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RADIUS OF CURVATURE MATCHING SYSTEM FOR A SPACE BASED SEGMENTED TELESCOPE

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ABSTRACT

As space based telescopes continue to get larger and larger it has become necessary to split the primary mirror up into multiple segments. This allows the telescope to be folded up within the launch fairing and deployed once on orbit. While there are obvious advantages with this segmented approach it is not without its technical challenges. One of these challenges is to match the radius of curvature (RoC) for all segments, thus allowing them to act as a single large mirror. Errors in the RoC matching will add to the total wavefront error of the telescope and therefore must be minimized. There are several methods which can be employed for RoC matching. Examples include RoC actuation, RoC precision polishing, and deformable or fixed compensation optics. This paper focuses on the method and results utilized by the James Webb Space Telescope (JWST), that of RoC actuation. This method carries with it many attractive advantages such as the relaxation of RoC polishing requirements and thus polishing time, as well as the ability to perform real-time matching to compensate for changing environmental conditions, which helps guarantee a fully optimized wavefront. This method was especially advantageous given the 45 Kelvin nominal operational temperature of the JWST primary mirror. JWST's primary consists of 18 hexagonal segments, each approximately 1.5 meters point to point and made of optical grade beryllium. A RoC actuation system on each segment uses a single actuator and six struts attached to the back of the mirror. Presented here is the RoC manufacturing methodology, as well as the measured RoC performance of both individual segments and the full primary mirror.

INTRODUCTION

The James Webb Space Telescope, shown in Figure 1, is a large cryogenic infrared space based telescope. The primary mirror is 6.5 meters in diameter and is comprised of 18 hexagonal segments. Additionally, the JWST design employs a deployable sunshield and secondary mirror support structure. This allows the telescope to be folded in such a way as to fit within an Arianne 5 fairing. This basic segmented primary mirror design type, using either hexagonal mirrors or petals, is becoming the norm for larger space-based telescopes. This also means that the number of deployments and adjustments required once on-orbit are ever increasing.[1]

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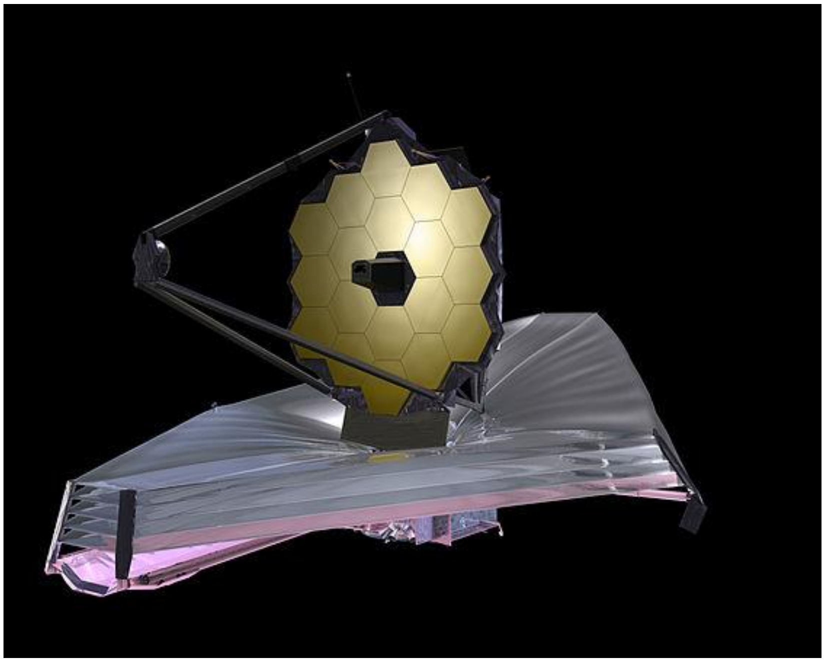

Figure 1: James Webb Space Telescope (JWST)

The JWST Optical Telescope Element (OTE) is shown in Figure 2. It consists of a segmented primary mirror, as well as secondary, tertiary, and fine steering mirror assemblies. Ball Aerospace & Technologies Corporation is responsible for the design and build of the OTE mirror assemblies. The telescope's mirror substrates are made of beryllium, to leverage this material's unique properties at cryogenic temperatures. The primary mirror segments are mounted to a three piece graphite composite backplane support structure, which allows the outer three mirrors on each side, referred to as the wings, to fold backwards. Once on orbit the wings are deployed and then each segment is commanded off its launch locks.[1]

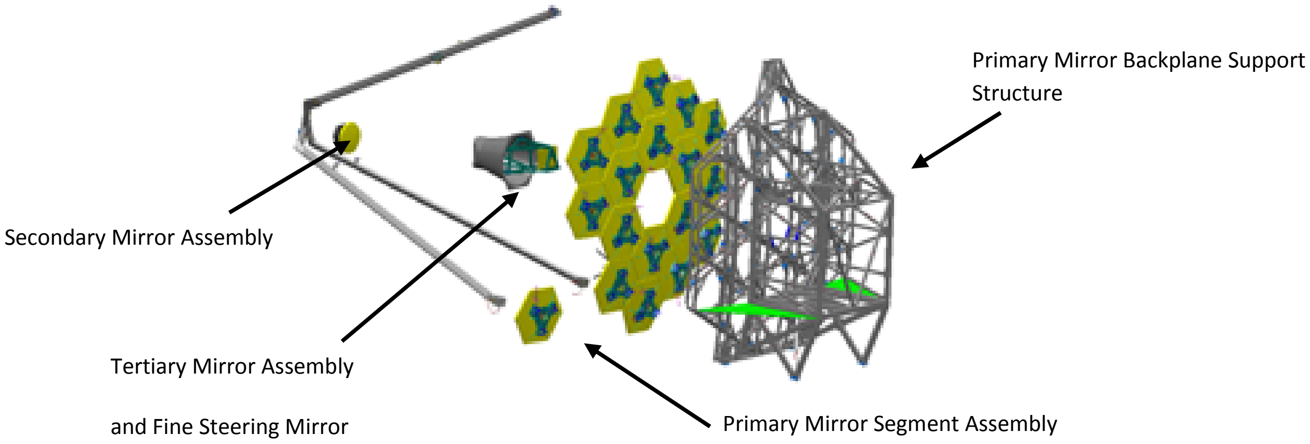

Figure 2 – OTE Subassemblies

The primary and secondary mirror segments can be adjusted in six degrees of freedom using six actuators per mirror, oriented in a hexapod configuration. Additionally, the primary mirror segment assemblies (PMSAs) contain a seventh actuator giving them radius of curvature (ROC) adjustment capability. This RoC system is separate from the hexapod system (see Figure 3). After launch and deployment, a wavefront sensing and control algorithm is used to align the individual primary segments to form what is essentially one continuous mirror. Minor adjustments are then made on an as needed basis over the lifetime of the mission. A sunshield will protect the telescope from radiative heating from the sun and earth, allowing the telescope to passively cool to less than 50 Kelvin.[1]

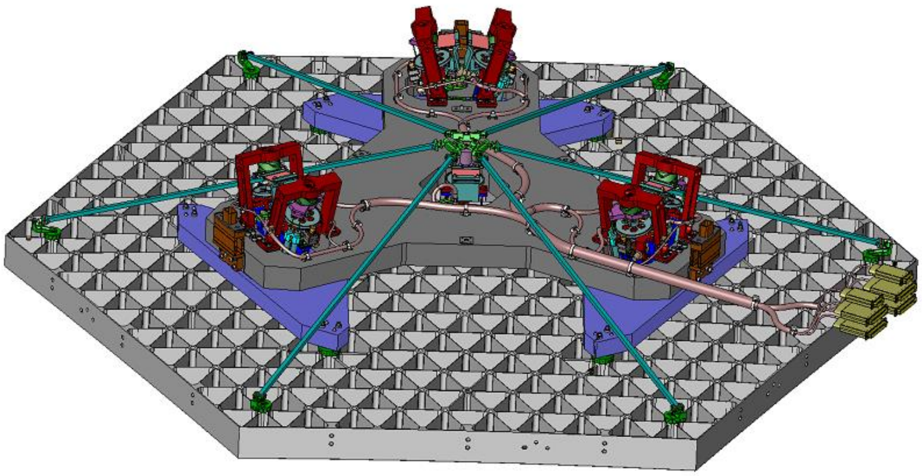

Figure 3: Primary Mirror Segment Assembly (PMSA)

PMSA ROC MECHANISM REQUIREMENTS

The driving requirements for the PMSA design are cryogenic operation, low mass, six degree of freedom (DOF) position control, radius of curvature adjustment, low gravity deformation, launch survivability, and excellent surface figure at operational temperature. Specifically, the primary mirror surface figure requirement at operating temperatures is 25 nm rms. This value is for the low to mid frequency portion of the composite primary mirror surface figure, which can be approximated by the first 36 fringe Zernike polynomials over each individual segment. While additional high spatial frequency error requirements exist, they will not be discussed within this paper. A sub-set of the general PMSA and RoC requirements are presented in Table 1.

The RoC requirements ensure that the mirrors can be cost effectively manufactured while ultimately meeting the in-flight performance goals through actuation. While the original specification did not allow for on-ground actuation of the mirror's RoC, that constraint was removed to reduce polishing time and allow for minor RoC correction from other processes such as vibration testing. This change has allowed the initial RoC requirements to be relaxed with negligible effects to the final performance.[2]

Table 1: PMSA Requirements and Capabilities at 45 Kelvin

Description	Requirement
General Requirements	
PMSA Mass	39 kg (20.1 kg for substrate only)
Nominal Operating Temperature	45 K
Surface Figure	≤ 25 nm rms
Conic	-0.9967 ± 0.0005
Radius of Curvature Requirements	
Radius of Curvature	15879.722
Absolute Error	± 1.0 mm from nominal
Fabrication Matching	± 0.150 mm from average of 18
Post Launch Matching	Actuated to ± 0.010 mm from average of 18
Adjustment Range Capability	± 10 mm
Adjustment Resolution	0.0004 mm
Curvature Adjustment Induced Surface Deformation	≤ 24 nm rms per mm RoC actuation

PMSA ROC MECHANISM DESIGN

Each primary mirror segment is comprised of four subsystems; a mirror substrate, three whiffle assemblies, a hexapod actuation system, and a RoC actuation system. The mirror substrate is made of light-weighted O-30H beryllium, an optical grade material, with a 1.5 meter point to point hexagonal shape. Beryllium has several advantages for cryogenic optical systems including high stiffness, extremely low CTE at cryogenic temperatures, and high thermal conductivity. The low CTE ensures that the mirror surface figure and radius of curvature will be stable over the PMSA operating temperature range. The high thermal conductivity of beryllium allows for virtually zero temperature gradients across the mirror substrates during in-flight operations. The segment whiffle assembles consist of titanium flexures along with 3 beryllium pieces acting as an interface between the mirror substrate and the hexapod mechanism. The design of the whiffle assembly reduces gravity deformation and stresses in the mirror substrate during launch. The hexapod actuation system is a six actuator design allowing the mirror segment to be moved in six degrees of freedom. This mechanism provides ultra-high resolution motion over a relatively large range. Finally, the RoC actuation system allows the mirror to change its basic curvature shape.

The RoC actuation system (see Figure 4) is comprised of a single actuator that pushes and pulls against the center of the mirror, and six struts to react that force at the six corners of the mirror. Six struts were chosen to most effectively change the curvature of the mirror while minimizing undesired deformations. However, the challenge of a six strut system is to ensure that all six struts receive equal load during actuation and that small temperature differences in the six struts do not deform the mirror surface.

A series of flexures self-balances the RoC system. The center actuator is attached to the mirror via a flexure which allows the actuator to tip and tilt relative to the mirror substrate without causing deformations to the mirror. At the top of the actuator, a series of flexures are used to ensure that equal load is distributed to all six struts. At the end of each strut, another flexure allows rotation of the strut with respect to the mirror. During the mirror manufacturing and test process, the RoC actuation system was removed and replaced several times with a repeatable effect on the surface of the mirror. The self-balancing design ensures that small differences between installations will result in no significant surface deformation. However, the radius of curvature of the mirror can change slightly during the assembly process. This change can easily be removed by simply adjusting the RoC actuator.[2]

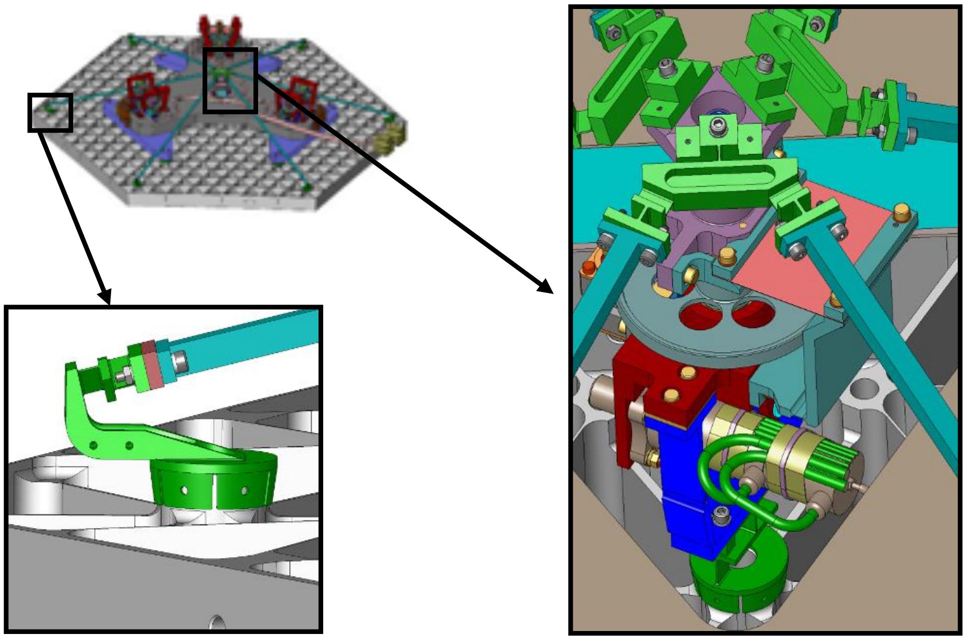

Figure 4: Radius of Curvature Actuation System

The design of the PMSA RoC actuation system has been optimized to deform the mirror in a power shape, while simultaneously being robust enough to survive launch effects and minimize both gravity and cryogenic mirror deformations. Due to the multitude of constraints, the RoC system produces some additional surface figure deformation above the pure RoC change. This figure change is known as RoC actuation residual. There is approximately 24nm rms of figure change per millimeter of radius of curvature actuation. Figure 5 shows the total bending shape of the mirror from RoC actuation, as well as the residual figure error.

The RoC actuation residual is predominately segment level spherical aberration and hexafoil. While the RoC actuation residual is undesirable on-orbit, it is actually quite useful during the integration and test (I&T) process to determine to how much the mirror is actuated. The mirror figure prior to installing the RoC actuation system is subtracted from the figure at any point in the I&T process and then the remaining hexafoil shape is determined. From this the amount of RoC actuation can be determined. This method allows the mirror to be place in a “RoC free-state” where RoC actuation is minimized and therefore, mirror stresses are also minimized.[2]

Since the RoC actuation residual degrades the overall telescope performance, the amount of actuation on-orbit must be limited. As an example, if a segment required 1mm of RoC actuation the penalty would be 24 nm rms of figure error. This is nearly all of the 25nm rms total surface figure requirement. Therefore, the mirror’s radius of curvature is manufactured to a relatively tight tolerance to minimize the need for on-orbit RoC actuation. However, this is not to say that the RoC actuation system cannot be used to ease the manufacturing requirements. Indeed, the RoC system can significantly reduce polishing times, as discussed in the next section.

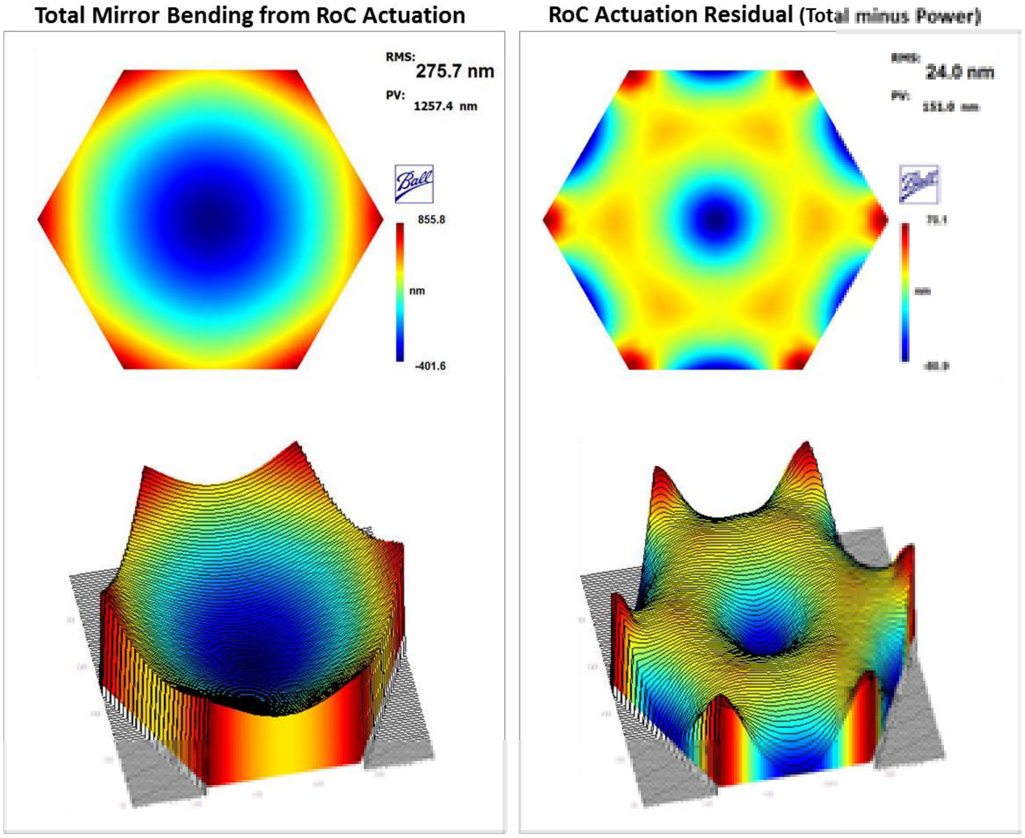

Figure 5: Mirror Bending from RoC Actuation

RADIUS OF CURVATURE FABRICATION METHOD

To assure that the radii of all eighteen mirrors match each other to the given requirements, a RoC fabrication & actuation plan was developed. This plan was part of a larger mirror production flow (see Figure 6). This included the HIP'ing (Hot Isostatic Press) of the beryllium blank by Brush Wellman Inc., machining and light-weighting of the mirror substrate by Axsys Technologies, grinding and polishing by Tinsley Labs, assembly and testing by Ball Aerospace, coating of the mirror's optical surface by Quantum Coating Inc., and cryogenic testing by Ball Aerospace and Marshall Space Flight Center at the XRCF (X-Ray Cryogenic Facility). While at first glance it appears that the mirror segments travel a lot during the manufacturing process, this flow was optimized to limit the number of shipments while still allowing each facility/company to perform operations for which they specialize in. Additionally, this flow allows the mirror's hexapod and RoC systems to be removed before polishing and coating operations and then reinstalled for final verification. An important step since this reduces the risk to flight actuators and other components from potential damage or contamination during manufacturing facility operations.

As a complement to the manufacturing flow a series of metrology systems were developed at Tinsley, Ball Aerospace, and the XRCF to assure the radius of curvature, figure, and other parameters could be measured both before and after each processing step. Cross-checks and comparisons were made of the metrology systems from each location to assure that results matched each other to within the defined uncertainties.

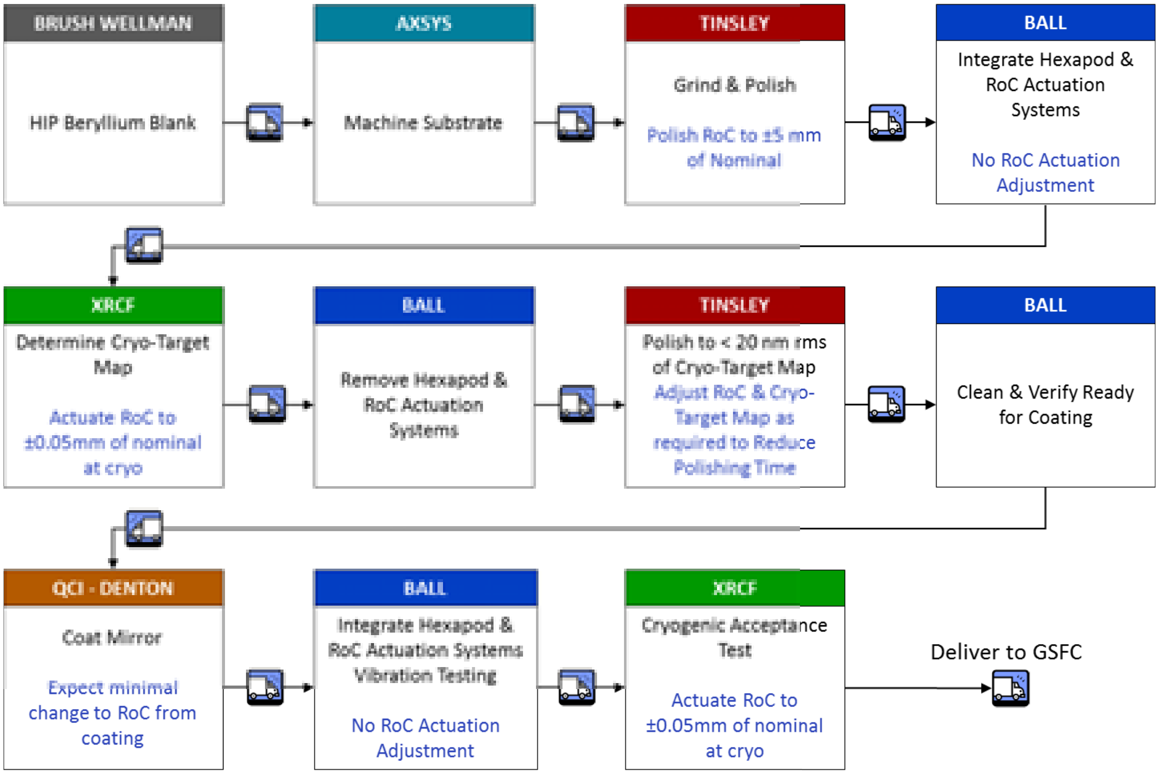

Figure 6: PMSA Manufacturing Flow & RoC Fabrication Plan

The RoC fabrication plan took into consideration the fact that the initial grinding and polishing process was the longest duration task. This phase of manufacturing involved grinding and polishing the mirror surface until the figure was down from tens of microns to less than 150 nm rms. To reduce the duration of this phase of the manufacturing, the requirement on radius of curvature was increased from 0.15mm to 5mm of the nominal value. This relaxation of the RoC requirement was only possible thanks to the ability of the RoC actuation system to change the RoC to within the final required value.

As discussed earlier, RoC actuation does not produce pure curvature but rather introduces a RoC actuation residual to the surface figure. Therefore, when the RoC is actuated to the nominal value during the first cryogenic test the surface figure will be degraded by the introduction this RoC residual error. For example, if the radius of curvature is 2 mm off the nominal value at 45 Kelvin and is actuated by this amount for RoC correction then approximately 48 nm rms of figure error will be introduced. This error is simply part of the overall 45K measurement which establishes the cryogenic deformation of the mirror. This change from ambient to cryo is used as a target map, along with an integration map, for the final polishing of the mirror. This way, when the mirror is returned to the XRCF for the final cryogenic acceptance test the mirror will be actuated to the same RoC value that was set during the first test and no RoC actuation residual will be present. That is, the final test will include the negative of the RoC residual error from the first test. So, the mirror figure will be optimized when the radius of curvature is set to nominal.[2]

RADIUS OF CURVATURE METROLOGY

A RoC test method was established as part of the overall mirror metrology system. The same test methodology was applied at the three test locations; Tinsley, Ball, and the XRCF. Since testing occurred in three separate locations it was essential that repeatable and consistent results were attained. “Repeatable” refers to the measurement to measurement results at a given facility and “consistent” refers to the facility to facility absolute RoC variation. Due to the mirror’s large size and very long radius of curvature, a test mirror with the same attributes located within each test setup was impractical. Rather a test method was developed and replicated at each location that relied on the design of a CGH (computer generated hologram) and an ADM (Absolute Distance Meter). The CGH was used as a diffractive null lens and the ADM set the spacing between the mirror segment and the CGH. The CGH was designed to produce the desired wavefront, with the correct RoC and conic, at a specific distance away.

The ADM was a polarization-based absolute distance measuring device built by Leica. This device operated at 780 nm, with a coaxial red alignment beam. The ADM used the specularly reflected beam from the surface of the mirror under test. The ADM measured the optical path length (OPL) which was converted to a physical distance after accounting for the refractive index of the test path. The quoted performance of the ADM was ±50 µm absolute accuracy and repeatability was tested and shown to be ±10 µm. The use of this device for RoC measurements was first developed on the Advanced Mirror System Demonstrator (AMSD) program by the University of Alabama in Huntsville.[3]

The RoC measurement method relied on the fact that the optimum test wavefront for a mirror segment was generated by the interferometer and CGH combination at a specified distance from the CGH. Therefore, when the mirror was placed at this “perfect” test location any errors in the measured wavefront could be considered errors in shape of the mirror. Of course, metrology errors also perturbed the wavefront and therefore had to be maintained within the allowable error budget. To first order, RoC errors in the mirror shape were observed as power in the measured surface figure and were proportional to an error in the distance of the CGH to mirror optical surface.

The general steps for the RoC measurement involved aligning the CGH to the interferometer using alignment features on the null and alignment CGH’s. Next the mirror segment was aligned to the CGH in decentration and tilt using the interferometer null return and fiducials mounted to the sides of the mirror. The distance from the CGH to the mirror was then set to nominal using ADM measurements. Decentration and tilt alignments were repeated, surface figure measurements made, and finally the CGH to mirror spacing was measured. The RoC could be calculated by analyzing the measured surface figure of the mirror and compensating for the actual CGH to mirror spacing and PMSA bulk temperature. Figure 7 shows a general layout of the test setup.[4]

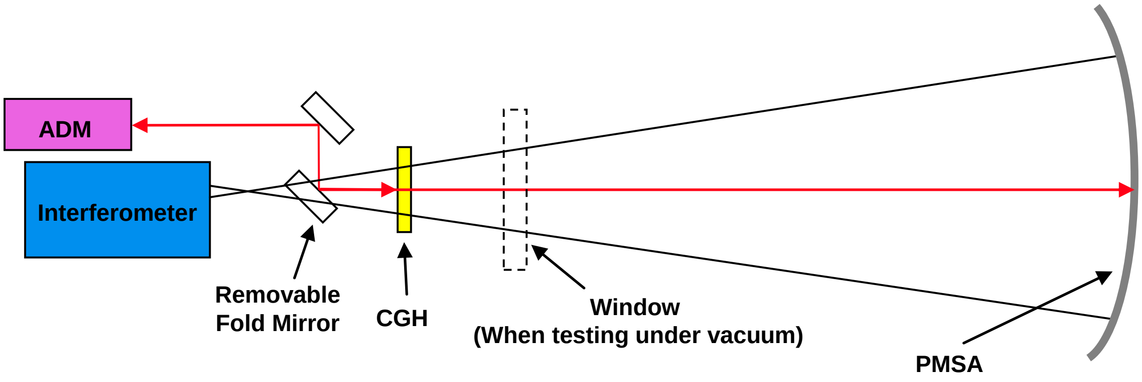

Figure 7: RoC Measurement System Layout

RADIUS OF CURVATURE VERIFICATION

As mentioned, it was important to assure that the absolute RoC values measured at each of the three test locations were consistent and accurate over the roughly 3-year test program. Therefore, a calibration optic was manufactured (see Figure 8) and sent to Tinsley, Ball, and the XRCF for RoC measurements. This mirror, known as the Radius of Curvature Optic (ROCO), was a 20" diameter spherical mirror with the radius of curvature specified such that the R/# matched those of the primary mirror segments, or approximately R/10.5. This was required to keep the power nulling or Zernike fitting uncertainty as close as possible to that of the PM segment, since power fitting is one of the largest contributors to the RoC error budget. The purpose of the ROCO mirror was to demonstrate the accuracy and reproducibility of the PMSA RoC metrology, therefore every effort was made to match the PM segment error budget as it pertained to RoC. It was also essential to closely follow the same RoC measurement procedures used. For these reasons a ROCO CGH was implemented. Obviously, a CGH or null lens is not required for testing a spherical mirror, so one was manufactured that simply introduced power into the measurement to allow for a similar methodology of setting the spacing between the CGH and the optic under test. Finally, to assure accuracy of the RoC measurements, an independent measurement of the radius of curvature was taken of the ROCO mirror at the University of Arizona using an alternate measurement method. This independent measurement had an error of less than 0.040 mm for RoC.[5]

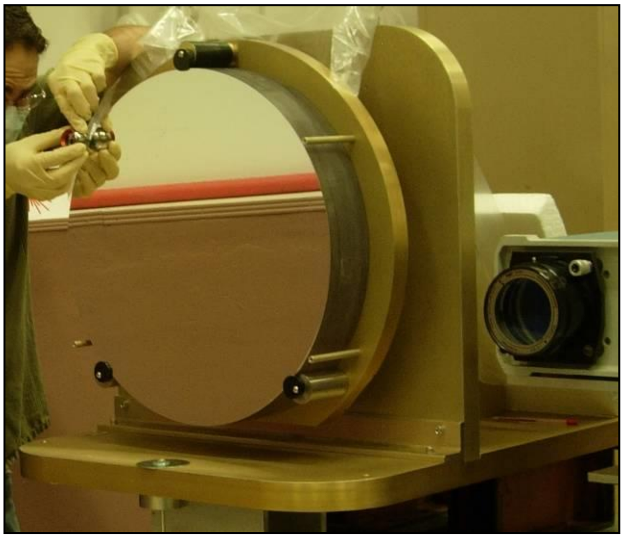

Figure 8: The ROCO mirror used for RoC metrology calibration

While two ROCO's were manufactured, only one saw RoC measurements at all three test locations. These measurements confirmed that all three locations could measure the radius of curvature of a PM segment to less than +/- 0.250 mm absolute and +/- 0.100 mm reproducibility. These results were consistent with the PMSA error budget.

VERIFICATION AT TELESCOPE LEVEL

Testing of the entire assembled telescope was conducted at both Goddard Space Flight Center (GSFC) and Johnson Space Center (JSC) over a one year period. The testing at GSFC was not designed to measure RoC but rather look for changes in the mirror shape due to vibration and acoustic testing. The metrology setup was similar to that used during mirror manufacturing in that it was a center of curvature test with each segment tested individually. However, no ADM was used to set the spacing between the CGH and mirror under test. Rather the spacing was adjusted by nulling the power in the measured wavefront. If the RoC of a mirror had changed due to the vibro-acoustic testing the spacing between the CGH and mirror would have been altered as the wavefront power was nulled.

To provide a rough check of the RoC the location of the center of curvature point for each mirror, as defined by the focus of the interferometer once aligned, was measured with a Leica Laser Tracker relative to the telescope global coordinate system. See figure 9 for an image of the test layout. This location was compared to the predicted location based on the previously measured RoC for each mirror, the gravity sag prediction, the mirror deployment location, and other modeled effects. Results show that the absolute RoC was -0.93mm from the nominal value. However, the mirror to mirror variation was ±1.57mm. While this variation was rather large, the results were quite acceptable given the RoC uncertainty of this test, which was never intended to measure radius of curvature. These results provided confidence that the measured RoC values during the manufacturing process were correct and that the I&T process could continue with no concerns as related to radius of curvature.[6]

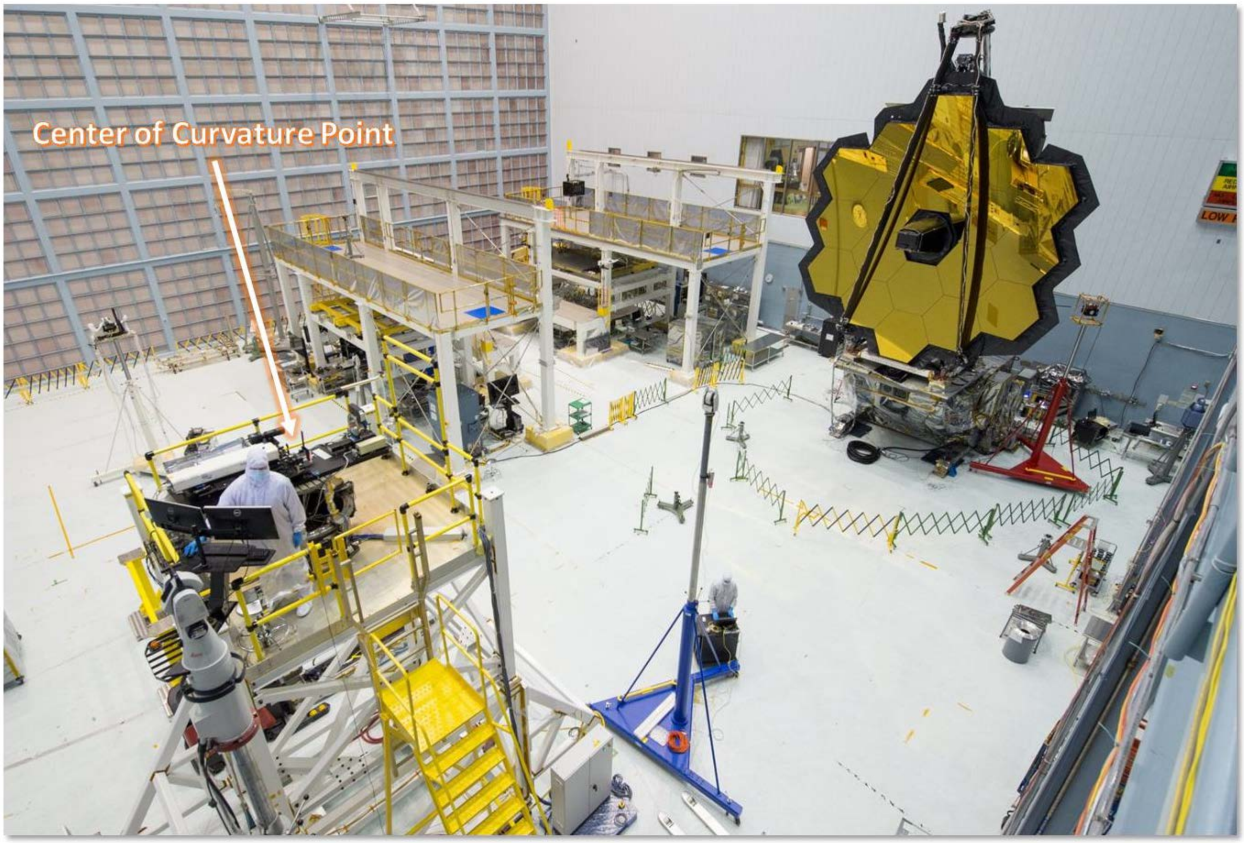

Figure 9: Center of Curvature Test Setup at GSFC

The next opportunity to verify the RoC of the mirrors was during testing of the telescope at JSC. This test was meant to confirm or at least provide confidence in the expected performance of the telescope once on orbit. To this end a series of tests were performed to show functionality of the various systems at cryogenic temperature, as well as to verify a number of critical alignments and mirror actuator range capability. The JSC test is well beyond the scope of this paper and therefore we will only discuss results of RoC testing.

As part of the JSC test the primary mirror was measured using a combination of a multi-wave interferometer and null lens placed at the center of curvature of the primary. This metrology method allowed the individual segments to be phased together to act, optically, as a single monolithic mirror. The phasing effort included the six degree of freedom motion of the mirrors, as well as RoC adjustments. Figure 10 shows a modeled image of the test setup and a picture of the telescope prior to being installed into the chamber. After phasing was complete the spacing between the null lens and a SMR (spherically mounted retroreflector) attached to the side of the primary mirror was measured. This spacing along with the measured wavefront were used to calculate the RoC of the primary.

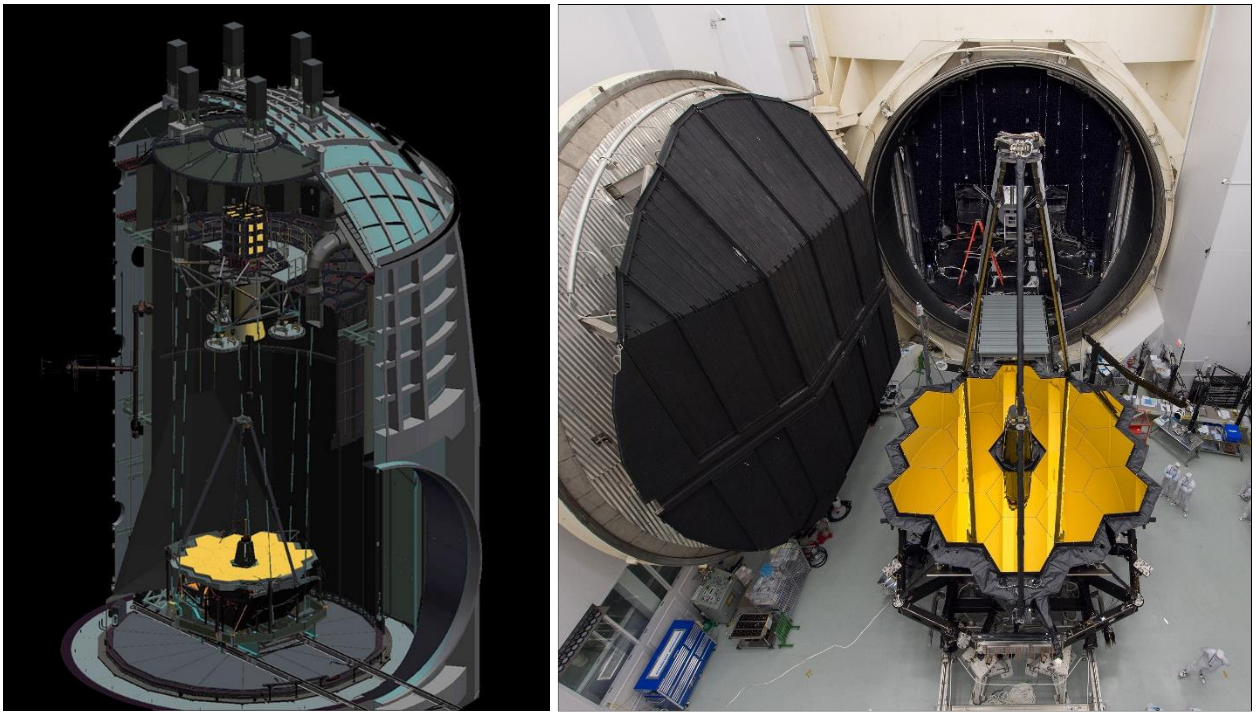

Figure 10: Telescope Test Setup at JSC

The data captured in support of RoC measurements were analyzed by two independent teams using different methods. These two methods agreed to each other to within 0.2mm. Additionally, the results showed that the cryogenic RoC matched the predicted value to less than 0.2mm.[7] These results provided confirmation that the RoC manufacturing process for the mirrors had met the needs of the observatory.

SUMMARY

Ball Aerospace successfully developed a methodology to manufacture and test the JWST primary mirror segments, which included a radius of curvature actuation system. This system was robust in nature and provided numerous advantages including the reduction in mirror polishing time and the ability to change the RoC after launch. Measurements of both the radius of curvature and the RoC actuation residual confirmed that both of these parameters had met the requirements put forth. Telescope level testing confirmed the ability to phase the mirrors in both 6-DOF motion and RoC matching. Therefore, due to the numerous advantages, this type of RoC actuation system should be considered for future segmented telescopes.

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