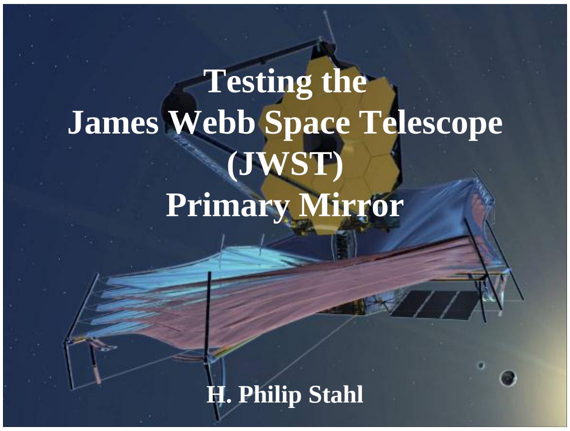


Optical Testing Challenge

JWST

In-Process Optical Testing

Requirement Compliance Certification Verification & Validation

is probably the most difficult metrology job of our generation

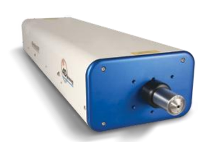
But, the challenge has been met:

by the hard work of dozens of optical metrologists,

the development and qualification of multiple custom test setups, and

several new inventions, including 4D PhaseCam and Leica ADM.

4-D PhaseCam & Leica ADM



PhaseCam

Simultaneous Phase-Measuring Interferometer enables ability to test 16 m ROC JWST PMSA.
Camera: 2k x 2k
(1.3 mm/pixel at PMSA)
Precision: 0.5 nm rms

Absolute Distance Meter

Polarization Phase-Modulation
Beam can be interrupted
Range: 1.7 to 50 meters
Resolution: 1 µm
Absolute Accuracy: 25 to 50 µm
Reproducibility: 10 to 20 µm

Metrology Guiding Principles

Based on my 30 years of optical testing experience, a lot of mistakes, a lot of learning and a lot of experience:

JWST Metrology was performed via these 7 guiding principles:

1. Fully Understand the Task
2. Develop an Error Budget
3. Continuous Metrology Coverage
4. Know where you are
5. 'Test like you fly'
6. Independent Cross-Checks
7. Understand All Anomalies

Rule #1: Fully Understand the Task

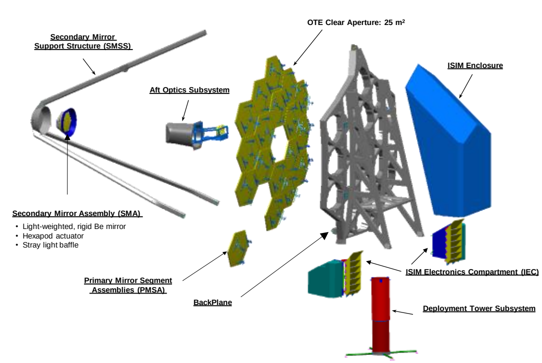
Make sure that you fully understand your task:
- who is your customer;
- what parameters do you need to quantify;
- to what level of uncertainty you must know their value; and
- who is your manufacturing interface?

Before accepting any testing task, study your customer's requirements and understand how they relate to the final system application.

Then summarize all requirements into a simple table which can be shared with your customer and your manufacturing methods engineer.

Make sure that your customer agrees that what you will quantify satisfies their requirements and the manufacturing methods engineer agrees that they can make the part based upon the data you will be providing.

OTE Architecture Concept



JWST Optical Testing Needs

The principle JWST optical testing needs include:

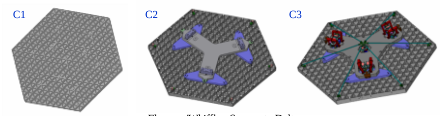
Optical Component Assemblies
- Primary Mirror Segment Assembly (PMSA) 18 + 3 spares
- Secondary Mirror Assembly (SMA) 1 + 1 spare
- Tertiary Mirror Assembly (TMA) 1

Observatory Elements
- Primary Mirror Assembly (PMA)
- Optical Telescope Element (OTE)

Additionally, there are multiple other optics such as the fine steering mirror and various instrument optical components.

Optical Component Configurations

There are 3 mirror configuration 'states':
- Configuration 1 = Substrate Only
- Configuration 2 = Flight Flexures & Whiffle and Surrogate Delta Frame
- Configuration 3 = Flight



Substrate Only — Flexures/Whiffles Surrogate Delta Frame — Fully Assembled

JWST Optical Component Specifications

All Components have Cryogenic Performance Specifications

Since components are fabricated at Ambient it is necessary to Cryo-Null Figure, i.e. compensate for ambient to cryo changes

All Components have:
- an Initial Requirement which must be met before Cryo-Testing
- a Final Post Cryo-Null Figuring Requirement, and
- a Final Cryogenic Performance Requirement

Segment Fabrication Requirements & Tolerances

Parameter	Specification	Tolerance	Units	Comments
Requirements for initial figuring				
Clear Aperture (based on Edge Specification)	1.4776	Minimum	mm^2	*Different for 3 segments
Scratch-Dig	80-50	Maximum		
Conic Constant	-0.99666	+/- 0.0010		
Radius of Curvature	15899.915	+/- 1	mm	
Prescription Alignment Error				
Decenter	*	≤ 0.35	mm	*Different for 3 segments
Clocking	0	≤ 0.35	mrad	
Piston	N/A			Measure only, no requirement
Tilt	N/A			Measure only, no requirement
Total Surface Figure Error:				
Low/Mid Frequency (≥222 mm/cycle)	150	Maximum	nm rms	
High Frequency (222 to 0.08mm/cycle)	20	Maximum	nm rms	
Slope Error	25	Maximum	μrad	
Requirements for cryo-null figuring				
Clear Aperture (based on Edge Specification)	1.4776	Minimum	mm^2	*Different for 3 segments
Scratch-Dig	80-50	Maximum		
Conic Constant	-0.99666	+/- 0.0005		
Radius of Curvature	*	+/- 0.10	mm	*Radius value supplied
Prescription Alignment Error				
Decenter	*	≤ 0.35	mm	* Decenter value supplied
Clocking	0	≤ 0.35	mrad	
Piston	N/A			Measure only, no requirement
Tilt	N/A			Measure only, no requirement
Total Surface Figure Error:				
Low/Mid Frequency (≥222 mm/cycle)	20	Maximum	nm rms	Relative to cryo-target map
High Frequency (222 to 0.08mm/cycle)	7	Maximum	nm rms	Relative to cryo-target map
PSD Spike Requirement	Spike Limit			
Surface Roughness	4	Maximum	nm rms	

Metrology Plan for Each Requirement

Parameter	Spec	Tol	Units	Verification	Validation
Clear Aperture (Edge Specification)	1.4776 (5)	Min (Max)	mm^2 (mm)	Measure edges at ambient using Tinsley HS Interferometer	Measure area at cryo using XRCF CoC Interferometer
Scratch-Dig	80-50	Max		Ambient Visual Inspection	Independent Visual
Conic Constant	-0.99666	+/- 0.0005		Measured at cryo and defined by null geometry for XRCF CGH CoC test	Ambient test at Tinsley, compare CGH CoC test with auto-collimation test
Radius of Curvature	*	+/- 0.15	mm	Set at XRCF using ADM	ROCO Comparison
Prescription Alignment Error					
Decenter	*	≤ 0.35	mm	Cryogenic test at XRCF, defined by residual wavefront error relative to CGH CoC test and fiducial alignment	Ambient test at Tinsley, compare CGH CoC test with auto-collimation test
Clocking	0	≤ 0.35	mrad		
Piston	N/A			Ambient CMM measurement at AXSYS	Ambient CMM measurement at Tinsley
Tilt	N/A				
Total Surface Figure Error:					
Low/Mid Frequency	20	Max	nm rms	Cryo-Test at XRCF	Cryo-Test at JSC
High Frequency	7	Max	nm rms		
Surface Roughness	4	Max	nm rms	Ambient Chapman measurement at Tinsley	NONE

Rule #2: Develop an Error Budget

Develop an error budget for every specification & tolerance.

Error budget predicts test accuracy and reproducibility (not repeatability) of the metrology tools.

- Reproducibility is the ability of 'independent' measurement executions to achieve the same answer, e.g. take down and re-set a test.

All elements of error budget must be certified by absolute calibration and verified by independent test.

An error budget has multiple functions.
- Convinces your customer that you can actually measure the required parameters to the required tolerances;
- Defines which test conditions have the greatest impact on test uncertainty;
- Provides a tool for monitoring the test process.

If the variability in the test data exceeds the error budget prediction, then you must stop and understand why.

Error Budget Contingency

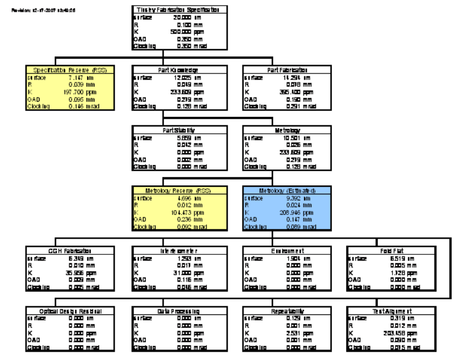
An Error Budget MUST have Contingency Reserve.

No matter how much one things about every potential contingency risk or how careful one executes, errors happen.

On JWST, as the primary mirror segment fabrication process improved, the segments were greatly below their requirement. But, an incorrect calibration file was used on two PMSAs resulting in residual excess power (of approx 1/3rd of its figure requirement). But, the primary mirror still met spec.

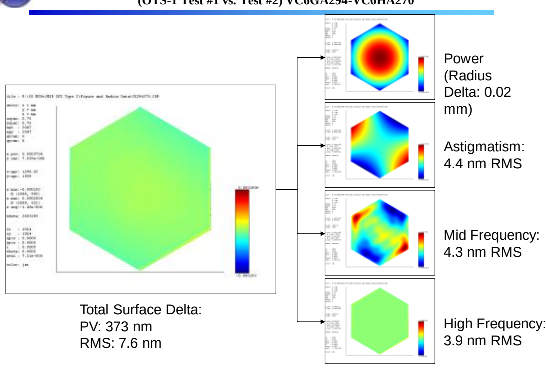
A good value for Reserve is 33% of the Requirement.

JWST PMSA Error Budget



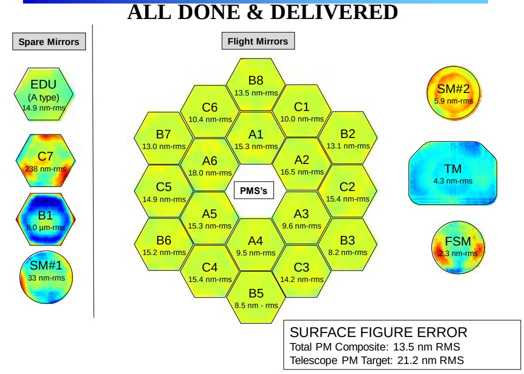
Tinsley Test Reproducibility

(OTS-1 Test #1 vs. Test #2) VC6GA294-VC6HA270



Mirror Status at L-3 SSG-Tinsley – 11 July 12

ALL DONE & DELIVERED



Rule #3: Continuous Metrology Coverage

Third, have continuous metrology coverage:

- 'you cannot make what you cannot test'
- (or 'if you can test it then you can make it').

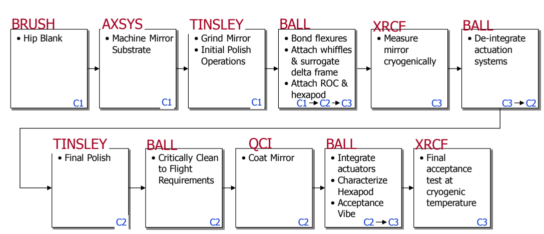
Every step of the manufacturing process must have metrology feedback and there must be overlap between the metrology tools for a verifiable transition.

Failure to implement this rule typically results in one of two outcomes:

- very slow convergence, or
- negative convergence.

Optical Component Manufacturing Flow

Manufacturing flow is nearly identical for all optical components



There are Metrology 'Gates' between each processing step. Components must meet their requirements to go to the next step.

Continuous Metrology Coverage

JWST developed overlapping tools to measure & control
- conic constant,
- radius of curvature,
- prescription alignment and surface figure error

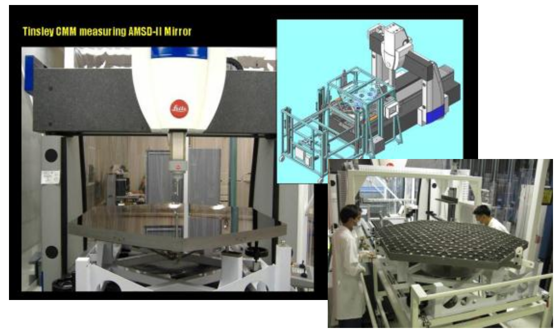
throughout the fabrication process.

During rough grinding, used a Leitz Coordinate Measuring Machine (CMM) for radius of curvature & conic constant.
- Over course of program, software and process improvements dramatically reduced cycle time and increased data density

During polishing, meterololgy was provided by a Center of Curvature (CoC) interferometric test.

Leitz CMM

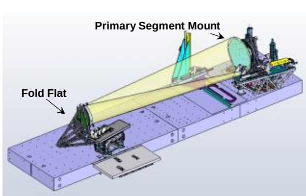
CMM was sized to test PMSA Full Aperture

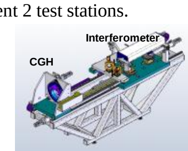


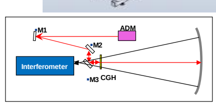
Full Aperture Optical Test Station (OTS)

Center of Curvature Null Test measured & controlled:
- Prescription,
- Radius &
- Figure

Results are cross-checked between different 2 test stations.







Continuous Metrology Coverage

Ordinarily, optical fabricators try to move directly from CMM to optical test during fine grinding. But, given the size of JWST PMSAs and the mid-spatial frequency specification, this was not possible.

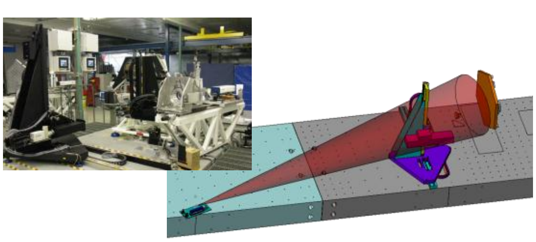
Bridge data was provided by a Wavefront Sciences Scanning Shack Hartmann Sensor (SSHS).
- Its infrared wavelength allowed it to test surfaces in a fine grind state.
- And, its large dynamic range (0 to 4.6 mrad surface slope), allowed it to measure surfaces which were outside the interferometer's capture range.

Wavefront Sciences Scanning Shack-Hartmann

SSHS provided bridge-data between grind and polish, used until PMSA surface was within capture range of interferometry

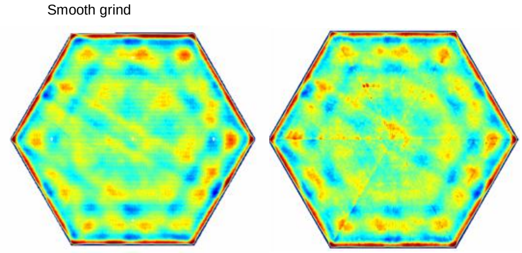
SSHS provide mid-spatial frequency control: 222 mm to 2 mm
- Large dynamic range (0 – 4.6 mr surface slope)

When not used, convergence rate was degraded.



Comparison (222 - 2 mm spatial periods) 8/1/06

Smooth grind



SSHS
4.7 µm PV, 0.64 µm RMS

CMM
4.8 µm PV, 0.65 µm RMS

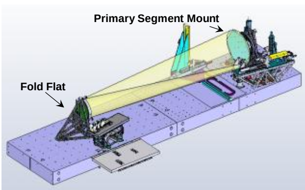
Point-to-Point Subtraction: SSHS - CMM = 0.27 µm RMS

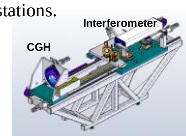
Full Aperture Optical Test Station (OTS)

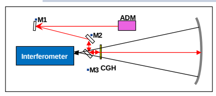
Center of Curvature Null Test (Prescription, Radius & Figure)

- PMSAs measured in 6 rotational positions to back-out gravity
- ADM – measures spacing between CGH and segment
- CGH – generates aberrated wavefront
- Quad cells – mounted to segments measure displacement of spots projected through CGH to determine parent vertex location

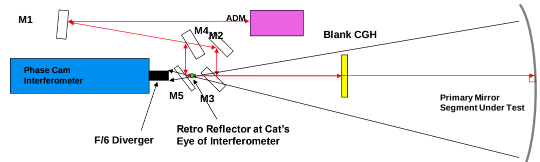
Results are cross-checked between 2 test stations.







Radius of Curvature Test Setup in Optical Test



Using ADM, measure distances from:

- Interferometer Cat's Eye Focus to CGH
- CGH to PMSA Center

Results are certified via ROCO (Radius Of Curvature Optic)

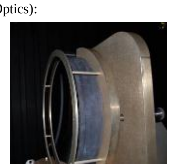
(Reference Optical Test: Segment Alignment Procedure and Radius of Curvature Test Procedure: Tinsley Documents 1136 and 1095, respectively)

ROCO

Two ROCOs provided 'calibrated' radius standard for RoC measurements at Tinsley, BATC and XRCF for initial certification and periodic recertification.

Radius Of Curvature Optic, or ROCO (made by Coastal Optics):

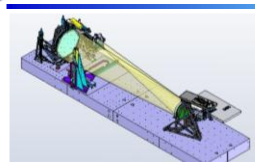
- Surface Shape: Sphere
- Material: Corning ULE TSG
- Diameter: 508 mm
- Design RoC: 5080 mm (R/10)
- Coating: protected aluminum
- SFE: <17 nm-rms

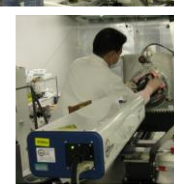


RoC of each ROCO measured at Univ of Arizona to uncertainty <0.050 mm.

"Null" CGH designed & built (two) to simulate PMSA measurement (only has power).

Full Aperture Optical Test Station (OTS)



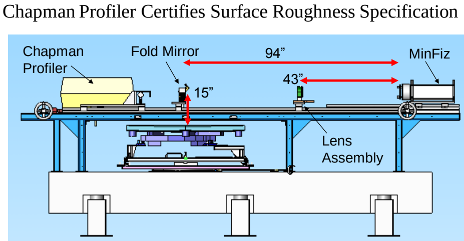


High Spatial-Frequency Interferometer (HS) & Chapman Surface Roughness Profiler

HS Interferometer:

- Certifies High-Spatial Surface Compliance by measuring multiple sub-apertures
- Certifies Clear Aperture Edge Specification

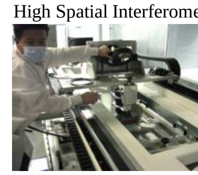
Chapman Profiler Certifies Surface Roughness Specification



High Spatial-Frequency Interferometer (HS) & Chapman Surface Roughness Profiler

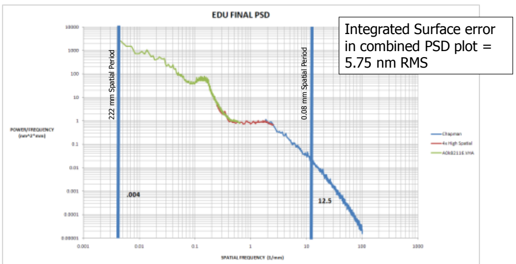
Chapman Profiler

High Spatial Interferometer



Final Mid- & High-Spatial Frequency Certification

Paragraph	Description	Tol	Requirement	EB Required	Actual	P/F	T°C	Tools	Comments
3.2.8	High Frequency RMS	Max	7 nm	6.4 nm	5.8 nm	Pass	20.0	OTS and HS Interferometer	



Rule #4: Know where you are

It might seem simple, but if you don't know where a feature is located on the mirror, you cannot correct it. This requires fiducials.

There are two types of fiducials: Data Fiducials and Distortion Fiducials.

Data fiducials are used to define a coordinate system and locate the measured data in that coordinate system. Sometimes this coordinate system is required to subtract calibration files, other times it is required to produce hit maps.

Distortion fiducials are used to map out test setup pupil distortion. Many test setups, particularly those with null optics can have radial as well as lateral pupil distortion. Distortion can cause tool mis-registration errors of 10 to 50 mm or more.

Fiducials

Fiducials can be as simple as a piece of tape or ink marks on surface under test or as sophisticated as mechanical 'fingers' protruding into clear aperture.

For computer controlled processes, fiducial positional knowledge is critical.

Because test setups might invert or flip the imaging, I highly recommend an asymmetric pattern. The pattern which I have always used is:
- 0/180 degree fiducials produce a central axis for the data set,
- 90 degree fiducial defines left/right, and
- 30 degree fiducial defines top/bottom.

For rotationally symmetric systems, one option for distortion fiducials is multiple marks along a radius.

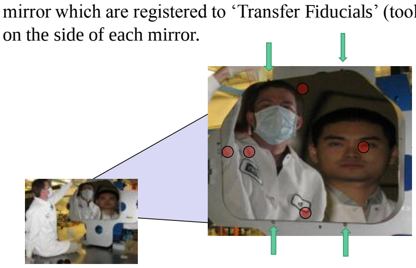
But for asymmetric systems, a grid of marks is required.

Finally, if you have a clear aperture requirement, place marks inside and outside of the required clear aperture.

Master Datums and Fiducials

Mirrors are manufactured in Observatory Coordinate Space as defined by 'Master Datums' on back of each mirror substrate.

Figure error is measured using 'Data Fiducials' on front of each mirror which are registered to 'Transfer Fiducials' (tooling balls) on the side of each mirror.

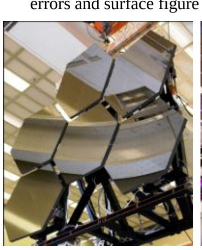


Master Datums and Fiducials

Data, Distortion and Edge Fiducials are used for PMSA testing.

Transfer Fiducials register these to the Master Datums on back.

This knowledge is critical because of redundancy between alignment errors and surface figure errors



Rule #5: 'Test like you fly'

You must 'Test like you fly'.

JWST operates in the cold of space. Therefore, we must certify
- 30K optical performance in the MSFC XRCF, and
- 'zero-g' performance via a 6 rotation test at BATC BOTS.

Observatory level qualification < 50K is done at JSC Chamber A.

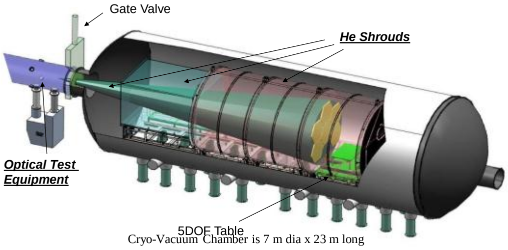
Also, 'test as you fly' is not limited to space telescopes. Ground based telescopes can have large gravity sags.

Therefore, they must be tested in their final structure (or a surrogate).

PMSA Flight Mirror Testing at MSFC XRCF

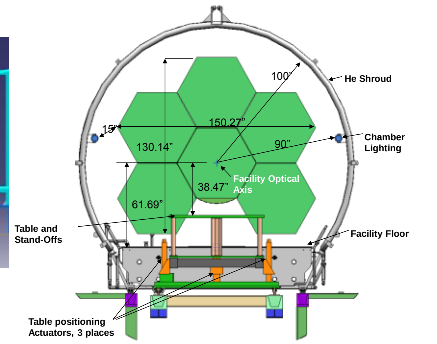
Cryogenic Performance Specifications are Certified at XRCF

Because JWST mirrors are fabricated at room temperature (300K) but operate < 50K, their shape change from 300 K to 30K is measured to generate a ‘hit-map’, and cryo-null polish the mirrors.

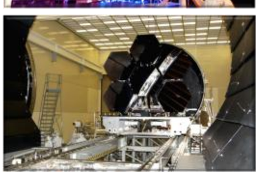


Cryo-Vacuum Chamber is 7 m dia x 23 m long

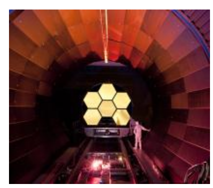
JWST Flight Mirror Test Configuration

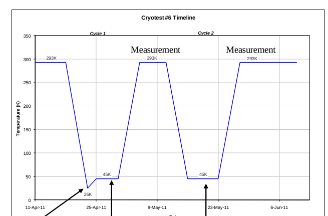


Primary Mirror Cryogenic Tests



XRCF Cryo Test





- Survival Temperature

- Cryo Deployment
- Nominal Measurement
- Hexapod Deformation Pose
- RoC Actuation Test
- Hexapod Envelope Test
- Pullout Current & Redundant Test (3 of 6 PMSAs)

- Set RoC
- Nominal Measurement
- Hexapod Tilt Test
- Pullout Current & Redundant Test (3 of 6 PMSAs)

Flight Mirrors in XRCF

Rule #6: Independent Cross-Checks

Probably the single most ‘famous’ lesson learned from Hubble is to never rely on a single test to certify a flight specification.

Every JWST optical component specification had a primary certification test and a confirming test.

Every Requirement has Independent Validation

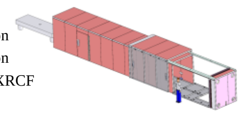
Parameter	Spec	Tol	Units	Verification	Validation
Clear Aperture (Edge Specification)	1.4776 (5)	Min (Max)	mm^2 (mm)	Measure edges at ambient using Tinsley HS Interferometer	Measure area at cryo using XRCF CoC Interferometer
Scratch-Dig	80-50	Max		Ambient Visual Inspection	Independent Visual
Conic Constant	-0.99666	+/- 0.0005		Measured at cryo and defined by null geometry for XRCF CGH CoC test	Ambient test at Tinsley, compare CGH CoC test with auto-collimation test
Radius of Curvature	*	+/- 0.15	mm	Set at XRCF using ADM	ROCO Comparison
Prescription Alignment Error					
Decenter	*	≤ 0.35	mm	Cryogenic test at XRCF, defined by residual wavefront error relative to CGH CoC test and fiducial alignment	Ambient test at Tinsley, compare CGH CoC test with auto-collimation test
Clocking	0	≤ 0.35	mrad		
Piston	N/A			Ambient CMM measurement at AXSYS	Ambient CMM measurement at Tinsley
Tilt	N/A				
Total Surface Figure Error:					
Low/Mid Frequency	20	Max	nm rms	Cryo-Test at XRCF	Cryo-Test at JSC
High Frequency	7	Max	nm rms		
Surface Roughness	4	Max	nm rms	Ambient Chapman measurement at Tinsley	NONE

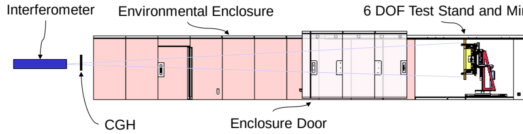
Ball Optical Test Station (BOTS)

Tinsley ambient metrology results are 'cross-checked' at BATC

BOTS measurements:

- Measure Configuration 1 to 2 deformation
- Measure Configuration 2 to 3 deformation
- Create a Gravity Backout file for use at XRCF
- Measure Vibration Testing Deformation
- Measure Vacuum Bakeout Deformation
- Measure Configuration 2 mirrors for BATC to Tinsley Data Correlation





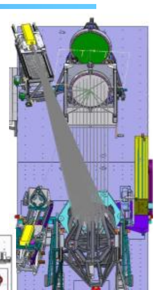
Auto-Collimation Test

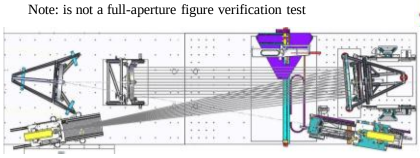
Auto-Collimation Test provides independent cross-check of CGH Center of Curvature Test

Verifies:

- Radius of Curvature
- Conic Constant
- Off-Axis Distance
- Clocking

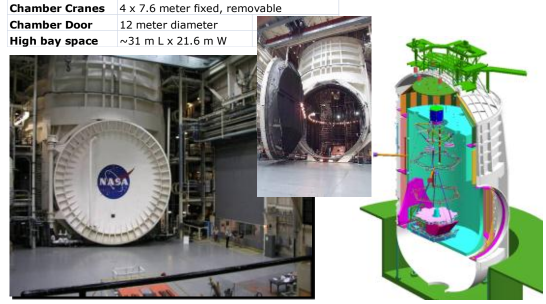
Note: is not a full-aperture figure verification test





Final Cross-Check performed at Observatory Level

Johnson Space Center Chamber A	
Chamber size	16.7 meter diameter, 35.6 meter tall
Existing Shrouds	LN2 shroud, GHe panels
Chamber Cranes	4 x 7.6 meter fixed, removable
Chamber Door	12 meter diameter
High bay space	~31 m L x 21.6 m W



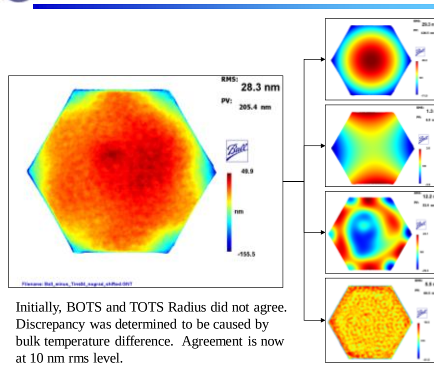
Rule #7: Understand All Anomalies

Finally, understand all anomalies.

Of all the rules, this one maybe the most important and must be followed with independent rigor.

No matter how small, one must resist the temptation of sweeping a discrepancy under the metaphorical error budget rug.

BATC to Tinsley Initial Comparison too large



Initially, BOTS and TOTS Radius did not agree. Discrepancy was determined to be caused by bulk temperature difference. Agreement is now at 10 nm rms level.

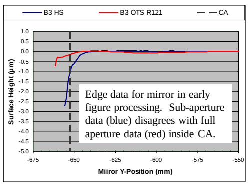
Clear Aperture Edge Specification

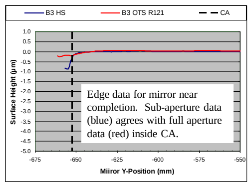
Center of Curvature test and High-Spatial Frequency test gave entirely different answers for compliance with Edge Requirement – 15 mm difference.

Which one was right had significant cost & schedule impact.

HS was right, CoC was wrong.

Problem was caused by depth of focus and Fresnel diffraction.





Other Anomaly Examples

OTS#1 & OTS#2 gave different measures for radius of curvature.

Cause: a slipping translation motor.

Neither Tinsley nor Ball OTS data were repeatable enough.

Cause: too much thermal PMSA variation.

Initial XRCF cryo-test had very large deformations.

Cause: mechanical interference with an electrical cable.

Conclusions

Based on 30 years of optical testing experience, I have defined seven guiding principles for optical testing.

- Fully Understand the Task
- Develop an Error Budget
- Continuous Metrology Coverage
- Know where you are
- 'Test like you fly'
- Independent Cross-Checks
- Understand All Anomalies

With maybe an 8th of deliberately disturbing or randomizing the test.

JWST optical component in-process optical testing and cryogenic compliance certification, verification & validation was accomplished by a dedicated metrology team used these principles.

All JWST optical components meet their requirements.

ANY QUESTIONS?