50 Hz and Random input. Reproducibility measurements are taken by repeating the data collection process for particular mirrors on a different day. This reproducibility data was key to assuring that measured changes were real.

One method to analyze the data is to look at the transfer function gain and phase parameters at a particular frequency. The global data is analyzed to find frequencies where we have high quality data for all segments. We then map out the transfer function over a circular aperture, for Zernike fitting purposes, applied to each mirror surface. A full primary mirror composite image of correlated response is constructed to aid in visually looking for differences. Figures 8, 9, 10 and 11 show the results for rigid body and astigmatism at 43.0 Hz.

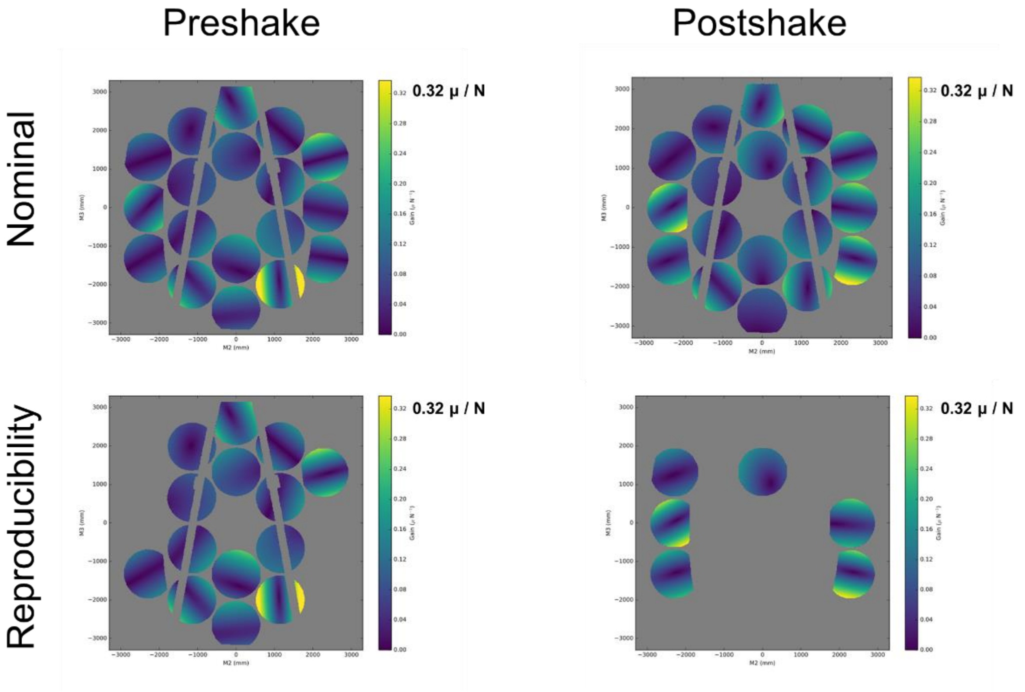

Figure 8. Rigid Body (Z1-Z3) at 43.0Hz, Transfer Function Gain

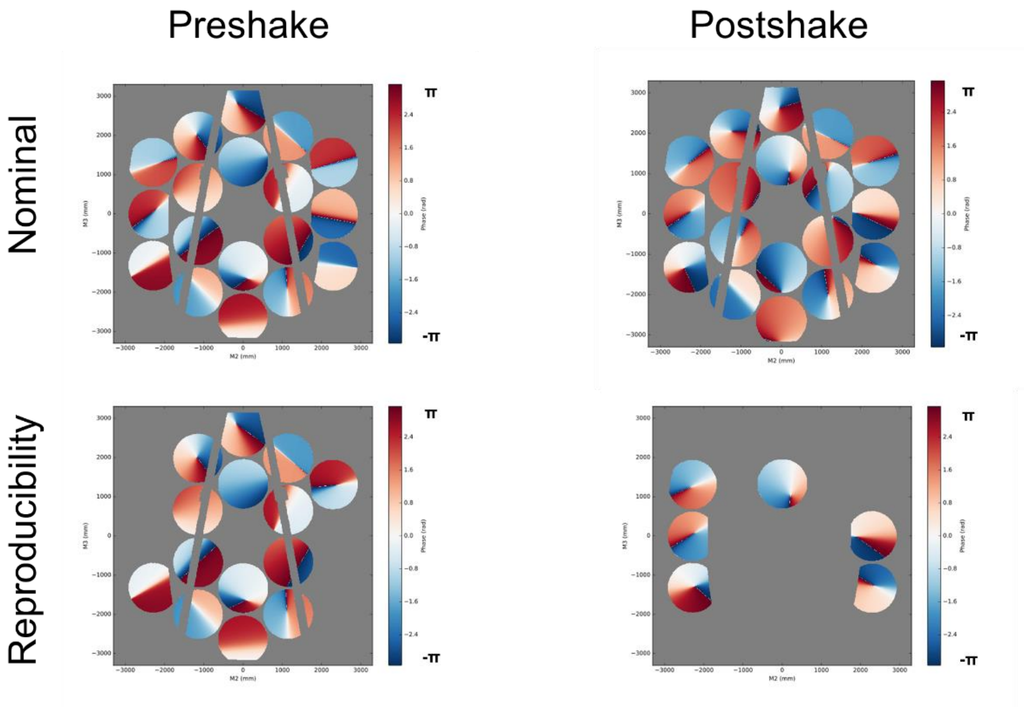

Figure 9. Rigid Body (Z1-Z3) at 43.0Hz, Transfer Function Phase

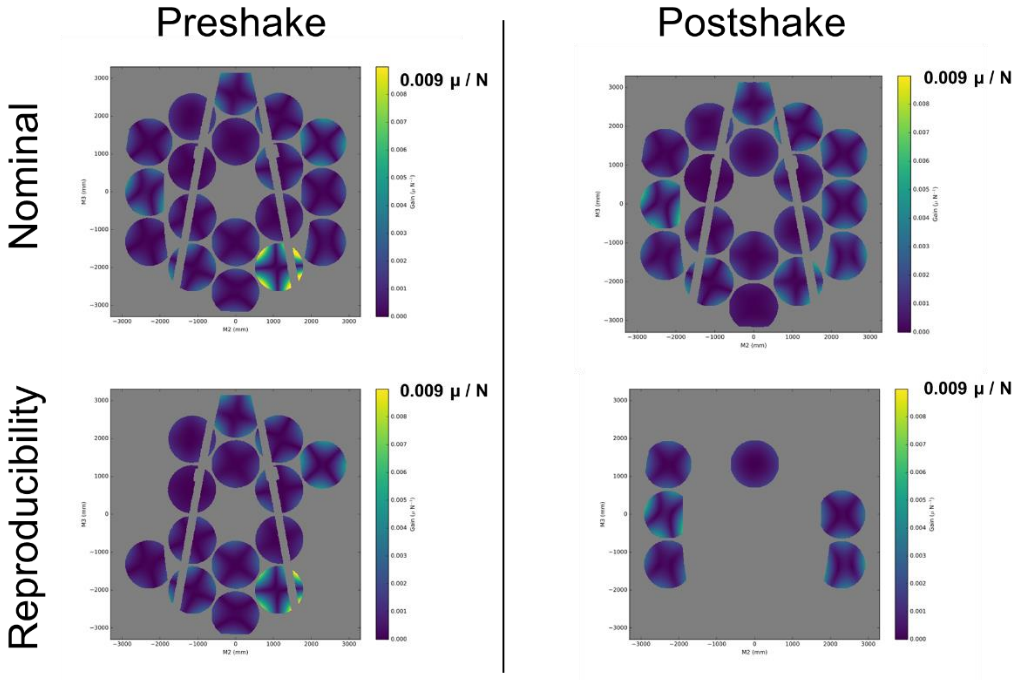

Figure 10. Astigmatism (Z5-Z6) at 43.0Hz, Transfer Function Gain

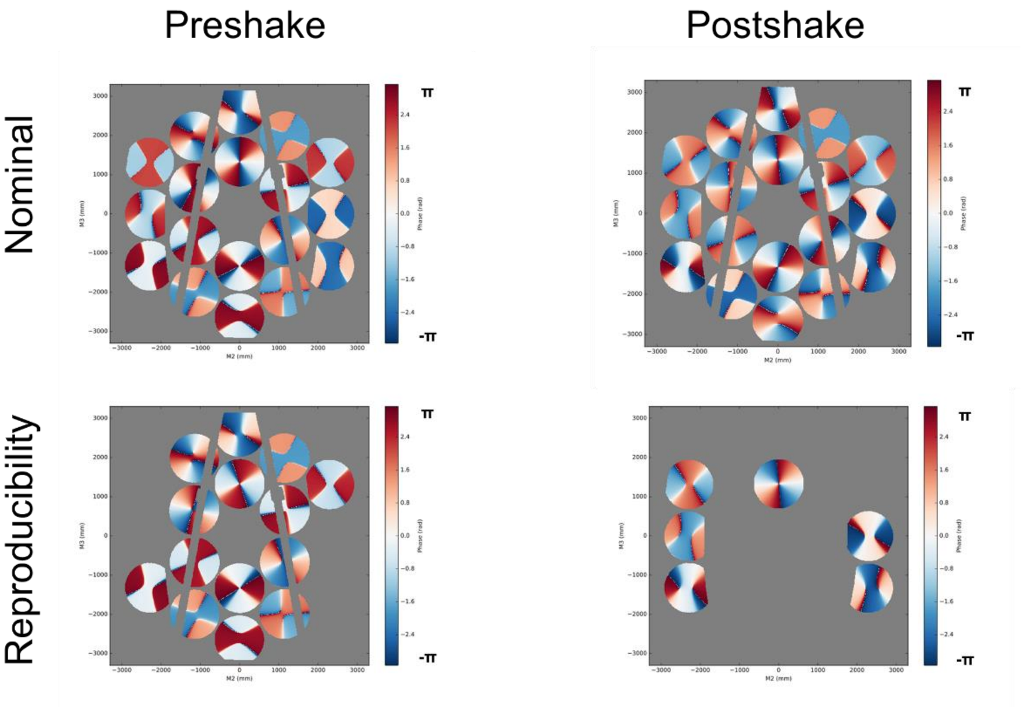

Figure 11. Astigmatism (Z5-Z6) at 43.0Hz, Transfer Function Phase

This type of analysis provides a good visual indication of vibrational characteristic changes. The phase and gain transfer functions do not individually show surface figure shape. The gain is the actual motion of the mirror for a given input stimulus on a pixel by pixel basis. The phase is similar except it can be thought of as the time required for an input force to travel through the OTIS structure and cause a motion of the mirror surface. The surface shape is really a combination of both the gain and phase. Figure 10 looks like an astigmatism shape because these surface motions have been filtered for this one Zernike term.

3. SUMMARY

Before shipping the JWST telescope and instrument assembly OTIS to JSC for performance testing at cryogenic temperature, a series of vibration and acoustic tests were performed in order to verify its launch worthiness. As part of this testing sequence a center of curvature (CoC) optical test was performed before and after these environmental tests to inform about the health of OTIS before shipping it to JSC. The CoC tests included both a static mirror figure testing and a dynamic mirror response test.

Static CoC testing met its goal to measure mirror changes to an accuracy sufficient to conclude that the mirrors were not adversely affected by environmental testing allowing the OTIS assembly to move forward to the cryogenic test. Results showed that no changes occurred to any mirror segment's surface figure or astigmatism shape greater than the calculated metrology uncertainty. The new alignment method that did not require any fiducials to be attached to the mirrors worked well for aligning the mirrors. Finally, a study of the worst case measured result, the pB3 astigmatism, was conducted to show that even if it were real it could be compensated for in flight with a -0.25 mrad clocking of the mirror.

The dynamics portion of the CoC test successfully measured the opto-mechanical modes of the telescope in low amplitude stimulation to nanometer precision. The dynamic results confirmed that no unacceptable change occurred to the OTIS assembly. The successful CoC test increased our confidence in moving forward with the OTIS optical test at cryogenic temperature at JSC. The cryogenic test was successfully completed in October 2017.

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