JWST pathfinder telescope risk reduction cryo test program

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ABSTRACT

In 2014, the Optical Ground Support Equipment was integrated into the large cryo vacuum chamber at Johnson Space Center (JSC) and an initial Chamber Commissioning Test was completed. This insured that the support equipment was ready for the three Pathfinder telescope cryo tests. The Pathfinder telescope which consists of two primary mirror segment assemblies and the secondary mirror was delivered to JSC in February 2015 in support of this critical risk reduction test program prior to the flight hardware. This paper will detail the Chamber Commissioning and first optical test of the JWST Pathfinder telescope.

Keywords: JWST, Telescope, Alignment, Integration, Test

1. INTRODUCTION

The James Webb Space Telescope (Figure 1) is the successor to the Hubble Space Telescope. JWST will operate in the infrared region of the electromagnetic spectrum to allow the science community to observe far red shifted stars and galaxies as they were originally forming after the Big Bang 13.8 billion years ago. The scientists call JWST the first light machine since it will actually observe the first stars "turning on" and early galaxy formation. Even though the light from these early stars and galaxies was created billions of years ago, that light is just getting to our solar system now. They are moving away from us at nearly the speed of light Doppler-shifting the visible light into the infrared. In order to image this phenomenon, the telescope must also image in the infrared spectrum. This means that the telescope and all the systems that create that image must be very cold. That is why JWST operates at 40K. This extreme temperature creates many challenges for the engineers and scientists that are building and testing the observatory. This paper will provide an overview of the Alignment, Integration, and Test (AI&T) program and provide specific details on the Pathfinder telescope integration that occurred in 2014.

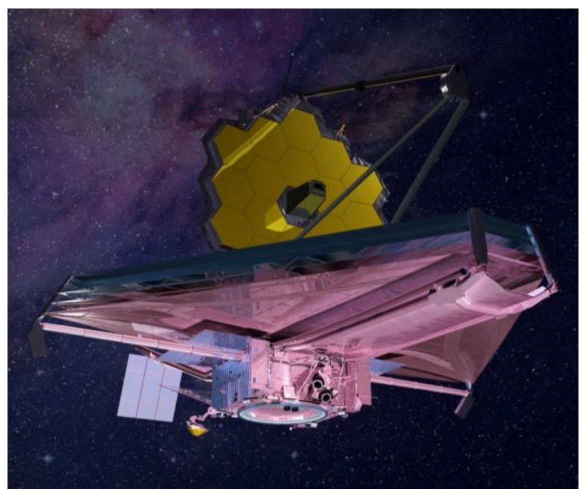

Figure 1: The James Webb Space Telescope in its fully deployed configuration.

2. ALIGNMENT, INTEGRATION, AND TEST

The AI&T phase of the program is fast approaching. But it has been in the planning stages since the inception of the program. It was recognized very early that the integration and test would be critical in the successful execution of the program. There are really two distinct aspects of JWST that are unique to the program – the optical configuration and operating temperature. The optical configuration for JWST represents the first space-based telescope that is segmented and deployable on orbit which provides a set of interesting challenges to be able to build an 18 segment primary mirror on Earth with the assurance that once on-orbit in zero gravity, it can be aligned to create a monolithic-like optical surface. The operating temperature is truly the biggest challenge for testing. In order to verify the performance, the largest cryogenic environmental test system in the world has been created. Given the fact that it takes a month to cool down and another two weeks to warm the system, a test configuration has been developed that will operate with the accuracy and dependability to satisfy the verification program.

The initial phase of the program will be to build what is called the Optical Telescope Element (OTE). This is the 6.5m telescope as shown in Figure 2. It is comprised of the large optical elements and the main structures that make up the system. Once the telescope is completed, the Integrated Science Instrument Module (ISIM) shown in Figure 3 is aligned and mated to the telescope. This major subsystem is called the OTIS which is comprised of the OTE and the ISIM.

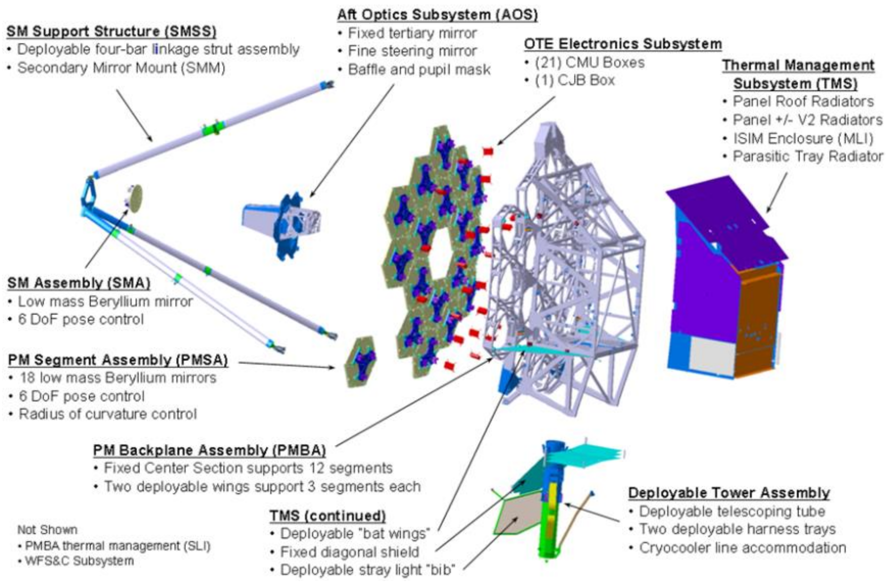

Figure 2: The major components of the Optical Telescope Element are shown above.

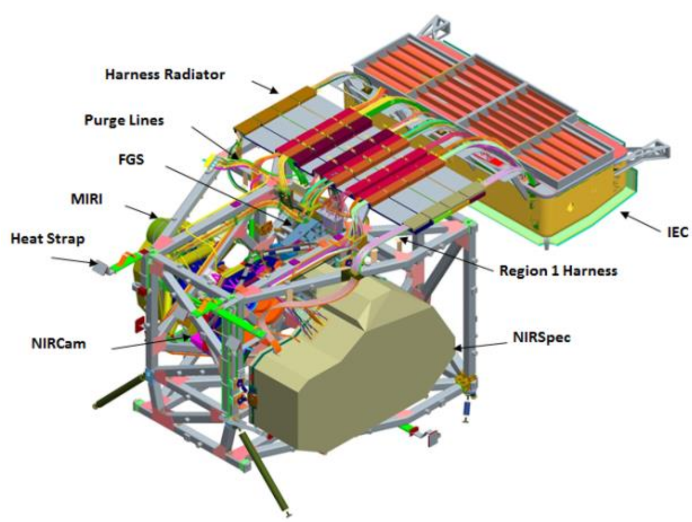

Figure 3: The Integrated Science Instrument Module consists of the instrument assembly and the Integrated Electronics compartment.

The final success of the AI&T portion of the program will be driven by careful planning and demonstrations prior to building the flight telescope and observatory to insure that the program can stay on plan during this critical path phase of the program

To aid in this very difficult task, a risk reduction Pathfinder Integration and Test program has been included in the plan since the original JWST proposal submitted by Northrop Grumman.

3. THE PATHFINDER PROGRAM

The Pathfinder program has been a part of JWST since the very beginning of the program. The combined experience of the NASA/contractor team placed a high value of making the investment in a risk reduction, alignment, integration and test program. In essence, the Pathfinder program has two distinct parts; the telescope integration phase and the cryo test phase. This paper focuses on the alignment and integration phase of the Pathfinder program. Paper SPIE 9575-3 discussed the integration of the three mirrors onto the composite backplane structure (Figure 4).

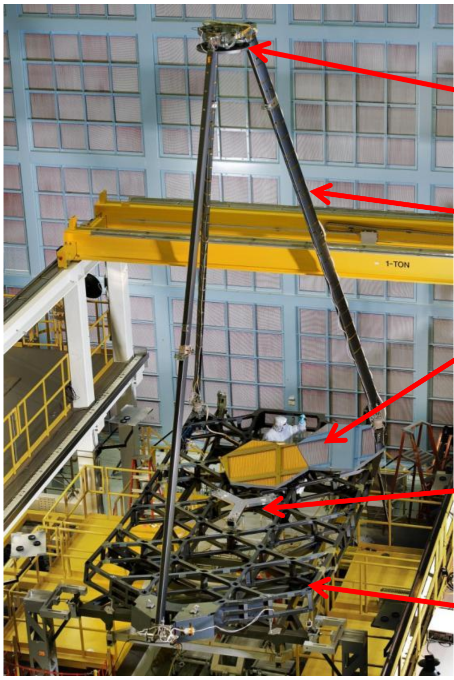

Figure 4: The Pathfinder telescope contains two; spare primary mirrors segments assemblies (OMSA) and the spare secondary mirror assembly (SMA). The flight aft optics assembly (AOS) will be installed after delivery to JSC.

The two PMSA's and the secondary mirror are all flight spares that are fully representative of the flight optics in every way. It should be noted that only one of the primary mirror segments are coated. The other two mirrors are polished Beryllium with no coating. For the purposes of the risk reduction program, this slight difference in reflectance is not considered to be a problem for the test equipment.

The test phase of the Pathfinder program is to check out all the cryo test equipment against a representation of the flight telescope. The Pathfinder telescope was shipped to the Johnson Space Center in Houston and installed in the large cryo, vacuum chamber. Over the past several years, the Apollo era vacuum chamber has been transformed into a state-of-the-art optical test system with specialized optical test equipment inside the giant thermal shrouds that operate at less than 20K using a 12.5KW Helium regeneration refrigeration system. The vacuum chamber and the connected clean room are shown in Figure 5.

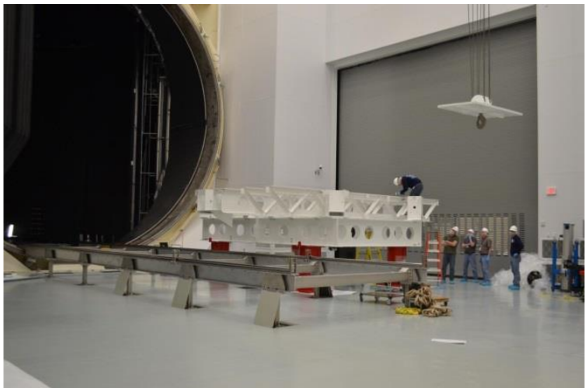

Figure 5: The JSC clean room will be used to stage the Pathfinder and flight system into the large refurbished cryo vacuum chamber.

The cryo test risk reduction program has four parts that will be executed over a period of 18 months. These tests are designed to add complexity as the confidence in the previous test is gained. Each step adds modest complexity and as much as possible, each test program can stand on its own merits. The tests are as follows:

- Chamber Commissioning Test (CCT): The CCT is the initial cryo test of the Optical Ground Support Equipment (OGSE) hardware and chamber system that will be used in the subsequent test program. It should be noted, that some additional test hardware will be added as the test program proceeds but all the major elements were present at the CCT test. The CCT was envisioned to check out the functionality of all the test hardware prior to starting the formal hardware testing with the Pathfinder telescope. It also served as final cryo load test of the OGSE hardware prior to introducing any critical optical hardware.
- Optical Ground Support Equipment #1 (OGSE#1): OGSE#1 is the first test that uses the Pathfinder telescope. This test program checks out the chamber dynamic control system, the center of curvature test system and the photogrammetry system. During the test, the team will also load test the AOS interface where the flight hardware will be placed for OGSE#2.
- Optical Ground Support Equipment #2 (OGSE#2): The next step in complexity is to add the Aft Optics Subsystem (AOS) to the Pathfinder telescope which allows the half pass and the pass and a half test to be demonstrated. In addition to the AOS, the source plate will also be included in this test that illuminates the full telescope system. In order to be able to understand the telescope performance, an instrument simulator called the Beam Image Analyzer (BIA) was developed by NASA and included in the OGSE#2 test. By the end of OGSE#2, the entire optical system test program will have been demonstrated.
- Thermal Pathfinder (TPF): The TPF program is a unique test that simulates how the flight system will react as the chamber temperatures are changed. Mirror simulators and thermal control surfaces similar to the flight hardware will be added to the Pathfinder structure. This is a non-optical test that is designed to better understand the thermal characteristics of the flight hardware under test conditions. Due to the severity of thermal environment, a TPF-like test program will be able to identify how small errors in modeling or hardware integration can influence not only the test program, but also the flight system.

The Pathfinder AI&T risk reduction program provides an unprecedented ability to practice and fine tune these critical integration and test processes well off the critical path of the program. The team can them make modifications and prepare for the flight operations with a high degree of confidence that the schedule can be maintained during the upcoming phase of the JWST program.

4. CRYO OPTICAL GROUND SUPPORT EQUIPMENT (OGSE)

As discussed earlier, the cryogenic testing will take place at the Johnson Space Center (JSC) in Houston, Texas. The JSC Chamber A is a legacy vacuum chamber that was originally built for the Apollo program in the 1960's. It was never intended to be an optical test chamber or a cryogenic test facility capable of creating a 20K test environment. So a major retrofit was in order that took several years.

The basic chamber was fully functional and with its large 40 foot (12.2m) diameter door, it was really a perfect choice for JWST. So the original solar lamps that illuminated the Apollo Command Module (Figure 6) were removed and the existing liquid Nitrogen (LN_2) shrouds were refurbished. While that was going on, an inner set of thermal shrouds were fabricated and installed that would support the gaseous Helium (GHe) cryogen enabling a 20K test environment. Once that work was completed, it was time to start to install all the Optical Ground Support Equipment (OGSE) that will allow the ground test of the JWST OTIS.

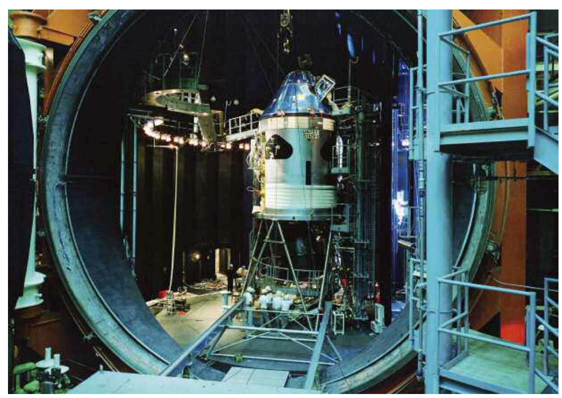

Figure 6: Chamber A was originally built to test Apollo spacecraft and has been refurbished for its new role to test JWST.

Figure 7 is a CAD model of the chamber with the OGSE installed. A brief description of each major piece of OGSE will be discussed below:

- Starting at the top of the chamber, there are six isolators manufactured by Minus-K. These six isolators allow the test team to transform the very noisy Apollo vacuum chamber into a quiet environment capable of supporting a precision optical test program. These six isolators support a total suspended mass of aboout 60,000 pounds (27,000 kg).

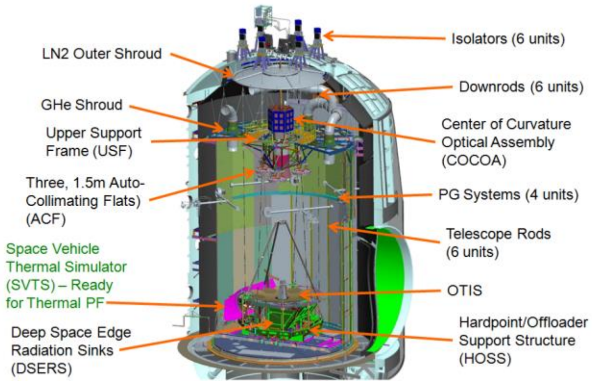

Figure 7: The JWST cryo test configuration is shown inside Chamber A

Figure 8: The Upper Support Frame (USF) is shown in the JSC clean room. The step ladder shown is 12 feet (3.7m) tall.

- Connected to the isolators are six downrods. These downrods also make the transition from the external air environment to the internal vacuum environment via a set of stainless steel bellows. These downrods are vertical and reach down to suspend the optical test system below.
- The main support structure is called the Upper Support Frame (USF) and is shown in Figure 8. The USF provides interfaces for the Center of Curvature Optical Assembly (CoCOA), the three, 1.5m autocollimating flats (ACF's), and the six telescope rods that support the OTIS at the bottom of the chamber.
- The CoCOA (Figure 9) is one of the major optical test systems for the JWST cryo test. The essence of the CoCOA is basically a two element null and a 4D multiwavelength interferometer (MWIF). The MWIF allows the test team to quickly align and phase the segmented primary mirror. It also provides a full aperture evaluation of the primary mirror since we only sample the end-to-end system aperature through our three subaperture ACF's. There are various features within the CoCOA to aid in the identification and alignment of the primary mirror. See Reference 2 for a complete discussion of the CoCOA.
- The three ACF's are lightweight borosilicate mirrors manufactured by HEXTEK (Figure 10). Borosilicate was used for the ACF's since the operating temperature of the mirrors is at the zero coeficient of expansion (CTE) of the glass. Therefore, the surface figure is very stable at the cryo test temperatures. The ACF's are cryo null figured at the operating temperature prior to installation at JSC.

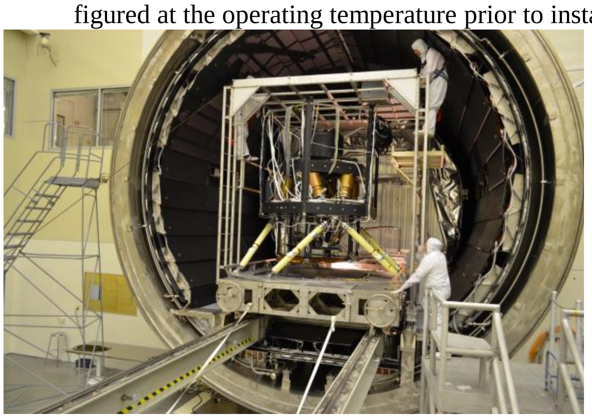

Figure 9: The Center of Curvature Optical Assembly (CoCOA) is shown at the Marshall Space Flight Center during early risk reduction testing. Note that the thermal panels have not yet been installed in this photo.

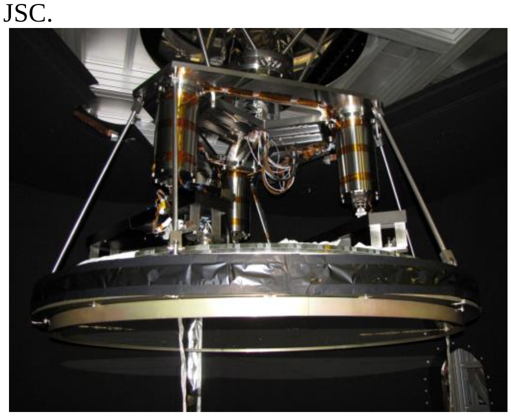

Figure 10: The ACF assembly is shown with the three actuator assemblies suspending the 1.5m lightweight mirror underneath.

There are six telescope rods that hang from the USF and support the Hardpoint/Offloader Supprt Structure (HOSS). The very large stainless steel structure (Figure 11) holds the flight OTIS in a kinematic configuration of 2 monopod struts on one end and two sets of bipods on the other end.

Figure 11: The Hardpoint/Offloader Support Structure (HOSS) is shown after painting. The structure is approximately 30 feed (9m) in length and width.

There are four photogrammetry (PG) systems manufactured by Johns Hopkins University Instrument Development Group that are attached to the walls of the chamber (Figure 12). The camera systems in inside pressure tight enclosures that are thermally controlled. Each system rotates in a windmill fashion through 360 degrees of rotation. This PG system allows the test team to understand where the hardware is in the chamber to about 100 microns.

5. OGSE INTEGRATION

Over the period of 8 months, all this equipment was installed into the JSC chamber and prepared for an initial Cryo Commissioning Test.

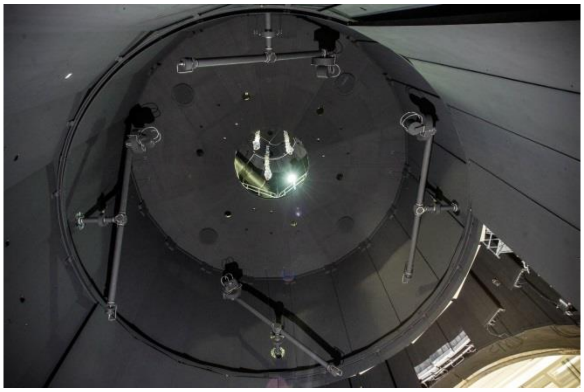

Figure 12: The four photogrammetry systems are shown in their final "windmill" configuration in the JSC vacuum chamber.

During the time leading up to the final integration into the JSC vacuum chamber, the CoCOA and the photogrammetry canisters were tested at their operating temperatures. This risk reduction provided high confidence that the equipment would work, but this is the first time that the system was configured and expected to work seamlessly as a system.

The major assembly that is installed near the top of the chamber is the ACF/CoCOA/USF (ACU) assembly. This is a very large optical assembly with the complexity on par with flight hardware. To add to this complexity, the system is so large that even at ground level, the technicians were working 30 feet (9m) in the air. A specially designed and built piece of ground support equipment was needed for this task (Figure 13). This ACU Dolly as it is referred to be the assembly station and also allowed the entire subsystem to be rolled into the chamber and lifted into position via a set of three hoists at the top of the chamber.

Figure 13: The ACU dolly provided the added ground support equipment to build up the CoCOA and ACF's onto the USF prior to rolling it into the chamber on the rails.

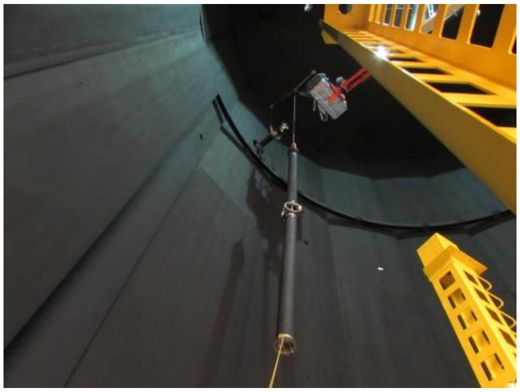

Figure 14: One of the PG "windmills" being raised into position inside the vacuum chamber.

The Photogrammetry system was one of the first assemblies that were lifted into position. Figure 14 shows the technicians working on one of the booms. We refer to the systems as windmills and a completed system is shown in Figure 15.

Figure 16 shows the CoCOA on its assembly stand. After the CoCOA risk reduction testing was completed in 2012, the system was stored at the Marshall Space Flight Center in Huntsville, Alabama until it was moved and reassembled at JSC. After integration on the USF, the CoCOA electrical and optical system was fully verified.

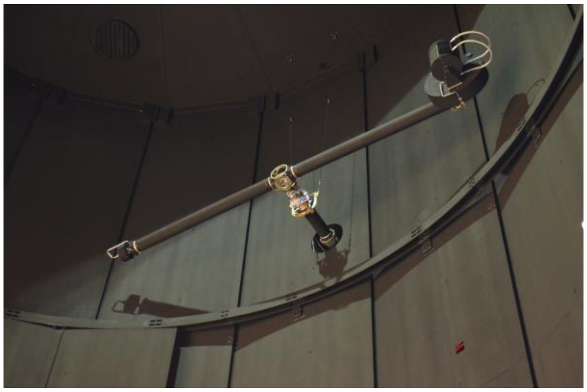

Figure 15: A completed photogrammetry "windmill" system. Note that camera canister on one end and the ballast mass on the other.

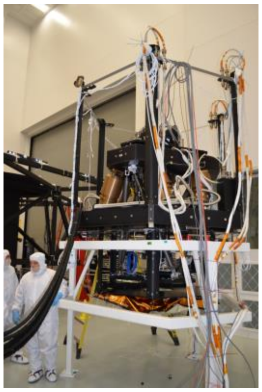

Figure 16: The CoCOA was reassembled after being shipped from MSFC. It was them placed on the USF.

One of the ACF mirrors is shown being installed in Figure 17. This is a two part operation where the actuator assembly is installed first followed by the ACF assembly. Like the CoCOA, the ACF system was fully tested as a system at the operating temperature before being shipped to JSC.


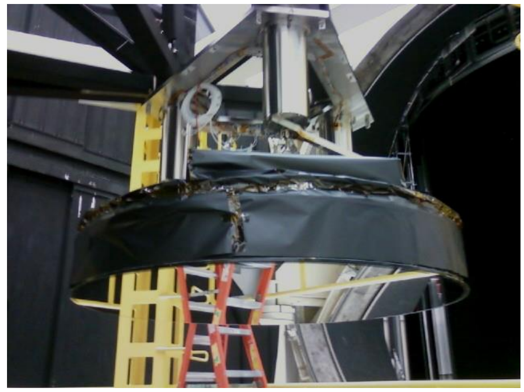

Figure 17: The ACF actuator assembly (left) and the entire assembly (right) is shown in the pictures above.

Once the whole ACU assembly is completed, it is rolled into the chamber on the rail system (Figure 18) and the long process of lifting the assembly into final position is started. As the system is lifted, the telescope rods are attached. The telescope rods are 16 foot (4.9m) sections that also have thermal diodes and also photogrammetry targets so all the cabling and other integration work was a serial effort. It was a long arduous process that took 3 days to raise and get into final position (Figure 19).

Figure 18: The ACE assembly is ready to be rolled in and lifted into position at the top of the chamber.

Figure 19: The ACU assembly being prepared to be raised into position. This effort took three days to complete.

The final configuration with the 2X mass simulator is shown in Figure 20.

6. CHAMBER COMMISSIONING TEST

We are now ready to check out the system. In addition for an initial path to check out the systems operationally, we also used this configuration as a load test for the hanging system. This test was the first time that the OGSE was taken cold and an excellent risk reduction run prior to starting actual testing with the Pathfinder telescope.

In general, the system operated as expected. As with any highly complex system, we did come away with some lessons learned from the experience. Several issues were identified during the Chamber Commissioning Test (CCT) as discussed below:

- We did have a significant leak in one area of the CoCOA equipment. One of the sealing flanges that allow the CoCOA equipment to stay at ambient pressure was warped during manufacturing. So when the chamber was evacuated, there was effectively a small hole in chamber. A temporary fix was completed with slowed the leak to an acceptable level and the test proceeded.
- One of the photogrammetry booms stopped working as the system got colder. This was traced to some contamination in one of the bearings. The aluminum shards of contamination did not impact the warm operation, but as the system cooled, the clearances in the bearing got tighter. There became a point where the motor could not overcome the contamination.

Other than these minor issues, the OGSE and chamber worked as planned. At this point, the team completed the rework required to repair the air leak in the CoCOA system and the cause of the PG boom stalling was also repaired with new bearings with shields to prevent any new contamination from entering the system.

Prior to OGSE#1, there is one additional piece of OGSE called the Beam Image Analyzer (BIA). The BIA is actually an ISIM simulator that allows the test team to understand the end-to-end performance of the telescope. Even though the aft optics assembly (AOS) was not be included in OGSE#1, the test team wanted to have a dry run of the OGSE#2 operations to insure that the BIA was functioning properly.

At this point, we are ready for the Pathfinder and some actual optical testing!

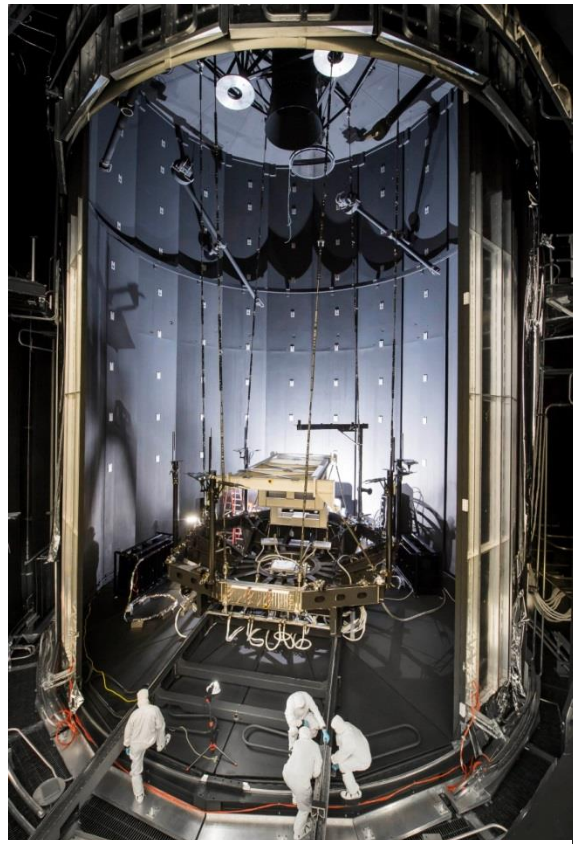

Figure 20: The configuration for the CCT is complete. The 2X OTIS mass simulator is shown and the rails system is in the process of being removed in preparation to close the door.

7. OGSE#1 PREPARATION

The Pathfinder was delivered to JSC and the work to configure for OGSE#1 was started. The Pathfinder was moved from the shipping container to the assembly cart as shown in Figure 21. The secondary mirror was then deployed (Figure 22) using the same support equipment that was used during mirror integration. That whole system was then moved over to the HOSS and placed on the six hardpoint struts. This is actually the same configuration and the same struts that were used at Goddard during the mirror integration.

Figure 21: The Pathfinder is shown just after being installed onto the assembly cart in the JSC cleanroom.

Figure 22: The Pathfinder is shown with the secondary mirror in the deployed configuration.

In order to monitor the thermal aspects of the test, about 800 thermal diodes were connected to the Thermal Telemetry Systems (TTS). The diodes were routed to connector panels on the HOSS and then connected to larger wire harnesses that run along the floor to the outside of the chamber (Figure 23).

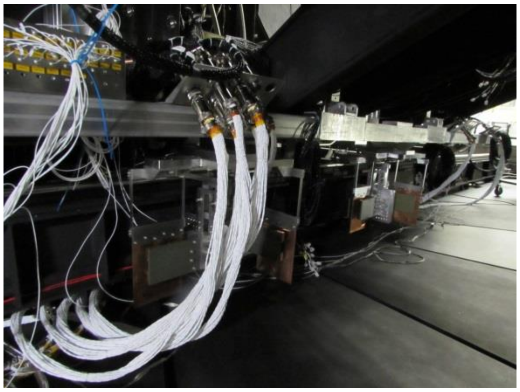

Figure 23: The thermal cables are routed across the chamber floor to the DSERS frame. From there they jump across to the HOSS.

8. OGSE#1 TEST

The OGSE#1 test is the first integrated test with something representing the flight telescope. As discussed earlier, this first Pathfinder cryo test will provide information on the following equipment (Figure 24):

- Isolation System
- CoCOA
- Photogrammetry System
- Fiducial Light Array Bars
- ASPA fiber Operation
- Beam Image Analyzer Operation

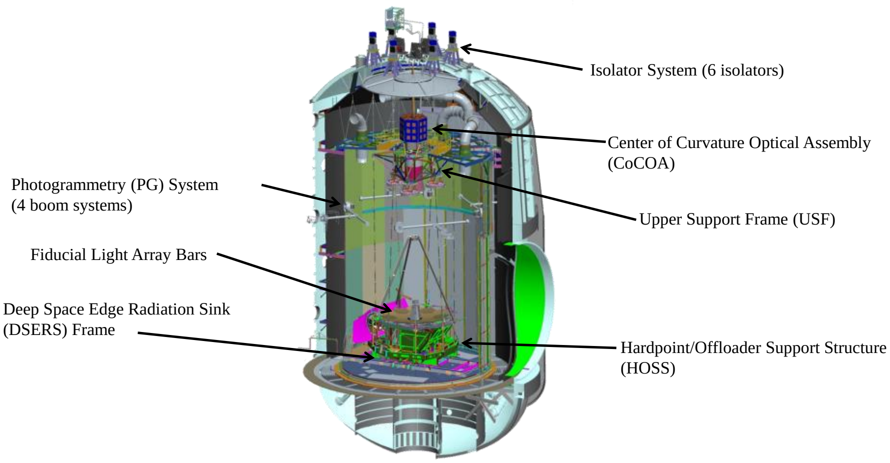

Figure 24: JSC cryo test configuration for the flight OTIS.

Isolation System

The isolation system had never been used in conjunction with obtaining optical data prior to OGSE#1. We did do a quick check of the system while we were waiting for the BIA delivery but this was not a comprehensive test and no optical data could be obtained during that test. The process involves adjusting the six isolators and equalizing the load in each one that allows the system to “float” within the balance point of the isolators.

We were able to float the system very easily in air and readjust it quickly for vacuum operations. There is a slight difference between air and vacuum since the system loses the air buoyancy and also due to the force on the downrod feed through bellows. As the mirror segments were adjusted, the fringes were very stable which indicated that the isolation system was working as designed. Figure 25 shows some dynamic data that shows a 6 order of magnitude decrease in response between 0.5Hz and 20Hz.

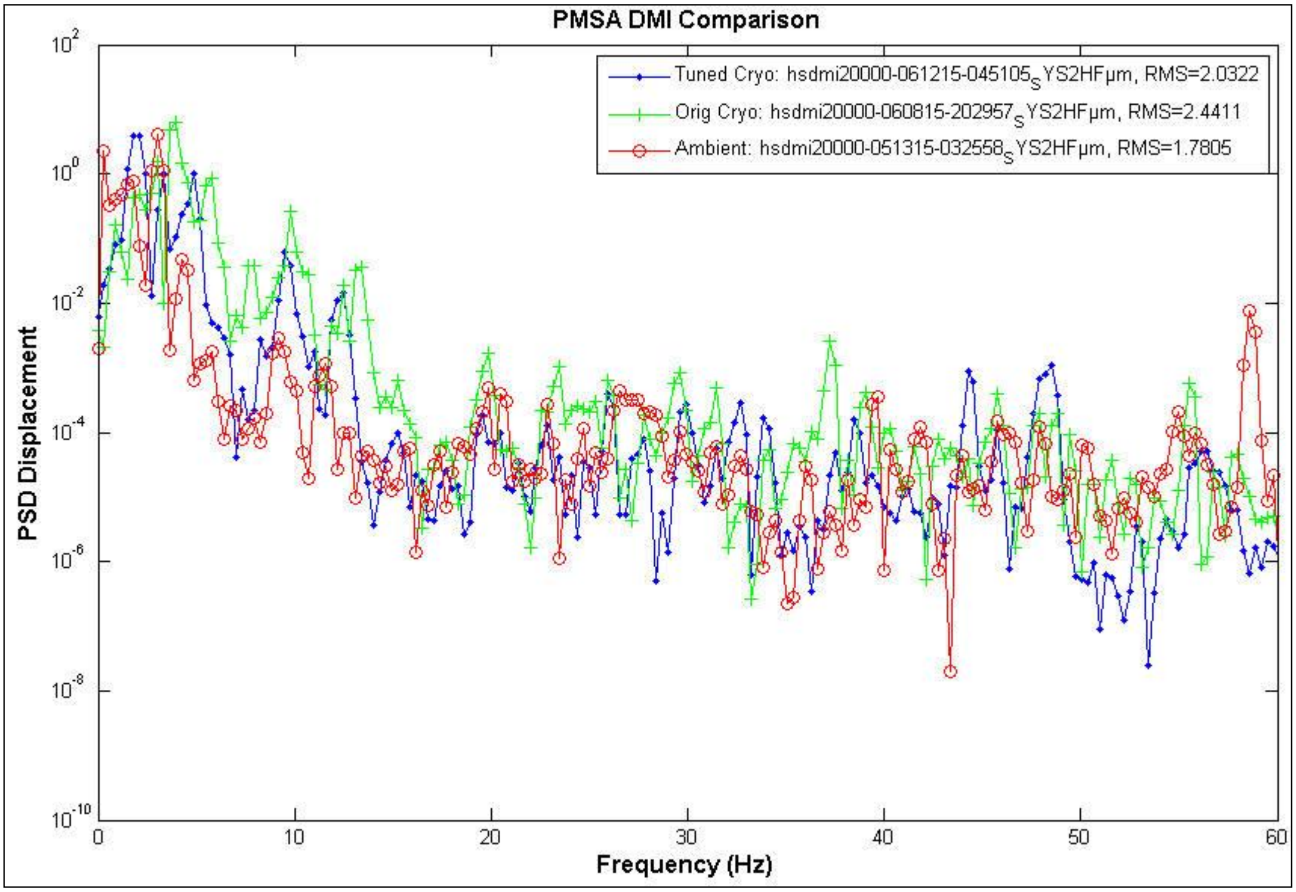

Figure 25: Mirror dynamic data from a high speed displacement measuring interferometer is shown above. Note that the response is reduced by 6 orders of magnitude between 0.5Hz and 20Hz.

But as the system cooled, we did identify an issue that would remain a mystery until after the test was over. As the temperature dropped and the long telescope rods got colder, the load on the isolators increased by about 680 kg (1500 pounds). In-situ testing indicated that the force acted like a large spring connected to ground. The cold optical testing had to work through this added disturbance until we could correct the problem in subsequent testing.

After the test was completed and the chamber door opened, the NASA/Harris team identified the issue as an interference of the DSERS frame and the HOSS magnetic damper system. A large cap head screw protruded from the DSERS frame where the mag damper system was located. This reduced clearance caused an interference to occur where we basically lifted the corner of the DSERS frame that was tied to ground. The resulting bending appeared to look like a large spring attached to the HOSS thus causing the increase in load as the system cooled. This condition has been corrected for the OGSE#2 test which will start in September 2015.

The other condition that was identified was that the damping system first fundamental mode was designed to be 0.5 Hz. During the test, we identified that this first mode was 0.8 Hz. There are isolator parameters that can be adjusted to move that first mode back down to 0.5 Hz and improve the overall performance of the system. This was done late in the test and the Harris test team was able to demonstrate very stable fringes on the interferometer.

CoCOA

The CoCOA had been though a cryo test in 2012 with WFE measured against a computer generated hologram at the Marshall Space Flight Center as part of a risk reduction effort. But this is the first time that the CoCOA would be operational in the JSC chamber while actually looking at flight primary mirror segment assemblies (PMSA). There are various features in the CoCOA that allow the test team to quickly adjust and phase the mirrors. Photogrammetry (PG) is used to set the position of the mirror relative to the Aft Optical Subsystem (AOS) position before the CoCOA determines where to move the mirrors to create a phased monolithic PM.

There are several features that help with this process. There are two camera systems within the CoCOA that allow the test team to fine tune the alignment of the PMSA’s. The Coarse Alignment Subsystem (CASS) is a very large screen that is illuminated by the mirror returns (Figure 26). These images are so far out of alignment that they would not get back through the hole in the null mirrors. The CASS images provide the knowledge to be able to better align the PMSA’s to the interferometer. The next step is the alignment to the Fine Alignment Subsystem (FASS). This is basically a camera looking at the hole going into the interferometer. Figure 27 shows the FASS images with respect to the interferometer reference hole. The returns are then easily driven back into the interferometer where the final alignment can take place.

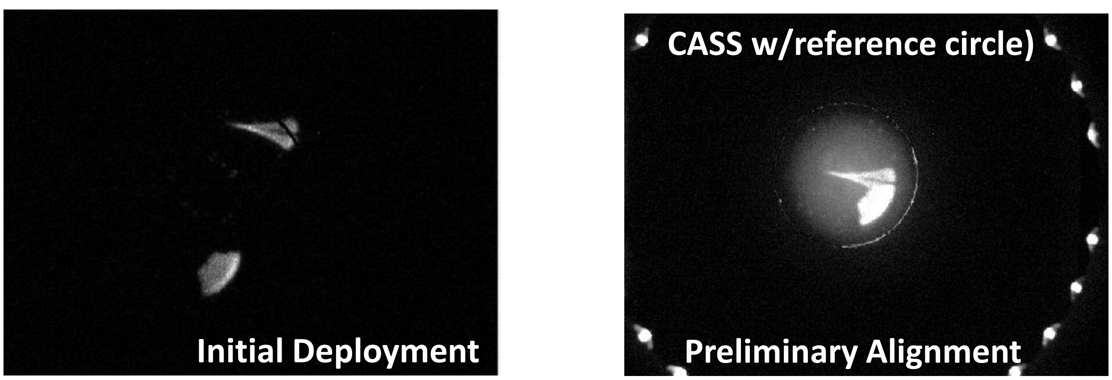

Figure 26: The CASS image on the left is just after the mirrors were deployed. As the mirrors are driven into alignment, the images converge. The fid lights that are barely visible in the image provide references for the initial alignment.

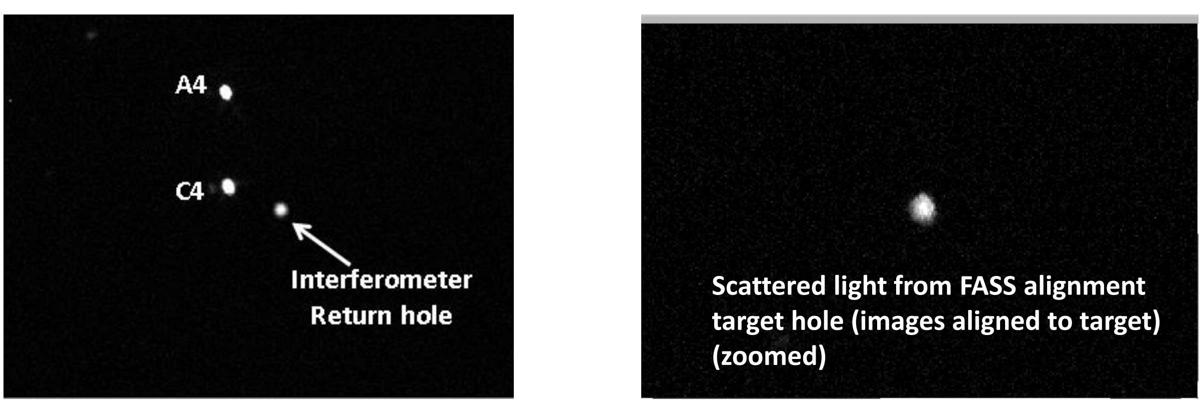

Figure 27: The left FASS image is the “handoff” image after the CASS alignment is completed. The next task is to drive the two PMSA images into the interferometer return hole as shown in the picture on the right.

The cameras and MWIF are mounted to a bench on actuators that are used to align the pointing direction of the COCOA optical axis using fiducial lights on the bars over the edge of the Pathfinder primary mirror location.

When all 18 mirrors are in place for OTIS, the returns could get very confusing. There is another feature that was verified during OGSE#1 that isolated each of the PMSA's to eliminate the confusion. By only illuminating one mirror at a time, it is very easy to drive their alignment position. This worked flawlessly during the test.

The fine phasing of the two segments using the multi-wavelength interferometer was also completed. Like the demonstrations that were completed on the Test Bed Telescope at Ball Aerospace, the ability to fine phase the two segments using the synthetic wavelengths was relatively easy. Figure 28 shows the mirrors phased to within 12.5 nm.

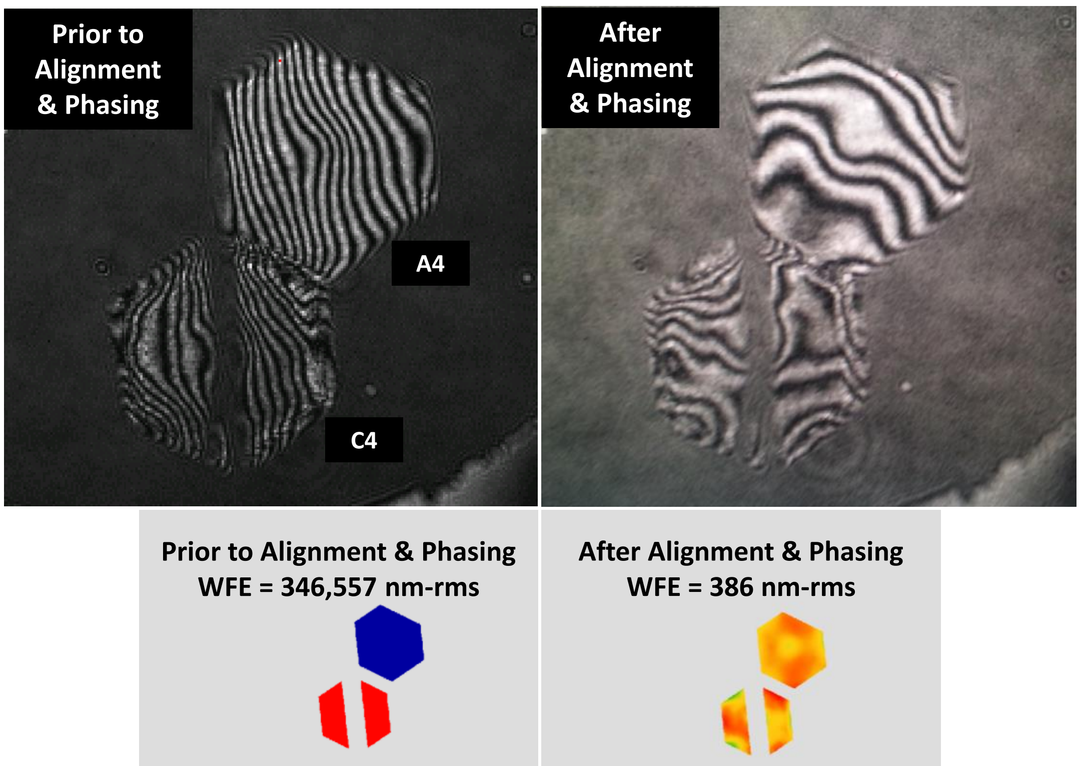

Figure 28: The two PMSA's were aligned to 12.5 nm using the multi-wavelength interferometer. This resulted in a total wavefront error of 386nm RMS.

The mirror figure in a vertical 1-g orientation was also checked during OGSE#1. To date, the mirrors were always tested using a multiple orientation horizontal test so this first vertical test was critically important. Figure 29 shows the predicted and measured surface figure as measured by the CoCOA. As can be seen, they are very close in both shape and overall RMS. This is a great outcome and provides high confidence as we continue towards the OTIS test.

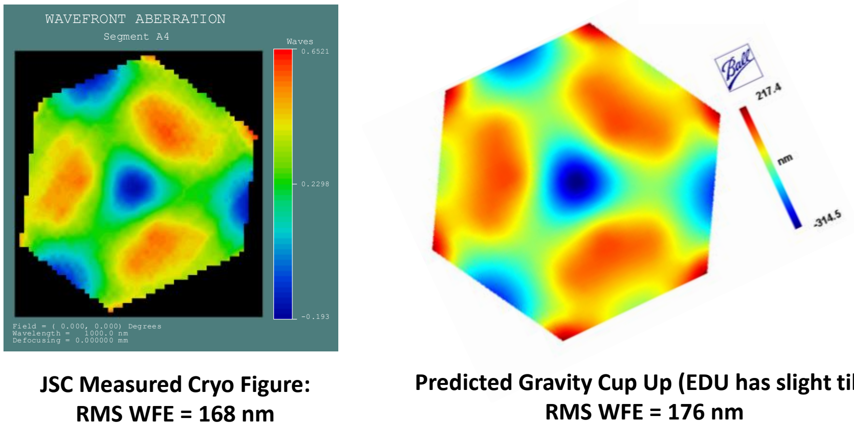

Figure 29: The comparison above shows the measured and predicted mirror wavefront error were very close. Note that the distortion has not been removed from the test image on the left.

Then many measurements were collected to characterize range, resolution, repeatability, sensitivity to adjustment, sensitivity to dynamic motion, and sensitivity to thermal distortion. In addition, processes were demonstrated in the event of a CASS or FASS failure.

The final aspect of the CoCOA is a pair of Displacement Measuring Interferometers (DMI). The DMI also provides high speed information at 7,000 measurements per second which could be evaluated in the time or frequency domain (Figure 25). This capability provides excellent cryo dynamic data for analysis comparisons. This device worked very well and provided some excellent dynamic feedback to the test team.

In general, the CoCOA worked as designed. There were some minor processing software upgrades that will be completed prior to OGSE#2, but these were easily worked around for this initial OGSE#1 test program,

Photogrammetry (PG) System

The PG system worked as designed during the test. There were many upgrades after the CCT which allowed a near flawless operational system for OGSE#1.

The result of the PG analysis show that the system is working extremely well. Figure 30 shows pictorially the absolute accuracy in the critical locations on the hardware when compared

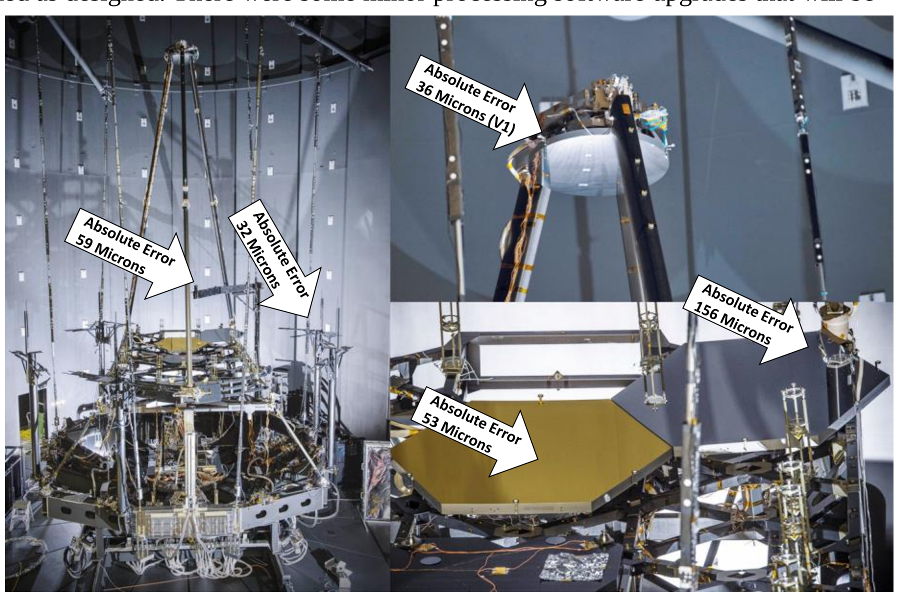

Figure 30: The PG results are well within expectations. This data was verified using laser radar as a cross check.

with a laser radar instrument at ambient temperature and pressure. Figure 31 shows the same data in tabular form.

	Average Absolute Error				RMS (2σ)			$2\sigma_{object}$			
	V1 (mm)	V2 (mm)	V3 (mm)	Mag. (mm)	V1 (mm)	V2 (mm)	V3 (mm)	V1 (mm)	V2 (mm)	V3 (mm)	# points
AOS- Base	0.0334	-0.0457	-0.0170	0.0591	0.0489	0.0225	0.0356	0.0129	0.0390	0.1212	3
ARM	-0.1136	-0.0809	-0.0364	0.1441	0.0420	0.0296	0.0376	0.0652	0.0513	0.1338	5
FLAB	0.0136	-0.0010	-0.0295	0.0325	0.0338	0.0858	0.0289	0.1201	0.0803	0.1560	13
PM-A4	0.0229	0.1584	0.0305	0.1629	0.0412	0.0273	0.0040	0.0943	0.0405	0.0626	2
PM-C4	0.0113	0.0521	0.0019	0.0533	0.0401	0.0268	0.0321	0.0327	0.0674	0.0908	5
SM	0.0362				0.1794			0.0308			4

Figure 31: The average absolute error is the result of comparing the laser radar and PG calculated locations. The RMS 2-sigma error is the calculated standard deviation across four independent PG runs. The 2-sigma object error is the standard deviation of the absolute errors of all the PG points that represent the object when laser radar and PG positions are compared.

In addition to providing location data using the PG targets, the test team was also able to create an actual picture of the Pathfinder at cryo temperatures. Figure 32 shows a view from one of the PG cameras that were put through a special processing algorithm to produce this very low light picture.

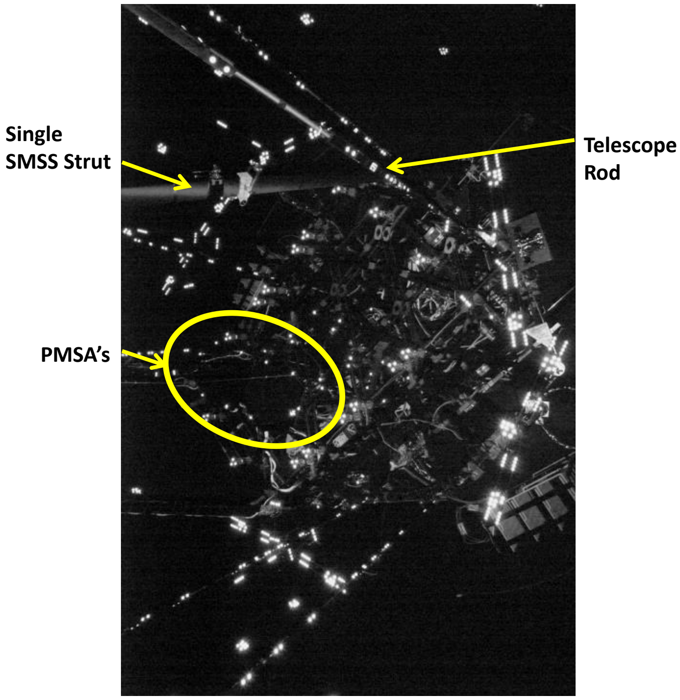

Figure 32: The rendered photograph taken with the PG cameras at cryo temperature show the many features of the Pathfinder OGSE#1 test configuration.

Fiducial Light Array Bars

This was the first time that the fiducial light bars were in a cryo test. In addition to centering the COCOA pointing direction, the light array will be used in the OGSE 2 and the OTIS tests to locate the relative alignment of the pupil apertures. Each LED within the capture window of the BIA peering around the edge of the AOS mass simulator peering towards the Secondary Mirror was checked for operating light with > 98% success! There was some concern regarding the wavelength change of the LED's as they got cold. Analysis and testing indicated that the shift would be within range of the detectors. This initial test demonstrated the fid lights are acceptable as the test program progresses.

ASPA Fiber Operation

In the CCT, we did observe some of the optical fibers were severely attenuating above 2 micrometer wavelength. The OGSE 1 test proved a slight modification to the bend radius features eliminated that problem for OGSE#2. This provides high confidence that the optical fibers that feed the source plate assembly will work as designed.

Beam Image Analyzer Operation

For OGSE#1, the operation of the detectors and the various stages were verified for operation. This was completed without issues. PG was used to verify the location of the detector head with respect to the Pathfinder location. The LED's on the Fid Bars were used as flat field and pupil imaging sources for the NIR detectors. The COCOA heat with a thermal shutter was used as a source to check function of the InSb detector. This will all be repeated for OGSE#2 when the Aft Optics Subsystem (AOS) is installed onto the Pathfinder. OGSE#1 verified that the various location could be viewed using the PG system.

9. SUMMARY

The early demonstrations and the Pathfinder Alignment, Integration, and Test program provided an excellent basis for process development and early detection of test equipment problems. These first two cryo tests provide additional confidence as the complexity of the next phases of the test program increase in OGSE#2 and Thermal Pathfinder. The value of such a robust, high fidelity Pathfinder program cannot be understated as the ultimate in risk reduction.

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