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JWST Mirror and Actuator Performance at Cryo-Vacuum

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ABSTRACT

The James Webb Space Telescope (JWST) telescope's Secondary Mirror Assembly (SMA) and eighteen Primary Mirror Segment Assemblies (PMSAs) are each actively controlled in rigid body position via six hexapod actuators. Each of the PMSAs additionally has a radius of curvature actuator. The mirrors are stowed to the mirror support structure to survive the launch environment and then must be deployed 12.5 mm to reach the nominally deployed position before the Wavefront Sensing & Control (WFSC) alignment and phasing process begins. JWST requires testing of the full optical system in a Cryogenic Vacuum (CV) environment before launch. The cryo vacuum test campaign was executed in Chamber A at the Johnson Space Center (JSC) in Houston Texas. The test campaign consisted of an ambient vacuum test, a cooldown test, a cryo stable test at 65 Kelvin, a warmup test, and finally a second ambient vacuum test. Part of that test campaign was the functional and performance testing of the hexapod actuators on the flight mirrors. This paper will describe the testing that was performed on all 132 hexapod and radius of curvature actuators. The test campaign first tests actuators individually then tested how the actuators perform in the hexapod system. Telemetry from flight sensors on the actuators and measurements from external metrology devices such as interferometers, photogrammetry systems and image analysis was used to demonstrate the performance of the JWST actuators. The mirror move commanding process was exercised extensively during the JSC CV test and many examples of accurately commanded moves occurred. The PMSA and SMA actuators performed extremely well during the JSC CV test, and we have demonstrated that the actuators are fully functional both at ambient and cryo temperatures and that the mirrors will go to their commanded positions with the accuracy needed to phase and align the telescope.

Keywords: James Webb Space Telescope, segmented mirror, mirror actuators, hexapod, radius of curvature

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1. INTRODUCTION

The James Webb Space Telescope (JWST) is a deployable, 6.5 m infrared astronomical observatory that will operate at cryogenic temperatures in an orbit about the second Lagrange point. JWST will study first light, assembly of galaxies, the birth of stars, proto-planetary systems, and the origins of life.[1]

Due to its large size, the observatory must be folded and stowed to fit within the volume constraints of the fairing of an Ariane 5 launch vehicle. Once on orbit, the observatory (including various optical elements within the Optical Telescope Element (OTE) must deploy from its stowed state and the telescope be optically aligned. The OTE consists of the segmented, deployable Primary Mirror (PM), the deployable Secondary Mirror(SM), and a fixed Tertiary Mirror (TM), housed along with a flat Fine Steering Mirror (FSM) inside the Aft Optical Subsystem (AOS). The stowed and deployed states of the observatory are illustrated in Fig. 1, along with an exploded view of the OTE in which the major components and subsystems are identified for reference. The mirrors are stowed to the mirror support structure to survive the launch environment and then must be deployed 12.5 mm to reach the nominally deployed position before the Wavefront Sensing & Control (WFS&C) alignment and phasing process begins. Managing[2,3] the uncertainty in the deployed position of the OTE optical elements, accommodating on-orbit alignment risk, and maintaining the precise alignment of the optics throughout the mission lifetime requires an active optical system with nanometer-level precision and stability for wavefront control.

Webb's primary mirror consists of 18 hexagonal, semi-rigid, light-weighted beryllium mirror segments. The PM segment assemblies (PMSAs) consist of the mirror substrate, a cryogenic hexapod system that provides six degrees-of-freedom adjustment, and a seventh actuator that allows adjustment of the segment's radius of curvature (RoC). These segment-level degrees of freedom allow the segmented PM the flexibility to deploy 12.5mm out of the launch constraints, align each segment assembly to the global PM, and phase to act as a monolithic optic. The SM assembly (SMA) consists of a light-weighted beryllium mirror with a cryogenic hexapod system for six degree-of-freedom rigid-body adjustment (the SMA has no RoC adjustment). In total between the PMSAs and the SMA, there are 132 actuator mechanisms that are used to achieve and maintain the optical alignment of the OTE. In addition to the PMSAs and SMA, the aft-optics subsystem (AOS) contains the light-weighted beryllium TM assembly and the FSM in a beryllium optical bench. These components comprise the OTE. The OTE was assembled in the Space Systems Development Integration Facility (SSDIF) at the Goddard Space Flight Center (GSFC), and integrated with the Integrated Science Instrument Module (ISIM). ISIM consists of a composite optical bench that supports Webb's Science Instruments (SIs). The OTE + ISIM combination (referred to as OTIS) results in the full optical payload of the Webb Observatory[4]

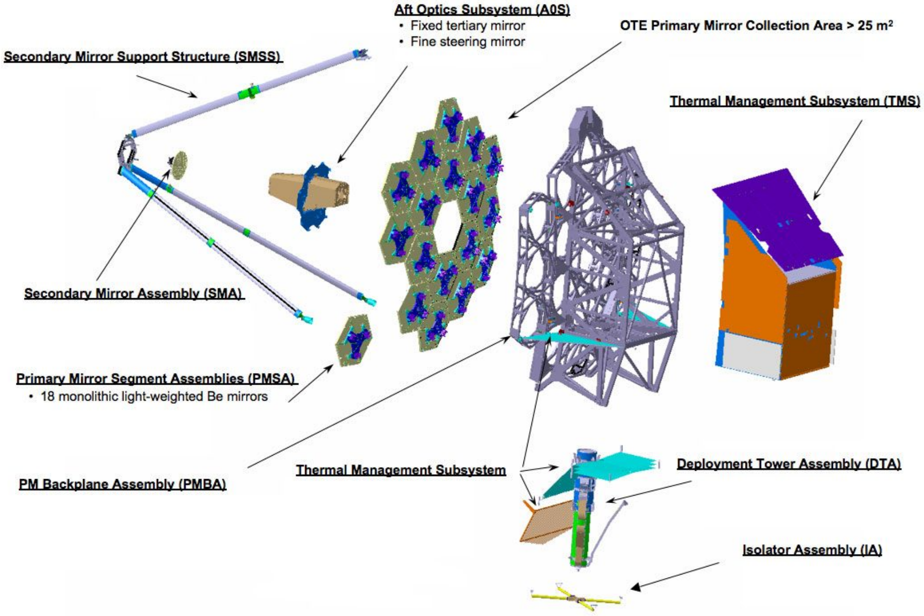


Figure 1. An exploded view of the OTIS with the various subsystems and components within the OTE identified[4]

1.1 Test Campaign

The OTIS test campaign began with ambient functional testing of the mirror actuators before and after acoustic and vibration environmental testing. This included actuator fine stage characterization tests[4], and center of curvature tests[5]. JWST requires testing of the full optical system in a cryogenic vacuum environment before launch, this next phase of environmental testing occurred at the Johnson Space Center (JSC) in the historic Chamber A.

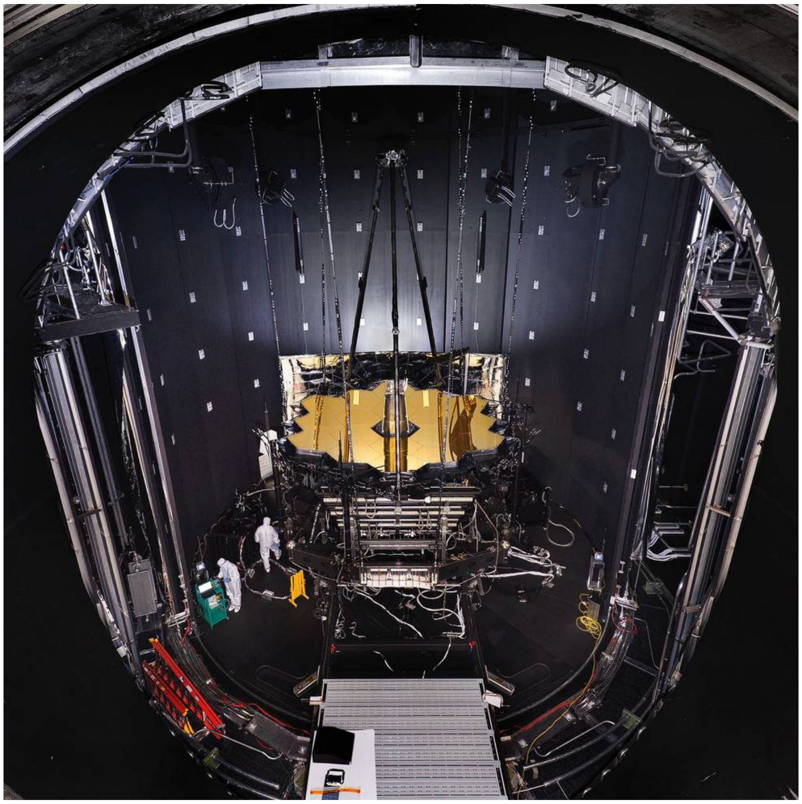


Figure 2. JWST in Chamber A for OTIS CV Test

The OTIS Cryo-Vacuum (OTIS CV) test campaign consisted of an ambient vacuum functional test, deployment of all the mirror segments 12.5mm out of the launch restraints to the nominally deployed position at both ambient vacuum and during the cooldown phase, a cryo stable test where the average PMSA temperature was 41K, a warmup test, and finally a second ambient vacuum test.

The System Functional Test (SFT) campaign first tested actuators individually, then tested how the actuators perform in the hexapod system. Telemetry from flight position sensors on the actuators and measurements from external metrology devices such as interferometers, photogrammetry systems and ISIM image analysis was used to demonstrate the performance of the JWST actuators.

During OTIS CV, the functionality of the mirror move commanding process was also exercised to demonstrate the WFSC process, using the flight data acquisition scripts and flight wavefront analysis software[6].

Motor resolver phase measurements were collected at ambient and cryo temperatures, which will be used for flight model correlation. The pullout current of all of the PMSA and SMA motors was assessed at cryo temperatures. Finally, the fine stages of the SMA Hexapod, the PMSA ROC, and select PMSA Hexapod actuators were characterized. Figure 2 depicts a timeline of actuator tests during the OTIS CV campaign.

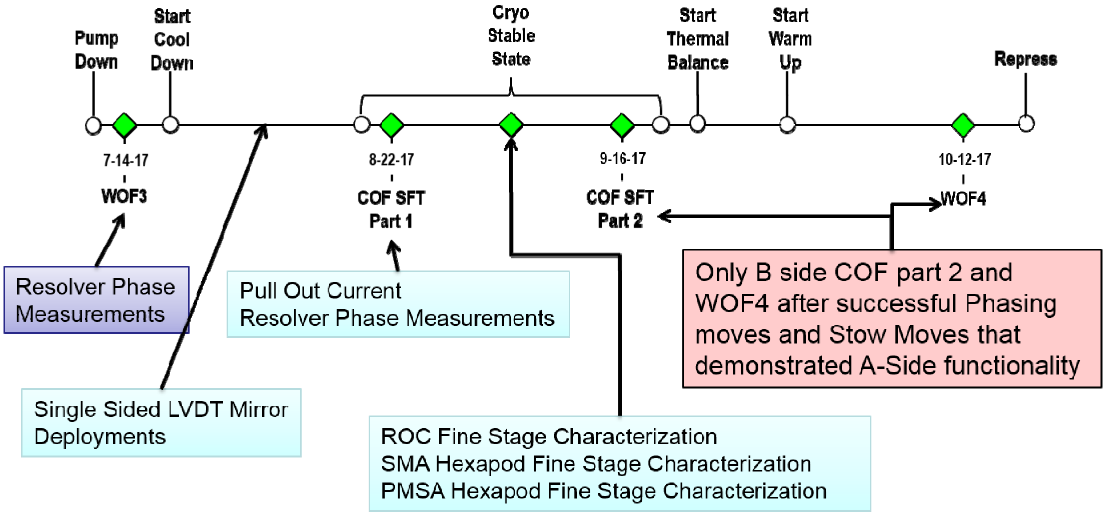


Figure 3. Timeline of OTIS CV Test Highlighting Actuator Tests Performed

1.2 Actuator Description

The hexapod assemblies that support and provide six degree of freedom rigid body adjustment of the PMSAs and the SMA are made up of 6 linear actuators assembled in three bipod assemblies, as shown in Fig.4[7]. The seventh actuator that provides RoC adjustment for the PMSAs is of the same design as the hexapod actuators. Designed by Ball Aerospace, the linear actuators[4] are capable of sub-10 nano-meter (nm) motion accuracy over a 20 millimeter (mm) range both at ambient and cryogenic conditions, as is required for precise control of mirror position after deploying 12.5 mm out of the mirror launch restraints during ground tests and on-orbit. Each of the 132 actuators has a gearmotor (GM). A GM is made up of a stepper motor, resolver, and gear head packaged together (see right of Figure 4 below). The motor bearings in the GM are a limited life item. The resolver senses gearmotor motion, at the level of individual motor steps. The coarse length change of each actuator is sensed by a linear variable differential transformer (LVDT).

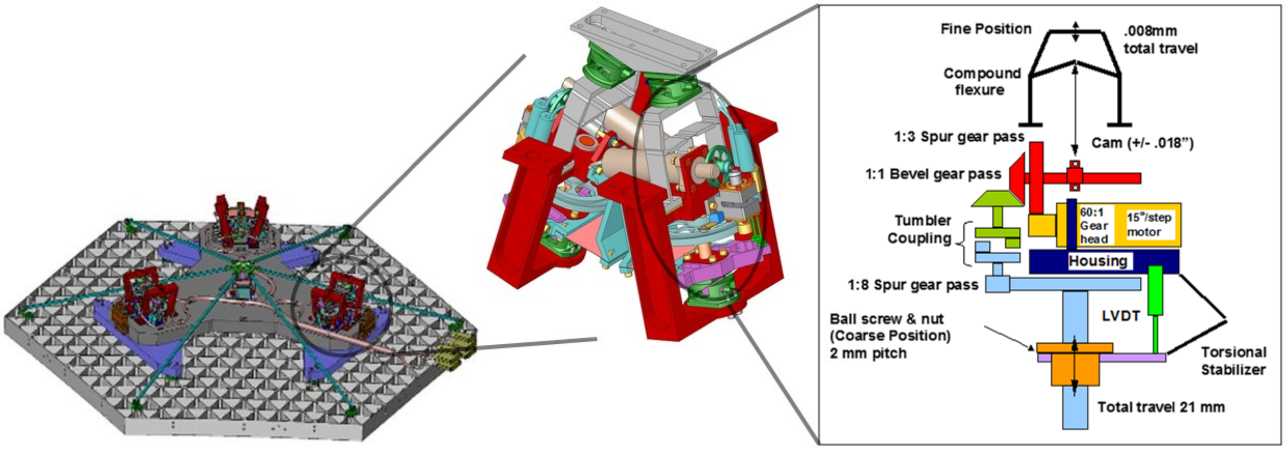


Figure 4. Overview of the PMSA hexapod mounting and the linear actuators. Left: Back of a PMSA, showing the six hexapod actuators (located inside of the red brackets). The SMA hexapod is of a similar design. The PMSA RoC actuator is in the center of the PMSA and is attached to the six struts that reach to the edge of the mirror substrate. Center: Zoom-in to one of the three bipod assemblies, which shows two individual actuators. Right: A cartoon view of the layout of the actuator drive train[4].

2. ACTUATOR TESTS

2.1 Functional Tests

The OTE SFTs, known as either the Warm OTE Functional (the WOF) or the Cryo OTE Functional (COF), are designed to check the health and safety of the powered assemblies and electronics of the OTE including deployable structures, actuators, launch restraint mechanisms, and the FSM. Only the portions of the WOF & COF that exercise the PMSA & SMA actuators are discussed here. This test ensures signal continuity to the electronics, the Actuator Drive Unit (ADU), both the primary, A side, and electrically redundant B side. The SFT also checks that OTE components are in working order by first performing a telemetry check of all temperature sensors, LVDTs, and resolvers on ADU side A, then performing single step moves on all mirror actuators on both the ADU A & B sides and using the resolver feedback on the ADU A side to verify the motor functionality and move polarity. Once confidence is gained in the connectivity of the system and stability of the commanding software, progressively larger moves on the mirror actuators are performed on the ADU A side to exercise the motors, resolver and LVDT feedback. After a successful "mini deployment" move of 125um in the piston direction, then the test is complete and either a stow operation is performed to return the mirrors to the launch stowed position, or if other testing is to proceed, then the mirrors are left in that position and further deployment or optical phasing tests commence.

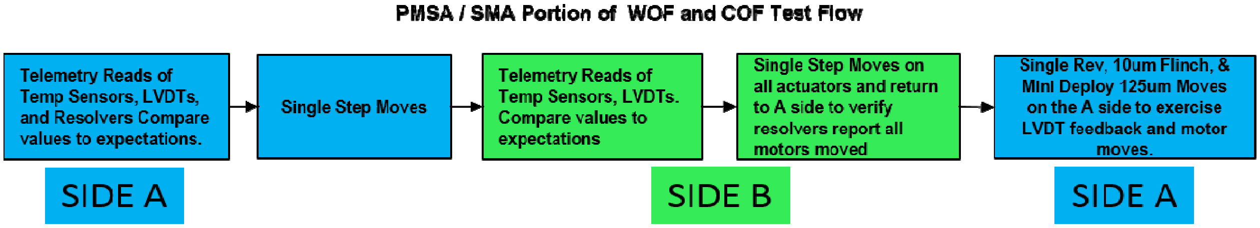


Figure 5. Functional Test Flow for both Warm OTE Functionals (WOFs) and Cryo OTE Functionals (COFs)

2.2 Resolver Phase Measurements

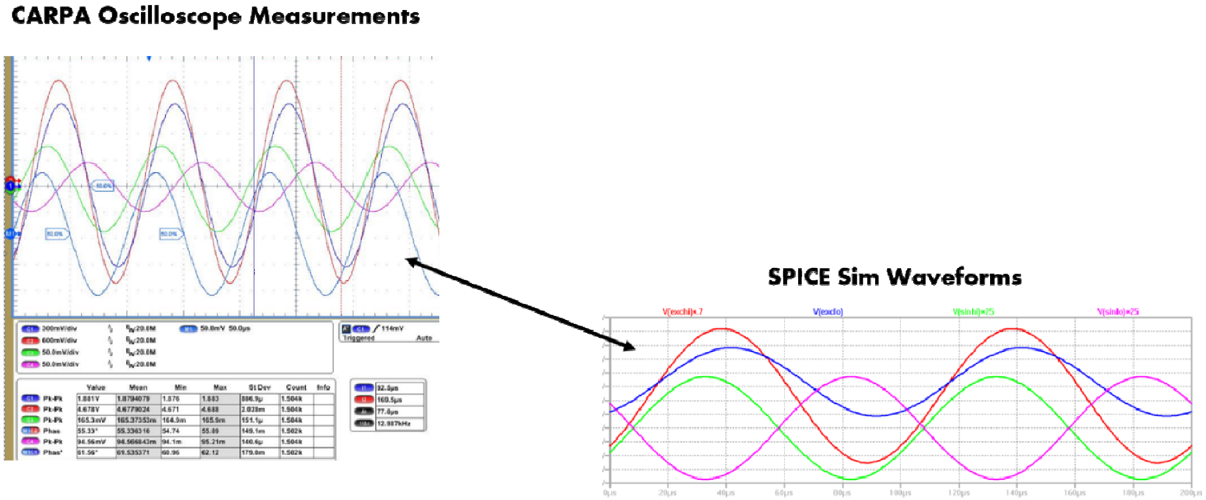
Each actuator gear motor has a resolver to sense gearmotor motion. The resolver system is sensitive to variations in the electrical circuit. The variations cause a phase shift in the returning signals from a resolver to the ADU. The resolver/ADU system was designed for a phase shift specific to the flight configuration. High Fidelity simulations using the Simulation Program with Integrated Circuit Emphasis (SPICE) environment are used to predict the phase shift at the Resolver-to-Digital Converter Integrated Circuit (IC) in the ADU electronics to ensure that the resolvers will function as expected in flight. Measurements during OTIS system level testing are used to correlate this flight model.

The OTIS test configuration, both ambient and cryo, operated using the Engineering Design Unit (EDU) ADU. At JSC, we used much longer cable lengths than the flight configuration will use. The resolver excitation signal phase shift to account for cable and resolver parasitics (capacitance, resistance, inductance) were modeled using SPICE, and the Cryogenic Multiplexer Unit (CMU) Test Set/ ADU Resolver Phase Shift Assembly (CARPA) box was used to adjust the resolver phase shift and provide test points to measure the resolver circuits.

In-line phase measurements at the CARPA box were made and compared to the SPICE simulations in 3 configurations:

- GSFC SSDIF OTIS **ambient** testing, short Flight length cables
- JSC **cryo chamber ambient** test, long test cables from ADU to Telescope
- JSC **cryo chamber cryo** tests (~40K), same long test cables

A total of six different CMU locations were tested on the PMSA & SMA to cover the range of on-telescope cable lengths in these test configurations. Phase shift measurement & waveforms were compared to the SPICE simulation phase shifts & waveforms.


CARPA Oscilloscope Measurements

SPICE Sim Waveforms

Figure 6. Example of Resolver Phase Shift Measurements compared to SPICE simulations.

Table 1. Resolver Phase Shift Measurement Summary.

Environment		SPICE Sim Phase Shifts Correlated to Test Measurements	Phase Shift Max PREDICTED RANGE (+/-70deg allowance)
GSFC SSDIF	Ambient	+/- 10 deg	+/-15 deg
JSC Chamber A	Ambient	-5 / +15 deg	+5 to +45 deg
JSC Chamber A	Cryo*	+3 deg to +16 deg*	+18 to +36 deg*

**with possible systemic offset due to colder JSC operation (~ 40 to 50degK) than 77K LN2-dunk cryo temperature that resolver impedance characteristics were measured at for the simulation models.*

The performance of the SPICE simulations was validated by these test measurements, giving the project confidence in the On Orbit flight resolver phase shift performance well within the +/-70 deg allowance for proper resolver circuit operation within the ADU.

2.3 Pull Out Current Tests

The motor bearings in the GM are a limited life item (see section 3.1 for limited life tracking). In addition to tracking motor revs, the health of the motor bearings can be assessed by measuring the Pull Out Current (POC). The POC is the minimum current required to step the GM. To perform the POC test, a GM is pulsed with smaller and smaller amounts of current until the GM does not step. The resolver detects the GM motion. One motor revolution is 24 steps, and the resolvers register a change in value of approximately 43 counters per motor step on average. The POC is defined as the smallest amount of current the GM successfully stepped with as detected by the resolver.

GM POCs were routinely measured during the integration and testing of PMSAs and SMAs. During the OTIS CV campaign, at the cryo stable plateau, the motor health was verified by stepping each GM with the “GO/NO GO” POC Current value. This value is defined as the average POC reported in the last 10 POC measurements made plus 0.045 amps. These values are plotted in Figure 7 below for all hexapod actuators.

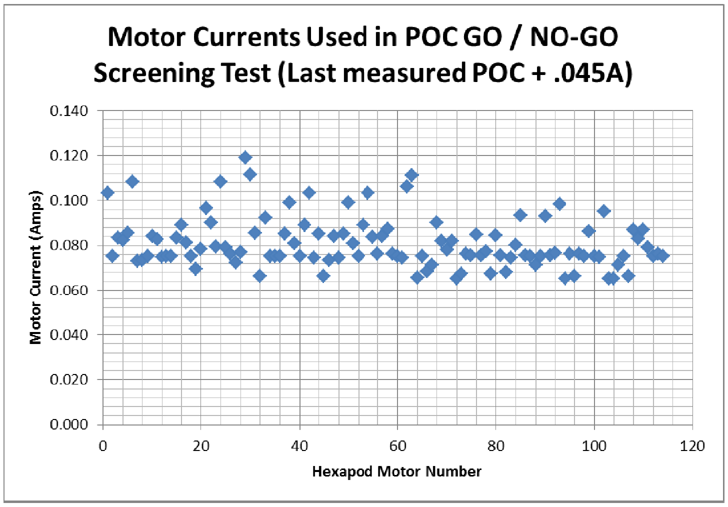


Figure 7. Pull Out Current GO/No GO Limits for each actuator

The test flow is shown in Figure 8 below. After the Mirror Control Software (MCS) is configured with the motor current values for test, each GM was stepped half a motor revolution (+12 steps) clockwise, then counterclockwise (-12 steps). Every GM successfully moved the commanded steps per the resolver readings at the low current value. All were within 7 resolver counts. This is an indication of no motor bearings experiencing degradation. If some GMs had not passed the GO/No GO test, a Problem Report (PR) is generated to document the result and a new pull out current would have been measured for that actuator and analyzed.

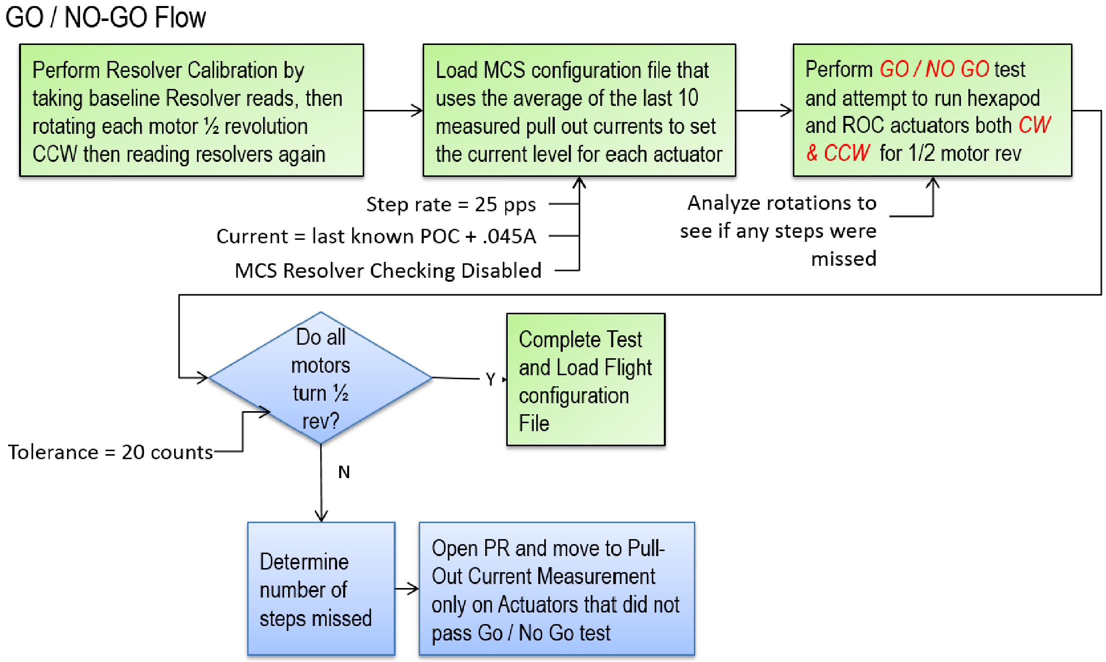


Figure 8. POC Test Flow Chart

2.4 Deployment & Stowing Tests

2.4.1 Deployments During Cooldown

One of the goals of the OTIS CV test was to demonstrate mirror deployment during Cooldown, in a transient thermal environment. On orbit the current commissioning timeline begins mirror deployments before the OTE is thermally stable, although a much smaller temperature change is expected during flight deployments. The 12 outer mirror segments were deployed 12.5mm at ambient vacuum to allow for phasing measurements to begin as early as possible in the timeline. The inner 6 mirror segments were successfully deployed from their stowed launch restraint position to the nominal deployed position during cooldown from approximately 200K to 135K.

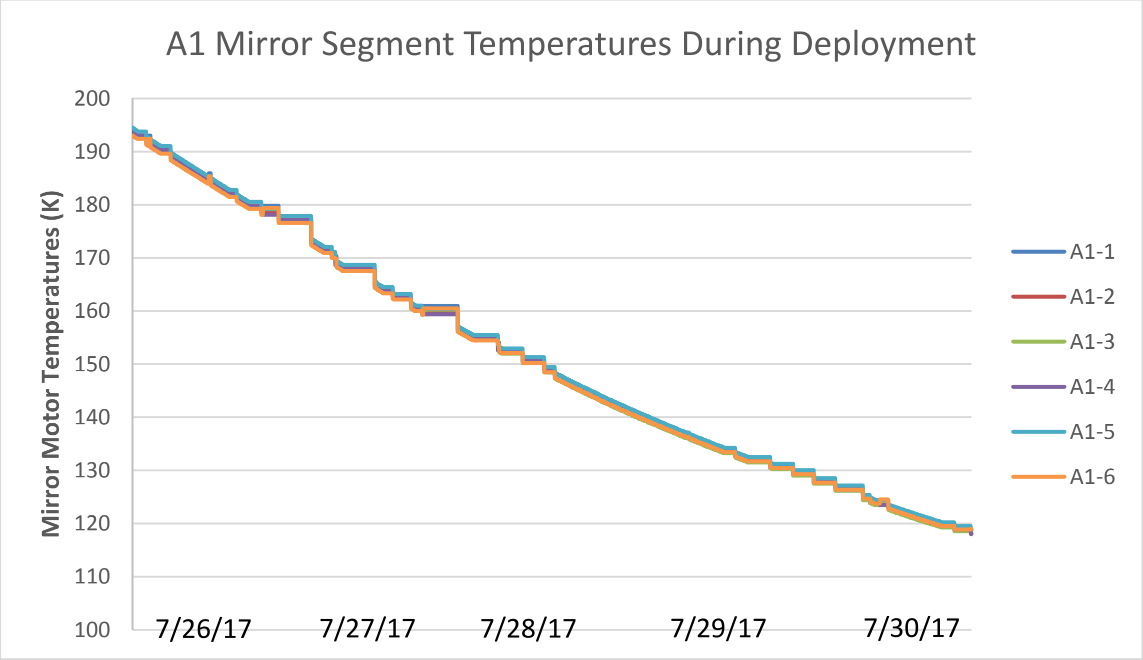


Figure 9. Cooldown Deployment Temperatures of a single mirror segments' 6 hexapod actuators.

2.4.2 Single Sided LVDTs

Each actuator's LVDT is made of up of two coils which the ADU electronics normally use in a differential form to provide temperature-independent position data. When a move is commanded the MCS calculates the expected actuator length from the coarse step count (CSC) of the motor. An algorithm then converts this length into the expected LVDT reading using a calibrated set of coefficients. If the LVDT reading in telemetry matches the predicted value to within a calibrated tolerance, the commanded move is confirmed.

On two separate PM Segments, one of the two coils on an LVDT is faulty, so a method to read those LVDT positions with only one coil was developed and tested at OTIS CV and used to confirm mirror moves in this Single Sided Operation Mode. This alternative method entails generating a temperature dependent set of coefficients for predicting the signal from the active coil, and configuring the Mirror Control Software (MCS) to use both the bad LVDT and its bipod 'mate' in single-sided mode. The reason for also configuring the bipod mate to single-sided mode is that the MCS performs a bi-pod difference check to guard against excessive flexure stress, and operating both legs of a bipod in the same 'single sided' mode provides a valid bipod check.

The chart below shows the comparison for a set of actuators, one of which has a faulty coil, but both of which are operated in single sided mode. During cooldown, the performance of the Single Sided linear variable differential transformer (LVDT) was successfully demonstrated

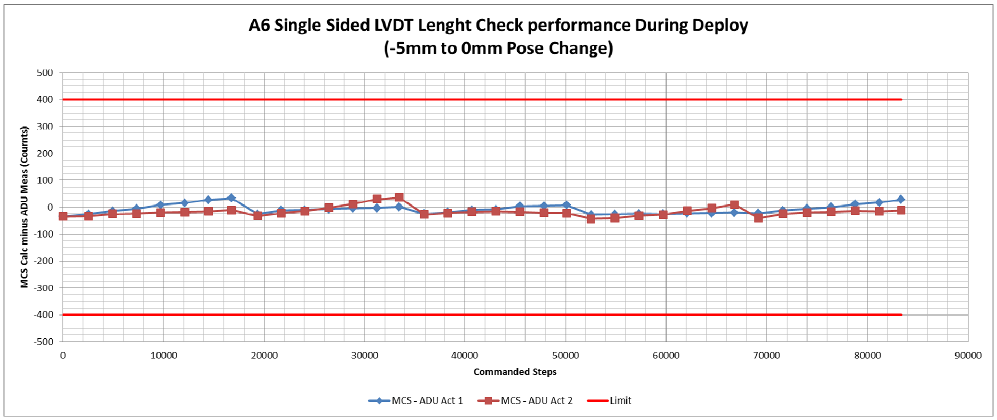


Figure 10. Error of Single Sided LVDT & it's Functional "mate" LVDT, demonstrated to meet positioning requirements during cooldown deployment activities.

2.5 Fine Stage Cross Check & ROC Characterization [4]

This section summarizes the OTIS CV results of the Fine Stage Characterization campaign that is detailed in the SPIE paper, "Characterization and calibration of the James Webb Space Telescope mirror actuators fine stage motion" written by Taylor Chonis, et al, 2018[4].

The nm-level motion of the 132 actuators were carefully tested and characterized before integration into the mirror assemblies. Using these test results as an initial condition, knowledge of each actuator's length (and therefore mirror position) has relied on software bookkeeping and configuration control to keep an accurate motor step count from which actuator position can be calculated. These operations have been carefully performed through years of JWST test operations using both ground support actuator control software as well as the flight MCS. While the actuator's coarse stage length is cross-checked using a LVDT, no on-board cross-check exists for the nm-level length changes of the actuators' fine stage. To ensure that the software bookkeeping of motor step count is still accurate after years of testing, and to test that the actuator position knowledge was properly handed off from the ground software to the flight MCS, a series of optical tests were devised and performed through the Center of Curvature (CoC) ambient optical test campaigns at the GSFC and during the thermal-vacuum tests of the entire optical payload that were conducted at JSC. During ambient testing of the PMSA hexapods at GSFC, the nm-level actuator length changes were measured with a custom laser deflectometer by measuring tilts of the PMSA. A sample of hexapod actuators were crosschecked at JSC with the CoC Optical Assembly (COCOA) to measure PMSA surface tilts. The PMSA RoC fine stage characterization was performed at JSC using multi-wave interferometric measurements with COCOA[8].

A comparison of 8 PMSA hexapod actuators' Fine Step Count (FSC) errors measured with COCOA to the deflectometer measurements at ambient agree to within 3σ. This illustrates excellent agreement between the FSC error measured at cryo compared to the independent measurement made at ambient. As such, the cross-check of the deflectometer measurements provided by COCOA yields a great deal of confidence in the ensemble FSC error measurement performed at ambient for the other 100 PMSA hexapod actuators.

All 18 segments' ROC actuators' Fine stages were characterized during OTIS CV, all resulting in FSC errors well below the acceptable FSC error limits set from a WFSC perspective.[4]

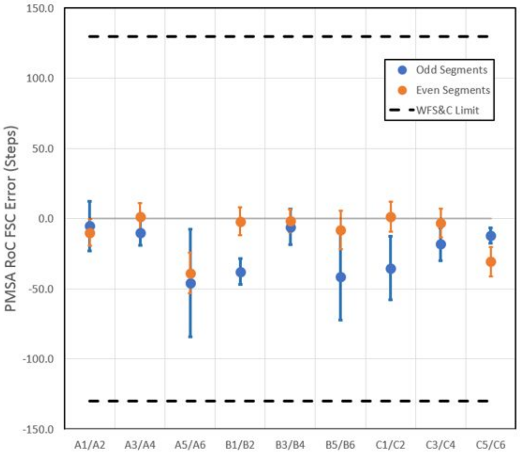


Figure 11. Radius of Curvature Fine Stage Count Errors measured during OTIS CV with COCOA, compared to the WFSC required limits.

2.6 Mirror Phasing & Wavefront Demonstration

The OTIS CV test was the first and only opportunity during ground development and testing to demonstrate the ability to phase the Primary Mirror using the actuators on each segment to create a monolithic phased PM[7]. In addition to demonstrating the ability to phase the PM, using optical feedback from the COCOA, the team was also able to demonstrate the mirror moves & imaging sequences planned for on orbit commissioning during the wavefront sensing & control phase. Flight scripts produced from the Astronomer's Planning Tool (APT) were executed to exercise the command and data paths to move mirrors and perform analysis with the Wavefront Analysis Software (WAS)[6].

3. RESULTS

3.1 Limited Life

Gearmotor life qualification testing was based on a definition of the gearmotors' 1x life that is budgeted throughout the testing and mission science life of the telescope. Every motor revolution is tracked and accounted for against this budget. There are separate budget allocations for ambient purged, ambient vacuum, ambient humid, and cryo (<100K) environments.

The plots below show the motor revolutions performed during OTIS System level testing, which includes the ambient humid testing performed before and after OTIS level vibration test at the GSFC SSDIF and the Center of Curvature test at the GSFC SSDIF, as well as all the testing performed at JSC during the OTIS CV campaign. All motor usage is well below the budgeted allocation for this OTIS system level testing phase, in each environment.

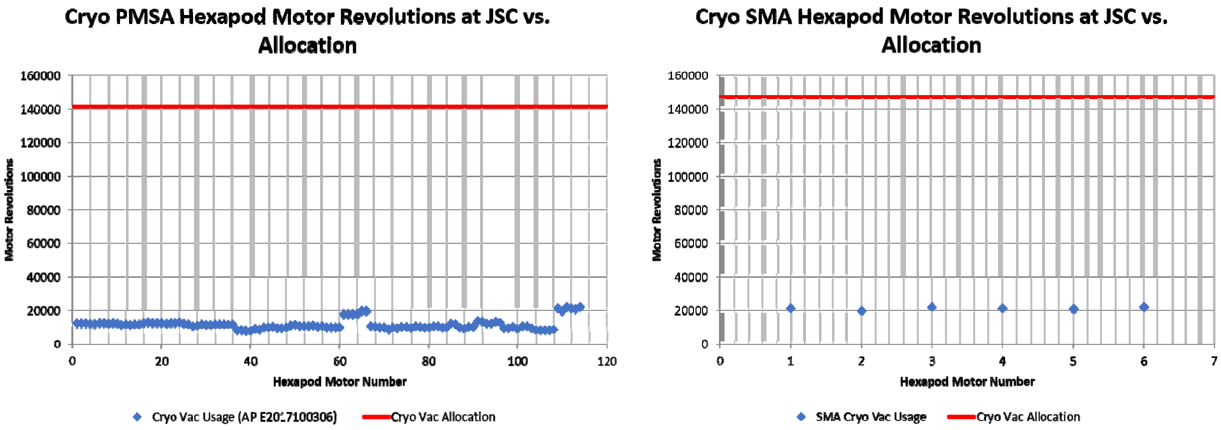


Figure 12. Motor Usage vs Allocated Motor Revs for 108 Hexapod actuators at Cryogenic Environment

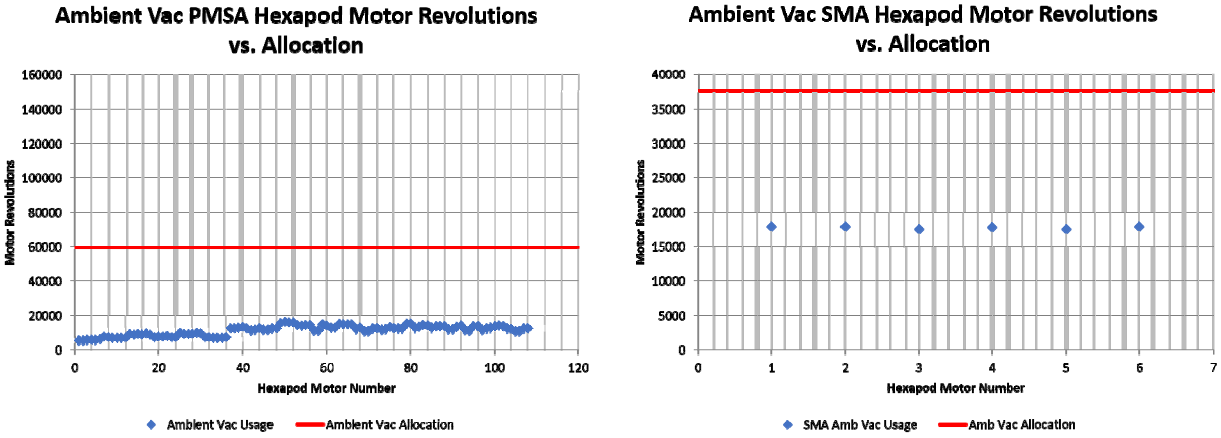


Figure 13 Motor Usage vs Allocated Motor Revs for 108 Hexapod actuators at Ambient/Vacuum Environment

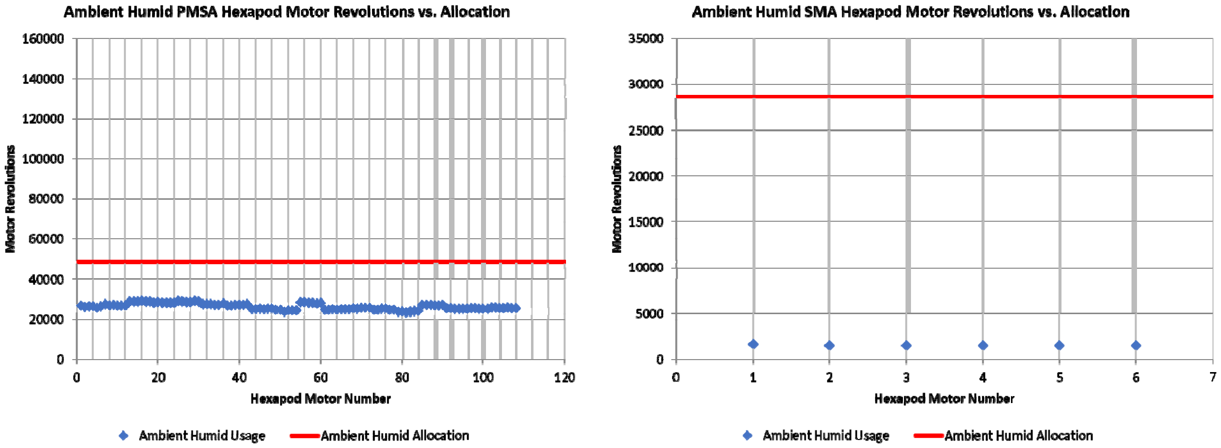
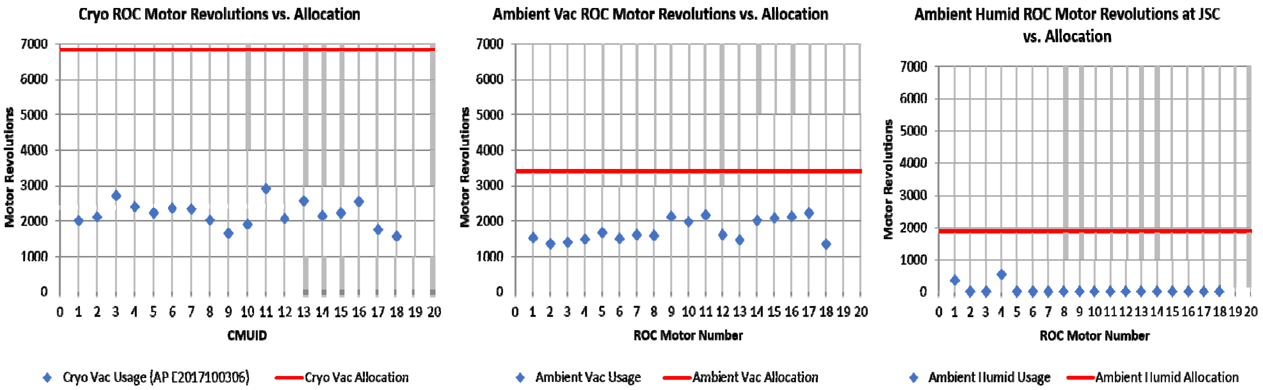


Figure 14. Motor Usage vs Allocated Motor Revs for 108 Hexapod actuators at Ambient/ Humid Environment

The SMA & PMSA Hexapod gearmotors are of the same design, so the design was qualified once for both assemblies. The ROC actuators on the PMSA segments are of a different design and so were qualified separately.

Figure 15. Motor Usage vs Allocated Motor Revs for 18 Radius of Curvature actuators in 3 environments.



3.2 Conclusions

All actuator testing performed during the OTIS CV test campaign was successful. The testing performed satisfied system test requirements and indicate healthy assemblies that are ready to be integrated with the Spacecraft for Observatory system level tests.

ACKNOWLEDGEMENTS

The James Webb Space Telescope project is an international collaboration led by NASA's Goddard Space Flight Center in Greenbelt, MD. Ball Aerospace would like to acknowledge and thank NASA for their leadership, funding, and support during the testing and analysis of the OTIS cryogenic testing campaign. We would also like to thank the many individuals, companies, and government institutions not previously identified who supported the integration and testing effort of the OTIS at both Goddard Space Flight Center and Johnson Space Center.

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