

JWST Pathfinder Telescope Integration

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ABSTRACT

The James Webb Space Telescope (JWST) is a 6.5m, segmented, IR telescope that will explore the first light of the universe after the big bang. In 2014, a major risk reduction effort related to the Alignment, Integration, and Test (AI&T) of the segmented telescope was completed. The Pathfinder telescope includes two Primary Mirror Segment Assemblies (PMSA's) and the Secondary Mirror Assembly (SMA) onto a flight-like composite telescope backplane. This pathfinder allowed the JWST team to assess the alignment process and to better understand the various error sources that need to be accommodated in the flight build. The successful completion of the Pathfinder Telescope provides a final integration roadmap for the flight operations that will start in August 2015.

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 40°K. 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.

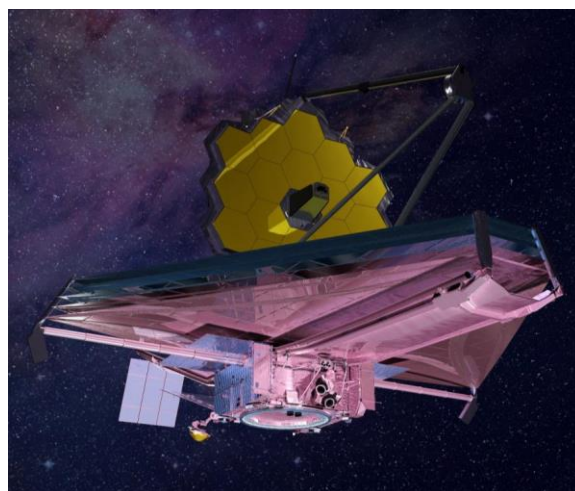


Figure 1: The James Webb Space Telescope in its fully deployed configuration.

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.

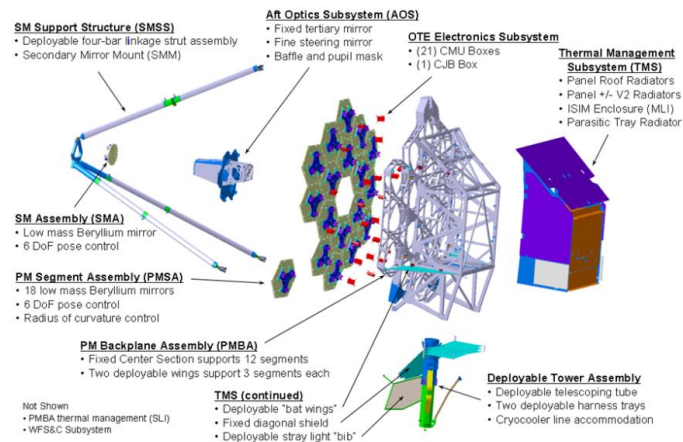


Figure 2: The major components of the Optical Telescope Element are shown above.

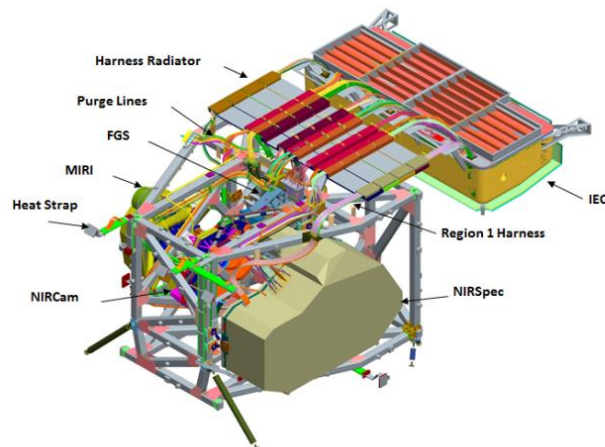


Figure 3: The Integrated Science Instrument Module consists of the instrument assembly and the Integrated Electronics Compartment.

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 Pathfinder 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 9575-4 will discuss the initial phases of the cryo test program.

The Pathfinder telescope is shown in Figure 4. It is comprised of a composite backplane that is similar to the flight system manufactured by ATK. For the purposes of the risk reduction program, the deployable wing elements were not included in the Pathfinder program to reduce the cost. But the main structural elements are represented. There are interfaces to accommodate the master telescope reference where the Aft Optics Subsystem (AOS) will attach plus two Primary Mirror Segment Assemblies (PMSA). This will allow the integration team to practice all the flight integration processes and procedures using the ground support equipment developed for those operations. There is also a secondary mirror system included on the Pathfinder telescope.

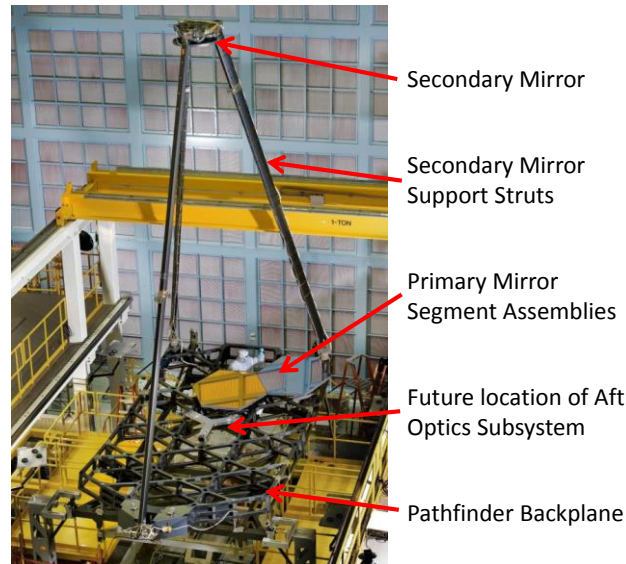


Figure 4: The Pathfinder telescope contains two, spare PMSA and the spare SMA. The flight AOS will be installed after delivery to Johnson Space Center.

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 (JSC) 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 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 the 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 then 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. TELESCOPE ALIGNMENT AND INTEGRATION

Building a 6.5m, segmented, deployable telescope is a unique undertaking requiring specialized equipment and processes. This activity will take place in the Goddard Space Flight Center (GSFC) Space Systems Development and Integration Facility (SSDIF) cleanroom (Figure 6). This large cleanroom was built for the Hubble Space Telescope and is now being utilized to build not only the JWST telescope, but also the ISIM. For telescope alignment and integration, a stable platform is required. This platform has to hold the telescope during integration and also provide assembly

personnel the ability to reach and access to the telescope without causing the any motion or disturbance to the flight hardware. To accomplish this, two structures were built. The Ambient Optical Alignment Stand (AOAS) was designed and built in the SSDIF cleanroom. This is an optical bench that will hold the telescope and another independent structure will hold the work platforms and other optical alignment hardware. An AOAS drawing with the telescope installed is shown in Figure 7. As can be seen, the telescope primary mirror is facing up during primary mirror integration. During alignment, the Primary Mirror Segment Assemblies (PMSA's) will be attached to the Primary mirror Alignment and Integration Fixture (PAIF). This fixture provides the ability to move the mirror is 6 degrees of freedom for fine alignment and bonding in place.



Figure 6: The OTE and OTIS will be integrated in the SSDIF clean room at Goddard Space Flight Center.

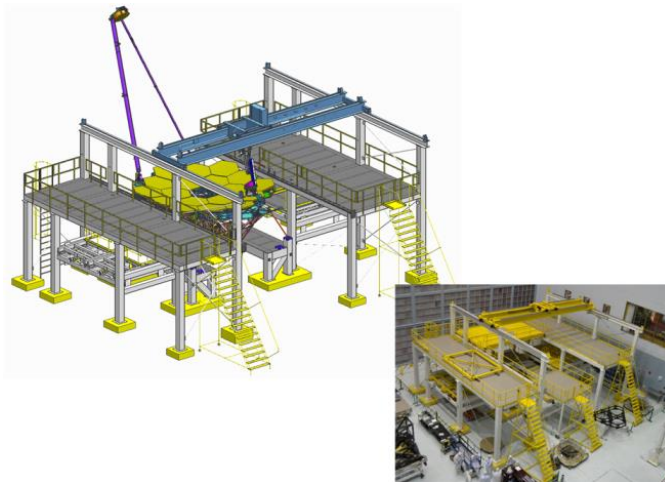


Figure 7: The AOAS will be used to integrate the primary mirror segments in the JWST telescope.

There are many activities leading up to the actual alignment of the telescope. Initially, the PMSA will be characterized on a Coordinate Measuring Machine (CMM) to understand where the optical surface is with respect to the telescope interfaces. In addition, the Primary Mirror Backplane Support Structure, PMBSS, will also be characterized to understand the interfaces to PMSA's. All this data is then combined to create a specialized tapered shim that is ground to precision tolerances such that the mirror will be in the proper location once it is in orbit.

To insure that this process is fully understood, there was a mirror handling demonstration completed in late 2013. A three segment simulator had been built earlier in the program to insure that the PMBSS would be stable over the large

temperature changes that the flight structure would endure. The Backplane Stability Thermal Assembly (BSTA) was set up on the AOAS as shown in Figure 8 to allow a full mirror placement demonstration to occur.

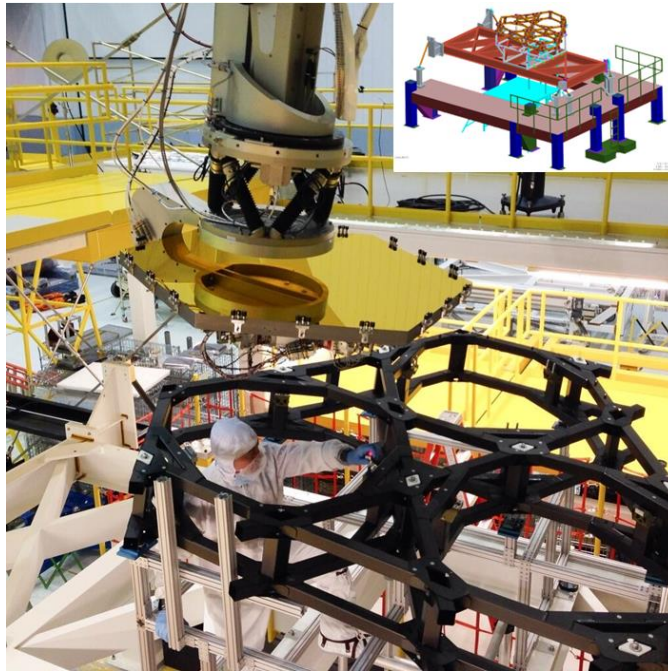


Figure 8: The BSTA was used to provide a full demonstration of the primary mirror installation process.

The Engineering Development Unit (EDU) PMSA was measured on a CMM as shown in Figure 9. The results of the BSTA interface characterization were combined with the CMM measurements to create the custom shims used between the backplane simulator and the PMSA. The PAIF (Figure 8) can be seen holding the EDU mirror while work is being done to prepare for the alignment of the mirror from below.



Figure 9: The Engineering Development Unit PMSA is shown being installed on the CMM at the Goddard Space Flight Center.

The results of the mirror demonstration were very successful. One minor issue was discovered and was readily corrected with a redesigned fixture. One of the main reasons to do early demonstrations was to discover these types of issues and correct them far off the critical path of the program. The next step in building up our confidence prior to building the flight OTE will be the Pathfinder program. During this effort, two spare PMSA's will be aligned and integrated into a flight-like PMBSS. This full dry run of the primary mirror alignment process will provide invaluable insight into building the flight OTE and will be a full dress rehearsal prior to starting the flight build in 2015.

The Secondary Mirror Assembly (SMA) will be installed with the Secondary Mirror Support Structure (SMSS) in the stowed configuration as shown in Figure 10. A fixture called the Secondary Mirror Alignment and Integration Fixture (SAIF) will be used to install the secondary mirror. It has also has a six degree of freedom alignment functionality but since it will only be used once, the mechanisms are all manual. There are no full scale SMSS simulators available so the only rehearsal that has been possible for the SMA installation has been a small fixture that replicates the angles and configurations of the flight hardware. Out first real experience of aligning an SMA will be during the Pathfinder integration activities. This is still well ahead of the flight hardware so any issues can be resolved prior to the flight integration.

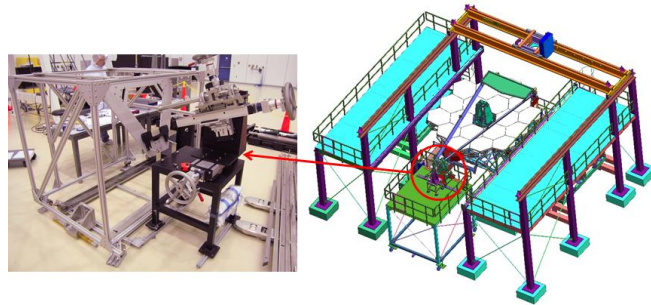


Figure 10: The Secondary Mirror Assembly will be integrated with the Secondary Mirror Support Structure in the stowed configuration as shown. The Secondary Mirror Alignment and Integration Fixture will be used to position the secondary mirror into the flight structure.

5. PATHFINDER TELESCOPE DELIVERY

In August 2014, the Pathfinder was delivered to the Goddard Space Flight Center (GSFC) Space Systems Development and Integration Facility (SSDIF) cleanroom. A specially designed shipping container called STTARS (Space Telescope Transporter for Air Road and Sea) seen in Figure 11 was used to move the Pathfinder structure from Northrop Grumman in Redondo Beach, California to the Goddard Space Flight Center in Greenbelt, Maryland. This also provides a practice run before the flight structure is shipped in the exact same way. The STTARS container only fits in two of the Air Force's C5-C's for transportation around the country. The Pathfinder arrived at Andrew's Air Force Base in Maryland and made its 20 mile trek to Goddard at night. The container was then staged into the large SSDIF cleanroom and the cover removed. The bagged Pathfinder structure can be seen in Figure 12.



Figure 11: The STTARS shipping container is used to ship the telescope and eventually the completed JEST observatory via a C5 aircraft.

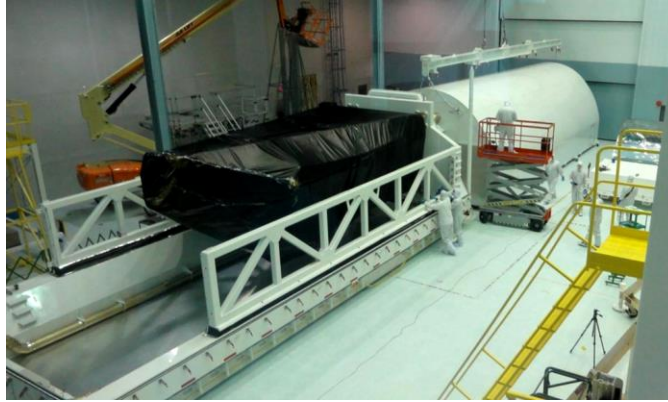


Figure 12: The bagged Pathfinder structure can be seen after the shipping container cover is removed inside the Goddard SSDIF clean room.

There is a special handling cart that the Pathfinder is placed on after being removed from the shipping container. The cart provides reach and access to the structure and a support mechanism to remove the aluminum structural support that was used for shipping the fragile Pathfinder. Much of the flight support structure was manufactured from aluminum to reduce the cost and this was removed prior to the mirror integration activities. The Pathfinder on the cart is shown in Figure 13.



Figure 13: The Pathfinder lacks some of the flight support structures so before being installed in the ASAS for mirror integration, it is moved to a cart that will allow these non-composite structures to be removed.

As the Pathfinder is lifted from the cart to the Ambient Optical Alignment Stand (AOAS), the aluminum Backplane Support Structure (BSF) remains on the cart and only the backplane is transferred to the integration stand as shown in Figure 14. As can be seen in the figure, the telescope is supported on the AOS via 6 hardpoint struts. There are two monopods on one end of the telescope structure and a set of bipods on the other end. This configuration provides for a kinematic connection between the alignment stand and the telescope. By keeping the interface analytically constrained, finite element modeling can predict the gravity displacement of the system as mirrors are added. This gravity “error” between the aligned condition and the zero-gravity provides a compensation that is included in the mirror alignment process. In effect, the mirrors are placed on the structure such that when gravity is removed, they are within the alignment tolerance provided by the mirror alignment actuators on the PMSA’s.



Figure 14: The Pathfinder is shown as it is being moved from the cart to the AOAS for mirror integration.

To provide access for the mirror integration system, the lower single secondary support strut is detached from the secondary mirror module and the dual secondary mirror struts are over-deployed on the telescope and effectively leaned against the HEPA filter wall in the SSDIF cleanroom as seen in Figure 15.



Figure 15: To provide access for the mirror alignment hardware, the single strut is detached from the secondary mirror mount and the dual struts are over-deployed and temporarily attached to the clean room HEPA filter wall.

The mirror integration effort can now start!

6. PATHFINDER INTEGRATION

With the Pathfinder Backplane now installed in the AOAS, the real task of installing the mirrors can begin. Prior to starting the integration effort, a specialized shim has to be determined as discussed earlier. It is now time to understand if those processes and the multitude of calculations have provided the proper shim that places the mirror in the proper location.

The mirror references have already been transferred from the Master Mirror Reference (MMR) that is on the backside of the mirror to the Primary Mirror Alignment Fixtures (PMAF). These fixtures are referenced to precision holes in the side of the mirror and contain Spherical Mirror Retroreflectors (SMR) as seen in Figure 16. These SMR's are then used by a set of Leica Laser Trackers using Spatial Analyzer software that allows them to effectively be tied together. This configuration allows the errors in each of the laser trackers to be minimized and the ensemble system to be much more accurate at the system level. To maximize the effectiveness of this system, the laser trackers are placed as orthogonal as possible with respect to each other. Typical laser tracker positions can be seen in Figure 17.

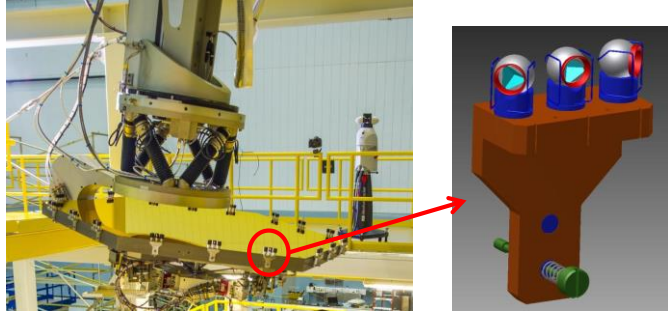


Figure 16: The ambient mirror alignment fixtures (AMAF) are attached to the sides of the mirror in precision holes. These AMAF's were referenced to the mirror master reference previously on a coordinate measurement machine (CMM). The AMAF's use Spherically Mounted Retroreflectors that allow a laser tracker system to position the mirror with respect to telescope master reference fixture.

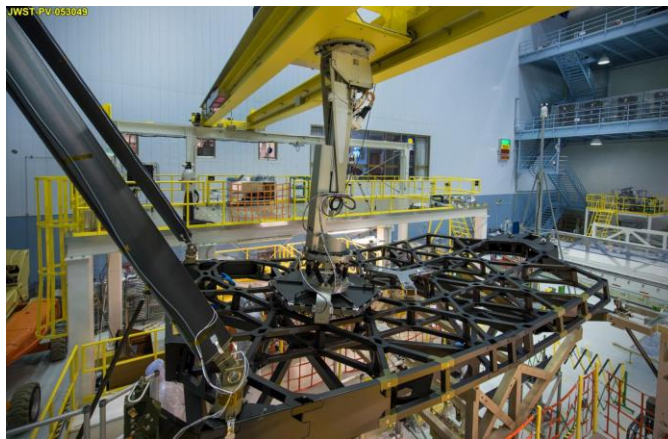


Figure 17: The three laser trackers are shown in the picture. To improve their system accuracy, they are placed as orthogonal as possible to each other. Their output is combined in software with calculated error bars for their location in space.

The first mirror is installed in the PAIF and brought over the backplane (Figure 18). The PAIF is able to place the PMSA within a few microns of the commanded position. It should be noted that the PAIF really only controls the location of the mirror in the two decenters and rotation as shown in Figure 19. The hard shim set actually locates the mirror in the tip/tilt/piston location. So it was with great expectations that the team waited anxiously as the mirror was commanded onto the Pathfinder Backplane with respect to the telescope reference fixture at the center of the structure to see if the shim calculations provided the correct mirror alignment.

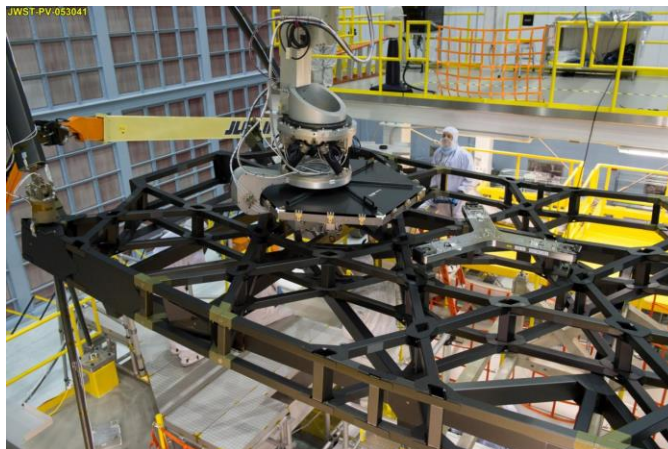


Figure 18: The first PMSA is shown in the PAIF as it is being aligned to the Pathfinder telescope.

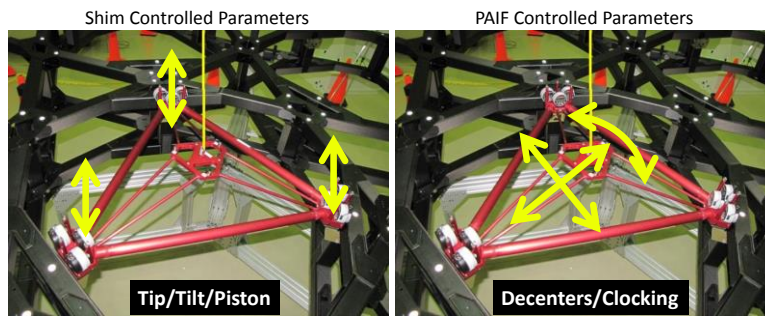


Figure 19: The shims control the final positional alignment of the PMSA in the tip, tilt, and piston. The PAIF controls the alignment in the two decenters and rotation.

As the process progressed, it was verified that the shims provided the proper alignment position within the approximate 200 micron alignment specification. We then had to verify that the repeatability of the process which is controlled by the vertical tower on the PAIF. This repeatability functionality is critical since a liquid shim has to be applied between the shim that is attached to the PMSA and the backplane. This liquid shim takes up any minor fit error created by the measurement processes and creates a very tight and stable bedding for the final assembly. With the repeatability verified, it was time to bond the first mirror in place using the liquid shim material which is a two part epoxy. The mirror is retracted and the epoxy applied. The mirror is then replaced using the PAIF and held in place during the 24 hour cure process. During that time, the team is very careful not to disturb either the PAIF or the backplane assembly. Once the cure is completed, a set of bolts are installed to react the high launch loads experienced during shipment and launch. The first PMSA was successfully install, aligned, and bonded into position well within the error budget allocations. This was a huge success for the JWST team.

Installing the first mirror was uneventful. This was not totally unexpected given the many demonstrations that had been done leading up to this point. What had not been demonstrated up until now was placing a second mirror right next to another PMSA and aligning that mirror to the system. It must be kept in mind that the alignment process during the SSDIF operations must be biased to include the effects of gravity on the structures. And these impacts change as more and more mass is sequentially added to the backplane. In order to determine the gravity bias, the telescope is kinematically supported on the AOAS so that precision modeling can be used to understand the resultant zero-gravity telescope. Calibrated Finite Element Models (FEM) is used to back-out the gravity error during the alignment process. The results from these models have been correlated against deflections of the Pathfinder structure to insure accuracy. In addition, the observed deflection as mirrors are loaded onto the backplane are compared against the expected deflection. The gravity back-outs are then adjusted as required as the system is assembled to minimize the zero-gravity error terms. So as each new mirror is installed onto the backplane, the zero-gravity location must be taken into account and accounted for in the shim parameters. These are the challenges posed to the integration team as they start to align the second mirror onto the Pathfinder. Stated a different way, as the primary mirror segments are integrated onto the backplane, the measured and calculated gravity deflection are continuously monitored such that as the next mirror is loaded onto the backplane, the gravity deflection due to the added mass is also within the alignment error budget for a zero-gravity condition that will not be observed until after JWST is launched.

The nominal mirror gap is about 6mm between the edges of the PMSA's. So now the PAIF is not only aligning the mirror to the telescope reference, it must control this new mirror so that it does not contact the mirrors already installed. As the second primary mirror segment was lowered into position, a general sigh of relief from the integration team as the gap between the mirrors was as expected. The process used for the first mirror was repeated. Some level of process refinement did occur as this mirror was aligned. The issue was that the first mirror was on the inner ring of the telescope at an angle with respect to gravity of about 3 degrees. The second mirror was outboard and the angle of the interfaces was much larger at about 6 degrees. After the liquid shim was applied and the mirror was translated into position, the entire PMSA slid around slightly on the viscous epoxy layer. Due to the lower angle, this was not a problem on the first mirror, but became a real problem as this second mirror was placed at the much steeper inclination. The team worked through this set back by cleverly using some additional features built into the PAIF in case this problem occurred. The Pathfinder was the perfect opportunity to find these issues and fine tune the process prior to building the flight telescope. Figure 20 shows both PMSA's being inspected after the removal of the PAIF.



Figure 20: The two primary mirror segments are shown being inspected after the PAIF was removed. Note that the one mirror has a flight gold coating applied and the other mirror is polished Beryllium. The difference in reflectivity will not impact the subsequent cryo test program.

The final mirror to be placed on the Pathfinder was the secondary mirror assembly (SMA). This alignment process was all new to the integration team. But before that can happen, the over-deployed secondary mirror support structure dual struts need to be returned to their stowed position and the remaining detached single strut reattached. This is done using the overhead crane and the walkout fixtures as shown in Figure 21.



Figure 21: The dual struts are seen being walked back down into their stowed condition. The single strut is being reattached to the secondary mirror module.

The Secondary Alignment Integration Fixture (SAIF) was ready to be used although untested in any real world experience. Unlike the PAIF which is all robotically controlled, the SAIF uses hand manipulated controls and precision slide assemblies since it will only be used once. The SAIF was placed on top of a stand that would allow access to the secondary mirror interfaces on the long composite struts. The plan was that the integration team would stand on the platform and align the mirror to the system. This did not work well. Any movement on the platform by the team caused the SAIF/SMA to move far more than the alignment tolerances allowed. It was clear that the people had to be removed from the platform if the process was ever going to work. The refined plan used two JLG man-lifts that would allow access to the SAIF while not touching the platform (Figure 22). It looks unconventional, but after much debate, the team decided it would work just fine for the flight telescope.



Figure 22: The secondary mirror was aligned using the SAIF while the integration team were suspended in JLG baskets for reach and access

Figure 23 shows the team preparing the liquid shim for the SMA and finalizing the successful alignment process. At the end of the mirror integration process, the electrical cabling was connected and the mirror actuators were driven with the actuator test set.



Figure 23: The integration team can be seen applying the liquid shim during the alignment process.

The Pathfinder telescope is now fully functional and ready for its next phase of program risk reduction. But first, it has to be packed away and shipped to JSC in Houston, Texas.

7. PATHFINDER SHIPMENT OF JSC

The shipping of the Pathfinder used the same STTARS container that delivered the Pathfinder structure to Goddard. The Pathfinder backplane is returned to the cart and the aluminum backplane support fixture is reattached. That whole assembly is now placed inside the shipping container as seen in Figure 24. But unlike the initial shipment, a bag frame is now used to protect the telescope instead of a bag attached right to the structure itself. Once the Pathfinder is inside the shipping container, the bag frame is placed over the entire assembly. This seals in the hardware inside a clean environment. The large lid is then placed on the container and that whole system is air barged out of the clean room. The final assembly ready to leave for Andrews Air Force Base is seen in Figure 25.



Figure 24: The Pathfinder is shown inside the shipping container. The top of the bag frame is seen on the right side of the photo.



Figure 25: The STTARS container is ready for delivery to Andrews Air Force Base for transportation to JSC.

8. SUMMARY

The early demonstrations and the Pathfinder AI&T program provided an excellent basis for process development and early detection of AI&T problems. In 2014, the Pathfinder telescope alignment and integration effort is the final dress rehearsal before flight operations start in 2015. The ability to practice and refine all the processes and procedures off the critical path of the program provides for significant schedule risk reduction and a high confidence that the alignment tolerances and analysis processes are achievable. The value of such a robust, high fidelity Pathfinder program cannot be understated as the ultimate in risk reduction.

REFERENCES

- [1] **Optomechanical integration and alignment verification of the James Webb Space Telescope (JWST) optical telescope element**
Conrad Wells, Matthew Coon, ITT Space Systems Division (United States)
Published in Proceedings Volume 7433: August 2009
- [2] **The center of curvature optical assembly for the JWST primary mirror cryogenic optical test: optical verification**

Conrad Wells, Gene Olczak, Cormic Merle, Tom Dey, Mark Waldman, Tony Whitman, Eric Wick, Aaron Peer, ITT Corp. Geospatial Systems (United States)
Published in Proceedings Volume 7790: August 2010

- [3] **Architecting a revised optical test approach for JWST**
Charlie Atkinson, Jonathan Arenberg, Northrop Grumman (United States); Gary Matthews, Mark Waldman, Alan Wertheimer, Tony Whitman, ITT (United States); Jim Oschmann, Ball Aerospace& Technologies Corp. (United States)
Published in Proceedings Volume 7010: August 2008
- [4] **The center of curvature optical assembly for the JWST primary mirror cryogenic optical test**
Conrad Wells, Gene Olczak, Cormic Merle, Tom Dey, Mark Waldman, Tony Whitman, Eric Wick, Aaron Peer, ITT Geospatial Systems (United States)
Published in Proceedings Volume 7739: July 2010
- [5] **JWST's cryogenic position metrology system**
Tony L. Whitman, ITT Exelis Geospatial Systems (United States); Randolph P. Hammond, Joe Orndorff, Stephen Hope, Stephen A. Smee, The Johns Hopkins Univ. (United States); Thomas Scorse, Keith A. Havey, Jr., ITT Exelis Geospatial Systems (United States)
Published in Proceedings Volume 8442: August 2012
- [6] **The integration and test program of the James Webb Space Telescope**
Randy A. Kimble, Pamela S. Davila, Charles E. Diaz, Lee D. Feinberg, Stuart D. Glazer, NASA Goddard Space Flight Ctr. (United States); Gregory S. Jones, Northrop Grumman Aerospace Systems (United States); James M. Marsh, NASA Goddard Space Flight Ctr (United States); Gary W. Matthews, ITT Exelis Geospatial Systems (United States); Douglas B. McGuffey, NASA Goddard Space Flight Ctr. (United States); Patrick H. O'Rear, NASA Johnson Space Flight Ctr. (United States); Deborah D. Ramey, NASA Goddard Space Flight Ctr. (United States); Carl A. Reis, NASA Johnson Space Flight Ctr. (United States); Scott C. Texter, Northrop Grumman Aerospace Systems (United States); Tony L. Whitman, ITT Exelis Geospatial Systems (United States)
Published in Proceedings Volume 8442: August 2012
- [7] **Assembly integration and ambient testing of the James Webb Space Telescope primary mirror**
Conrad Wells, Tony Whitman, John Hannon, Art Jensen, Eastman Kodak Co. (United States)
Published in Proceedings Volume 5487: October 2004
- [8] **Integration and verification of the James Webb Space Telescope**
Charles B. Atkinson, Pat Harrison, Northrop Grumman Corp. (United States); Gary Matthews, Eastman Kodak Co. (United States); Paul Atcheson, Ball Aerospace& Technologies Corp. (United States)
Published in Proceedings Volume 5180: December 2003
- [9] **James Webb Space Telescope system cryogenic optical test plans**
Lee D. Feinberg, NASA Goddard Space Flight Ctr. (United States); Allison Barto, Ball Aerospace& Technologies Corp. (United States); Mark Waldman, Sigma Space Corp. (United States); Tony Whitman, ITT Corp. Geospatial Systems (United States)
Published in Proceedings Volume 8150: September 2011
- [10] **James Webb Space Telescope primary mirror integration: testing the multiwavelength interferometer on the test bed telescope**
Gene Olczak, David J. Fischer, Mark Connelly, Conrad Wells, ITT Corp. Geospatial Systems (United States)
Published in Proceedings Volume 8146: September 2011
- [11] **James Webb Space Telescope (JWST) Optical Telescope Element (OTE) Pathfinder status and plans**

Lee D. Feinberg, Ritva A. Keski-Kuha, NASA Goddard Space Flight Ctr. (United States); Charles B. Atkinson, Northrop Grumman Aerospace Systems (United States); Andrew J. Booth, Sigma Space Corp. (United States); Tony L. Whitman, Exelis Geospatial Systems (United States)
Published in Proceedings Volume 9143: Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave: September 2014

[12] JWST telescope integration and test status

Gary W. Matthews, Thomas R. Scorse, Scott Kennard, John Spina, Tony Whitman, Exelis Inc. (United States); Scott Texter, Charles Atkinson, Greg Young, Northrop Grumman Aerospace Systems (United States); Ritva A. Keski-Kuha, James M. Marsh, Juli Lander, Lee D. Feinberg, NASA Goddard Space Flight Ctr. (United States)
Published in Proceedings Volume 9143: Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave: September 2014

[13] Use of a pathfinder optical telescope element for James Webb Space Telescope risk mitigation

Lee D. Feinberg, Ritva Keski-Kuha, NASA Goddard Space Flight Ctr. (United States); Charlie Atkinson, Scott C. Texter, Northrop Grumman Aerospace Systems (United States)
Published in Proceedings Volume 7731: Space Telescopes and Instrumentation 2010: Optical, Infrared, and Millimeter Wave: July 2010