Alignment and testing of critical interface fixtures for the James Webb Space Telescope

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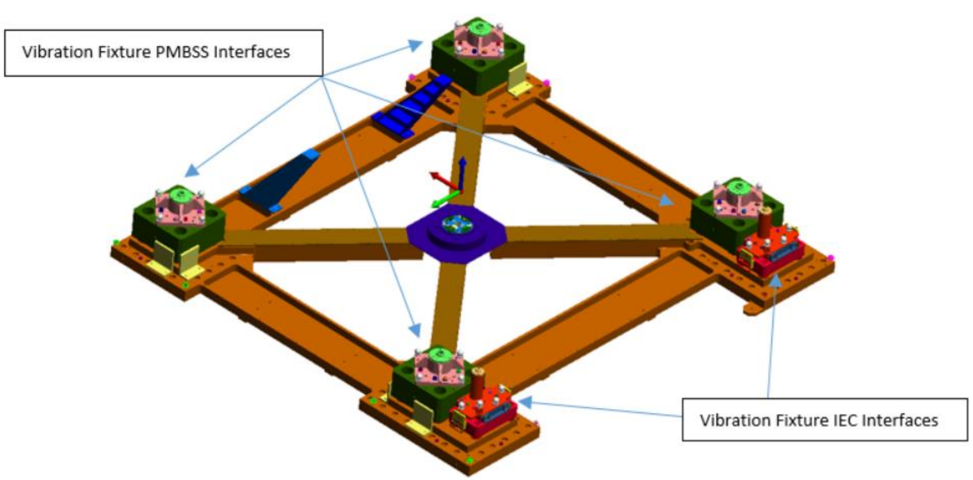
Introduction (1/2)

- **James Webb Space Telescope (JWST)**
  - NASA mission developed in conjunction with the European Space Agency and the Canadian Space Agency
  - Large infrared space telescope with a 6.5m diameter primary mirror
  - The observatory consists of two primary structures
    - Spacecraft (SC) bus
    - OTIS- Optical Telescope Element (OTE) and Integrated Science Instrument Module (ISIM)
- **The OTIS mates to the spacecraft bus via six cup/cone interfaces**
  - Four Primary Mirror Back Support Structure (PMBSS)
  - Two ISIM Electronics Compartment (IEC) interfaces
  - Cone interfaces-SC bus
  - Cup interfaces- OTIS
- **The telescope must survive:**
  - unforgiving launch conditions
  - space environment
  - handling and transportation during the integration and test phase of the program

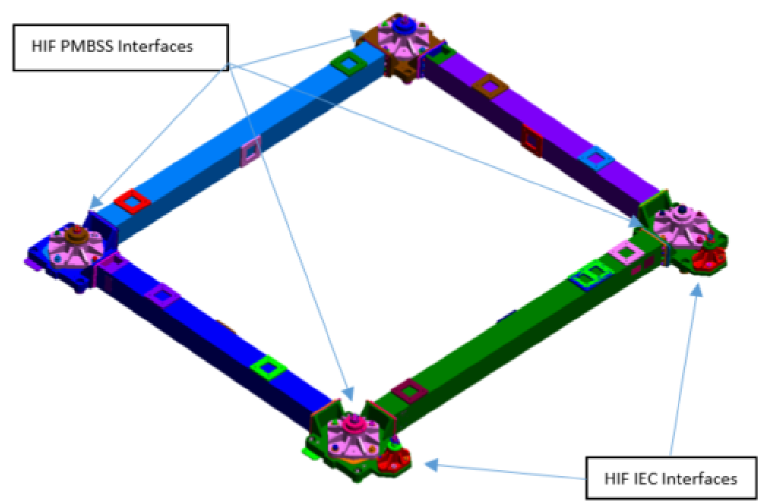
OTIS on the HIF for IEC integration at GSFC

Introduction (2/2)

- **To ensure the survival of the OTIS under these conditions we subject the telescope to environmental testing prior to launch**
  - Vibration testing
  - Acoustic testing
  - Thermal cycling
- **To support the environmental testing, NASA developed, aligned, and test two interface fixtures which emulate the six SC bus cone interfaces**
  - Vibration fixture (VF)
  - Handling and Integration Fixture (HIF)



OTIS Vibration Fixture

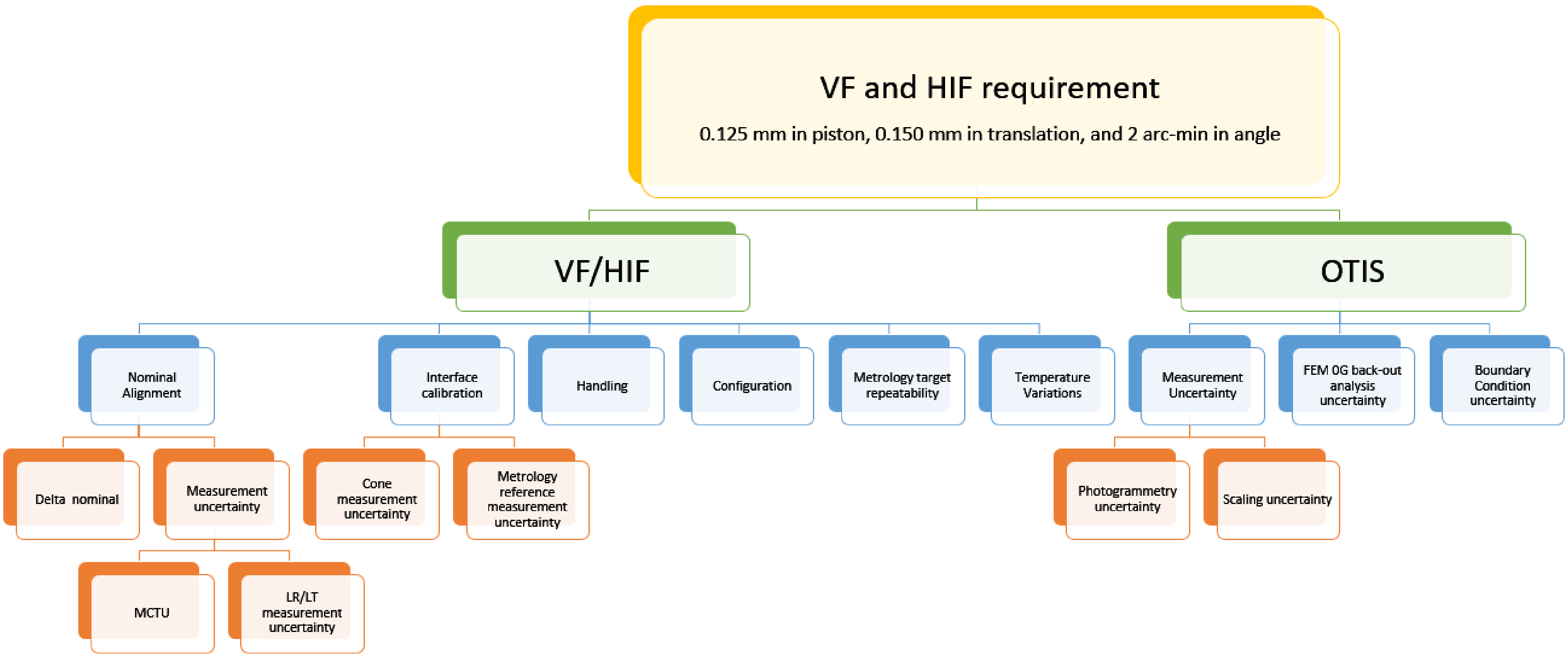


OTIS HIF

Alignment requirements

- **The HIF and vibration fixtures six cone interfaces had to be aligned in both position and angle to a very tight requirement relative to the size of the fixtures**
  - 0.125 mm in piston
  - 0.150 mm in translation
  - 2 arc-min in rotation (tip tilt only)
- **The requirements were derived from structural analysis of the OTIS when subjected to vibration testing and transportation loads**
  - The ridged non kinematic fixtures force large joint loading into the OTIS structure which dictated the small alignment requirement
- **The requirement included multiple uncertainty and errors factors from both the OTIS side as well as the HIF/vibration fixture sides**

HIF/Vibration Fixture error budget terms



Nominal Prescription

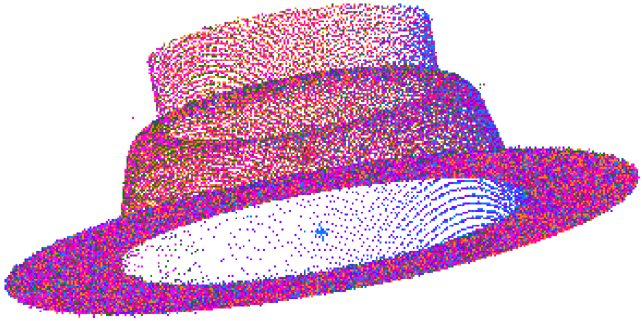
- **Why can we not just use the spacecraft interface cone locations for the nominal HIF/VF alignment?**
  - Alignment discrepancies between the spacecraft to OTIS is acceptable
  - The HIF and VF are much stiffer than the spacecraft
    - The HIF and vibration fixture carried a much smaller alignment requirement than the spacecraft
- **As a results we had to develop a new alignment prescription based on the as-built OTIS**
  - Minimize integration loads on the spacecraft, HIF, and VF
  - HIF defines the OTIS IEC interface locations relative to the OTIS PMBSS interfaces

HIF nominal prescription development (PMBSS Interfaces)

- **NASA GSFC received the OTIS prior to IEC integration**
  - The only interfaces available on the OTIS were the PMBSS cone interfaces
- **To define a nominal PMBSS interface locations for the HIF/VF cones the OTIS PMBSS cup interfaces were measured with OTIS hanging from a crane using photogrammetry**
  - Photogrammetry target placed on a sphere placed in the cup interface as well as the mating surface
  - Local coordinate frame was created at the center of the four interfaces
  - For consistency purposes, the measured interface angles and positions were analytically defined in a zero gravity state using a Finite Element Model (FEM)
- **Cross-check metrology was completed to verify the photogrammetry results**
  - The OTIS was positioned in the Ambient OTE Assembly Stand (AOAS) and the interfaces were measured both with the primary mirrors facing up (cup up) and the primary mirror facing down (cup down) using two methods
  - Method 1: Direct Laser Radar (LR) [1] scan method
  - Method 2: Placed a tooling ball in the interface for position, and an optical flat on the interface for angle

HIF nominal prescription (PMBSS Interface metrology cross-check Method1)

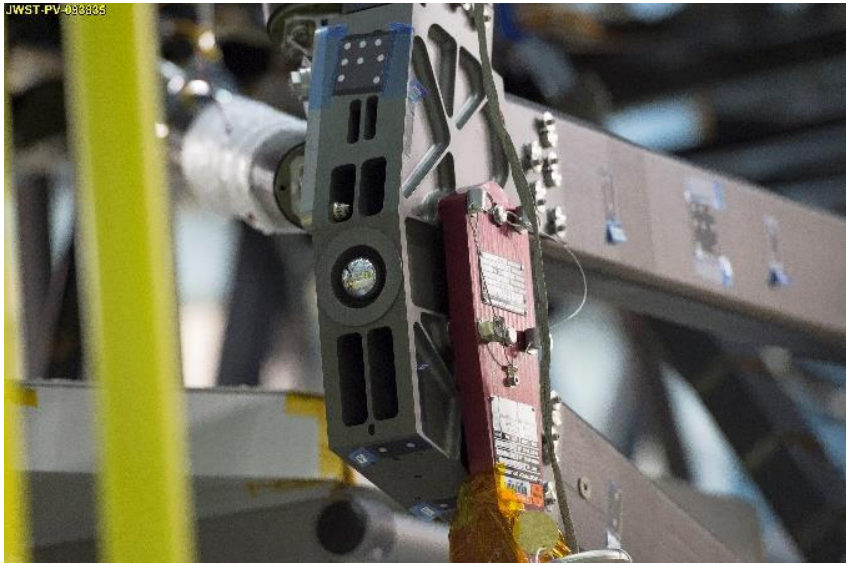
- **Method 1: Direct LR scan method**
  - Vision scan of the four OTIS PMBSS cup interfaces
  - Each interface measured from at least five laser radar stations
  - Data processed in Spatial Analyzer (SA) [2]
  - Cone and a plane best fit to the interface scans
  - Intersection of the cone axis and the plane defines the interface position.
  - Interface plane defines the angular component



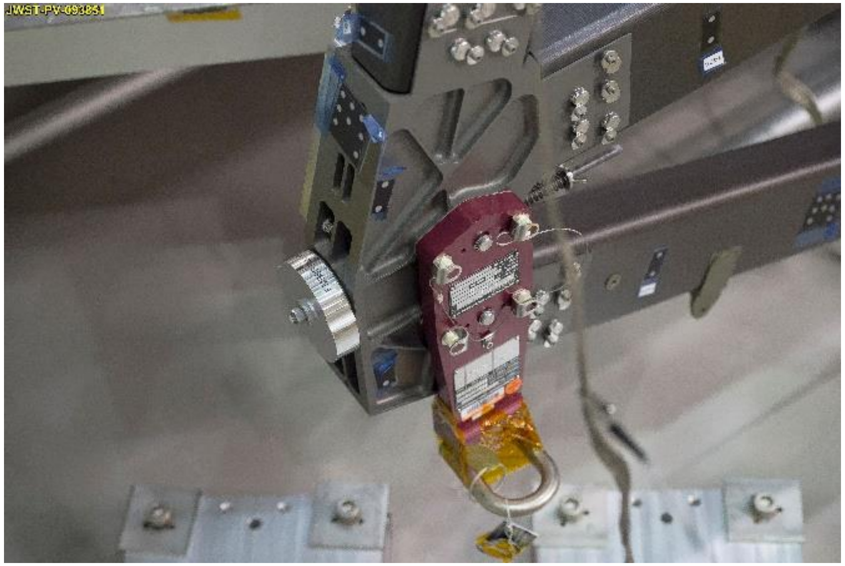
OTIS PMBSS cup interface LR scan

HIF nominal prescription (PMBSS Interface metrology cross-check Method1)

- **Method 2: Placed a tooling ball in the interface for position, and an optical flat on the interface for angle**
- **Tooling ball placed in each of the four interfaces**
  - measured using LR and related to tie points
- **Tooling ball was removed and the optical flat was placed on the interface**
  - Optical flat calibrated prior to use on the OTIS
  - LR measured optical flat using a Direct and Through method [3] and related to the tie points from the positional measurements



OTIS PMBSS Interface with tooling ball



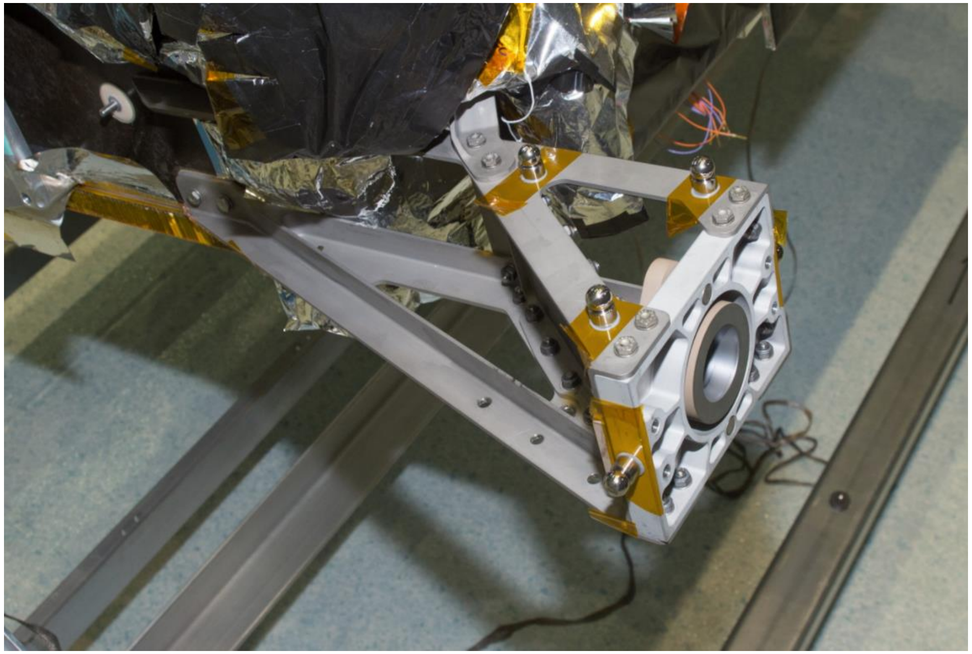
OTIS PMBSS Interface with optical flat

HIF nominal prescription (PMBSS Interface metrology results)

- **The two LR methods agree within 0.020mm in position and 30 arc-sec in angle**
- **LR results corrected to the 0G state for comparison purposes to the primary metrology**
- **The LR methods agreed with the OTIS hanging photogrammetry technique within measurement uncertainty**
  - A large uncertainty was associated with the FEM corrections
  - The OTIS hanging with photogrammetry method was the primary data set used because of the lower FEM uncertainty
    - Boundary conditions had little effect on the hanging configuration vs the LR method where OTIS was supported near the interfaces

HIF nominal prescription (IEC Interface metrology)

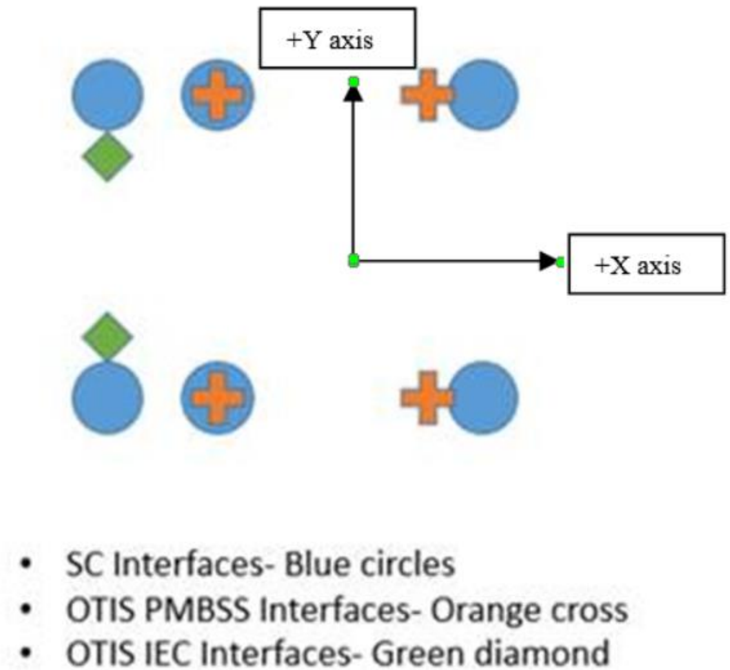
- IEC interfaces were measured prior to integration to OTIS to help predict the interface locations
- IEC positioned in the horizontal position
  - Metrology nests were bonded onto the OTIS IEC "feet" as references
- LR measured the IEC interface cup directly using a vision scan similar to the PMBSS interface cup scans
  - Interface locations related to the local metrology nests
- IEC turned to the vertical configuration (with similar to the boundary conditions when integrated to OTIS)
  - Metrology nests measured
  - Using a Monte Carlo Transformation Uncertainty (MCTU) code [4] interface calibration was transformed to the measured interface target location



OTIS IEC cup with metrology reference nests and tooling balls

HIF nominal prescription

- **SC interface positions not used directly to define nominal prescription**
  - The six spacecraft cone interfaces were used as a template to define the nominal HIF cone interface locations
- **It was important to preserve the relative distance between IEC interfaces and the two –X PMBSS interfaces**
- **OTIS IEC cup interfaces were transformed to the spacecraft IEC cone interfaces using the two points**
  - Defined five degrees of freedom from the two points
  - Forced the two sets of interfaces to be centered and in line with one another
  - Last degree of freedom (rotation about Y) the individual interface angular errors were minimized
- **The OTIS PMBSS interfaces were transformed to the spacecraft using the –X interfaces as the primary points similar to the IEC transformation**
  - defining five degrees of freedom from the two points
  - The +X PMBSS interfaces were used to define the rotation about Y
- **Transformed OTIS interfaces define the nominal HIF locations and angles**



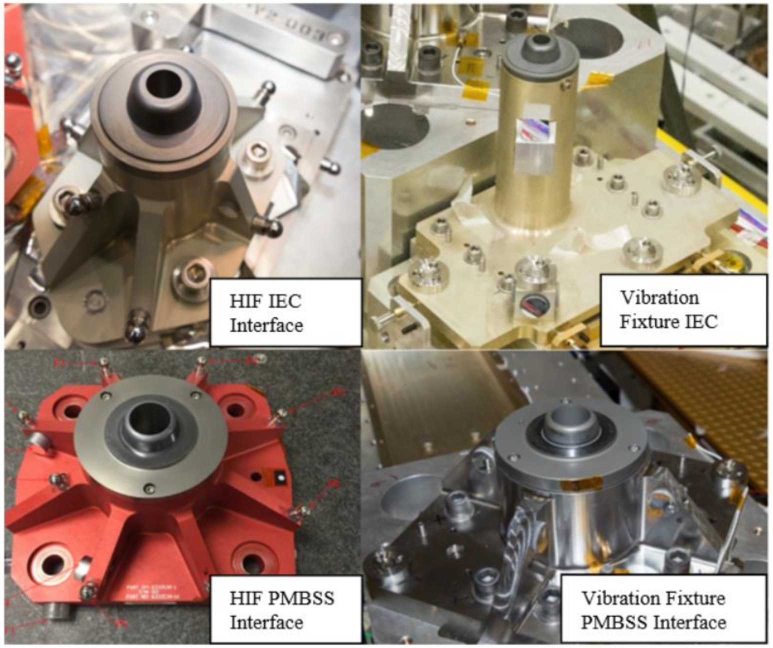
Visual representation of the HIF nominal position definition

Vibration fixture nominal prescription

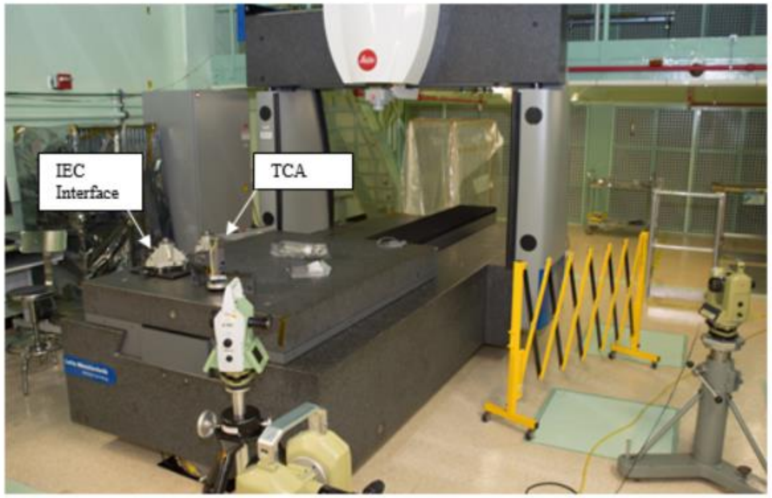
- **The HIF was aligned, and the as-built HIF locations and angles were defined**
  - HIF defines the nominal alignment between the OTIS IEC and PMBSS cup interfaces
- **VF nominal alignment prescription was based on the as-built HIF**
  - VF nominal developed in a similar manner as the HIF nominal, but with the as-built HIF used as the template
- **Additional complication is the VF warms up during testing on the slip table (horizontal shaker) and the head expander (vertical shaker)**
  - Nominal VF operational temperature 24C
  - Alignment temperature was ~20C
- **The nominal prescription of the HIF was adjusted using the coefficient of thermal expansion of the vibration fixture to ensure proper alignment during vibration testing**

Interface calibrations

- **Each of the HIF and vibration fixture interfaces had a cone feature which was identical the mechanical spacecraft interfaces that mate to the OTIS**
  - Included Tooling ball (TB)/ Spherically mounted retro-reflector (SMR) metrology nests and optical flats
- **A contact probe Coordinate Measuring Machine (CMM) was used to calibrate the cone interface with respect to reference targets on the body of the cone interface adaptors**
  - Measured multiple points on each of the interface cones and planes, as well as TBs in the nests, and optical flats
  - HIF IEC interface calibration also utilized theodolites with a Transfer cube assembly (TCA) [5]
  - Using geometry fitting a cone and plane was fit to each of the features. The intersection of the cone axis and the plane defines the position of the cone
- **This created an interface calibration of the cone relative to the metrology reference targets that allowed for an indirect measurement of the interfaces**



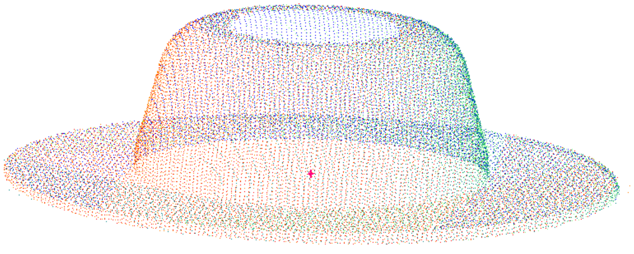
HIF and Vibration fixture interfaces



HIF IEC cone interface calibration on the Leitz PMM-C 700 [6] with the TCA and interface mounted to the granite table

Interface calibration cross-check

- **A cross-check metrology was performed for each type of interface to verify the measurements of the CMM calibrations**
  - LR used to measure the cones, metrology nests with tooling balls, and the optical flats
    - Cones measured using vision scan from multiple stations
    - Optical flats measured using the direct and through technique
    - The (SA) Unified Spatial Metrology Network (USMN) [7] process was used to bundle the LR stations
- **LR results compared to the CMM calibrations**
  - Results showed an errors in one of the interface calibrations (2 mm in piston)
  - Probe diameter was not properly accounted for which could have resulted in a structural failure of OTIS during testing and transportation
  - Demonstrates the importance of additional verification measurements



HIF PMBSS interface laser radar vision scan

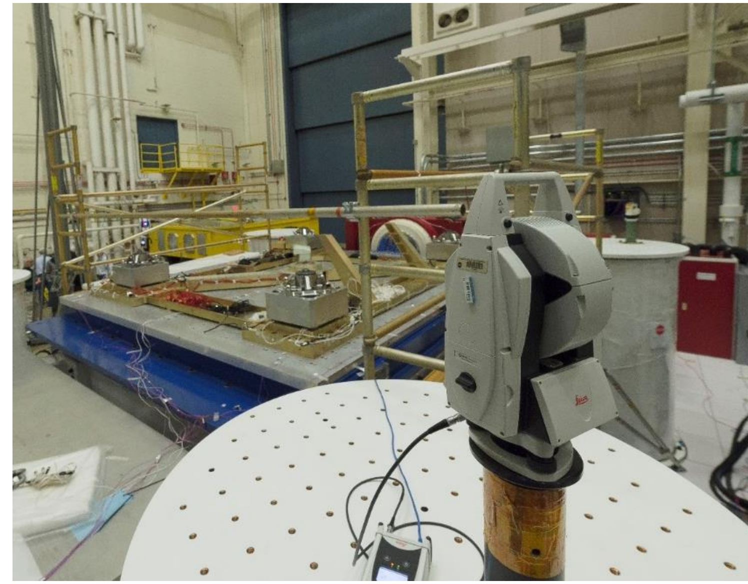
HIF alignment

- **HIF was aligned using a combination of LR and Laser Tracker [8]**
  - Interfaces aligned in angle and piston first, then position
  - Metrology nests measured with LR/LT
  - Interface calibration transformed to measured metrology nest locations
  - Interfaces shimmed and translated until aligned to the nominal prescription within specification
- **Interfaces distorted near the optical flats (optical flats not used)**
- **Final calibration completed after alignment using laser radars**
  - Each metrology nest measured from at least three stations
  - LR scanned cones directly as a cross-check
  - LR stations bundled using USMN function
  - Interface calibrations transformed to the USMN group using MCTU code
- **Alignment of the HIF met the nominal misalignment sub allocation**
  - 0.025mm in piston, 0.040mm in translation, and 30 arc-sec in angle

HIF alignment on the yellow IIS

Vibration fixture alignment

- **VF PMBSS cone interfaces were aligned using LT (Leica AT401) and theodolites**
  - Interfaces aligned in angle and piston first, then position
  - Metrology nests measured with LT (Leica AT401)
  - Interface calibration transformed to measured metrology nest locations
  - Angles aligned using theodolites and the optical flats
    - Theodolites also measured transfer cube assemble (TCA)
    - LT measured TCA using direct and through technique
  - Interface shimmed and translated until aligned to the nominal prescription within specification
- **Interfaces distorted for the IEC cone interfaces once torqued**
  - Metrology nests and optical flats on the base were not dependable
  - Alignment cube added to the interface "post"
  - Calibrated with respect to the optical flats
- **IEC interfaces were aligned using a LR scanning the cones and theodolites for angle**
  - LT used for intermediate translations

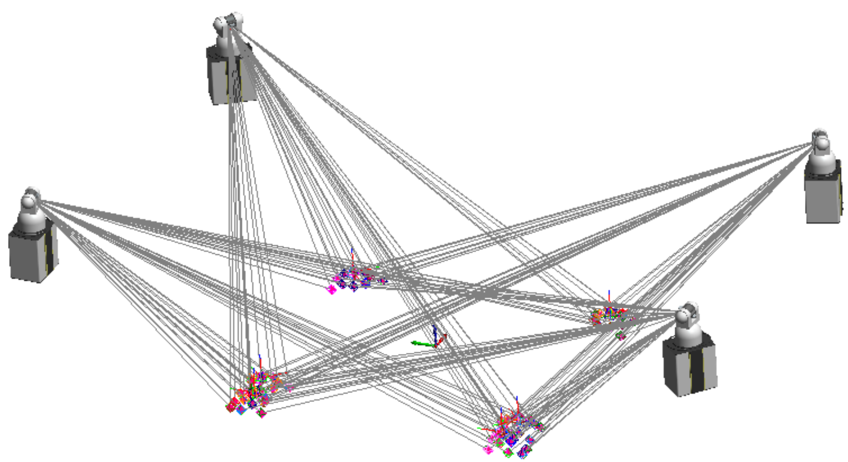


Vibration fixture on slip table during alignment

- **Alignment verification completed in a similar manner to the HIF, with exception for LR scans used as the primary tool to measure the IEC interfaces and theodolites for angle**
- **Alignment of the VF met the nominal misalignment sub allocation**
  - 0.025mm in piston, 0.040mm in translation, and 30 arc-sec in angle

Alignment verification

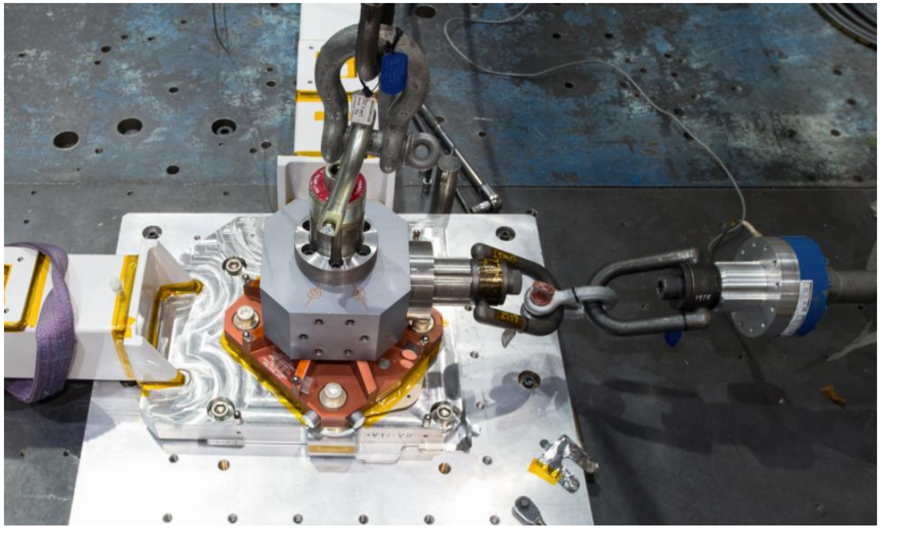
- **HIF and VF used on multiple structures and configurations though the integration and testing phase of the OTIS**
- **Multiple alignment checks were performed to insure proper alignment to capture errors associate with these configurations**
- **All verification metrology tests were performed in a similar manner**
  - LR and/or LT measured each metrology nest from a minimum of three stations
  - The USMN process used to bundle the stations together
  - Interface calibrations transformed to the USMN group using MCTU code



HIF alignment verification

Alignment verification: HIF proof test

- **The HIF was subjected to static load proof testing to ensure the HIF could survive the forces of OTIS during transportation**
- **Metrology post proof test showed the interfaces translated ~0.150 mm**
  - Shift between the HIF and cone interfaces was a result of the shear forces breaking the friction between the two parts
  - Once the load shear load was removed from the interfaces some of the misalignment induced was held in place by friction
  - Fasteners holding the interfaces to the HIF were released and re-torqued to the HIF, and the interface positions improved near the original alignment
- **Demonstrate importance of metrology before and after proof testing**
  - Additional and larger pins were added to mitigate this problem



HIF static load proof test

Alignment verification: HIF pre-OTIS integration

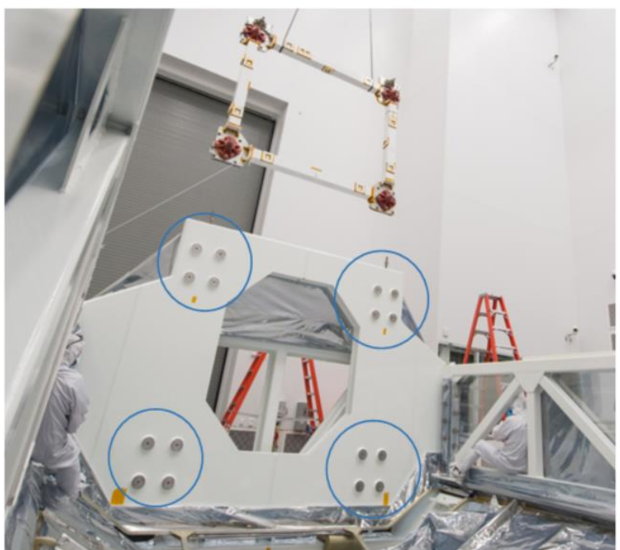
- **Alignment during integration of the OTIS was important to ensure any misalignment was not locked into the system once integrated**
- **HIF alignment checked on the High Capacity Roll Over Fixture (HCROF) and the Space Telescope Transportation Air Road and Sea (STTARS) shipping container prior to OTIS integration**
  - Shims added between the HIF and the mating interface to insure proper alignment in piston and angle

HIF on STTARS

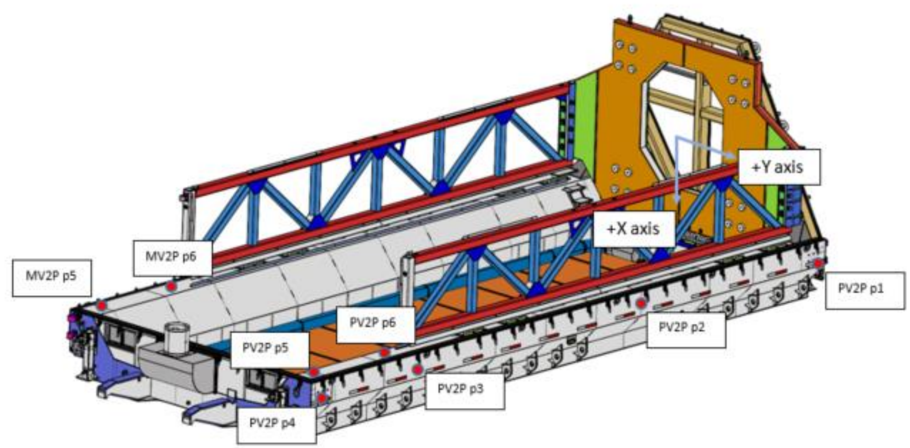
HCROF with OTIS and HIF

Alignment verification: STTARS (for HIF) (1/2)

- Another factor affecting the alignment of the HIF when on the STTARS, is distortion of the container during transportation
- A displacement on one end of the STTARS can cause distortion at the STTARS HIF mating surfaces which results in alignment changes of the HIF cone interfaces
- A metrology test was completed to characterize these affects and were correlated to a mechanical Finite Element Model (FEM)
- Metrology targets were positioned at various points on the STTARS
- Using a LT, displacements were applied using leveling jacks at the corners of the STTARS, then a metrology survey was completed

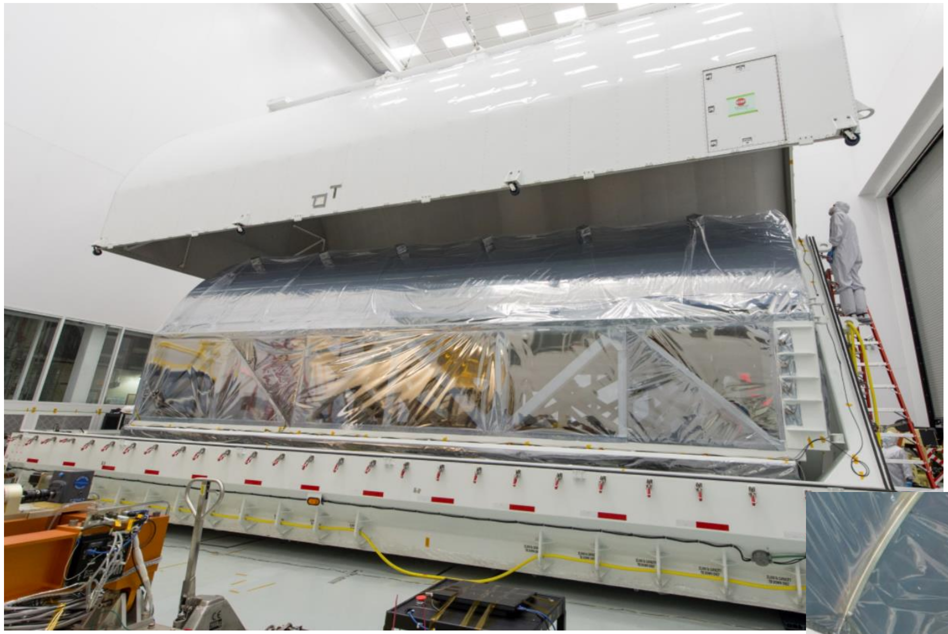


STTARS HIF interface locations (16 bolt holes)



Metrology target locations on STTARS during distortion testing

Alignment verification: STTARS (for HIF) (2/2)



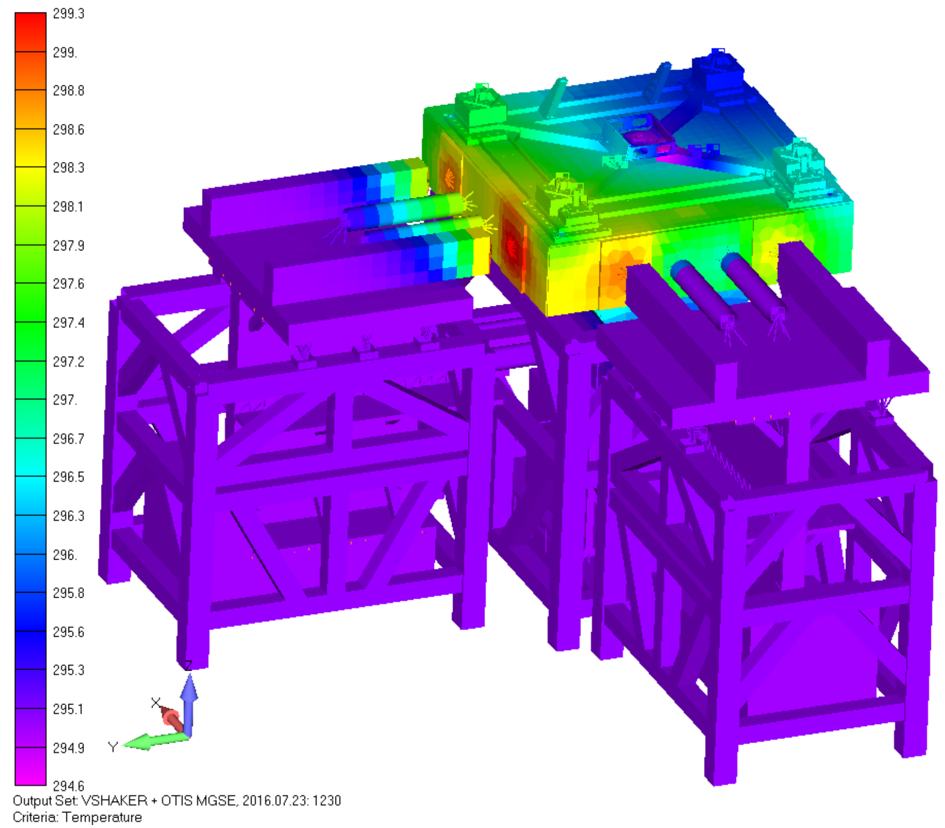
Lid integration to STTARS

- **The test was completed with difference magnitudes of displacements at different corners**
  - With the lid on and the lid off

Leica AT401 positioned in the STTARS with the lid on, measuring the STTARS HIF interfaces (View from the HIF interface end of STTARS)

Alignment verification: Vibration fixture temperature

- **The VF was aligned at a lower temperature than the operational temperature**
- **The VF was warmed up to the 24C and measured in two different orientations on the slip table (Horizontal shaker)**
  - Slip table warms up uniformly
- **VF fixture place on the head expander (vertical shaker)**
  - Head expander does not warm up uniformly
  - The objective of the head expander metrology was to correlate the thermal model as the head expander temperature increases
  - The alignment deviations due to thermal variations on the head expander were accounted for in another error budget



Vibration fixture on the head expander thermal model

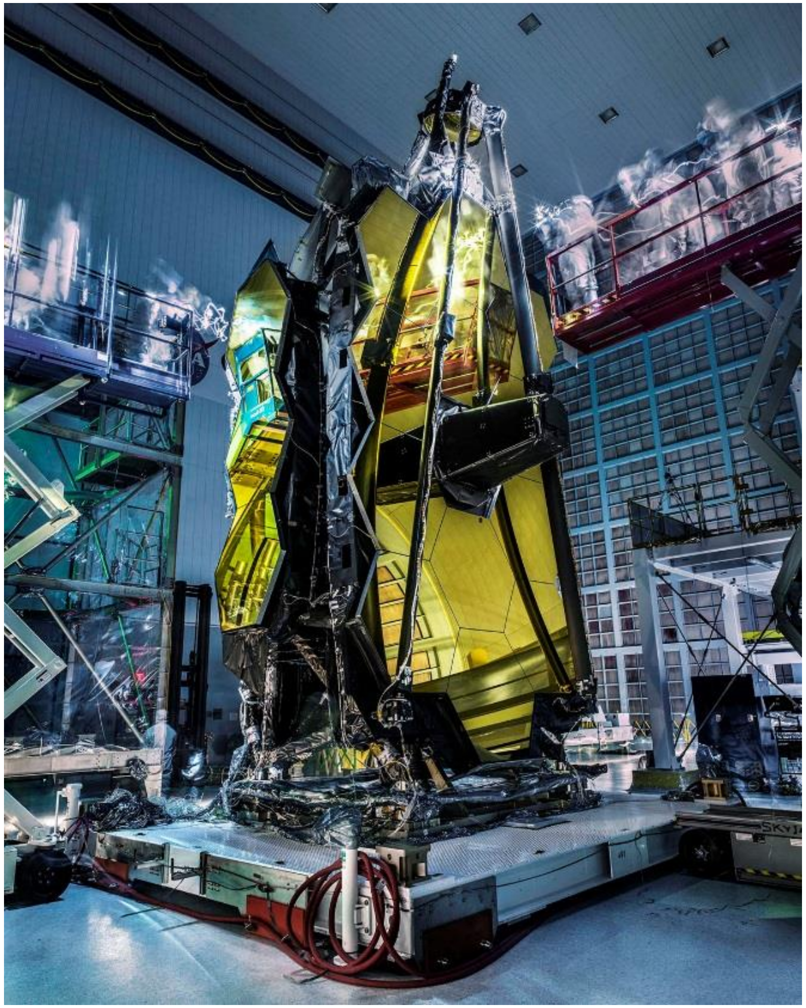
Alignment verification: Vibration fixture proof test

- The vibration fixture, slip table, and head expander underwent proof testing using a mass simulator that interfaced with the vibration fixture PMBSS cones
- Measurements were completed before and after each axis to insure the vibration fixture remained aligned

Vibration fixture with mass simulator on head expander for proof testing

Alignment verification: Vibration fixture pre-OTIS integration

- **To ensure proper alignment during OTIS integration the vibration fixture was measured on the OTIS dolly**
  - For repeatability purposes the dolly was leveled using three points
  - Shims added between the VF and the mating interface to insure proper alignment in piston and angle
- **Prior to the OTIS integration to the vibration fixture, the SSDIF temperature was increased to 24C, which allowed for the vibration fixture to expand to the nominal position which decreased the integration loads**



Vibration fixture with OTIS on the dolly

Conclusion

- Provided an overview of the alignment, testing, and verification processes used at the NASA GSFC in preparation of the HIF and vibration fixture for OTIS use
- The OTIS successfully completed both vibration and acoustic testing on the vibration fixture, and the OTIS was successfully transported in STTARS to Johnson Space Center on the HIF for cryogenic testing prior to integration with the spacecraft and flight

References

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