TRL-6 Qualification of JWST Mirror Segments

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Introduction

Since JWST's inception, Mirror Technology was identified as a (if not the) critical capability necessary to achieve the Level 1 science goals.

A never before demonstrated space telescope capability was required:

6 to 8 meter class primary mirror,

diffraction limited at 2 micrometers and

operates at temperatures below 50K.

Launch vehicle constraints placed significant architectural constraints:

maximum payload fairing diameter is ~ 4.5 meters – resulting in segmented PM

mass limits the PM to ~ 1000 kg – resulting in 20 kg/m2 areal density

Such mirror technology had never been demonstrated – and did not exist.

Pre-JWST Technology Readiness

Assessment of pre-1996 state of art indicated that necessary mirror technology (as demonstrated by existing space, ground and laboratory test bed telescopes) was at TRL-3

1996 JWST Optical System Requirements State of Art						
Parameter	JWST	Hubble	Spitzer	Keck	LAMP	Units
Aperture	8	2.4	0.85	10	4	meters
Segmented	Yes	No	No	36	7	Segments
Areal Density	20	180	28	2000	140	kg/m2
Diffraction Limit	2	0.5	6.5	10	Classified	micrometers
Operating Temp	<50	300	5	300	300	K
Environment	L2	LEO	Drift	Ground	Vacuum	Environment
Substrate	TBD	ULE Glass	I-70 Be	Zerodur	Zerodur	Material
Architecture	TBD	Passive	Passive	Hexapod	Adaptive	Control
First Light	TBD	1993	2003	1992	1996	First Light

Mirror Technology Development

A systematic development program was undertaken to build, test and operate in a relevant environment directly traceable prototypes or flight hardware:

Sub-scale Beryllium Mirror Demonstrator (SBMD)
NGST Mirror System Demonstrator (NMSD)
Advanced Mirror System Demonstrator (AMSD)
JWST Engineering Test Units (EDU)

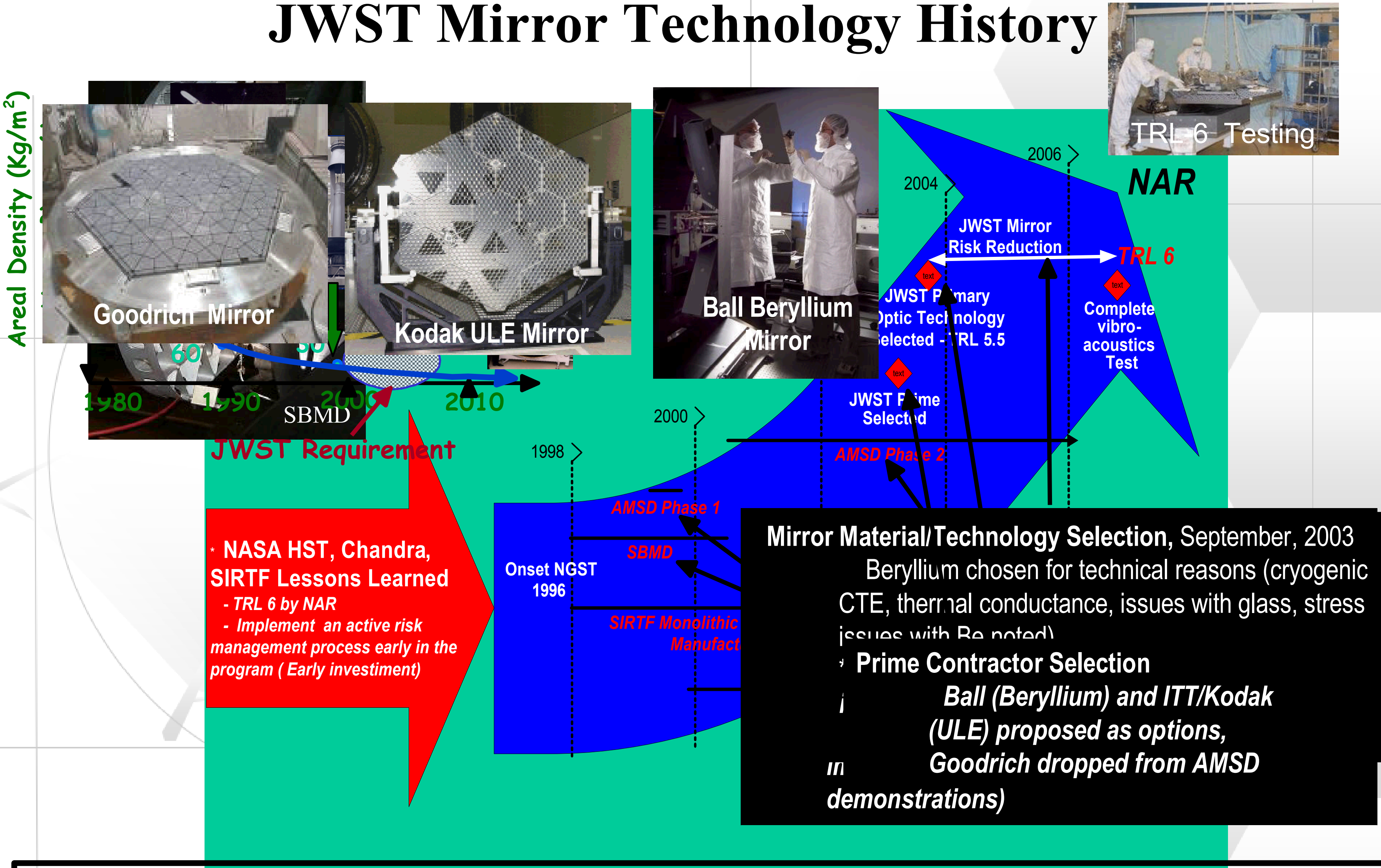
Goal was to dramatically reduce cost, schedule, mass and risk for large-aperture space optical systems.

A critical element of the program was competition – competition between ideas and vendors resulted in:

remarkably rapid TRL advance in the state of the art
significant reductions in the manufacturing cost and schedule

It took 11 years to mature mirror technology from TRL 3 to 6.

JWST Mirror Technology History



Based on lessons learned, JWST invested early in mirror technology to address lower areal densities and cryogenic operations

PMSA Requirements Traceability

PMSA Requirements are fully traceable from Level 1 Science Requirements to Level 2 Mission Requirements to Level 3 Observatory Requirements.

PMSA Requirement Traceability

Level 1 Requirements	Level 2 Requirements	PMSA Technology
L1-01: Spectral Range	MR-211: Optical Transmission	PMSA-110: Spectral Reflectance 0.6-28 µm
		PMSA-530: Operational Temp 28-50K
L1-04: Celestial Coverage	MR-115: EE Stability	PMSA-170: Thermal Change < 0.3 nm rms/K
L1-12: L2 Orbit	MR-099: Mass	PMSA-410: Mass < 39.17 kg
	MR-283: Launch Loads	PMSA-180: Launch Distortion < 2.9 nm rms
L1-13: PM Collecting Area	MR-198: PM Collecting Area	PMSA-70: Polished Surface Area > 1.46 m^2
L1-14: Observ Strehl Ratio	MR-228: OTE WFE	PMSA-150: Uncorrectable Fig < 23.7 nm rms
		PMSA-195: Creep < 1.8 nm rms
		PMSA 1560: ROC Resolution < 10 nm sag
		PMSA 370: 6 DOF (Resolution < 10 nm)
L1-16: Thermal Environment	MR-122: Thermal Emission	PMSA-530: Operational Temp 28-50K

Comparison of JWST Requirements with pre-JWST State of the Art

JWST Mirror Technology vs State of Art			
PMSA Technology	JWST Requirement	Hubble	Spitzer
PMSA-110: Spectral Reflectance 0.6-28 µm PMSA-530: Operational Temperature 28-50K	Gold Coating on O-30 Be with 28K Survival	UV/Visible	Uncoated
PMSA-170: Surface Figure Thermal Change	< 7.5 nm rms for 30 to 55K		
PMSA-410: Mass < 39.17 kg	Areal Density < 26.5 kg/m2	180 kg/m2	28 kg/m2
PMSA-180: Surface Distortion from Launch	< 2.9 nm rms		< ~ 20 nm rms
PMSA-70: Polished Surface Area	1.3 meter diameter Segment	2.4 meter	0.85 meter
PMSA-150: Uncorrectable Surface Error	< 23.7 nm rms Surface Error	6.4 nm rms	75 nm rms
PMSA-195: Surface Change from Creep	Design to O-30 Be PEL	ULE PEL	I-70 Be PEL
PMSA 1560: ROC Adjustment Resolution	< 10 nm pv sag	None	None
PMSA 370: Hexapod 6 DOF	< 10 nm step Actuators at 30K	None	None
PMSA-530: Operational Temperature 28-50K	Operates 28-50K	300K	4.5K

Success Criteria & Results Summary

Mirror Technology Success Criteria			
PMSA Technology	**Success Criteria**	**Achieved**	**Method**
PMSA-110: Spectral Reflectance 0.6-28 µm	Gold Coating on O-30 Be with 28K Survival	Gold Coating on O-30 Be with 28K Survival	SBMD
PMSA-530: Operational Temperature 28-50K			
PMSA-170: Surface Figure Thermal Change	< 7.5 nm rms for 30 to 55K	7 nm rms from 30 to 55K	AMSD
PMSA-410: Mass < 39.17 kg	Areal Density < 26.5 kg/m2	Areal Density = 15.6 kg/m2 Areal Density = 26.1 kg/m2	AMSD JWST B1
PMSA-180: Surface Distortion from Launch < 2.9 nm rms	Less than metrology error budget of 14 nm rms	10.6 nm rms Surface Change from Vib & Acoustic Test	JWST B1
PMSA-70: Polished Surface Area > 1.46 m2	1.3 meter diameter Segment delivered from AXSYS	1.3 meter diameter 1.5 meter diameter	AMSD JWST
PMSA-150: Uncorrectable Surface Error	< 23.7 nm rms Surface Error	18.8 nm rms 30K Figure 19.2 nm rms 300K Figure	SBMD AMSD
PMSA-195: Surface Change from Creep < 1.8 nm rms	Design to O-30 Be PEL	Designed to ensure < 1500 psi residual stress	SBMD AMSD JWST
PMSA 1560: ROC Adjustment Resolution	< 10 nm pv sag	0.8 nm pv sag	AMSD
PMSA 370: Hexapod 6 DOF	< 10 nm step Actuators at 30K	7.5 nm step Actuators at 30K	AMSD JWST
PMSA-530: Operational Temperature 28-50K	Operates 28-50K	Operated at 28-50K	AMSD

Gold Coating on O-30 Be with 28K Survival

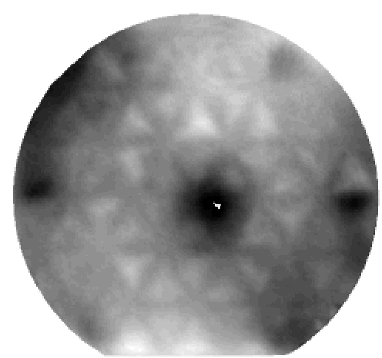
SBMD survival tested to 28K

- Gold Coating provides Spectral Range
- Adhesion demonstrates Operational Temperature

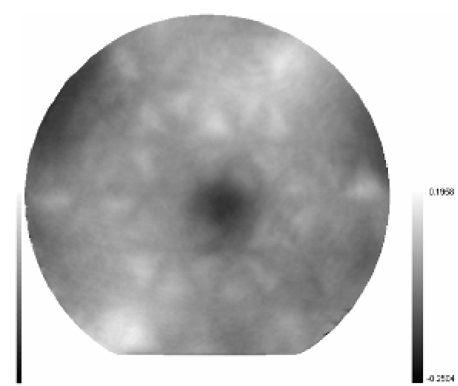
Adhesion of Gold on O-30 Be at 28K was technology needing to be demonstrated for TRL-6. Not ability to coat.

No significant Figure Change

SBMD Uncoated
Figure @ 30K
52.8 nm-rms



SBMD Coated
Figure @ 30K
53.9 nm-rms



Cryo-Null Figuring Demonstration

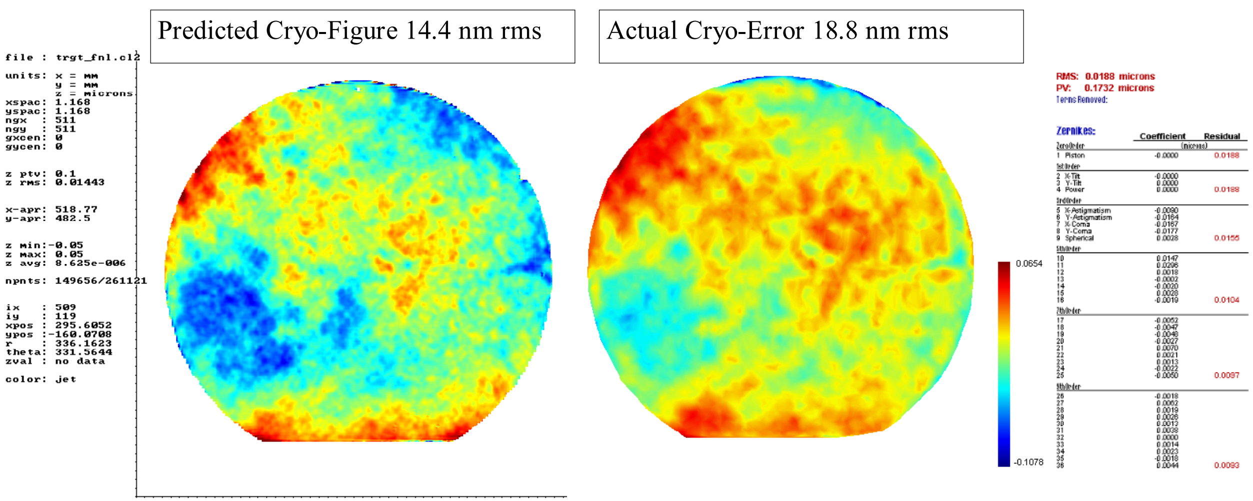
SBMD exhibited a cryo-deformation of approximately 90 nm rms.

Shape changed consisted of low-order mount induced error & high-order quilting error (rib structure).

SBMD was cryo-null figured using Tinsley small tool CCOS technology.

Predicted final cryogenic surface figure was 14.4 nm rms.

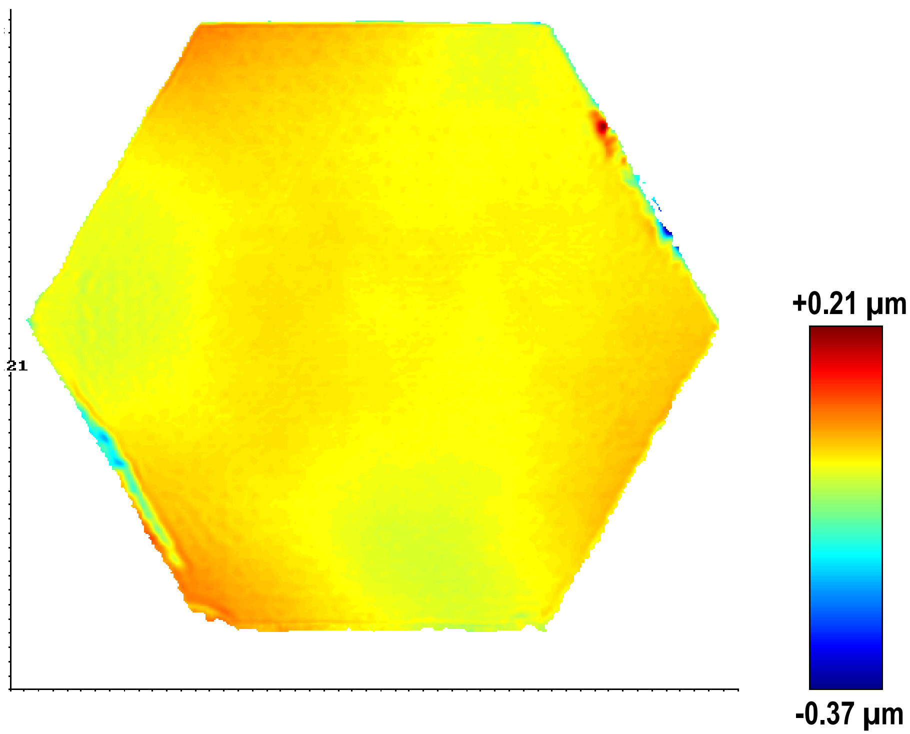
Actual final cryogenic surface error was 18.8 nm rms.



AMSD Key Technology Results

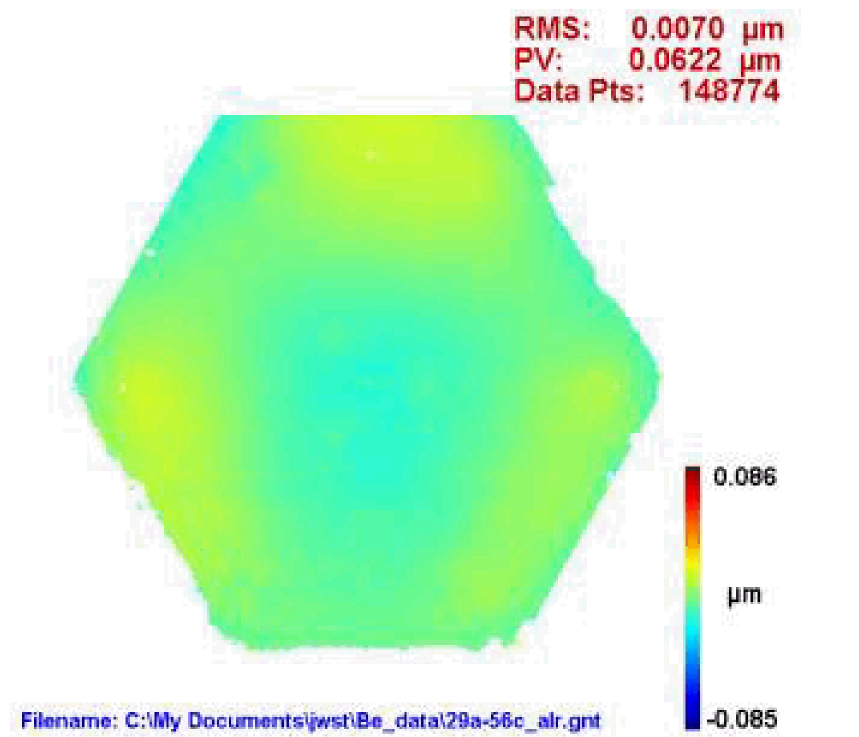
Results of AMSD 20 nm-rms convergence
RMS = 19.2 nm
Area of Mirror = 97.1%

Requirements PMSA-150 & 70



Results of AMSD-II 30 to 55 Kelvin Operational range
Delta = 7 nm-rms (0.28 nm-rms/K)

Requirement PMSA-170



Four PMSA Technology Demonstrators Were Used to Show TRL-6

Technology Demonstrator	Technology Developed	Validity to JWST
SBMD	Cryogenic Coating	SBMD developed a low stress gold coating application that can be applied to any beryllium mirror. Coating of large mirrors (like JWST) is not material specific and has been developed on other flight programs.
AMSD Mirror	Figuring, cryogenic performance, actuation capability	All differences between the JWST PMSA and the AMSD mirror improves manufacturability, cryogenic performance, and provides more actuation degrees of freedom (See next slide).
AMSD Stress Coupons	Long term material stability	JWST PMSA's are manufactured using the exact processing developed on AMSD III to assure low residual surface stresses and low material creep.
JWST Flight Segment	Low Launch distortion Actuation Capability	JWST flight segment used to show technology readiness

JWST Mirror Design Builds on AMSD Heritage

AMSD Mirror

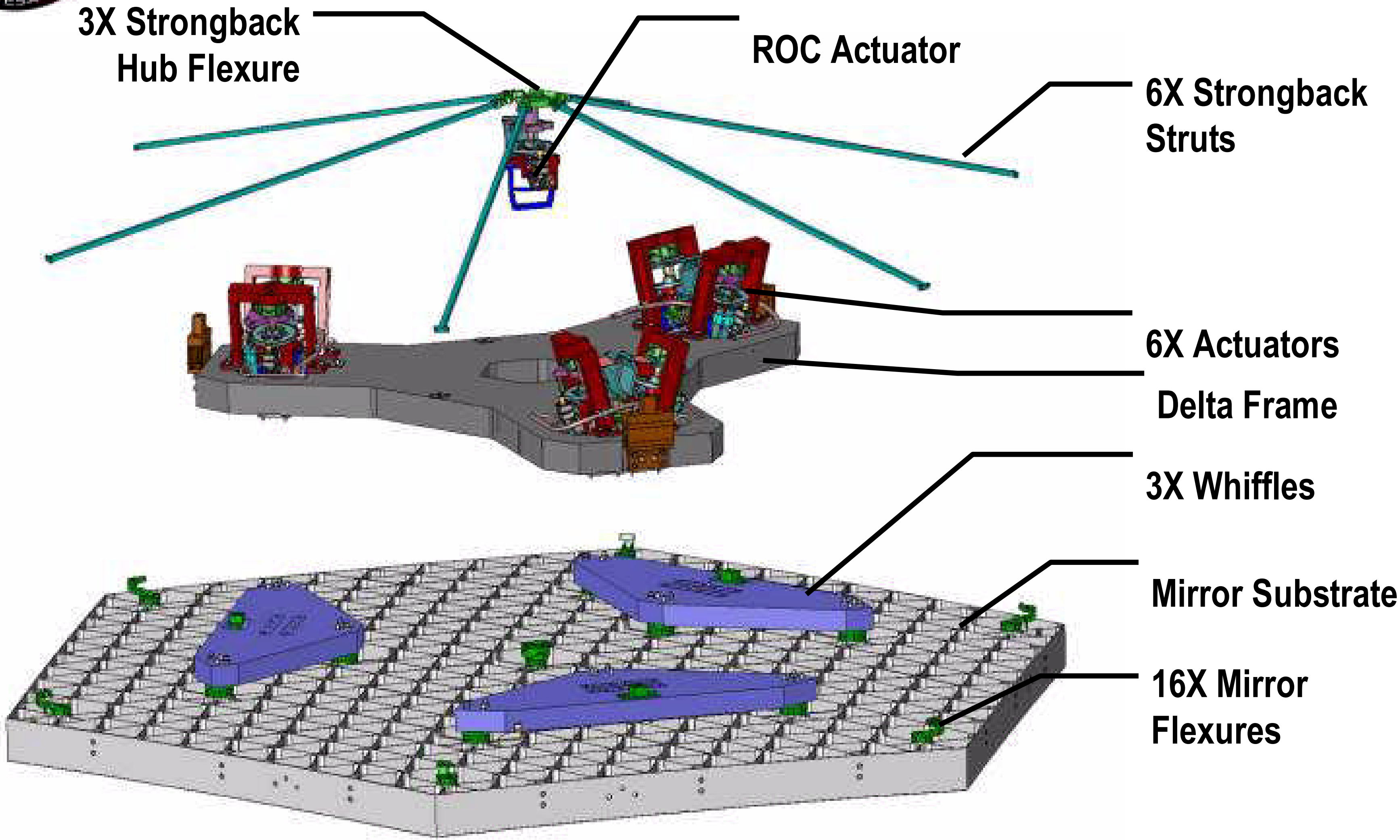
Photos shown approximately to scale

JWST Mirror

JWST flight mirror design improves producibility, performance and reduces risk relative to AMSD

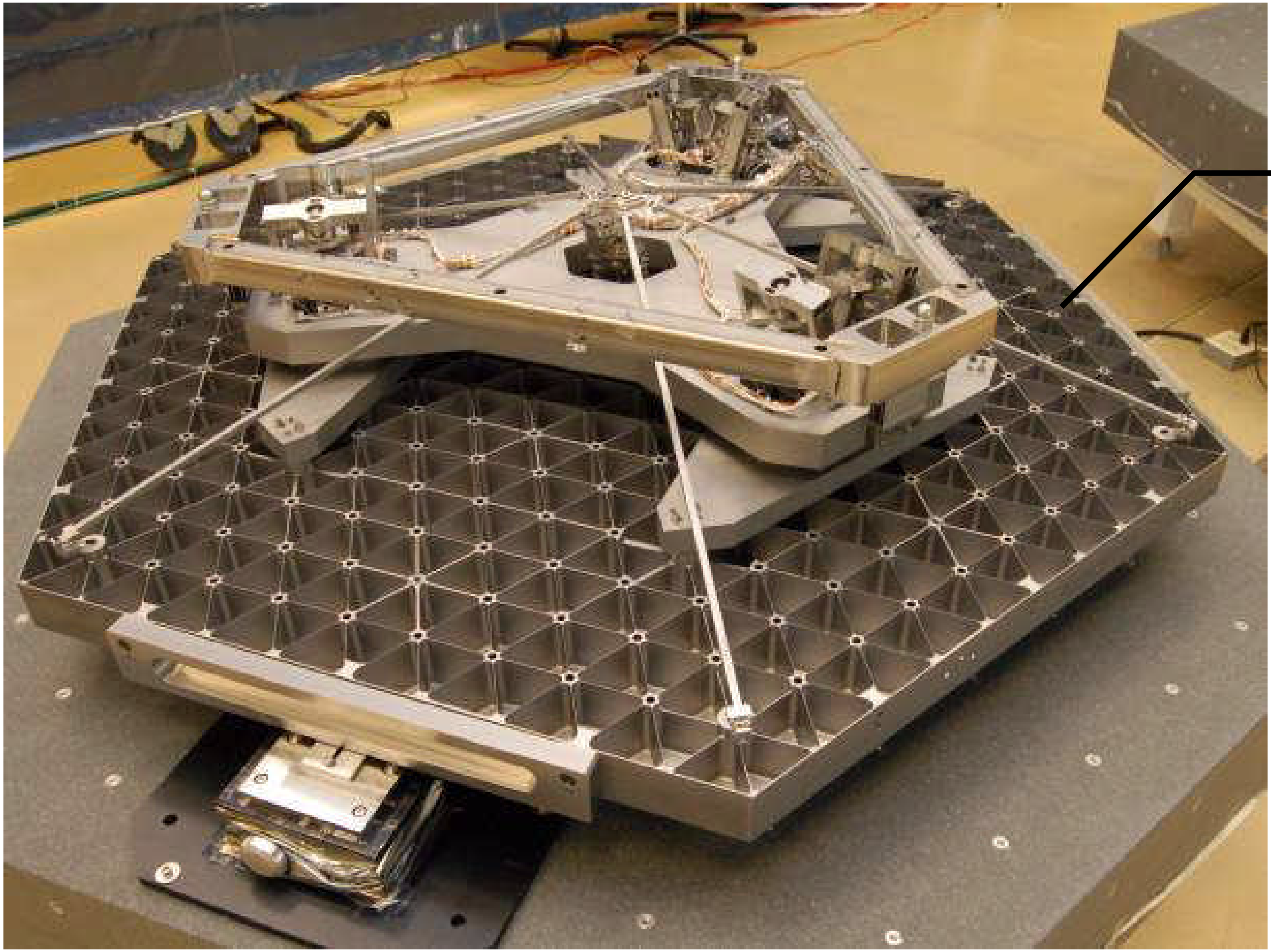
Key Design Parameter	AMSD	JWST
Material	Be O-30	Be O-30
Point to point dimension	1.4 m	1.52 m
Number of pockets	864	600
Substrate thickness	60 mm	59 mm
Stiffness (f-f first mode)	180 Hz	260 Hz
Substrate areal density	10.4 kg/m^2	13.8 kg/m^2
Assembly areal density	19.1 kg/m^2	26.2 kg/m^2
Surface figure (assy level)	22 nm-rms	24 nm-rms

PMSA Component Definition



Mirror Substrate focus of technological development

Mirror required Technological Development



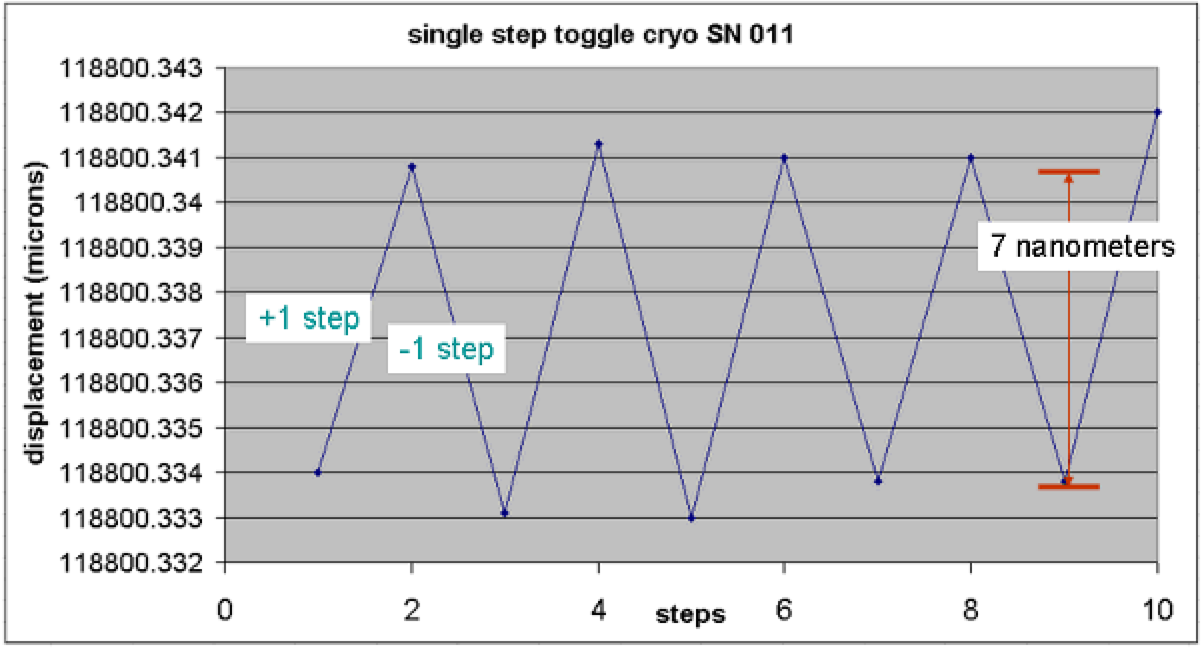
Mirror Substrate

Cryogenic Actuators

24 JWST actuators have been tested from 25 to 35K

JWST engineering unit actuators have resolution of 7 nm

Actuator performs single step moves, without backlash, to accuracy of 0.6 nm rms.



ROC Actuation Demonstrated at Cryogenic Temperatures on AMSD Mirror

ROC actuation demonstrated on AMSD mirror at ambient & 30K

35 course Steps = 38 nm PV (smallest measurable change)

1 Fine Step = 0.24 nm PV sag (by calculation)

ROC Actuation Resolution

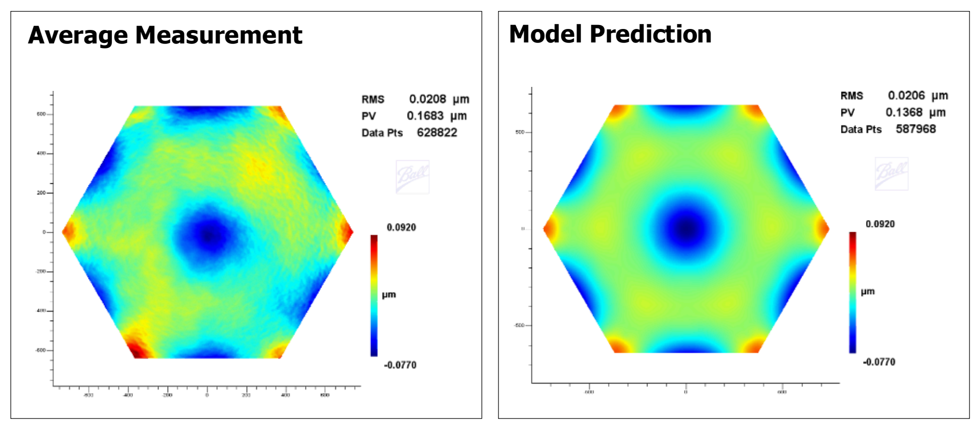
Mirror	Requirement (nm PV)	Cryo Demonstration (nm PV)	Capability (nm PV)
AMSD	50	38*	0.24
JWST	10	-	0.4

* Limited by Metrology

JWST RoC actuation design has been optimized to reduce residual figure error by 2X

JWST RoC actuation showed measurement within 1% of model prediction

ROC Actuation Residual Figure Error (JWST Mirror)



Relevant Test Environment Requirements for TRL-6 Vibro-Acoustic Demonstration

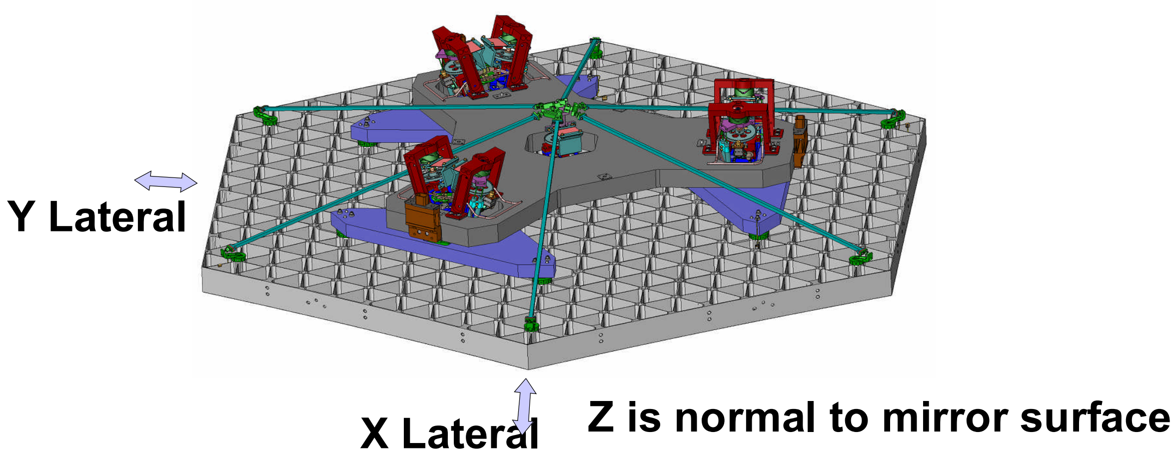
Launch limit loads (maximum expected flight load) for Mirror Substrate

- **15 G's load parallel to mounting surface (lateral direction)**
- **2930 N force normal to mounting surface (axial direction, = 7.6 G's)**

Sine burst testing applied loads higher than limit loads in all axes

Success Criteria:

- **Measure figure change below the 14 nm-rms figure measurement uncertainty of the Electronic Speckle Pattern Interferometer**
- **Show by analysis that flight units meet 2.9 nm-rms figure change**

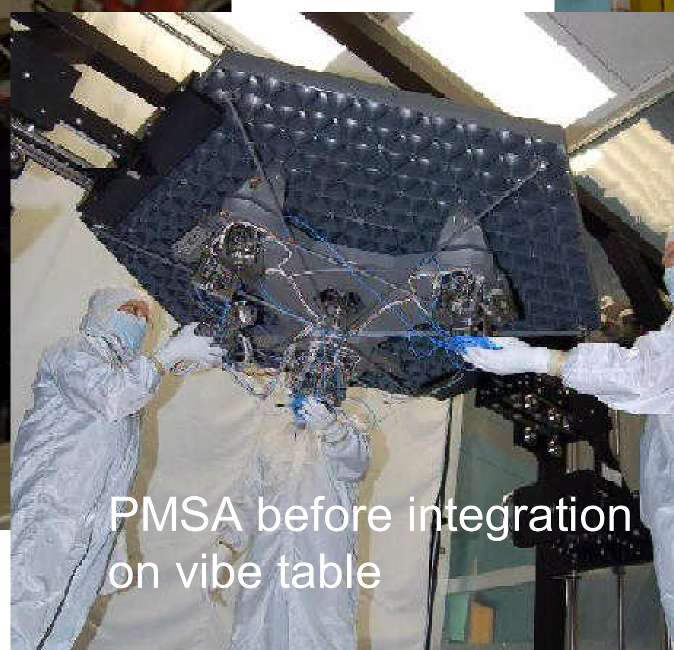


Mirror TRL-6 Load Testing

TRL-6 vibro-acoustics testing completed in August

Pre to post ESPI measurement indicated changes were below measurement error

Mirror saw loads (17.6 G's in X, 16.3 G's in Y, 8.5 G's in Z – Sine Burst) that enveloped worst case flight loads in all three axes.



Pre to Post change after TRL-6 vibe

	Measurement (nm rms)	Metrology Uncertainty (nm rms)
Figure	9.8	14
Astigmatism	4.2	10
Power	11.5	70

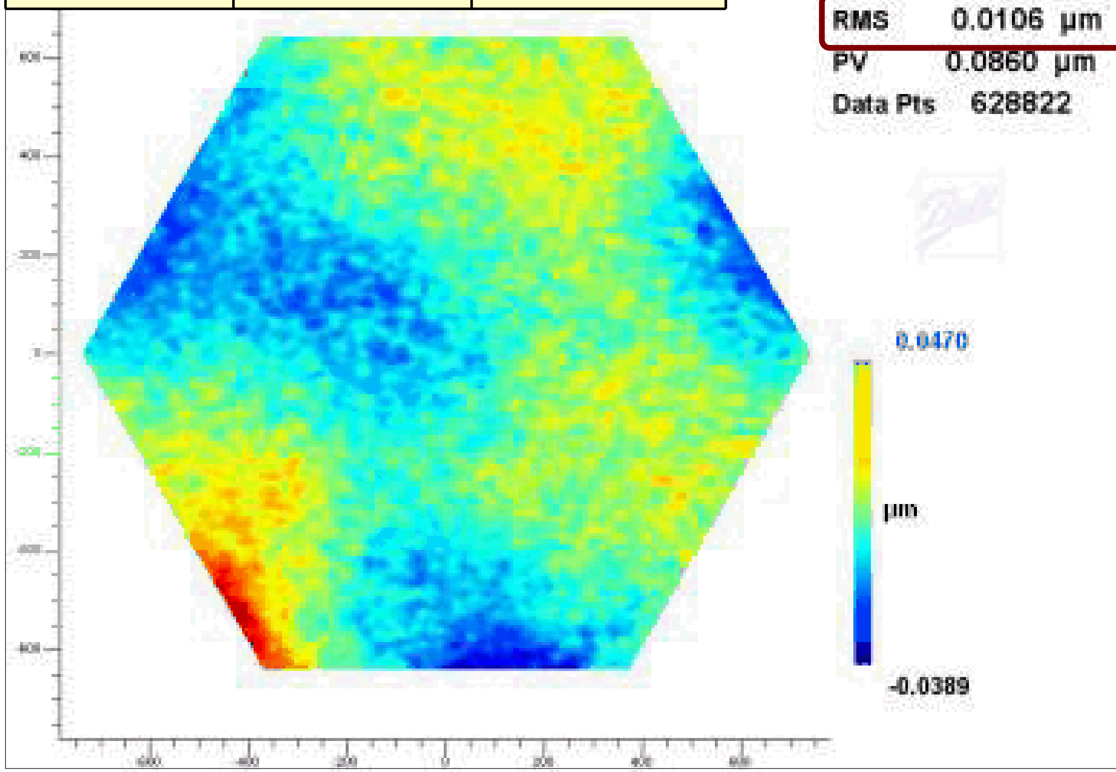
Measured Figure Error is Below Metrology Uncertainty

Measured Astigmatism is Below Metrology Uncertainty

Measured Power is Below Metrology Uncertainty

Mirror Loads:

17.6 G's in X, 16.3 G's in Y, 8.5 G's in Z



Total change measured is 10.6 nm rms

"All Measurements are within the Test Uncertainty of the State-of-the-Art ESPI metrology device"

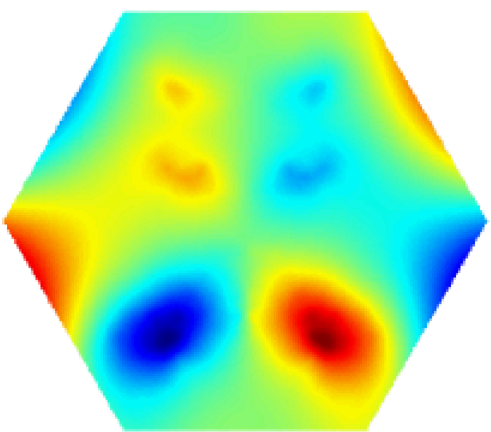
Minus piston, tilt, power

Analysis predicts mirror surface launch deformation meets requirement

Load	Piston/Tip/Tilt/Astigmatism Removed, Power Actuated Out
X = 18.75 g	1.0
Y = 18.75 g	1.1
Z = 5670 N	0.5
RSS	1.6

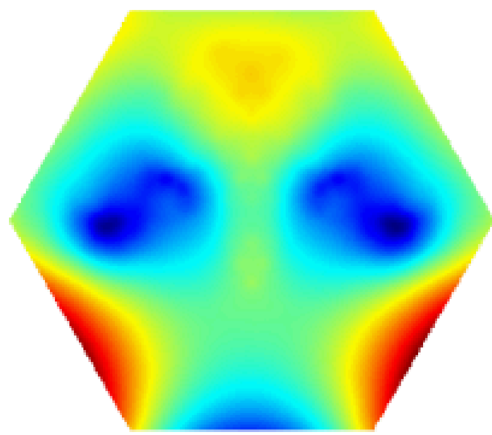
PMSA-180 requirement is < 2.9 nm rms surface figure error for launch loads

X = 18.75 g
Terms Removed: Piston, Tip/Tilt, Astigmatism



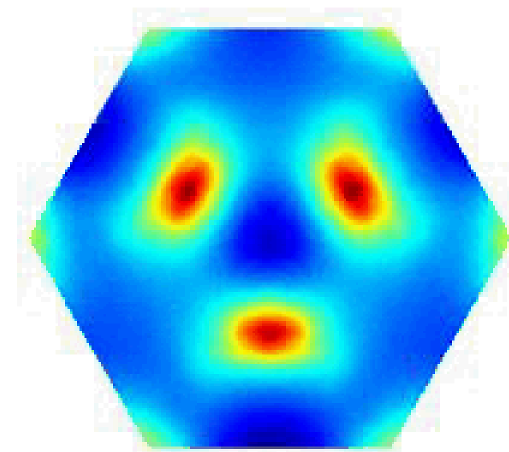
RMS: 0.00095 microns
PV: 0.00628 microns

Y = 18.75 g
Terms Removed: Piston, Tip/Tilt, Astigmatism



RMS: 0.00112 microns
PV: 0.00671 microns

Z=5670 N
Terms Removed: Piston, Tip/Tilt
Power Actuated Out



RMS: 0.00047 microns
PV: 0.00304 microns

Conclusion

Since 1996, all key mirror technology for a JWST Primary Mirror Segment Assembly (PMSA), as defined directly from the JWST Level 1 Science Requirements, have been developed and matured from a Technology Readiness Level (TRL) of 3 to 6.

This has occurred as the result of a highly successful technology development program including"

- Sub-scale Beryllium Mirror Demonstrator (SBMD)
- Advanced Mirror System Demonstrator (AMSD)
- JWST flight mirror fabrication

Directly traceable prototypes (and in some cases the flight hardware itself) has been built, tested and operated in a relevant environment.

Back-Up

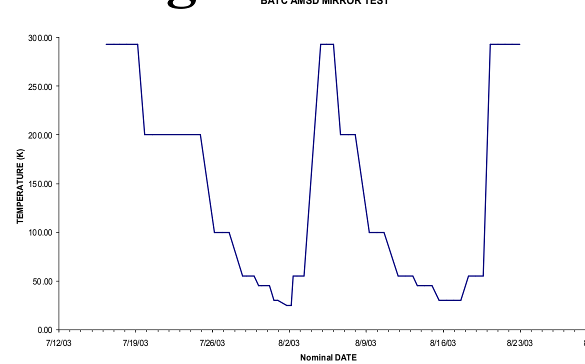
Beryllium Mirror Technology has history of surviving cryo temperatures without performance degradation

Beryllium Mirror Technology has history of surviving cryogenic temperatures

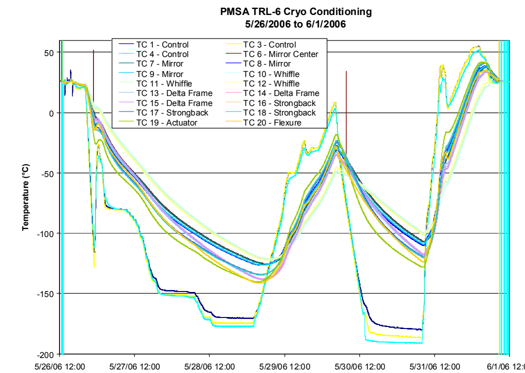
- SIRTF (Spitzer) beryllium primary and secondary mirrors experienced cryogenic temperatures during testing and vibration loads during test and launch. Mirrors operating at 5K.
- SBMD mirror successfully optically tested at $\leq$ 30K
- AMSD mirror successfully optically tested at $\leq$ 30K
- PMSA mount development program demonstrated strength of adhesive mirror mount after exposure to 15K temperatures.
- PMSA cycled to $\leq$ 150K prior to vibro-acoustic testing.
  - Thermal cycle achieved ~88% of beryllium cryo strain and >70% of adhesive mount strain.
- Optical repeatability of mirrors during testing indicates no damage to the substrate or structure for the above tests.

AMSD Achieved $\leq$ 30K Temperature

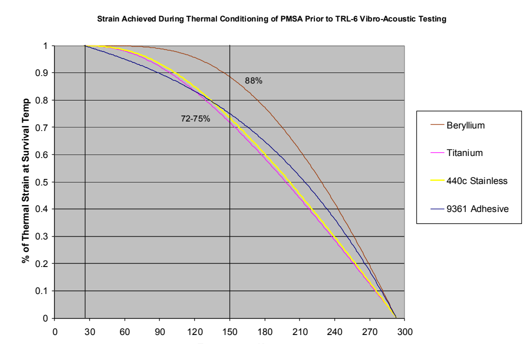
- AMSD mirror was cycled twice to $\leq$ 30K.
- Initial settling thermal cycle showed a mount induced change in the optic.
- Subsequent cycle showed that the mirror had stabilized.
- Mount induced change has been mitigated by PMSA mount development plan. Final verification will be performed on EDU in 2007



AMSD XRCF Thermal Cycle Profile



PMSA Thermal Cycle Profile



Beryllium Integrated Strain

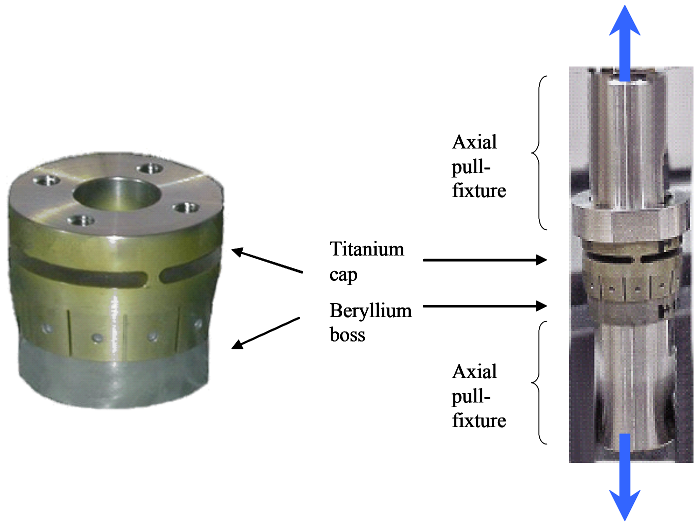
JWST mount development shows high margin of safety and minimal strength degradation from thermal cycling

Mount development samples were cycled 3X between 15K and 383K.

7.4 Margin of safety after thermal cycling

Ultimate strength decreased ~ 12% after thermal cycling.

PMSA mount is robust to thermal environment and no difference is expected between TRL-6 and qual testing.

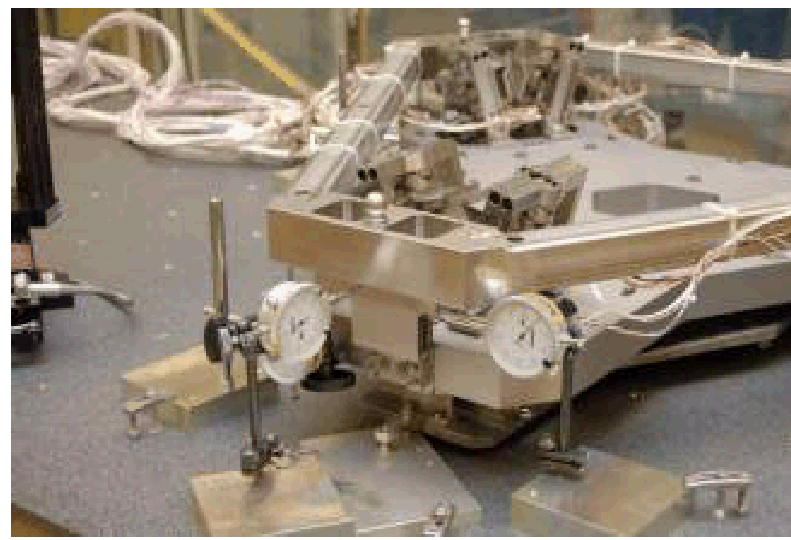


	Average Strength (lbf)		Required Strength (lbf)		Margin of Safety	
	Axial	Lateral	Axial	Lateral	Axial	Lateral
Nominal Samples	3220	N/A	221	399	10.7	N/A
Samples after thermal cycle	2841	3714*	221	399	9.3	7.4

* Test stopped at 4000 lbf for two of 6 samples

MS=strength/(requirement*1.25)-1

Hexapod testing in support of TRL-6 demonstrated rigid body control, including mirror deployment and stowage



TRL-6 PMSA hexapod fully integrated & tested prior to and after environmental testing

Demonstrated capabilities

- **Fine range of motion (9.5 – 10.5 microns)**
  - Verified throughout TRL-6 testing via global clocking move of hexapod
- **Deployment**
  - Several stow / deploy cycles throughout test
- **Controllability demonstrated in actuator test (ambient and cryogenic temperatures)**
  - Actuator testing <8 nm resolution, Requirement < 10 nm
  - Actuator single step performance meets accuracy requirements at ambient and cryogenic temperatures of < 2.15 nm error standard deviation

PMSA level hexapod testing

- **Surface figure change during rigid body motion shown to be below EPSI noise level**