Verification approach for large, complex optical systems: lessons from the James Webb Space Telescope

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ABSTRACT

As ever larger and complex optical imaging systems are envisioned, it will become increasingly difficult to perform full-aperture verification of the optical system in the flight configuration as required for the typical "test as you fly" approach. Full aperture testing is challenging due to both the cost and technical feasibility. As segmented apertures grow larger, not only may the ground-aligned configuration not match the flight-aligned configuration due to degeneracies in the alignment process, but the full aperture may never be integrated prior to launch for cases with aperture sizes that require in-space assembly. The optical verification approach pioneered on the 6.5 m segmented James Webb Space Telescope provides a framework that can be scaled to future complex, large aperture spaceborne optical systems and allows both for strong confidence in on-orbit performance prior to launch, cost savings, and the possibility to relax integration alignment requirements to facilitate integration whether on the ground or in space. The Webb Telescope optical verification approach will be discussed including the system level road-mapping approach, the robust analysis validation program based on testing from the component level to the integrated telescope level, system-level analysis, and the supporting budgets used to track and cross check expected on-orbit performance and uncertainty propagation.

1. INTRODUCTION

The driving science requirements for the James Webb Space Telescope (JWST) lead to an optical architecture that is technically very challenging to test to requirement-level in the flight configuration. Specifically, the key flight requirements driving test configuration include: large aperture (6.6 m diameter primary mirror), being diffraction limited at a wavelength of 2 micrometers (which leads to 150 nm WFE and operation at cryogenic temperatures of 30-55 K), and needing 3% radiometric stability over a 14 day period (induced by a temperature change ~ 0.15 K). To fully "test as you fly", the combination of these requirements would require a large cryogenic test chamber, stable to less than 0.1 K, with a 6.6 m diameter cryo flat, or other source of collimated light. While some of these test criteria are technically achievable, they drive to a test program that is programmatically unfeasible. As larger and more complex systems are developed, these issues will become even more challenging than for the Webb Telescope. Because a test configuration cannot be devised to directly verify 150 nm WFE performance over the full JWST aperture, a verification approach was developed that relied on the use of data from high-fidelity testing at lower levels of assembly, combined with system-level alignment data obtained during full telescope/science instrument testing. This data is then interrogated analytically to predict in-flight performance of the integrated observatory. A key aspect of this verification approach includes developing a test and analysis validation plan that gives confidence to the use of component-level data and analysis to predict final performance.

The optical test and verification program for the Webb Telescope was designed to support this final verification by analysis. Specifically, the program emphasized:

- High-fidelity verification at lower levels of assembly
- Focusing system-level testing on measuring data that cannot be obtained at a lower level, such as alignment between major components
- Inclusion of "crosscheck" tests at the integrated system level to confirm lower-level test data can be relied upon
- An extensive model validation program supported by crosscheck testing and independent modeling efforts

- Verifying predicted alignment range on-orbit; because the optical system isn't aligned until in flight, margin in actuator range gives added confidence in the ability to achieve an aligned and phased state on orbit.

2. JWST ARCHITECTURE

The JWST Observatory consists of the Optical Telescope Element, the Integrated Science Instrument Module (ISIM) Element, and the Spacecraft Element. The Optical Telescope Element contains the optics and structure required for the three mirror antistigmat JWST telescope. Specifically, a segmented 6.6 m primary mirror, the Secondary Mirror Assembly (SMA) attached to the primary mirror backplane via 3 composite beams, and the Aft Optics Assembly (AOS) which contains the tertiary mirror and a fine steering mirror used to stabilize the image. The ISIM Element contains the suite of four science instruments and guider. Each instrument is attached to a composite structure (ISIM Bench) which in turn interfaces directly to the primary mirror backplane. The spacecraft element contains both the spacecraft with C&DH, power, and propulsion subsystems, and the Sunshield – a 5-layer, tennis-court sized membrane designed to isolate the OTE and ISIM from the sun and passively cool the optics to 40 K (see Figure 2-1). The Spacecraft Element will not be discussed further in this paper.

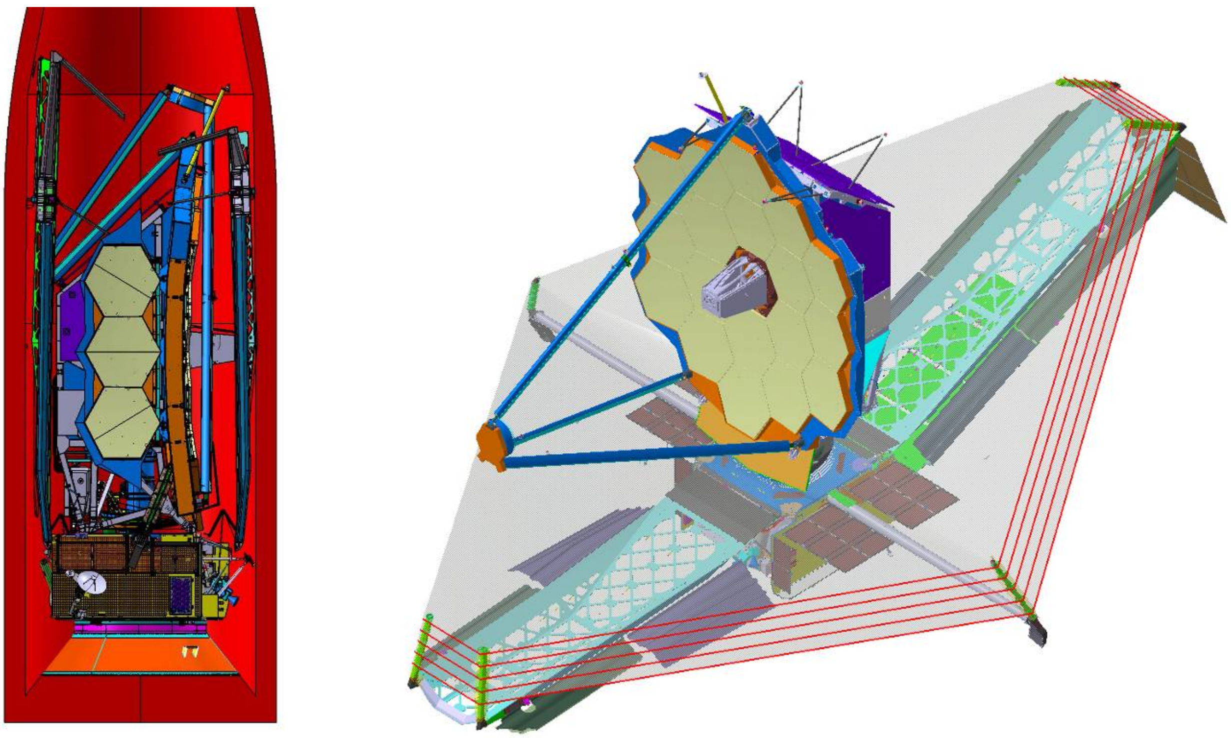

Figure 2-1 JWST Stowed and Deployed Configurations

Because this large Observatory must be launched in a standard launch faring, the telescope structure and sunshield membranes must be folded and stowed for launch (See Figure 2-1). This has two implications for the Observatory: 1) several large-structure deployments are necessary on-orbit; 2) the OTE must be alignable in space. There are three large structure deployments necessary to build the optical system. First, the entire OTE+ISIM is separated from the spacecraft via the Deployable Tower to help achieve thermal separation. Second, the three-boom Secondary Mirror Support Structure (SMSS) is deployed. Third, the Primary Mirror "wings", the three mirror segments on each side of the 18-segment array and the backplane structure holding them, fold into alignment with the center section of the primary mirror. There are no deployments in the ISIM. Because the large sunshield deploys prior to the SMSS and PM Wing deployments, the telescope deployment mechanisms must be designed to survive deployment when the structure is at cryogenic temperatures. Once the structure is deployed, the optical system is aligned to achieve optimal optical performance. This is achieved via adjustable Primary Mirror Segment Assemblies (PMSA) and the adjustable Secondary Mirror Assembly (SMA). Each PMSA is a hexagonal Beryllium mirror segment with a 7 degree of freedom actuation structure which controls the 6-DOF rigid body position of the segment using 6 actuators in a hexapod configuration and one radius of curvature actuator to control mirror figure. Each PMSA is controlled by a Cryogenic

Multiplexer Unit (CMU) electronics box located on the backplane near the PMSA. Similarly, the secondary mirror is also a Beryllium optic with 6-DoF hexapod control. Each of these OTE subsystems are shown in Figure 2-2. In flight, the PMSAs and SMA are adjusted via the image-based Wavefront Sensing & Control (WFS&C) process to achieve optimum performance in the science instruments. During ground integration, the ISIM is installed to critically align to the non-adjustable Aft Optical Assembly, which serves as the fixed reference for the system. In addition to the adjustable OTE optics, the NIRCam science instrument has a pick-off mirror that is adjustable in tip, tilt, and piston and the NIRSpec and Fine Guidance Sensor (FGS)/Near-InfraRed Imager and Slitless Spectrometer (NIRISS) instruments have a focus adjust mechanism. The mid infrared science instrument, MIRI, does not have a focus adjust mechanism because it is less sensitive to errors in focus alignment.

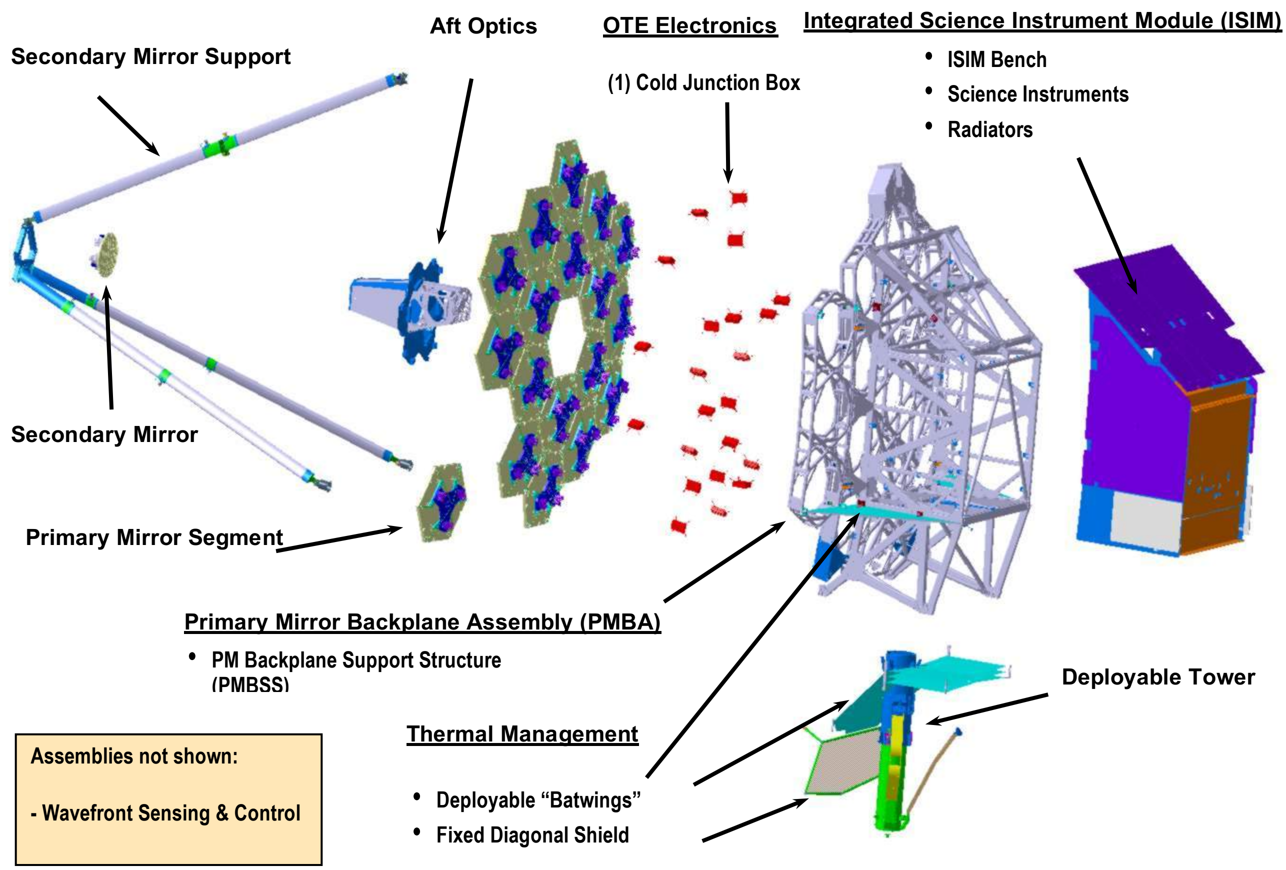

Figure 2-2 Expanded View of the Optical Telescope Element (OTE) + ISIM

3. MAJOR GSE USED FOR OPTICAL VERIFICATION TESTING

The optical testing of the OTE and ISIM requires several pieces of complex ground support equipment (GSE) designed to measure optical performance and alignment of the system under cryogenic-vacuum conditions. The architecture of this GSE is described in detail by Atkinson, et. al.[i]. The basic functions of these GSE are described here to give context and background to the verification test plans described in the next section. Basic layout of the GSE in the test chamber and further detail on individual metrology GSE can be seen in figure 4-2.

Center of Curvature Interferometer (COCI) – The COCI was used to measure the figure of the primary mirror. It sees all 18 PMSA segments simultaneously and was used when the telescope was at both ambient and cryogenic temperatures and was the primary piece of GSE used to measure PM WFE and PM figure change during the cryo-distortion validation test. The COCI image was also used to determine the relative piston and tilt between adjacent segments and thus can be used as optical feedback to validate PMSA motion during alignment.

AOS Source Plate Assembly (ASPA) – The ASPA attaches to the front bulkhead of the AOS and is aligned so as to put fiber-fed sources in the Cassegrain image plane. The ASPA contains both inward facing sources, which sends light directly through the AOS to the ISIM. Sources were located in each of the SI fields of view. These sources were used to measure AOS optical performance, AOS+SI optical performance, and most importantly, alignment of the ISIM to the AOS. These measurements are made by performing phase retrieval on the images in each of the SIs. The ASPA outward facing sources are used for the "Pass-and-a-Half Test". The sources send light through the SMA and PM out to three auto collimating flats (ACFs) located near the COCI, when then reflect light back through the entire system to the SIs. These sources were used as a full-system optical crosscheck. The outward sources include a source at the Cassegrain (0,0,0) point which was steered to each of the SI fields of view using the ACFs. This gives the least aberrated image. Each ACF is 1.5 m in diameter and is located such that it is centered at the intersection of three PMSAs. Therefore the three ACFs sample the surfaces of nine of the eighteen PMSAs. In addition to offering a full-system optical performance crosscheck used to validate the JSC model predictions, the outward sources were used during the WFS&C process demonstration and influence function test performed during system testing at JSC. These tests are described in more detail in Contos, et. al.[ii].

Photogrammetry (PG) – In order to measure alignment of the major optical elements of the OTE, a photogrammetry system has been devised for the JSC chamber. Eight photogrammetry cameras were located on four horizontal-axis pinwheels located mid-way up the JSC chamber. These cameras view photogrammetry targets located on the edges of the SMA, the exterior edges of the PM (2-3 edges on 12 PMSAs), and on the AOS center and forward bulkheads. In this way, the photogrammetry system measures 6-DOF alignment of the PM relative to the AOS and the SM relative to the AOS. Additionally, relative alignment of the outer 12 PMSAs to each other can be measured.

All of the GSE described above was used to measure hardware during testing at Johnson Spaceflight Center (JSC). The performance of this GSE was validated during cryogenic optical testing of a Pathfinder telescope. During these tests, two spare PMSAs were attached to an engineering model backplane. An EDU SMA was used along with the flight AOS with ASPA attached. In place of the ISIM and instruments, the Beam Image Analyzer (BIA) was used to look at the light coming through the AOS from the inward source test and the Pass-and-a-Half test.

4. OPTICAL VERIFICATION APPROACH

In order to verify Observatory optical performance on-orbit, there are four main aspects that need to be understood:

1. Optical performance of each optical component
2. Alignment between the optics
3. Adjustability of the PMSAs and SMA
4. Performance of the WFS&C Algorithms

Because of the challenges associated with an end-to-end test of sufficient fidelity to directly test JWST performance requirements, the verification program concentrates on verification of each of the above elements. Verification is performed at the level of assembly at which the particular data in question is best able to be measured. As the

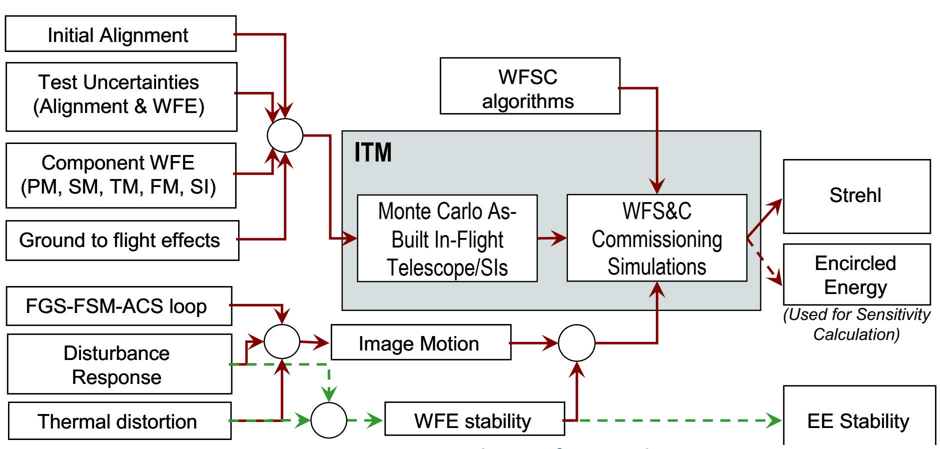

Figure 4-1 Image Quality Verification Flow

Observatory is integrated, crosscheck tests are performed to ensure the verification data collected earlier is still representative of the as-built system. Figure 4-1 shows how this data is combined analytically to predict final on-orbit performance.

The initial alignments and component wavefront error (WFE) input on the left side of Figure 4-1 come directly from test data. The integration level at which this test data is obtained is described in the following sections. This data is combined to create the As-Built Observatory Model that is used to complete the final performance verification by analysis. The Integrated Telescope Model (ITM) analysis tool, using the As-Built Observatory Model, begins with the telescope in the "nominally deployed" (pre-optical phasing) condition and then analytically aligns the telescope using the WFS&C software. Because the WFS&C process is not deterministic, it is necessary to include the flight alignment process in the analysis of final performance. Using this analytic technique, which outputs both Image Quality (in the form of Strehl and Encircled Energy metrics) and the PMSA and SMA actuator range used to reach that state, allows the verification analysis to include not just the nominal As-Built Model, but also a Monte Carlo of possible in-flight telescopes created by varying each of the primary input parameters (optic figure and alignment) by the uncertainty from the test that measured those as-built values. In this way the analysis is able to more accurately determine the effect of individual test uncertainty on the final performance of the WFS&C aligned Observatory, because the process of WFS&C will compensate some of these errors. In addition to using the As-Built Observatory model (with uncertainties applied) as an input, ITM also uses the final WFS&C software, as-built detector models for each SI used during WFS&C, the as-built hexapod models that have been created from actuator and hexapod testing, and validated outputs from Observatory Image Motion and WFE Stability analyses.

The following sections walk through the test plans for each of the four categories of analysis input data discussed above.

4.1 Optical Performance Verification for each Optical Component

The top-level optical verification path is shown in the flowchart below (Figure 4-2). Primary verification for each of the 21 optics in the OTE is performed at the component level. This allows detailed interferograms for each optic to be used in the as-built model interrogated to determine final telescope performance. This is of particular advantage for the Secondary Mirror (SM), Tertiary Mirror (TM), and Fine Steering Mirror (FSM), which cannot be directly and individually seen during system testing. Additionally, for the PMSAs, full fidelity of the mid and high spatial frequency WFE cannot be determined using the test setup at the system test, where each pixel has approximately 30 mm resolution. After mirror-level cryogenic acceptance testing, The PMSAs and SMA were delivered to telescope integration at GSFC. The TM and FSM were integrated in the AOS Bench structure at Ball Aerospace prior to delivery, but full AOS subsystem optical testing was not performed until the flight AOS was tested at JSC for the first time as part of the optical GSE test campaign. During this test, the downward sources on the AOS source plate were used to look single pass, full aperture through the AOS. The Beam Image Analyzer (BIA) was used to capture the data and assess AOS optical performance.

Meanwhile, the SIs were first tested optically at the instrument level prior to delivery to GSFC for integration to the ISIM structure. Because of the tight WFE knowledge requirements for those SIs used for WFS&C, and the need to understand the figure of the SIs when integrated and brought to a common focus with the other SIs, instrument optical verification data is collected at the integrated ISIM level. This cryogenic optical test, performed at GSFC, used an OTE Simulator (OSIM) to simulate the incoming light to the SIs.

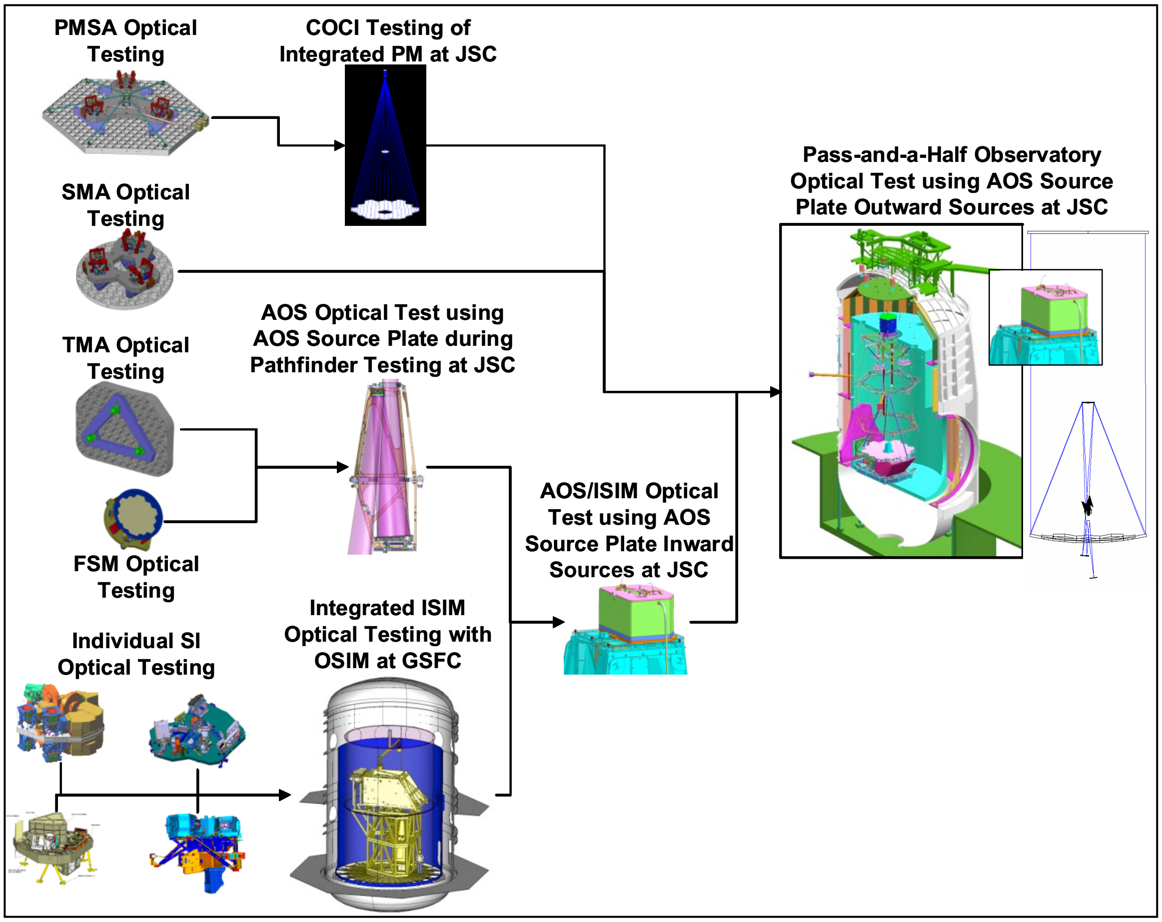

Figure 4-2 JWST Optical Test Flow

After integration of the OTE optics to the OTE structure and the ISIM to the OTE, this assembly underwent optical testing at Johnson Spaceflight Center (JSC). Most of the optical tests performed at this level are used to crosscheck the results obtained from the lower level verification tests.

Each optic saw several crosscheck tests in addition to the official verification. For example, each PMSA was tested in three independent ambient test facilities – the first at Tinsley, who was responsible for polishing the mirrors, the second in the Ball Optical Test Stand (BOTS) at Ball Aerospace, and the third during the system test with the Center of Curvature Interferometer (COCI) at Johnson Space Center Chamber A. The mirrors were tested in the first two ambient test stations multiple times during segment level I&T. Additionally, each PMSA was tested cryogenically using three independent sets of test metrology – the first during PMSA-level testing at the Marshall Space Flight Center X-Ray Calibration Facility (XRCF), the second was with the COCI at JSC, and the third was the end-to-end "Pass and a Half" optical test at JSC, where portions of 9 of the 18 PMSAs were seen along with the rest of the optical train. Each PMSA was tested twice in the XRCF facility during mirror fabrication and I&T. This flow, and the relative uncertainty of each measurement, is shown in Figure 4-3.

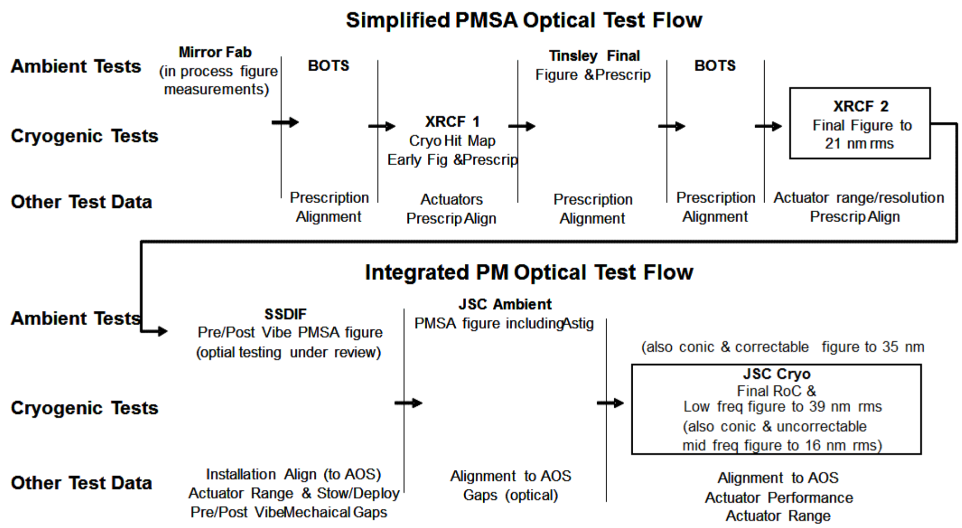

Figure 4-3 PMSA Optical Test Flow

In this manner, not only was each optic tested through independent means to ensure the validity of test data, but trending was established to lend credence to the use of the subsystem-level test data in final verification analysis. Following all optical verification tests, the total uncertainty due to optical testing is approximately 69 nm rms, mostly in low frequency error. As stated earlier, the possible errors from these test uncertainties will be partially compensated during the WFS&C process. This compensation process and the final uncertainty are discussed below.

4.2 Alignment Verification Between Each Optical Component

Alignment verification is critical to understanding optical performance for several reasons. First, misalignment of the optics is a large contributor to the total amount of actuator range – on the PMSAs, SMA, and SI focus adjust mechanisms –necessary to reach the optimal on-orbit state. The misalignment of the fixed optics, together with the compensation residuals from actuator compensation of alignment error, affects the best optical state that can be reached. Finally, the alignment state of the Observatory also affects stray light and vignetting performance. With the adjustable optics, it is possible to reach a state that meets the Observatory WFE requirements, but causes vignetting or significantly degraded stray light performance. It is necessary to understand the alignment sufficiently to avoid these alignment scenarios in flight. Therefore, an alignment test plan was developed to support a final WFE uncertainty due to alignment uncertainty of 15 nm rms.

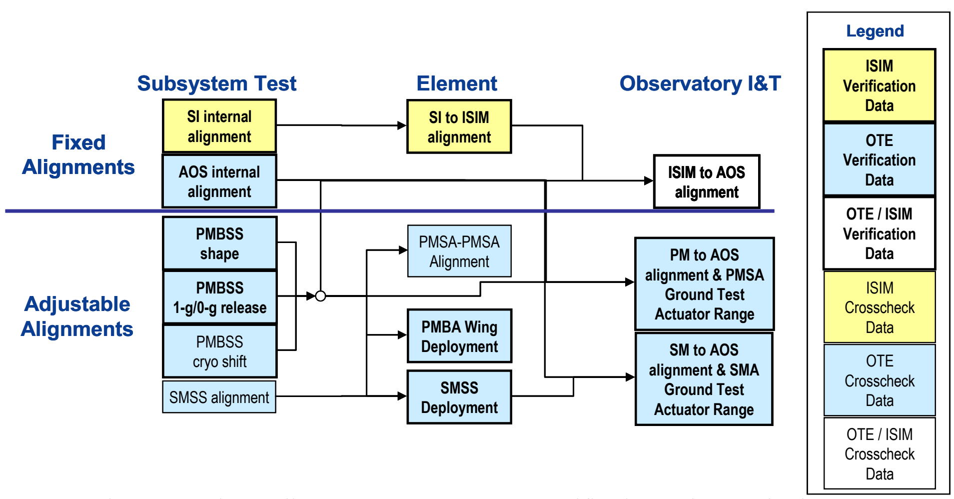

Figure 4-4 Direct Alignment Measurements – Verification and Crosschecks

Similar to figure of the individual optics, alignment between the optical components was verified incrementally as the system was integrated. Critical alignments which cannot be measured at the system level were verified at lower levels of assembly. For example, alignment of the Tertiary and Fine Steering mirrors within the AOS were verified during cryogenic alignment testing prior to delivery to telescope I&T. Alignment of each Science Instrument (SI) within the ISIM was verified during ISIM cryogenic testing with the OSIM at GSFC where the SI focus adjust mechanisms were set to bring all the SIs to a common ISIM focus.

To understand how the backplane holds the alignment of each PMSA with respect to the other PMSAs, two critical backplane structure tests were performed. The first was Backplane cryogenic characterization testing where structure was instrumented and brought down to operational temperatures, allowing validation of the Backplane thermal distortion model and the cryo-distortion predictions for each PMSA mount location. Critical alignment testing was also performed at the OTE Structure level. OTE Structure testing allowed deployment accuracy and repeatability testing of both the wings and the SMSS to be characterized.

At the system level, alignment was one of the key items verified during cryogenic testing at JSC. The photogrammetry system described earlier directly measured alignment of the PM and SM to the AOS to approximately 100 micrometers and 150 microradians. Alignment of the ISIM to the AOS was measured using the inward facing sources on the AOS Source Plate. Using phase retrieval to examine images at several different focus positions for each SI allowed 6 degree of freedom alignment to be calculated from focal plane alignment measured during this test. This test measured the 6-DOF alignment of the ISIM to the AOS to approximately 1.1 mm in piston, 0.34 mm in decenter, 0.37 mrad in tilt, and 1.5 mrad in clocking.

As with optic verification, cross check tests have been developed to measure each alignment using independent tests. Internal alignment of the AOS optics is crosschecked during the AOS optical testing at the JSC Pathfinder test. This data can be inferred from the final figure of the AOS subsystem, which is a combination of optic figure and alignment. AOS and ISIM alignment are both crosschecked when the inward sources were used during the JSC OTE+ISIM testing. Similarly, alignment of the PM and SM to the AOS was crosschecked during the Pass-and-a-Half test by looking at the signature change seen as the SM is optically placed in the "best aligned" configuration.

4.3 Adjustability Verification of the PMSAs and SMA

As mentioned previously, the adjustability of the PMSAs and SMA allows for correction and compensation of both alignment and figure errors in the system. Specifically, by adjusting the SMA in 5 degrees of freedom and by using the 18 PMSAs to adjust the global PM figure, low frequency error can be compensated to improve system performance. In order to ensure the ability of the adjustable optics to make this compensation, the following aspects need to be verified:

1. Range, Resolution, and Accuracy of the adjustable degrees of freedom of each PMSA and SMA
2. Errors, including uncertainty, that would lead to the need to use actuator range
3. Ability of the WFS&C software to align the system using images from NIRCam and the other SIs

As with the other performance areas, actuation performance was also verified at a low level and then crosschecked as the system was built up. Specifically, single-step resolution and accuracy could only be verified at the actuator level due to metrology limitations to verifying steps are less than 10 nm with a 3 nm accuracy during integrated PMSA or OTE testing. Actuator-level testing at both cryogenic and ambient temperature was used to build a hexapod actuation model for each segment. These calibrated models are used when analytically aligning the telescope during verification analysis using the Integrated Telescope Model (ITM) as discussed above. The resolution of the actuators is crosschecked at the 2-4 step level during PMSA cryogenic testing at XRCF and again to similar levels during COCI testing at JSC. Using actuator test data as the primary verification for hexapod resolution and accuracy is valid because the uncertainty in hexapod geometry introduced during hexapod/PMSA integration is controlled so as to be insignificant compared to actuator uncertainty. Actuated PMSA range is limited by flexures only present in the integrated configuration, and thus is verified at the integrated PMSA level. Range is crosschecked at the actuator level and again at ambient after segment installation.

Verifying the amount of actuator range that will need to be used during on orbit alignment is achieved through the optic and alignment verification described above, since it is these figure errors and misalignments that are being corrected and compensated with the actuators. The total amount of actuator range that may be needed on orbit is calculated in three ways. First, a detailed actuator range budget was developed, which defines every contributor to actuator range. These include both known errors, such as segment placement errors or mirror figure errors, and unknown errors that come from test uncertainty and ground-to-orbit changes like launch vibe. As the individual components of the Observatory were built and tested, this budget was updated with actual values. This allows a careful accounting of the amount of range needed on orbit. Secondly, this budget was crosschecked during system optical testing at JSC when the system was aligned. Accounting for the effects of aligning in a 1-g environment, the Actuator Range Budget was used to predict the range needed to align the telescope for this test. Actual actuator positions were then confirmed to be within the error bars of the budget prediction.

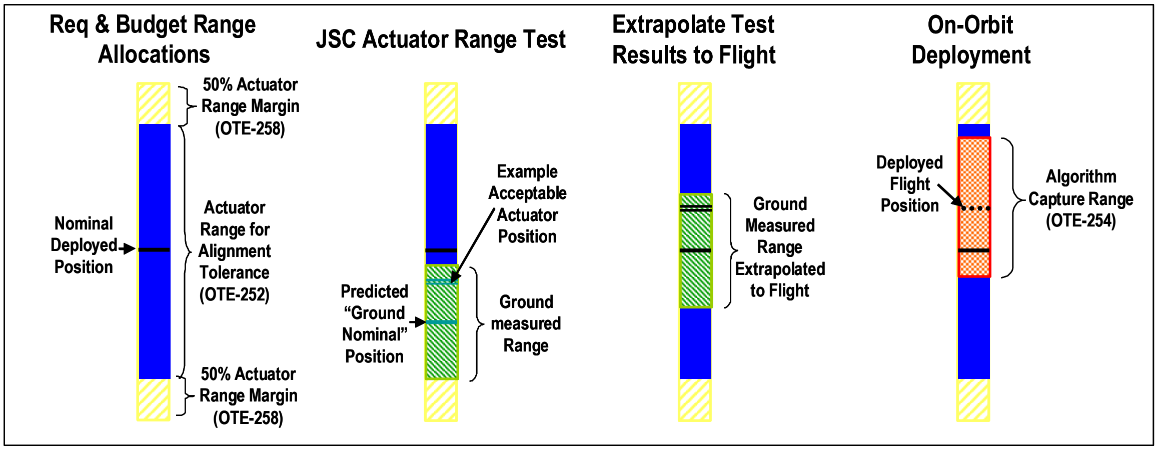

Figure 4-5 Ground and Flight Actuator Range

This ground alignment state is used to set the "Initial Deployed State" of the telescope in orbit. Gravity effects will be subtracted from the actuator settings determined during the system test, and in flight the PMSAs and SMA will be deployed to these positions prior to beginning WFS&C. In this sense, it is the uncertainty portion of the budget that determines how much additional range will be used during the WFS&C alignment process in flight. Range budgeting, the determination of the "Initial Deployed State," and the correlation of this to flight range is described pictorially in figure 4-5. This final range will be verified analytically as part of the optical verification analysis performed using the Integrated Telescope Model (ITM). During this analysis, each mirror is analytically "deployed" to the ground determined position. The actual location of this deployment will vary by the uncertainty in each of the constituent parameters through the Monte Carlo of possible as-built telescopes that is interrogated as part of this analysis. Finally, ITM tracks actuator range used during the WFS&C process and thus outputs range for all actuators along with the optical performance achieved for each Monte Carlo telescope analyzed.

The WFS&C software is verified through analysis using ITM prior to use for analytic alignment during Observatory verification analysis. Furthermore, the algorithms were initially developed on the Testbed Telescope (TBT) hardware. The TBT is a $1/6^{th}$ scale representation of the JWST OTE. Each of the 18 TBT PMSA segments and the TBT SMA segment include the same actuation architecture as the flight mirror segments including actuators with flight-like performance (i.e. same basic mechanical design with single step resolution per flight specification. Not only was the TBT used during initial algorithm development, but data from the TBT was also used to correlate the ITM model. In addition to software verification using ITM, a demonstration of critical steps of the WFS&C process was performed during system testing in JSC, though only the nine PMSA's seen through the ACFs could be controlled. In addition to demonstrating the WFS&C process, influence function testing was performed at JSC to calibrate the relationship between segment motion and changes in the NIRCam image. Finally, phase retrieval in all of the SIs, the fundamental aspect of wavefront sensing, was used for both the inward source test and the Pass-and-a-Half test. Along with these fundamental algorithm/software verification steps, each item in the WFS&C error budget, which range from filter manufacturing errors to algorithm performance uncertainty to plate scale, was verified separately through either test or analysis as appropriate. In this way, the uncertainty introduced by the WFS&C process itself is well understood prior to launch and will be accounted for in the final optical performance verification analysis performed using ITM. For more detail on WFS&C verification, see Contos, et. al. [2].

5. VERIFICATION PLANNING AND PERFORMANCE TRACKING

In order to communicate and track the complex verification plan to ensure all require tests, be they verification, crosscheck, or model validation tests, were understood both test and analysis tasks could be planned, a verification roadmap was developed to show how critical data from each of the tests were used to create the as-built model used for final verification. This roadmap is shown in figure 5-1. Additionally, key budgets and tracking tools were developed to track key performance parameters which were not all specifically tracked via direct requirement

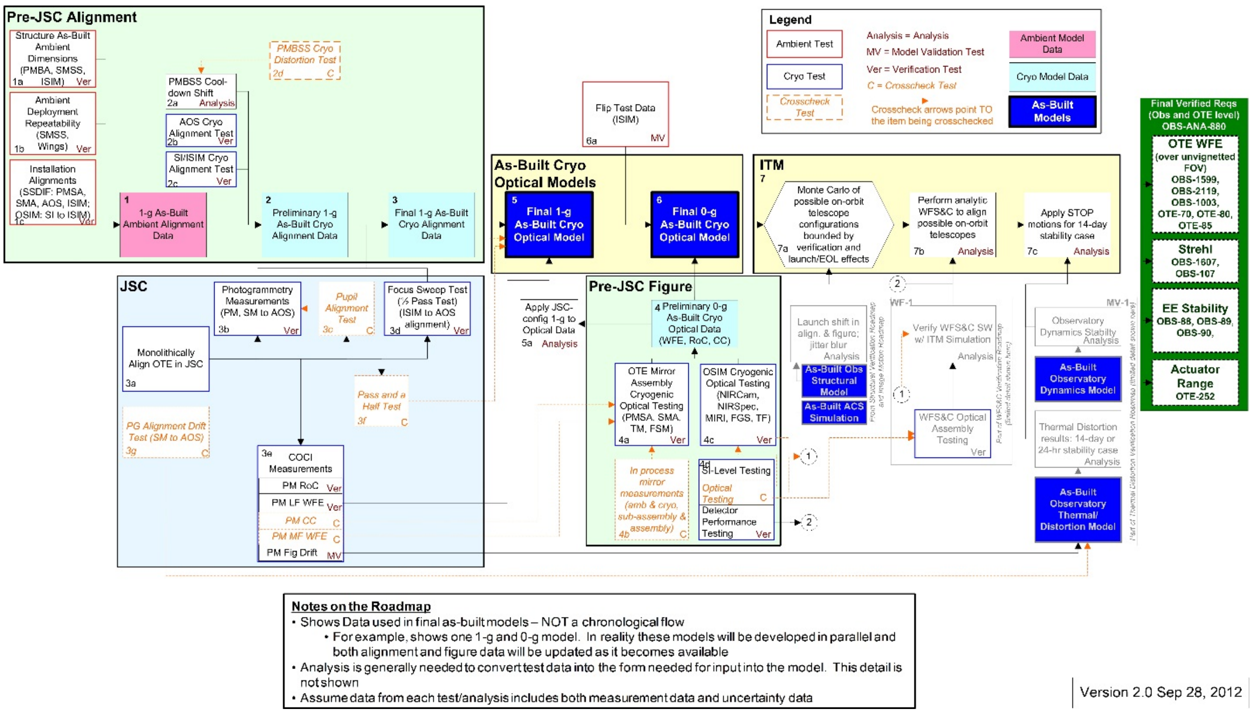

Figure 5-1 JWST Image Quality Verification Roadmap

verification. The optical performance budget used to allocate requirements and record predicted performance based on test and verification results was updated to include a record of the expected test or analysis uncertainty for each critical term. In this way, it could be understood early how the uncertainty of each individual test impacts the final uncertainty in our ability to determine final on-orbit optical performance. Detailed budgets were developed to track all contributors that result in use of actuator range. This includes direct terms such as manufacturing or integration errors impact on alignments, as well as indirect terms such as the amount of actuator range that will be used to compensate low frequency figure errors. These range budgets were developed for both the ground test configuration and expected range needed in flight. Since the optical performance budget assumes the system is alignable, it was critical to be sure the actuators would have the range needed to align the system. Finally, as is described in Section 4 and as can be seen in the Image Quality Verification Roadmap shown in figure 5-1, the verification program relied on many crosscheck tests to corroborate that the verification data collected earlier during subsystem testing still represented performance of the hardware. A matrix of these crosscheck tests was created to track each test that verified or crosschecked a particular parameter of the optical system (for example, PMSA WFE or AOS-to-ISIM alignment). The uncertainty of each of the test events was tracked and then, as the tests were performed, actual performance was trended to ensure the later crosscheck tests agreed with the early tests to within the established uncertainty. By creating these tools early in the program, the integrity of the full test program could be maintained and we could ensure mechanisms were in place to catch any inconsistencies that need further investigation and give confidence in finally on-orbit performance prior to completion of final verification analysis and prior to launch.

6. CONCLUSION

The combination of the data (results and uncertainty data) from the verification events described in section four, together with test-anchored analytic predictions for launch/vibe shift and end of life degradation give all the inputs necessary to create a Monte Carlo of possible on-orbit telescopes. Not only is testing to flight-performance levels prohibitive due to technical and cost concerns, but due to the JWST Observatory architecture, which is a telescope that is not aligned for the final time until flight rather than during ground I&T, it is more representative of final performance to analytically perform WFS&C on this suite of telescopes than to measure performance at one alignment state on the ground. Using the analytic method to predict final performance allows uncertainties in individual tests to propagate forward to final performance and actuator range in a representative way. Due to the risks associated with using low-level test data to predict final performance, the JWST verification program includes crosschecks of each key test input at various stages of integration through the fully integrated optical system (OTE + ISIM). This crosscheck data anchors the data used in the As-Built Observatory Model and ensures the data is still representative of the final integrated system. This same approach can be used and expanded for future telescopes. It is important to develop alignment and range budgets early to ensure the actuation system is designed with sufficient range to account for all manufacturing and integration tolerances and uncertainties as this can allow larger systems, or systems assembled in space, to be tested at the subsystem level and integrated to reasonable manufacturing tolerances while ensuring final optical performance.

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