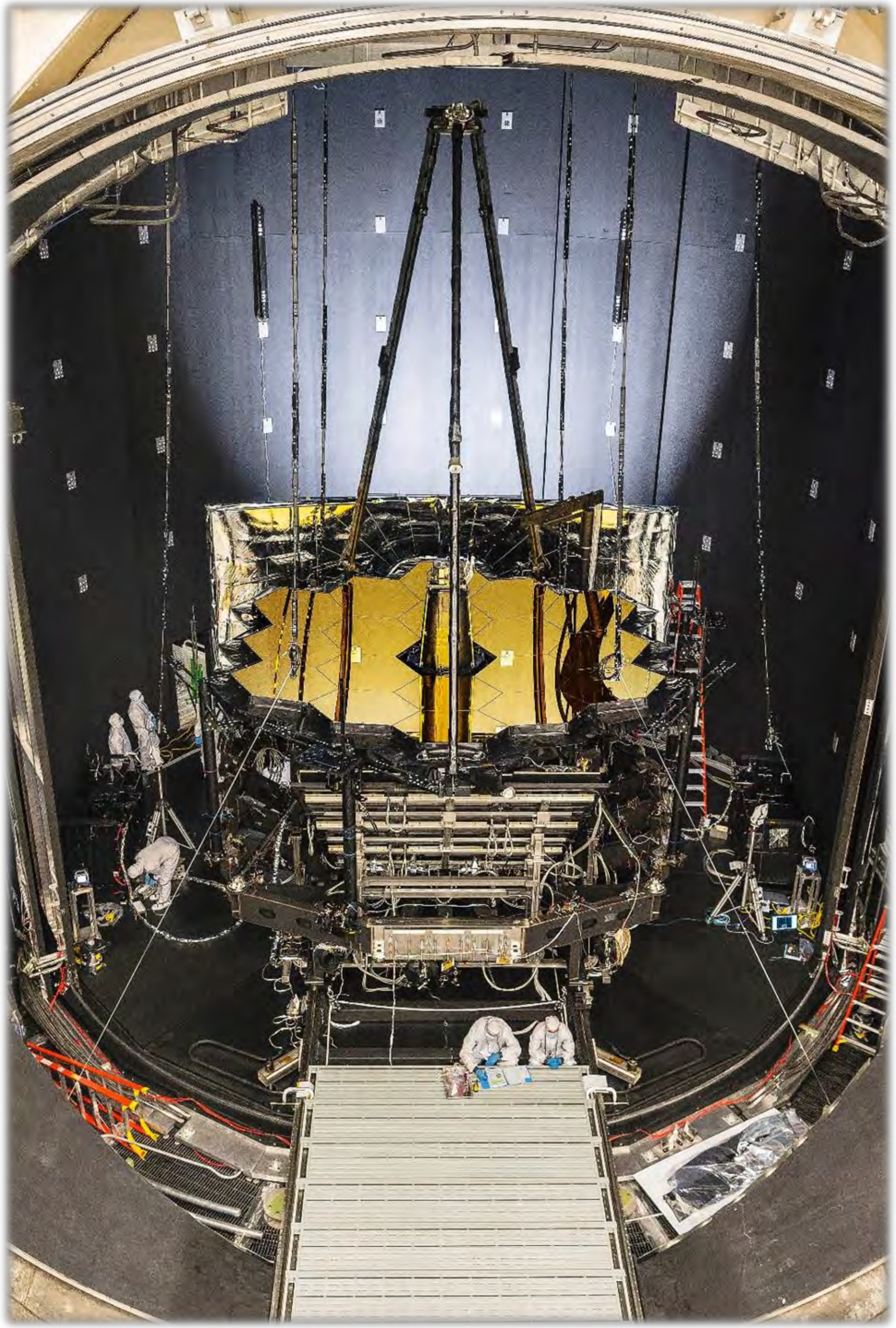

34th Space Symposium, 2018

VERIFICATION APPROACH FOR LARGE, COMPLEX OPTICAL SYSTMS: LESSONS LEARNED FROM THE JAMES WEBB SPACE TELESCOPE

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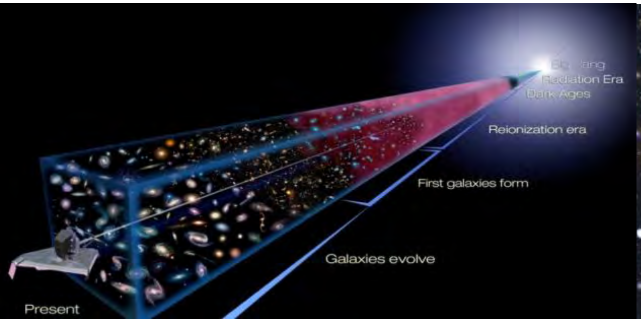
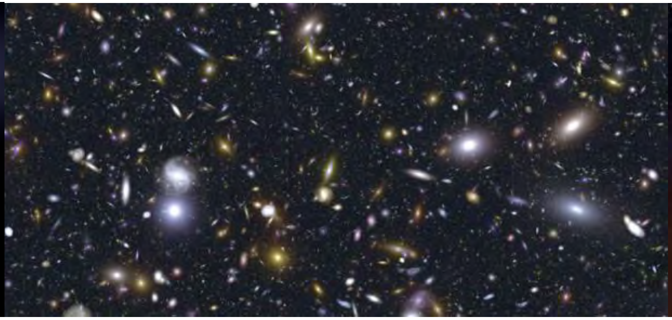
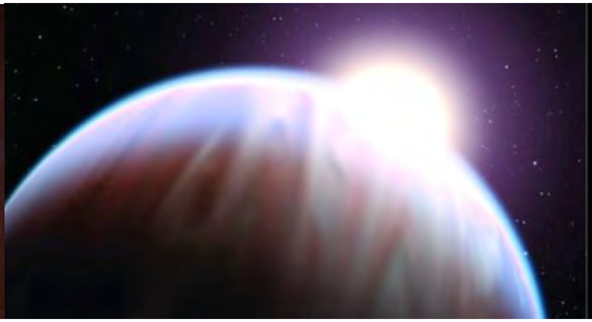
4/16/2018

JWST Overview

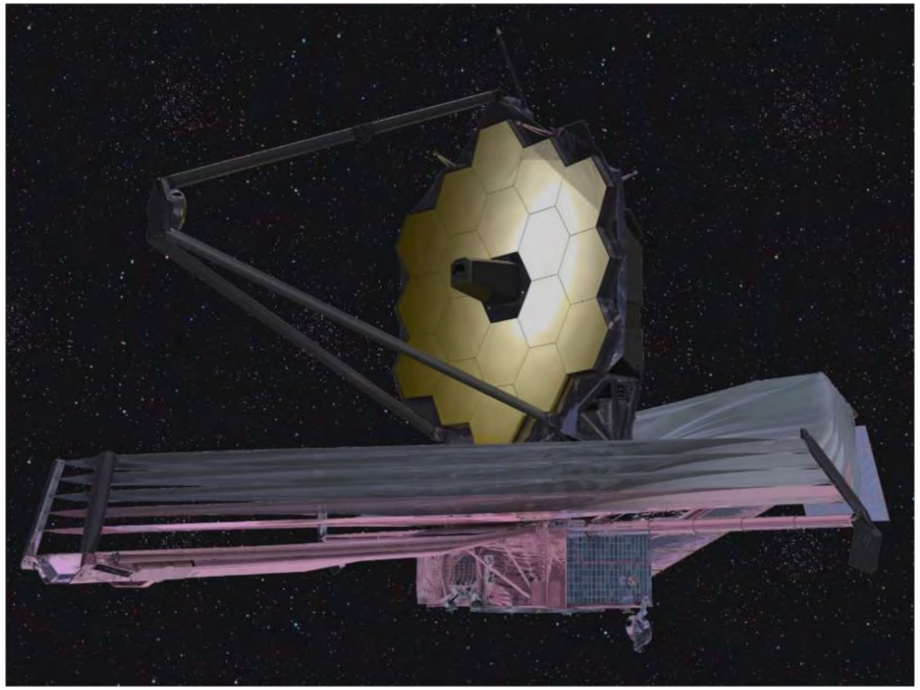






Webb Telescope architecture enables its four main science themes

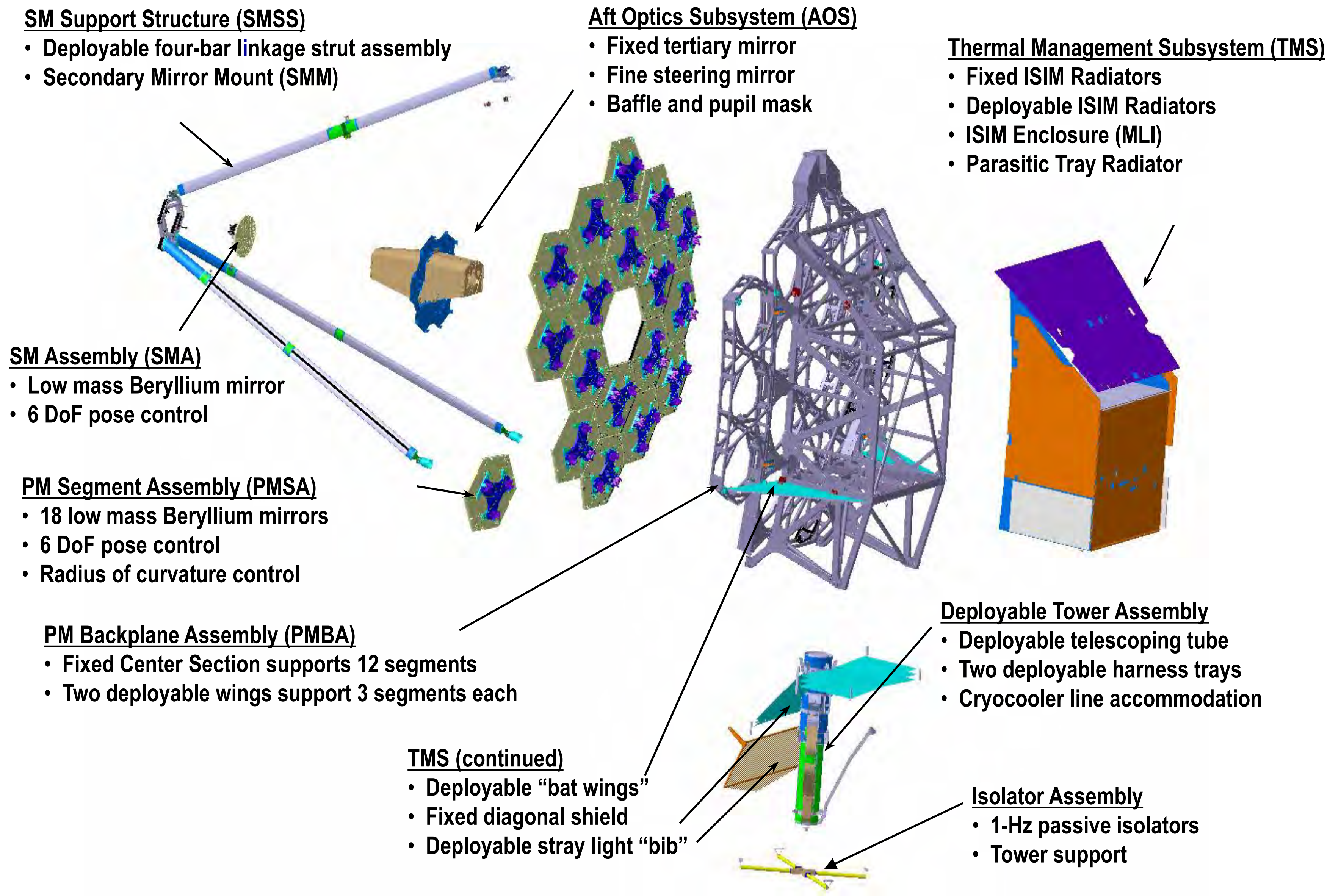
- 6.5 m diameter, >25 m^2 collecting area
- IR (0.6-27μm) telescope, diffraction limited at 2μm
- Passively cooled to <50K (Mid IR instrument actively cooled)
  - L2 Orbit
  - 5-layer Sunshield
- Folded configuration for launch, in-flight deployments



Webb has created many firsts

- First segmented astronomical space telescope
- 10 new technologies developed on Webb program
- Unique optical test/verification program required development of detailed analytical tools and techniques

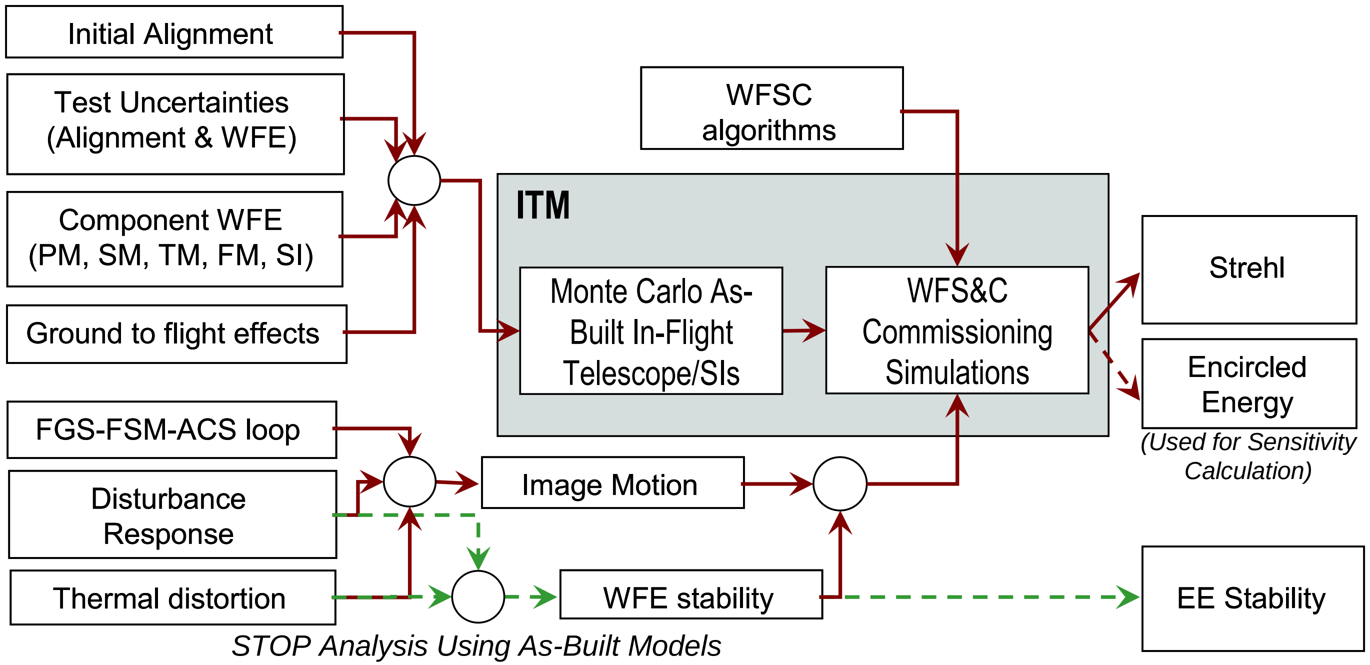
Optical Telescope Element Architecture



Optical Verification Methodology

- **Key Features of the JWST architecture make a traditional “test as you fly” ground test challenging from both a technical and cost perspective:**
  - 6.5 meter aperture
  - Passively cooled to cryogenic temperatures (<50 K)
  - Thermal Stability effects on Optical Performance (requirements allow $\Delta T \sim 0.15$ K)
  - Final flight configuration cannot be tested on the ground (alignment is not deterministic)

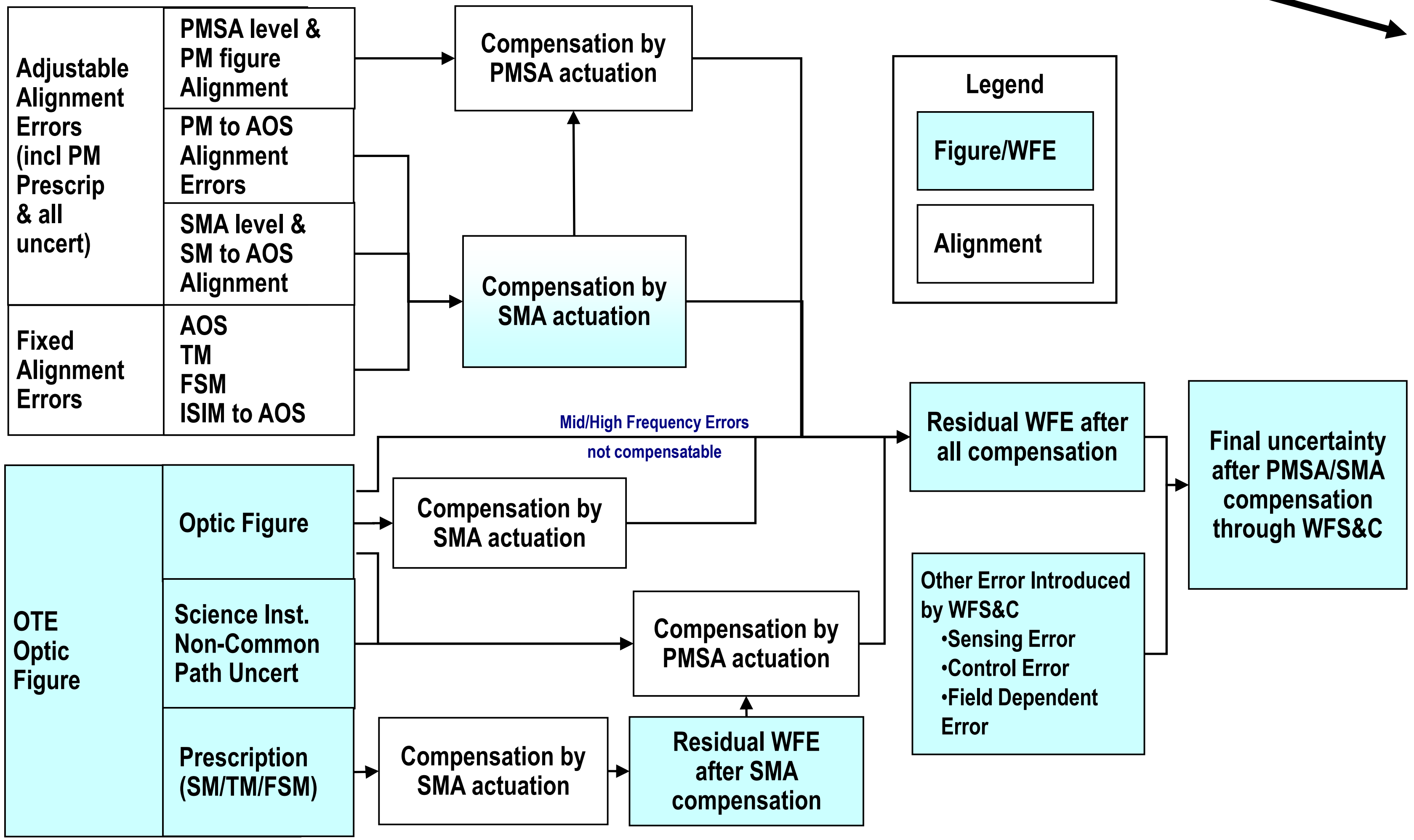
- **In order to verify Observatory optical performance on-orbit, there are four main aspects of the system that need to be understood:**
  1. Optical performance of each optical component
  2. Alignment between the optics
  3. Adjustability of the PMSAs and SMA
  4. Performance of the WFS&C Algorithms



- **Each of these pieces of data is then used by the Integrated Telescope Model (ITM) to analytically align the telescope and predict final performance**

Relationship Between Test Performance and Final Verification Uncertainty

- **During WFS&C commissioning, low frequency errors are compensated by the PM & SM**
  - Fixed alignment errors
  - Low frequency mirror figure errors



Therefore, the verification program must:

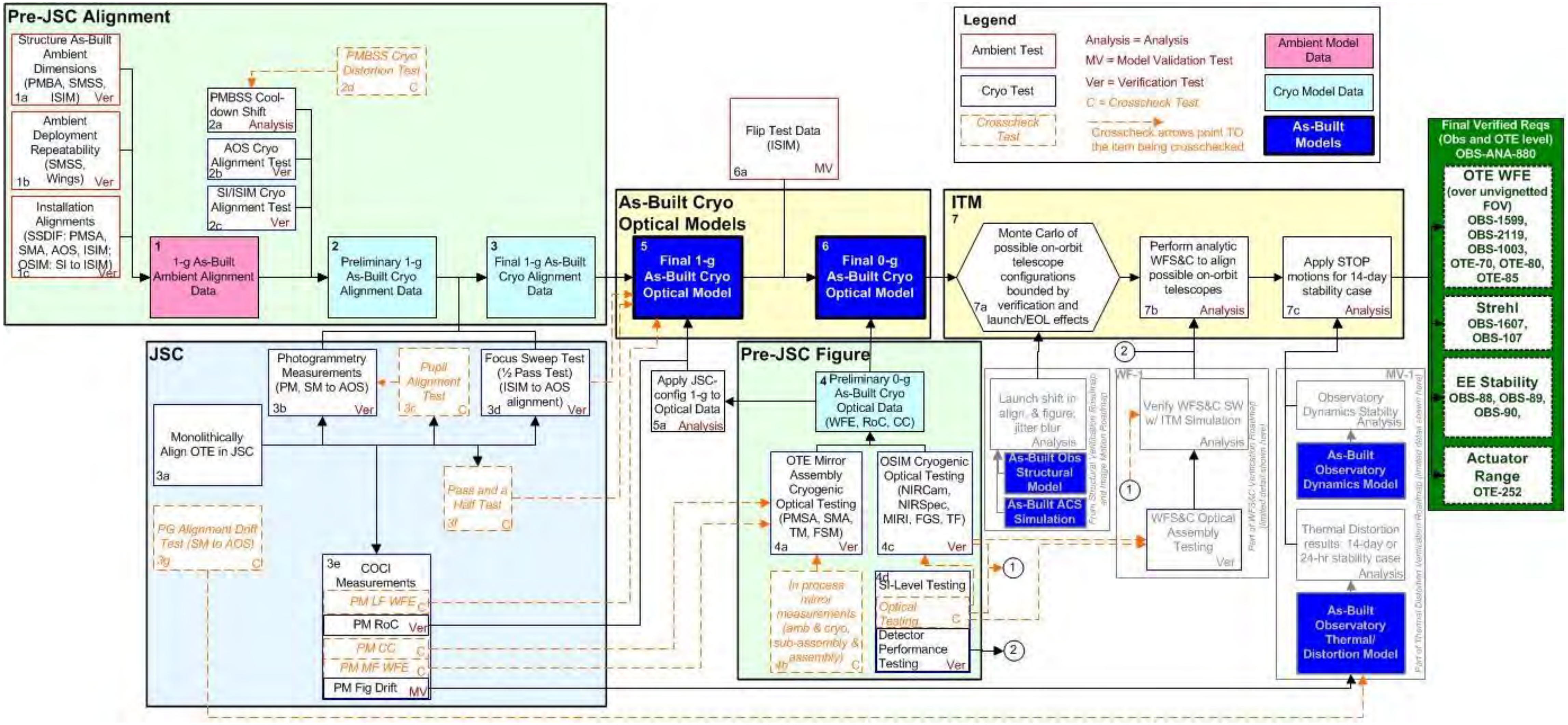
1. Show verification uncertainties of alignment and low frequency figure errors are within the capture range of the adjustable optics
2. Show the remaining uncertainties are sufficiently bound to ensure Image Quality requirements are met
   - Mid/High frequency optic figure
   - Actuator Control
   - Sensing

Optical Verification Methodology

- **Test program has been designed to support final performance verification via analysis**
  - High fidelity verification at lower levels of assembly
  - Focus system-level testing on measuring data that cannot be obtained at a lower level
    - Alignment between major components
  - "Crosscheck" tests at the integrated system level to confirm lower-level test data can be relied upon
  - Extensive model validation program
    - Supported by crosscheck testing and independent modeling efforts
  - Alignment range on-orbit
    - Because system is aligned in flight, margin in actuator range gives added confidence to ability to achieve aligned and phased state on orbit.

Image Quality/WFE Verification Roadmap

- Shows Data used in final as-built models – NOT a chronological flow
- Analysis is generally needed to convert test data into the form needed for input into the model. This detail is not shown
- Assume data from each test/analysis includes both measurement data and uncertainty data



Example: Optic Verification & Crosscheck Tests

PMSA Optical Testing

SMA Optical Testing

TM Optical Testing

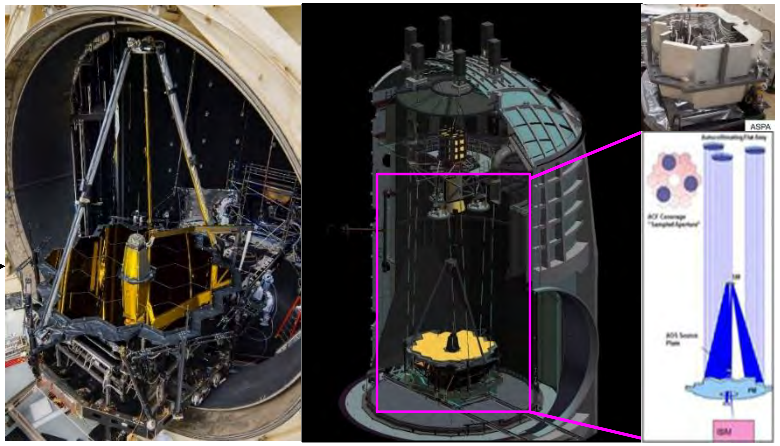
FSM Optical Testing

COCI Testing of Integrated PM at JSC

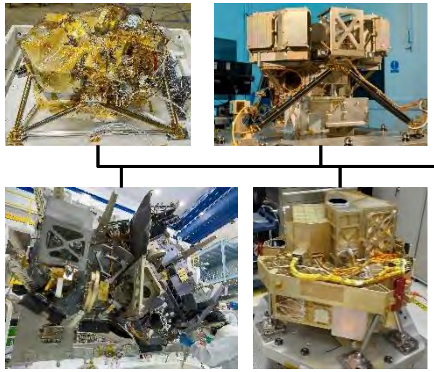
AOS Optical Test using AOS Source Plate during Pathfinder Testing at JSC

AOS/ISIM Optical Test using AOS Source Plate Inward Sources

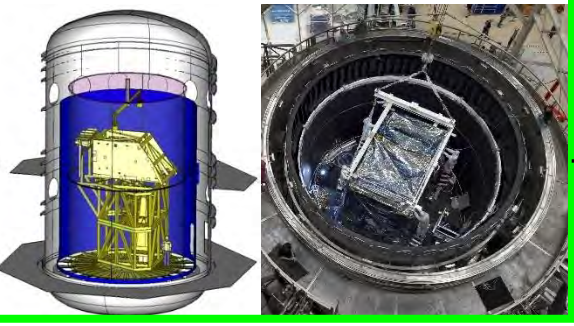
Pass-and-a-Half Observatory Optical Test using AOS Source Plate Outward Sources at JSC



Individual SI Optical Testing



Integrated ISIM Optical Testing with OSIM at GSFC



Tests with green box are verification tests

All others are cross-check tests of optical performance

Crosscheck Matrix

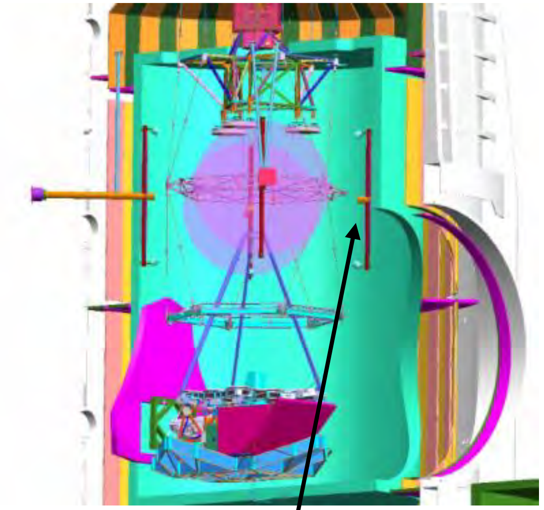
- Tool developed to track all tests & test uncertainty for each input parameter to optical performance
- Used to trend ALL measured test data with uncertainty to ensure as-built model inputs represent state of hardware at launch

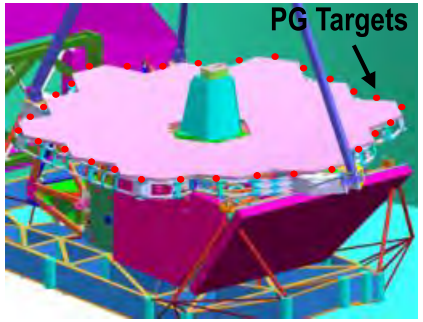
Critical Alignment Tests Occur at System Level

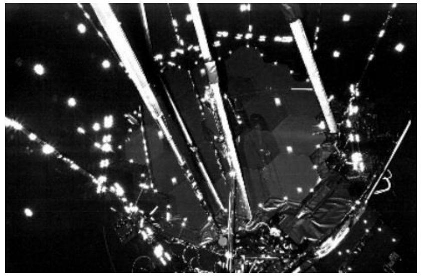
- **Alignment between major optical components is verified at cryogenic temperatures using photogrammetry and the inward sources on the AOS Source Plate (ASPA)**
  - Photogrammetry measured relative alignment of telescope optics to requirements of 100 micrometer / 150 micron
  - ASPA measured alignment of the AOS to the ISIM to <0.5 mm focus & decenter, <0.4 mrad tip/tilt, <0.2 mrad clocking
- **The “Pass-and-a-Half” optical test is a crosscheck to alignments measured in verification tests.**

Photogrammetry

Photogrammetry Measures alignment of:
- **PM to AOS**
- **SM to AOS**



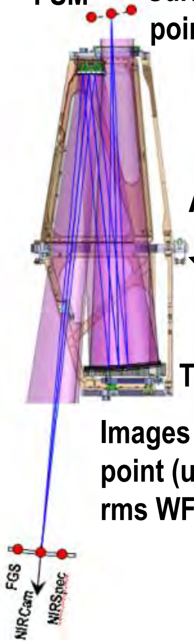




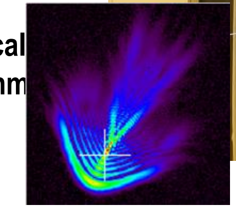
PG Cameras on four windmills

AOS Source Plate

AOS Source Plate inward facing sources are used during the Field Alignment Test to measure ISIM to AOS Alignment

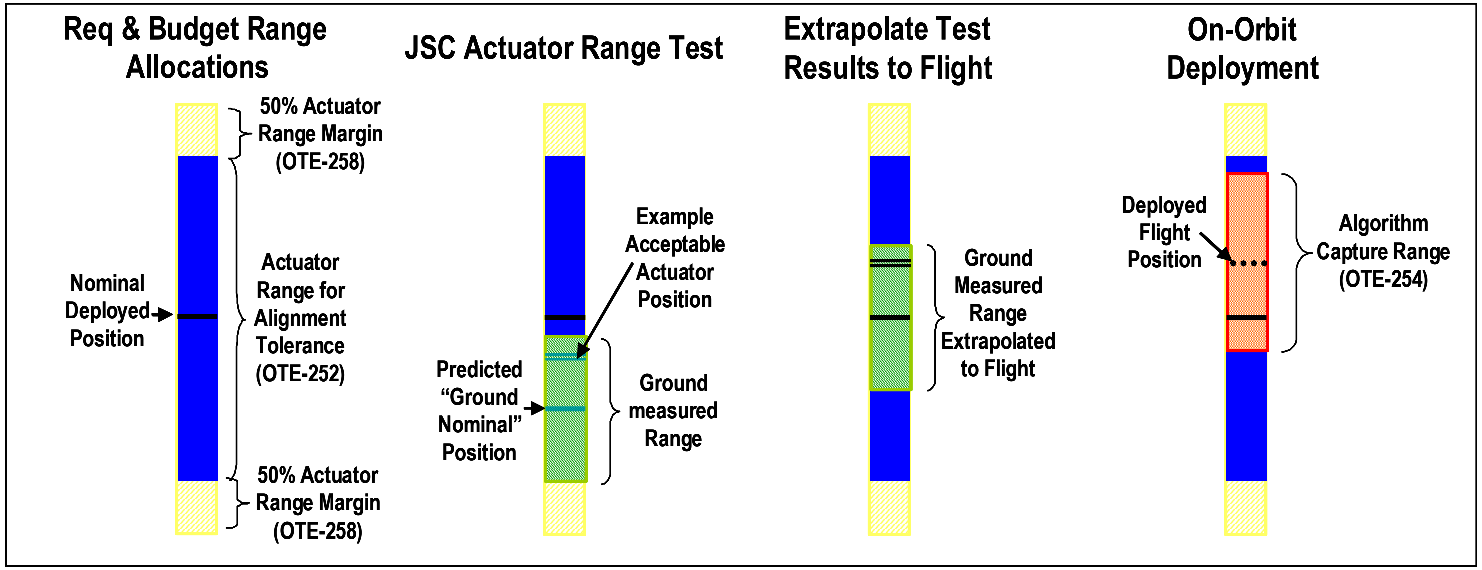


Images at AOS focal point (up to 3000 nm rms WFE)



Actuator Range Verification

- Optical performance budgets are based on the assumption that we have enough actuator range to reach an aligned configuration on orbit
- Test and analysis uncertainties combine to impact total range needed on orbit and magnitude of error that needs to be corrected using WFS&C
- Actuator Range Budget tracks each contributor that could require correction/compensation with mirror actuators
- Actuator Range is verified through a combination of:
  - Ground alignment during Observatory cryogenic testing in JSC Chamber-A
  - Careful tracking of uncertainties of each constituent of the range budget
  - Analysis of ground to orbit alignment and figure changes



Adjustability Verification of PMSAs & SMA

PMSA/SMA Adjustability Verification

- **PMSA/SMA Adjustability is dominated by actuator performance; test program focuses on detailed verification at the actuator level**
  - Each actuator tested to sub-nanometer levels for resolution and accuracy at both ambient and cryogenic temperatures (requirements are 10 nm step size with 3 nm accuracy)
- **This detailed actuator data is combined to create a unique model of each PMSA/SMA hexapod**
  - Model is validated during ambient hexapod testing when integrated hexapod motion is verified to the nanometer-level in piston/decenter and few nanoradians in tilt/clocking level
- **Adjustability of the fully-integrated PMSAs and SMA are further tested during component cryogenic testing. During these tests, actuator performance is verified to the 2-4 step level**
- **Total actuator range is verified at all the test points above**
- **During the system-level cryo testing, adjustability is crosschecked when mirrors are exercised during PM alignment and when aligning the SMA for the Pass-and-a-Half test.**
  - PMSA motions can be measured to the 2-4 step level through the COCI.

Wavefront Sensing Verification

- **Performance of the algorithms is verified using ITM**
  - Both individual algorithm performance and full end-to-end commissioning simulation is performed
- **Performance of WFS&C components and SI detectors is verified at the component and SI level**

Summary of JWST Optical Test Approach

- **The JWST optical verification program balanced technical challenges with desire to "test-as-you-fly"**
- **Performance data from component level tests was used directly into the as-built Observatory model**
  - For all verification data obtained at the component or element level, multiple crosscheck tests were performed to allow data trending and to ensure workmanship errors not evident in component tests were caught prior to launch
  - Alignment between each optical component was measured so actuator range needs can be assessed
  - Uncertainties from each verification test is used in the model to create a Monte Carlo of possible on-orbit telescopes
- **With this data, WFS&C can be performed to align the analytical telescope in the same way the flight Observatory will be aligned on orbit**
- **This approach gives an accurate prediction of final performance**
  - Use of analysis minimizes technical challenge of proving performance meets requirements using an end-to-end test
  - Allows a more accurate verification and understanding of the effect of test uncertainties on the final in-flight alignment and optical performance of JWST
- **This approach and the detailed analytical tools developed for JWST can be readily extended to future space-based segmented telescopes**
  - Ensuring large segment-level actuator range allows easily achievable mechanical integration tolerances to support integration on the ground or in space
  - Hexagonal segmentation allows compensation of alignment and figure errors elsewhere in the system by providing actuation authority to "warp" the Primary Mirror to perform this compensation (following SM optimization)
  - Careful tracking of error sources and selection of key opportunities for crosscheck tests and data trending helps ensure a low-risk optical performance verification program even in the absence of end-to-end ground testing