# Commissioning the James Webb Space Telescope Optical Telescope Element

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## ABSTRACT

The James Webb Space Telescope (JWST) launched on December 25th, 2021. The observatory was deployed and commissioned during its first six months. The Optical Telescope Element includes both large deployments of the Deployable Tower Assembly, Secondary Mirror Support Structure and the Primary Mirror Wings and it includes the deployment and alignment of the 18 primary mirror segments and the secondary mirror. The initial phase included cooldown and ice mitigation efforts followed by telescope deployments, mirror deployment and wavefront sensing and control. This paper will discuss the entire OTE commissioning from deployment through alignment including a discussion of results and lessons learned.

**Keywords:** Commissioning, Webb, Optical Telescope Element, Telescope

## 1. INTRODUCTION

The JWST telescope commissioning began with the launch on December 25th. During the six month that followed, the observatory went through various phases led by different teams. A key element of the commissioning was the Optical Telescope Element[i] which consists of the 18 gold coated hexagonal mirror segments, their 132 actuators, the telescope deployments including the two wings, Secondary Mirror Support Structure, Deployable Tower Assembly, Aft Deployable ISIM Radiator, bib and frill, and the Fine Steering Mirror and Tertiary mirror along with the electronics, software and ground algorithms for aligning the telescope. The Optical Telescope Element (OTE) was part of all phases of commissioning from the initial deployments to mirror deployments to alignment to performance assessments and finally supporting science. The rest of this paper will work through the commissioning sequence[ii] focusing on the OTE.

## 2. LAUNCH AND MAJOR DEPLOYMENTS

### 2.1 Launch and Major Deployments

The first phase was to launch on December 25th, 2021 from French Guiana. Soon after launch the Actuator Drive Unit (ADU) began getting telemetry and radiators and mirrors began to cool rapidly. After fairing jettison but before separation the observatory underwent a saw tooth roll profile to smoothen temperatures across the telescope. Two video cameras on the rocket were able to capture the observatory as shown in Figure 1 below. Sunlight could be seen hitting the side and back of the mirrors as predicted. The team did not get real time temperature data of the mirrors and backplane during this phase but were able to later assure that no temperatures exceeded their limits. In addition, the telescope team turned on heaters that kept the Fine Steering Mirror warm enough to prevent ice from accumulating and the temperature was stepped down with time. On day 2, heaters on the SMSS inboard hinges were activated to remove moisture before the secondary mirror had gotten cold enough to form ice. The inboard hinges had hardware with a direct view of the secondary mirror so ice mitigation was an important consideration. The heater profile of the inboard hinge heater is shown in Figure 2 below.

Figure 1:  Ariane Video Camera View of the Observatory during Launch and Ascent

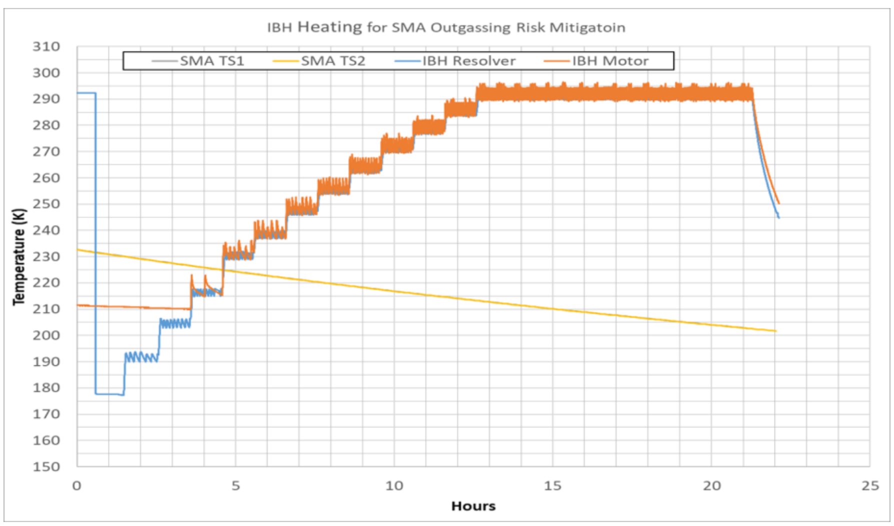


Figure 2:  Inboard hinge heaters turned on Day 2 to remove water

During the ensuing two weeks, all 50 large deployments were executed successfully.  This included the deployment of the SMSS which had already gotten cold.  The SMSS and the wings had latches which were torqued to have their strain match values seen during the JSC cryo test.  The expectation was that matching strain during final latching would settle the wings and secondary mirror to positions consistent with the alignment verification done during the ground cryogenic test.  A view of the starting and ending large deployment configuration can be seen in Figure 3.

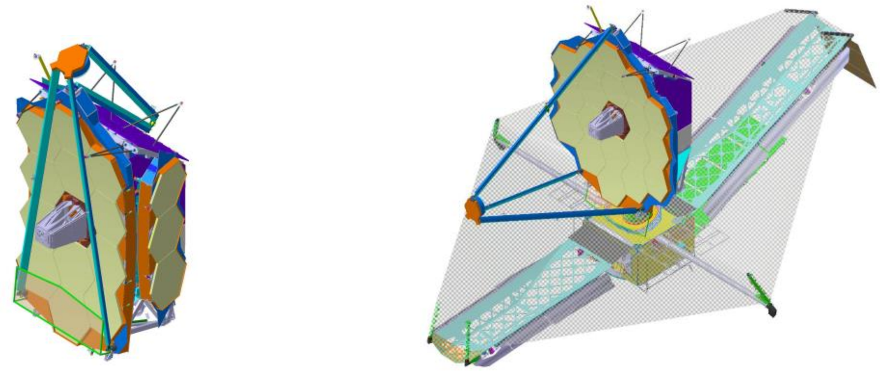

Figure 3:  Before and after large deployments

## 3.   MIRROR DEPLOYMENTS

### 3.1  Mirror Deployments

After the deployment of the wings, mirror deployments began.  Each primary mirror segment was launched with actuators in a snubbed position to avoid mirrors making contact during the vibration and acoustics loads.  Thus the mirrors were all deployed 12.5 millimeters forward from their launch position by moving the individual actuators of each hexapod in roughly millimeter increments.  There are  6 actuators on each primary mirror segment and the secondary mirror.  Radius of curvature actuators at the center of each segment did not have a snubbed position and did not need to be deployed but they were tested to assure motion.  Although the process took over a week, eventually each mirror was fully deployed and set to its best known starting position for optical alignment.  The figure below shows an early set of positions for each mirror followed by the full deployed 0 millimeter position (starting from -12.5mm).  Note that mirrors already were already quite cold during deployments but this was expected.

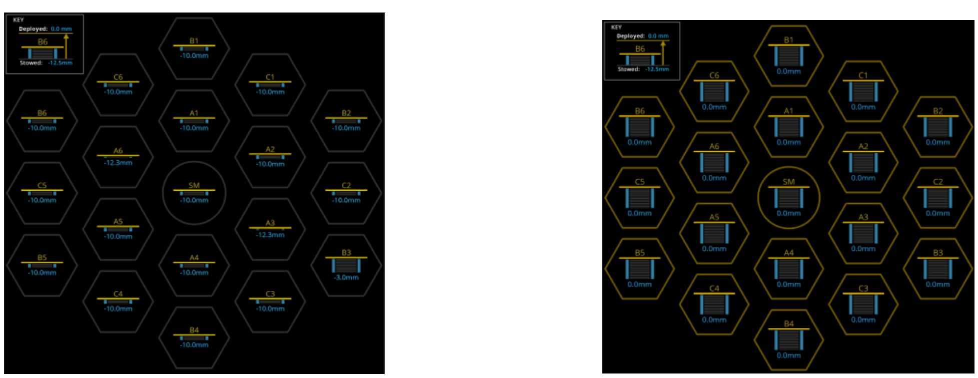


Figure 4:  Mirror deployments from -12.5mm to 0mm (all hexapod actuators)

## 4. ALIGNMENT

### 4.1 First Photons and First Light

The first step of optical alignment was to get photons onto the NIRCAM detectors. This started by waiting for the NIRCAM detectors to get cold enough which meant the dark currents were low enough. At this point te observatory was not yet guiding with the guiders as they needed to get even colder but short exposures were possible. Once cold enough, the telescope was pointed at the Large Magellanic Cloud where there were many expected stars and the first short exposures are shown below in Figure 5. As expected, there was a repeated pattern of 18 point spread functions as each segment had a unique signature based on its alignment and each star made 18 separate spots. This data was similar to models giving the team confidence we could start the actual alignment process of pointing at a bright isolated star. We chose the star HD 84406 which was available at that point in the orbit and was well isolated. After performing an image mosaic with the two NIRCAM short wavelength channels, all 18 spots were found, one for each mirror segment as shown below in Figure 6.

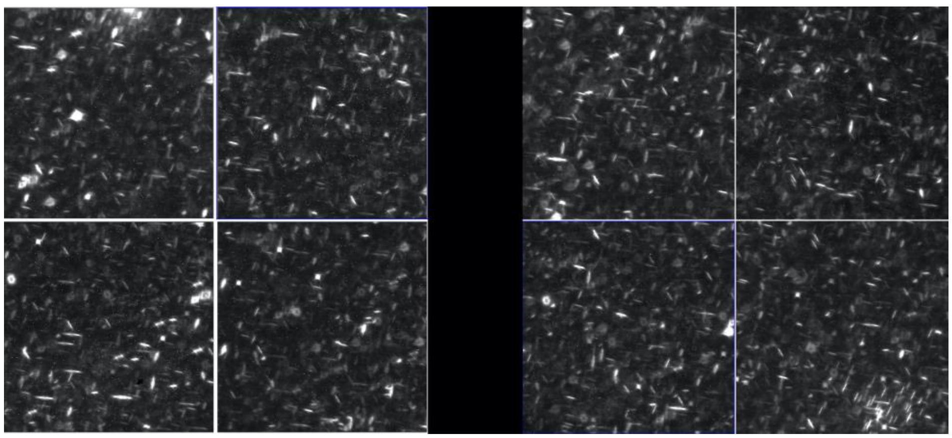

Figure 5: First photons on in NIRCAM February 2nd, 2022


Figure 6: 18 spots found, one for each segment

After finding the 18 spots, the alignment continues in 7 phases shown in Figure 7. After finding the 18 spots, the team did a focus sweep which assured the secondary mirror was at a reasonable focus and allowed for an initial gravity crosscheck of 11 mirrors using phase retrieval. Following this, the 18 spots were put into an array. One can note that bottom two lower corner segments have larger amounts of astigmatism. The team found that by sticking with the process that had been planned and tested they were able to align all 18 segments by, among other things, moving the secondary mirror and adjusting segment radius of curvature and clocking on the lower corner segments. After completing that phase of alignment, the team stacked the 18 nicely aligned separate telescopes to form a single stacked image that already represented the best infrared telescope ever. One key aspect of Segment Alignment was to perform a coarse Multi-Instrument Multi Field algorithm that used a Hartmann alignment method on 17 spots (the 18$^{th}$ used for guiding) which did an excellent job of aligning the secondary mirror. The phasing process included iterating between coarse and fine phasing in 3 iterations to assure actuators were at their ideal locations. At the end of the fine phasing, the team gathered to witness the first images together which showed not only a fully aligned telescope meeting its performance requirements in the NIRCAM channel but also showed many galaxies in fine detail that had not been part of the 20 years of simulations. The team then went on to perform Multi-instrument Multi-field alignment in two phases. The second iteration occurred after MIRI was turned on and the secondary mirror did not need any tilt or decenter adjustment on either MIMF iteration thanks to the great job Coarse MIMF had done. The only adjustment was a minor change in focus that was a compromise between MIRI which did not have a focus mechanism and cared about focus for coronography and the other SI's, especially NIRCAM which preferred not to adjust their focus.

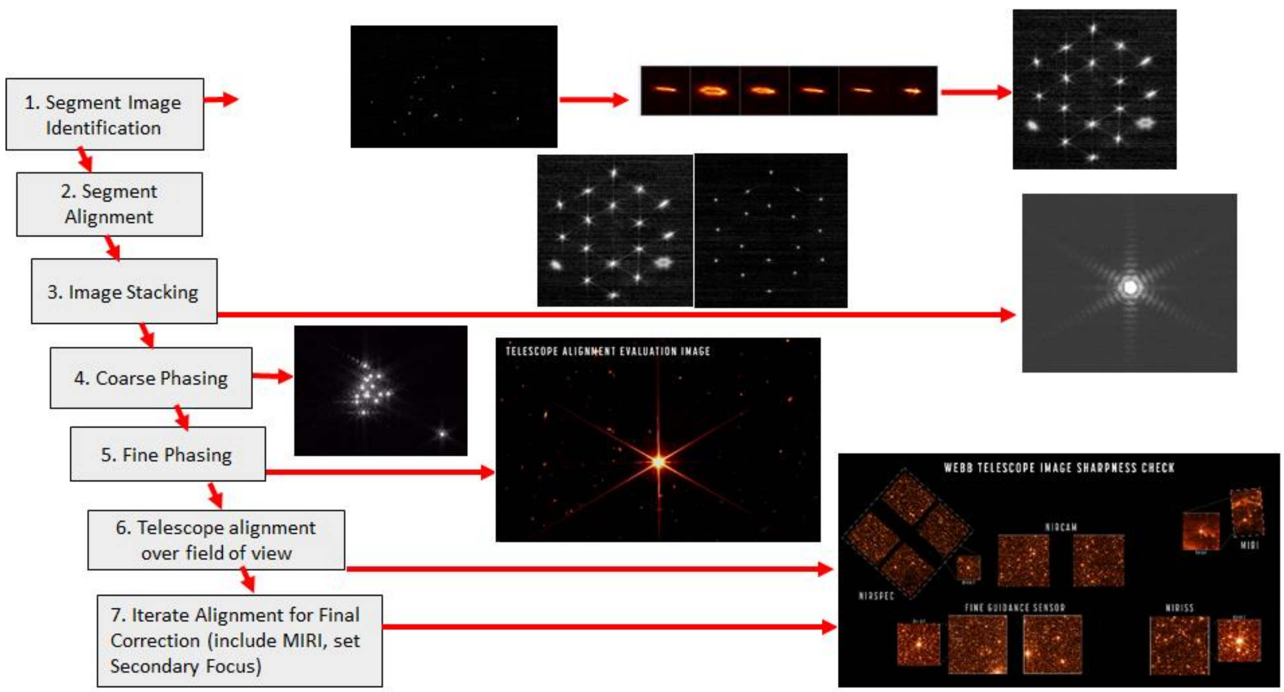


Figure 7: Alignment phases

## 5. PERFORMANCE

After completing the initial alignment the team evaluated the Full Width Half Maximum of the point spread function as shown in Figure 8. The FWHM was 2.54 pixels in NIRCAM which has 30 milli arcsecond pixels.

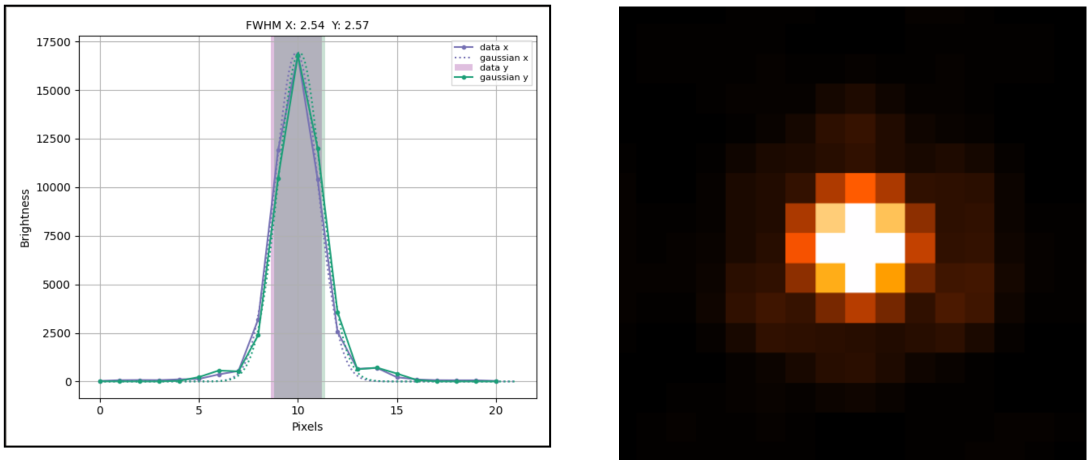


Figure 8: First FWHM in NIRCAM from Fine Phasing (NIRCAM F212N, 229 seconds subarray)

Further analyses evaluated the wavefront error of each channel and found the telescope to be diffraction limited at 1.1um in NIRCAM, well below the requirement of being diffraction limited at 2um. A full summary of the beginning of life optical performance is shown below in Figure 9. These values[iii] were as of the end of commissioning and include the effects of 6 mircometeoroid events including one on C3 that changed the overall RMS by approximately 9nm RMS. Micrometeoroids were expected and margins and budgets allow for a slow accumulation of wavefront error over time which primarily impact the shortest wavelength channels.

| | OTE WFE Mid /Hi | OBS Static measurement | OTE stability | Image Motion | Obs BOL | Obs Reqt | Obs margin |
|---|---|---|---|---|---|---|---|
| NIRCAM A SW | 37 | 65 | 13 | 18 | 79 | 150 | 128 |
| NIRCAM B SW | 37 | 85 | 13 | 18 | 96 | 150 | 115 |
| NIRCAM A LW | 37 | 100 | 13 | 18 | 110 | 301 | 281 |
| NIRCAM B LW | 37 | 119 | 13 | 18 | 127 | 301 | 273 |
| NIRISS | 37 | 85 | 13 | 18 | 96 | 180 | 152 |
| FGS 1 | 37 | 95 | 13 | 11 | 104 | 186 | 155 |
| FGS 2 | 37 | 85 | 13 | 11 | 95 | 186 | 161 |
| MIRI | 37 | 132 | 13 | 18 | 140 | 421 | 397 |
| NIRspec Sq Ap | 37 | 106 | 13 | 18 | 115 | 238 | 209 |

Figure 9: Wavefront error in each channel

After the alignment phase, the team did a thermal stability test where it soaked for 4 days, slewed and stared for 8 days, and then slewed back. This was a worse case hot to cold slew and using phase retrieval the team was able to assess the wavefront stability. The assessment was the Frill changed during the first 8 hours almost exactly as modelled (9nm RMS) followed by a longer time constant backplane stabilization that led to an 18nm RMS wavefront change due to thermal stability. There were a few small tilt events that occurred which are small sudden changes in tilt of segments and which died down considerably over time (eg, less than one every 10 days) and which should die down to zero eventually so are not included in the 18nm RMS assessment. Note though including these the total change after 8 days was 20nm RMS which is well under the 54nm RMS WFE end of life specification and right at beginning of life expectations. Achieving this level of thermal stability was incredibly challenging and involved understanding the CTE and thermal performance of every material and piece of hardware in the backplane and primary mirror system. There are metallic flexures, actuators, athermalization brackets, complex joints, large composite structures and of course the mirrors that all contribute to thermal stability. In addition, during testing at JSC it was found that Frill soft structure on the outskirt of the primary mirror was changing the stability of the primary mirror and this was fixed on the ground prior to launch. Since there was not a second cryogenic test, this flight test verified the fix of the Frill was done correctly.

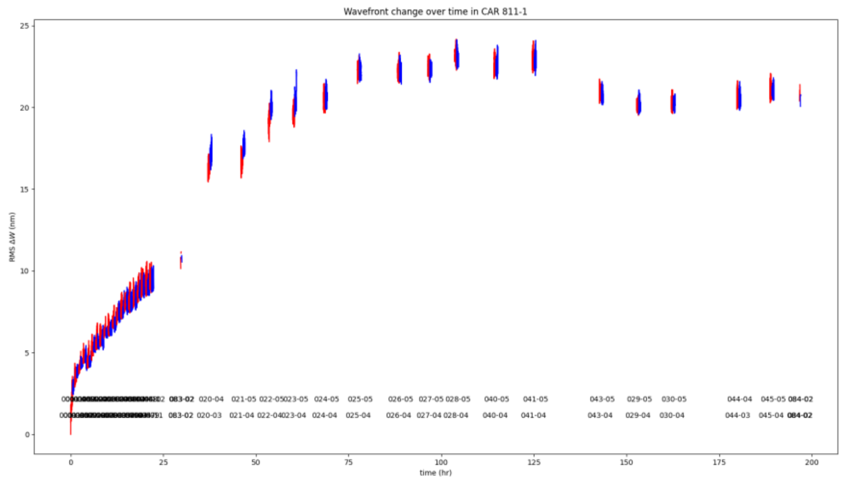


Figure 10: Thermal Stability test in nanometers

## 6. CONCLUSIONS

The commissioning of the Optical Telescope Element was a team effort across industry, NASA Goddard Space Flight Center and Space Telescope Science Institute. The lessons learned were numerous but one critical one was to stick with the process the team had planned and rehearsed. That process proved to be robust to cases where initial starting conditions were beyond the simulations. The true hero of OTE commissioning was the team that worked 24 hours a day 7 days a week for months on end and comprised nearly 100 engineers and scientists. Figure 11 shows the team who attended the final meeting where the performance of the telescope was reviewed and approved for moving on with science instrument calibration. No words can explain how hard this team worked, how brilliant the team performed, or how committed to a singular goal of building one of the most powerful and capable scientific instruments history.


Figure 11, the team that attended the final optical review of the telescope and observatory

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