JWST Primary Mirror Technology Development

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Outline

Introduction

Mirror Technology Development

TRL-6 Certification

Engineering Development Unit

Conclusions

Introduction

JWST was originally called the Next Generation Space Telescope (NGST)

In 1996 (based on the 1989 Next Generation Space Telescope workshop and the 1996 HST & Beyond report) NASA initiated a feasibility study.

OTA study in summer 1996

Science Drivers

Near Infrared	1-5 microns (.6-30 extended)
Diffraction Limited	2 microns
Temperature range	30-60 Kelvin
Diameter	At least 4 meters ("HST and Beyond" report)

Programmatic Drivers

25 % the cost of Hubble	Cost cap - 500 million
25 % the weight of Hubble	Weight cap ~3,000 kg

Baselines for OTA study

Atlas IIAS launch vehicle Low cost launch vehicle

L2 orbit	Passively cool to 30-60 K
1000 kg OTA allocation	Launch vehicle driven

Study Results

8 meter segmented telescope, mirror technology at <u><15 kg/m²</u>.

Introduction

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:

deployed/segmented primary mirror	(4.5 meter fairing diameter)
20 kg/m2 areal density	(PM 1000 kg mass)

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 Program

JWST initiated a systematic $300M effort

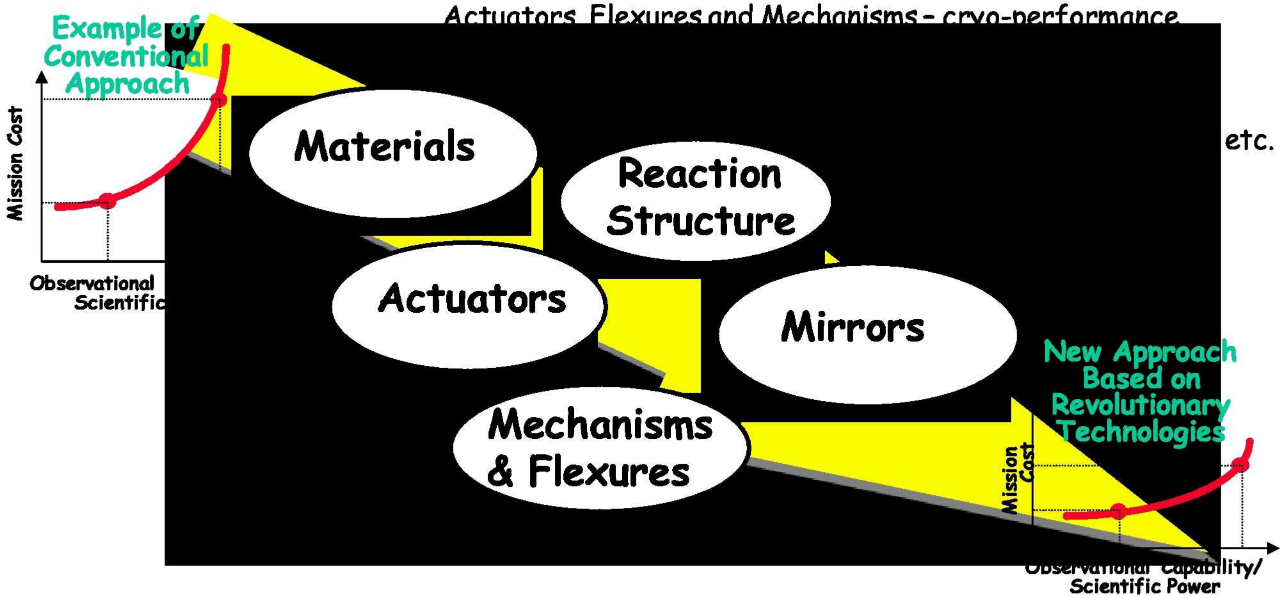
Several key technological and manufacturing advances have been developed

Cryogenic Materials – CTE uniformity, dynamic dampening, stiffness, etc.

Fabrication Techniques – ability to make size & areal density to required figure.

Cryogenic Performance Characterization – optical testing, cryo-behavior.

Actuators, Flexures and Mechanisms – cryo-performance.

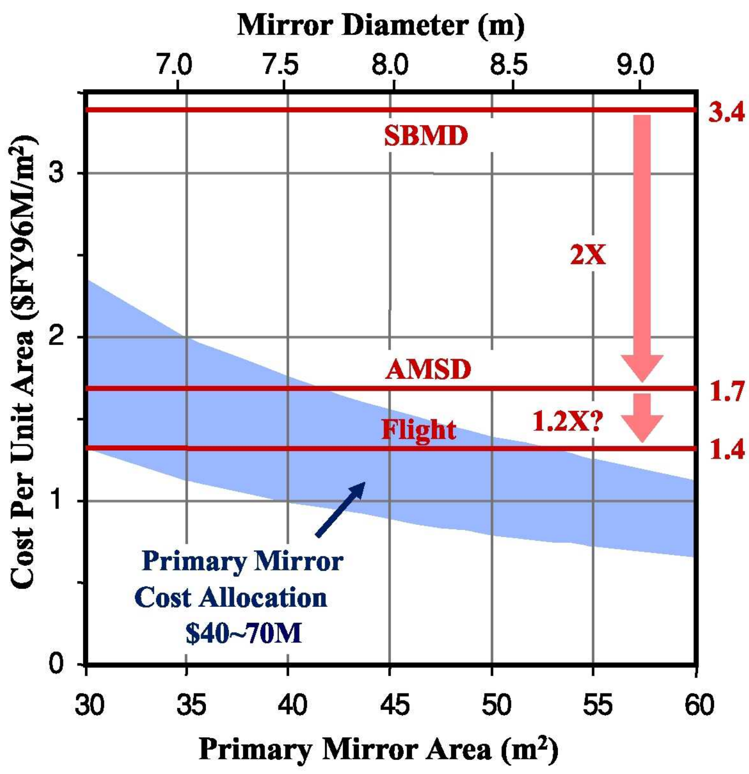


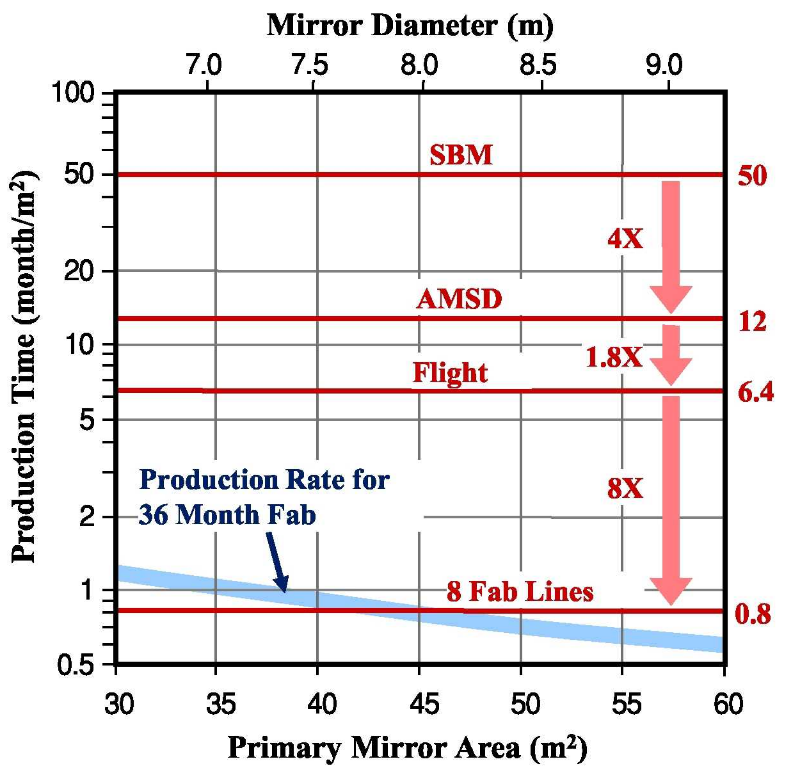
to dramatically reduce cost, schedule, weight and risk for large-aperture space optical systems.

Programmatic Challenge of NGST

In 1996, the ability to affordably make NGST did not exist.

Substantial reductions in ability to rapidly and cost effectively manufacture low areal density mirrors were required.



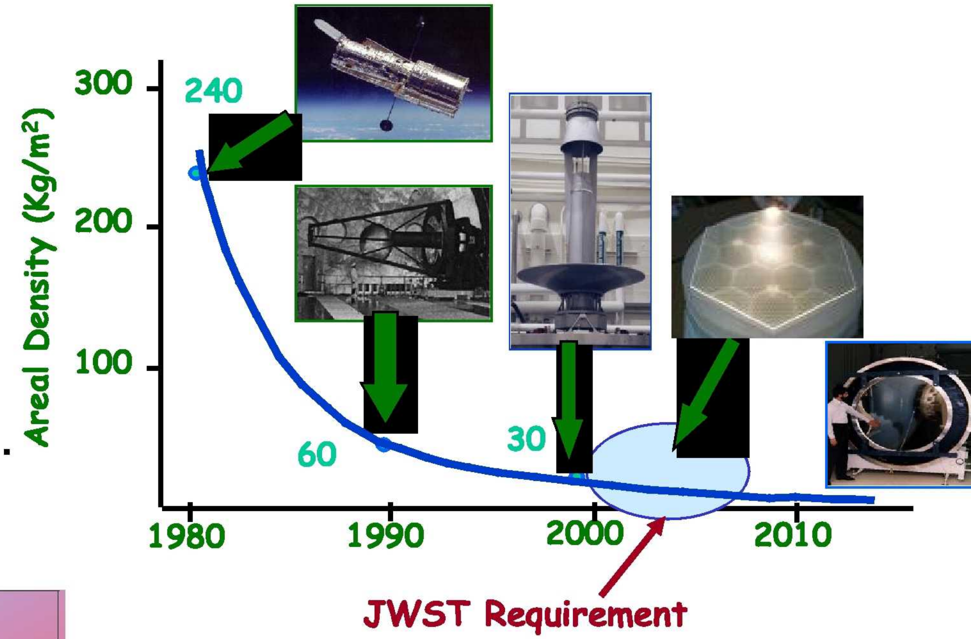


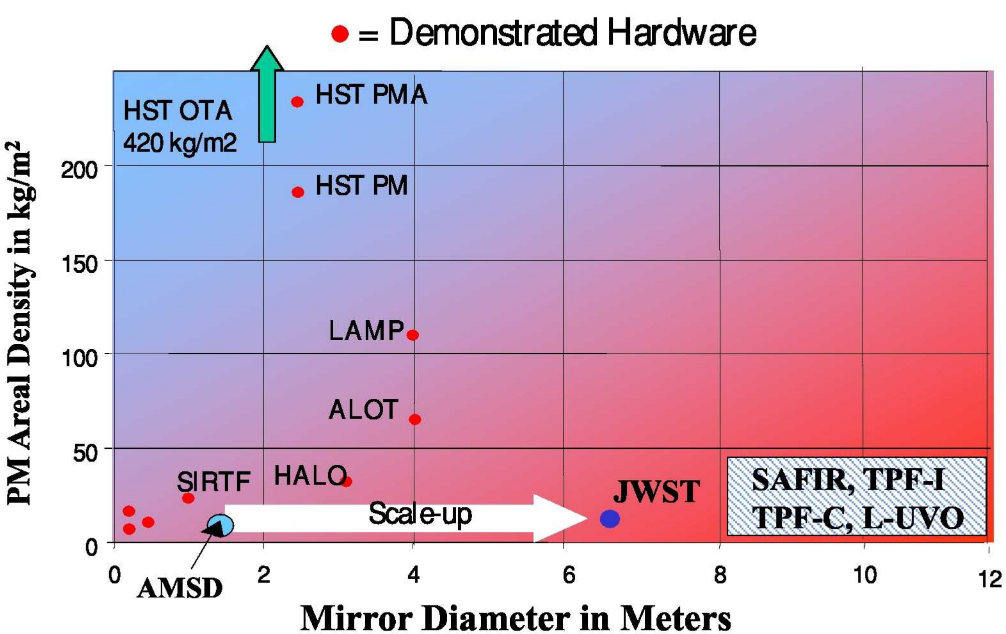
Mirror Technical Challenges

Challenges for Space Telescopes:

- Areal Density to enable up-mass for larger telescopes.
- Cost & Schedule Reduction.

Are order of magnitude beyond 1996 SOA.





Primary Mirror Time & Cost

HST (2.4 m)	§□□□²/yr	§□□□□0²P
Spitzer (0.9 m)	§□□□□²/yrP	§□□□□□0²P
AMSD (1.2 m)	§□□□□²/yrP	§□□□□0²P
JWST (8 m)	> 6 m²/yr	< \$3M/m²

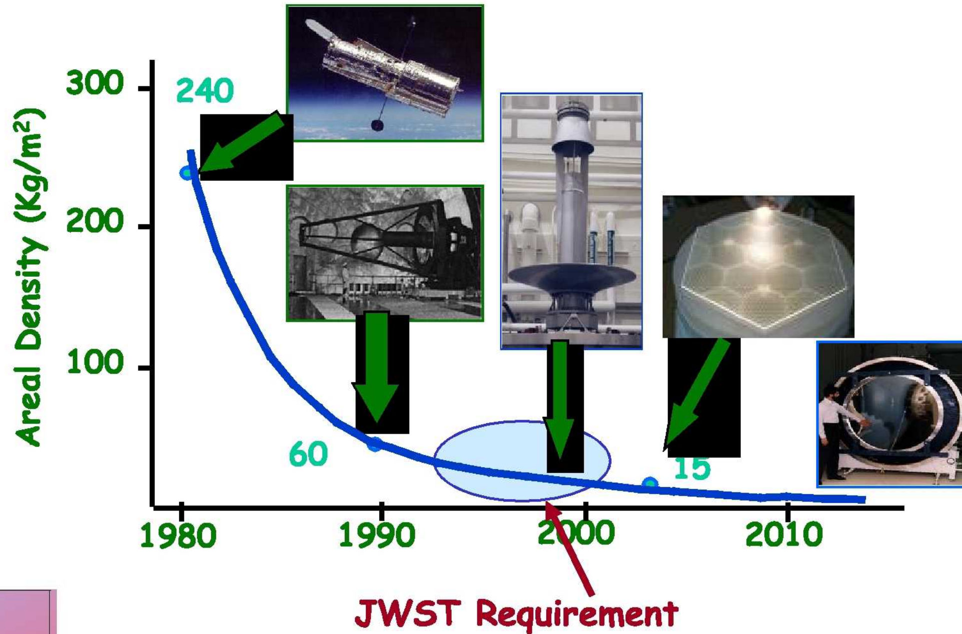
Note: Areal Cost in FY00 $

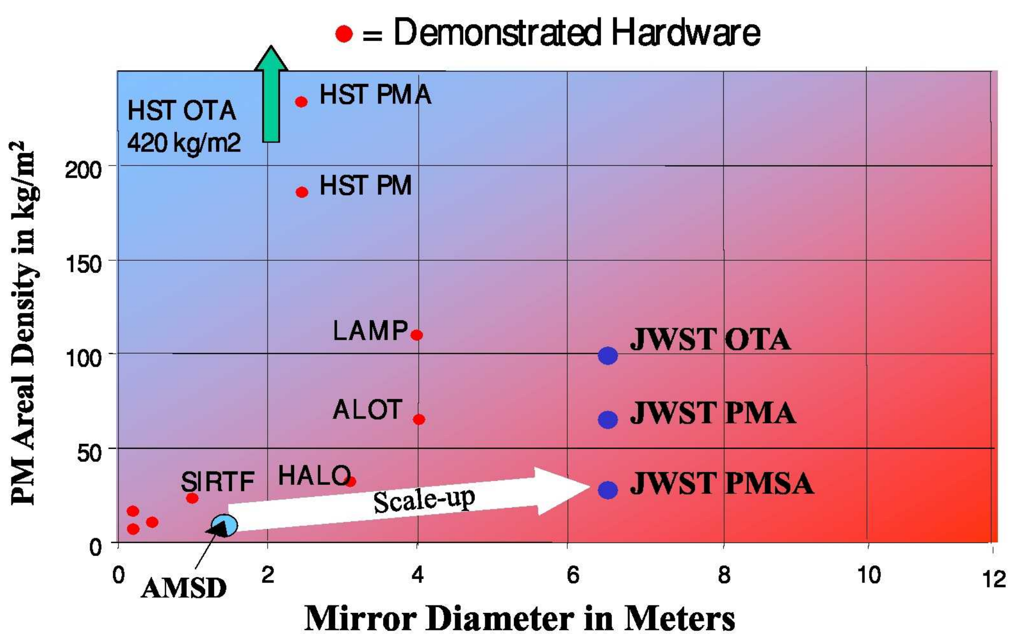
Mirror Technology Development 2010

Lessons Learned

Mirror Stiffness (mass) is required to survive launch loads.

Need another 10X Cost & Schedule reduction for larger telescopes



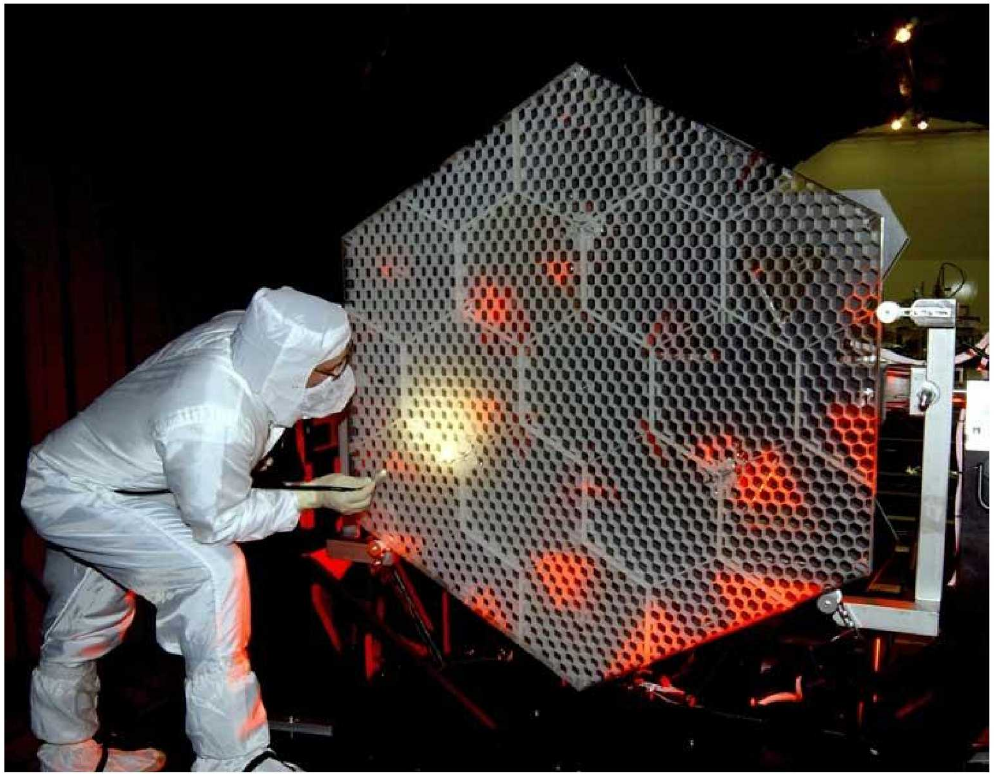


Primary Mirror Time & Cost

HST (2.4 m)	[illegible]	[illegible]
Spitzer (0.9 m)	[illegible]	[illegible]
AMSD (1.2 m)	[illegible]	[illegible]
JWST (6.5 m)	[illegible]	[illegible]

Note: Areal Cost in FY10 $

Mirror Technology Development Program



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.

Requirement was to achieve TRL-6 before Non-Advocate Review (NAR)

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 (and ~$40M) to mature mirror technology from TRL 3 to 6.

Mirror Technology Development

Systematic Study of Design Parameters

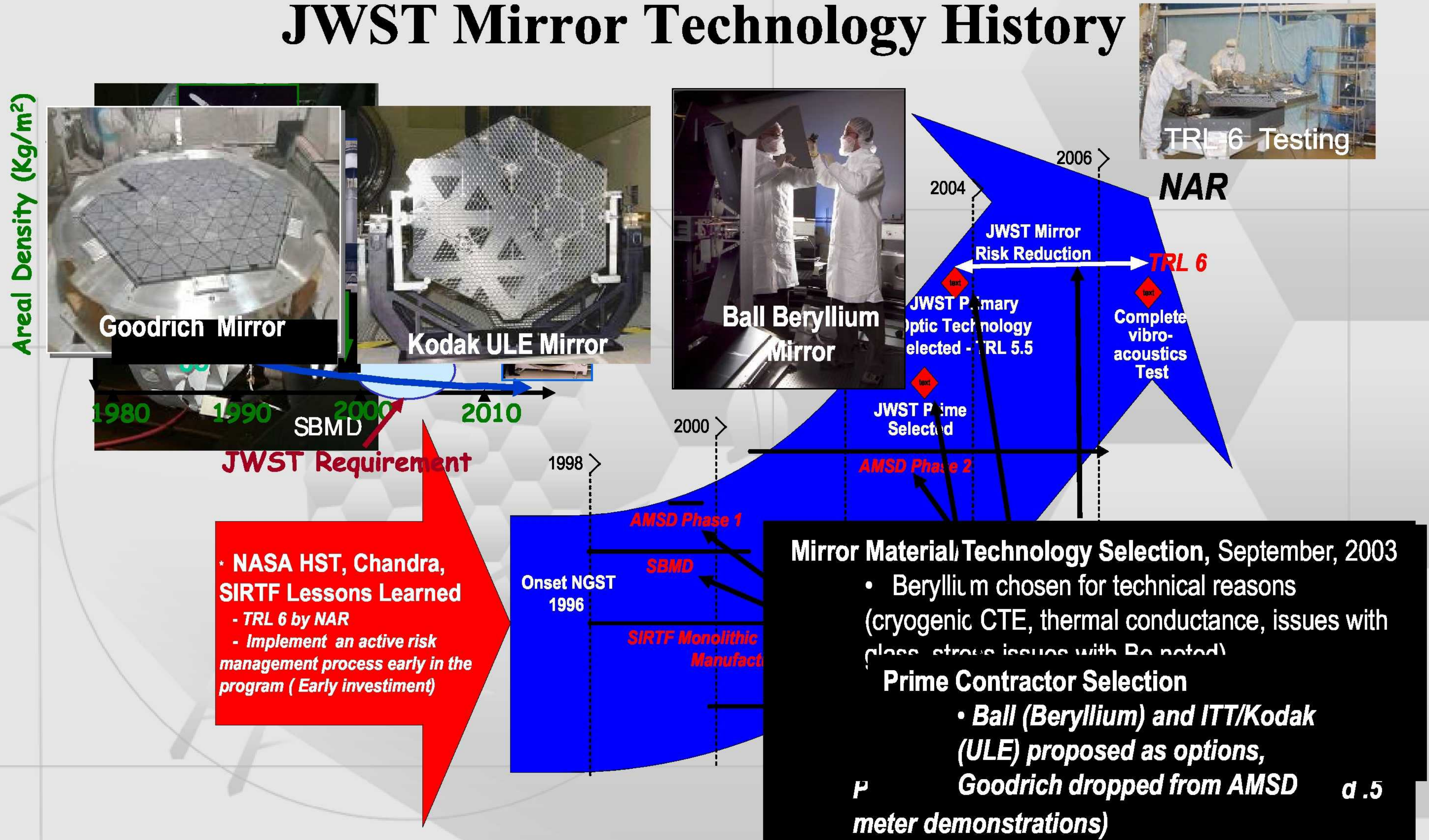
Item	SBMD	NMSD	AMSD
Form	Circle w Flat	Hex	Hex
Prescription	Sphere	Sphere	OAP
Diameter	>0.5 m	1.5 - 2 m	1.2 - 1.5 m
Areal Density	< 12+ kg/m2	<15 kg/m2	<15 kg/m2
Radius	20 m	15 m	10 m
PV Figure	160 nm	160/63 nm	250/100 nm
RMS Figure			50/25 nm
PV Mid (1-10 cm^{-1})	63 nm	63/32 nm	
RMS Finish	3/2 nm	2/1 nm	4 /2 nm

Mirror Technology Development

Wide Variety of Design Solutions were Studied

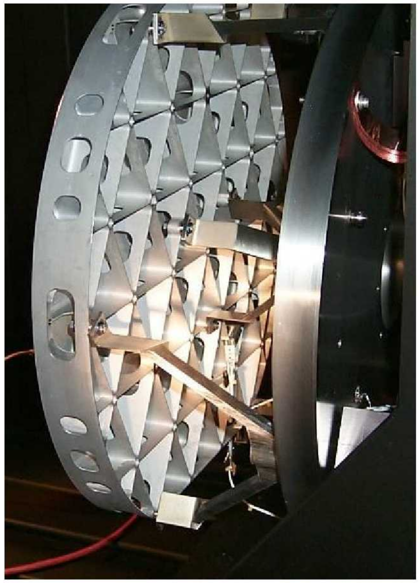
Item	SBMD	NMSD	AMSD
Substrate Material	Be (Ball)	Glass (UA) Hybrid (COI)	Be (Ball) ULE Glass (Kodak) Fused Silica (Goodrich)
Reaction Structure	Be	Composite	Composite (all)
Control Authority	Low	Low (COI) High (UA)	Low (Ball) Medium (Kodak) High (Goodrich)
Mounting	Linear Flexure	Bipods (COI) 166 Hard (UA)	4 Displacement (Ball) 16 Force (Kodak) 37 Bi/Ax-Flex (Goodrich)
Diameter	0.53 m	2 m (COI) 1.6 m (UA)	1.3 m (Goodrich) 1.38 m (Ball) 1.4 m (Kodak)
Areal Density	9.8+ kg/m2	13 kg/m2	15 kg/m2

JWST Mirror Technology History

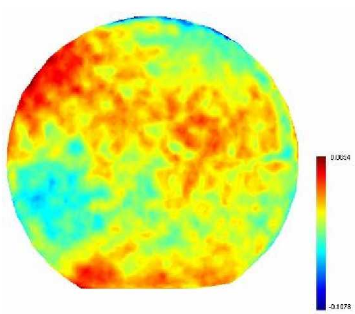


Based on lessons learned, JWST invested early in mirror technology to address lower areal densities and cryogenic operations

Ball Subscale Beryllium Mirror Demonstrator (SBMD)



0.5 m diameter, 20 m ROC, 9.8 kg/m^2 areal density, O-30 Beryllium Mirror

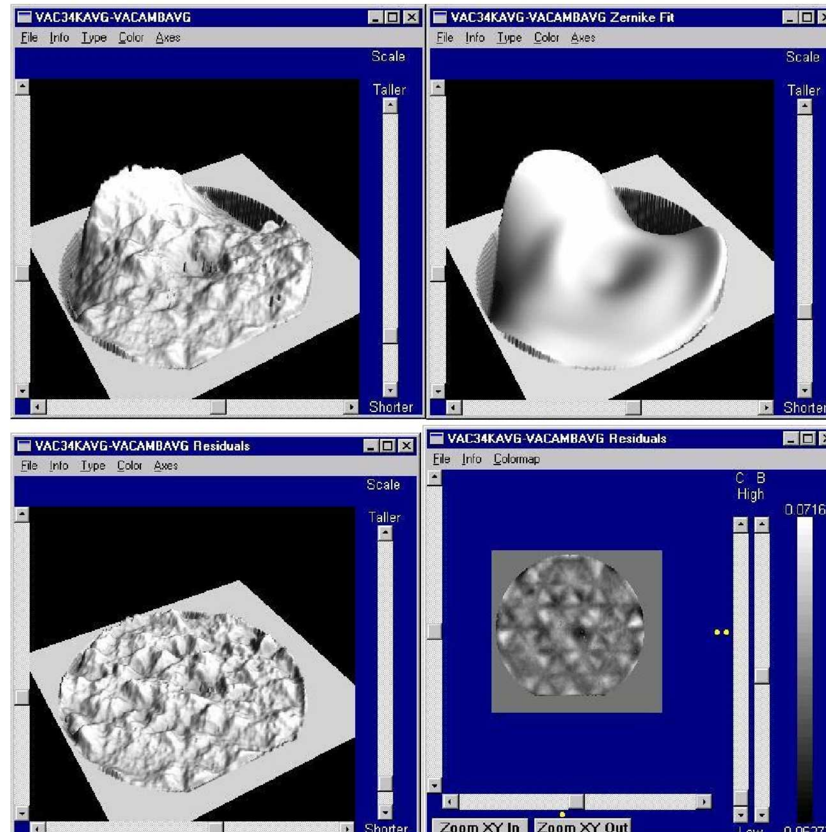


Cryo Tested at MSFC

Cryogenic Surface Error (34K -288K)

Total (0.571 μm p-v; 0.063μm rms)

Low Order (0.542 μm p-v, 0.062 μm rms)



Higher Order Residual (0.134 μm p-v; 0.012 μm rms)

SBMD Lessons Learned

SBMD's cryo-deformation was interesting:

- Initially, we were unable to model the quilting
- Mounting design issues introduced low-order error
- Interface issues resulted in a non-stable deformation

Lessons Learned:

- Learned how to optimize substrate light-weighting to minimize quilting
- Support structure design and interface to substrate is critical
- Very high stiffness of small mirrors means that extrapolating their results to large (low-stiffness) mirrors is unreliable

COI Hybrid NGST Mirror System Demo (NMSD)

Hybrid Concept

Zerodur Facesheet to Meet Optical Requirements

Conventional Grind/Polish Fab Methods

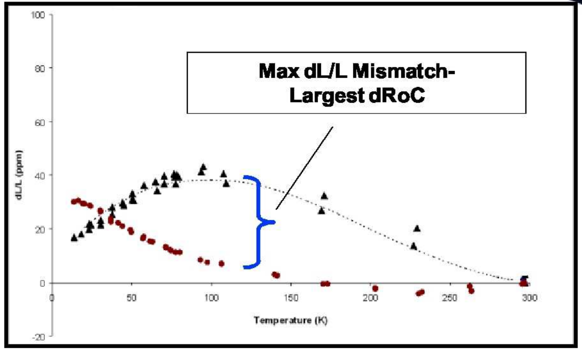
Composite Structural Support for Glass

Low Mass, High Stiffness

Match Thermal Expansion from Ambient to 35K

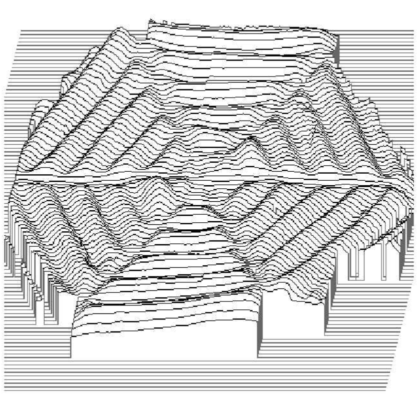
Specifications

Diameter	1.6 meter
Radius	20 meter
Areal Density	< 15 kg/m2
Areal Cost	< \$2.5M/m2

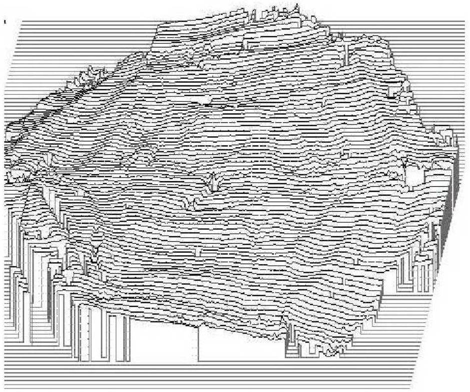


Delivered Polished with Cryo-Null Figure

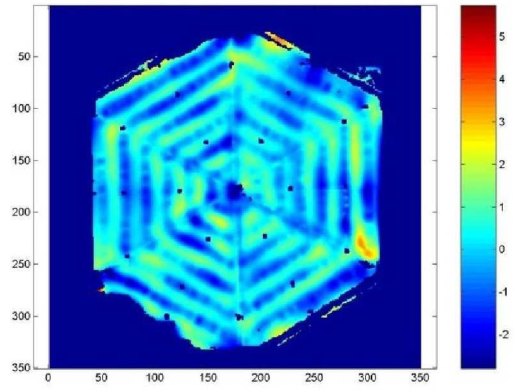
25K Figure	800 nm rms



Ambient Surface



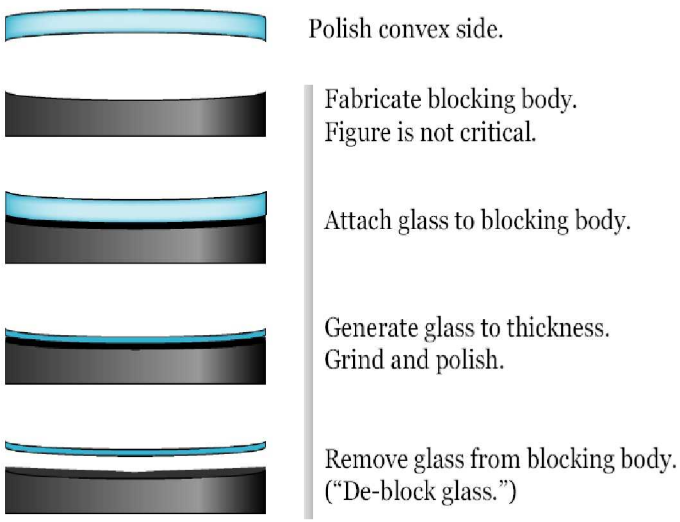
Surface at Cryo

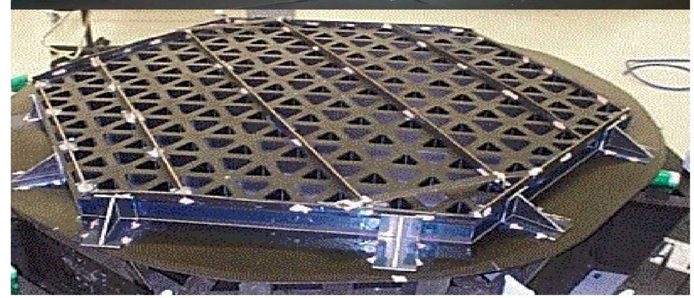


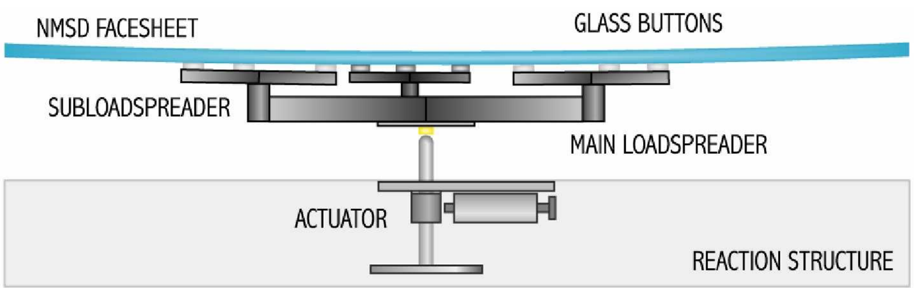
25K Figure (Low Order Zernikes Removed)
0.8micron RMS Full Aperture

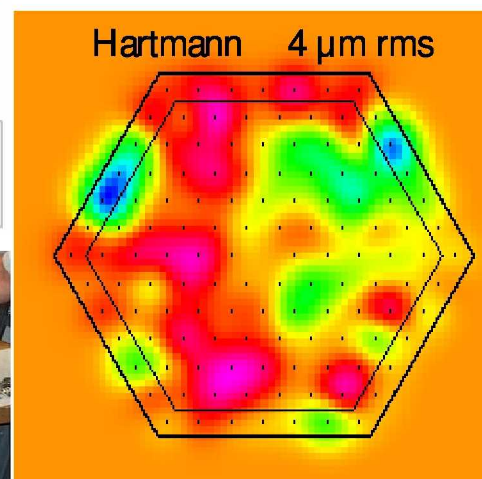
University of Arizona NGST Mirror System Demonstrator

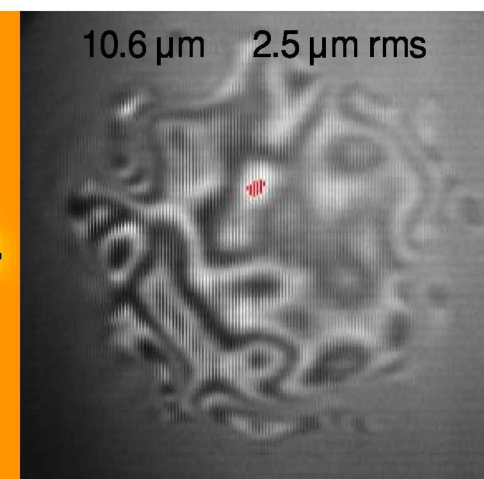
2m Dia 2 mm Thick Glass with Backplane, 166 Actuators, 9 Point Load Spreader











NMSD Lessons Learned

Both NMSD mirrors took significantly longer than expected and achieved significantly lower performance than expected.

CTE matching is difficult for a Cryo-Mirror.

Stiffness is much more important than Areal Density.

Stiffness is required for multiple reasons:

- Substrate/Facesheet Handeling
- Standard Fabrication Processes assume a given Stiffness
- Figure Adjustment and Stability

Expect a high infant mortality rate (~30%) on Actuators

Standard Processes and Intuition no not scale for large aperture low stiffness mirrors.

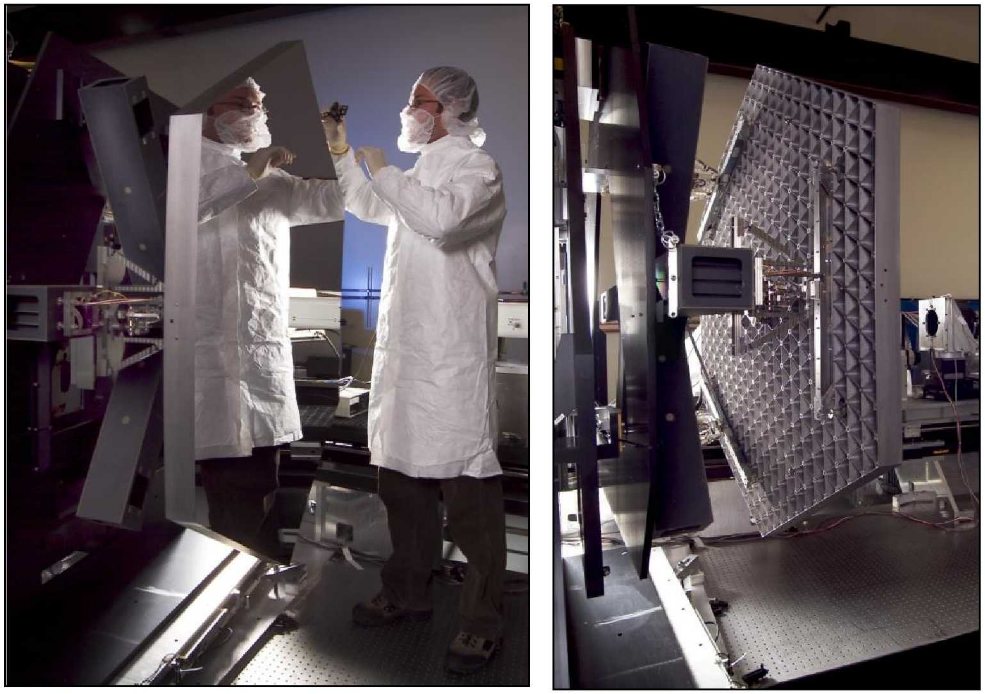
- Stiffness decreases with Diameter^2
- Stiffness increases with Thickness

Advanced Mirror System Demonstrator

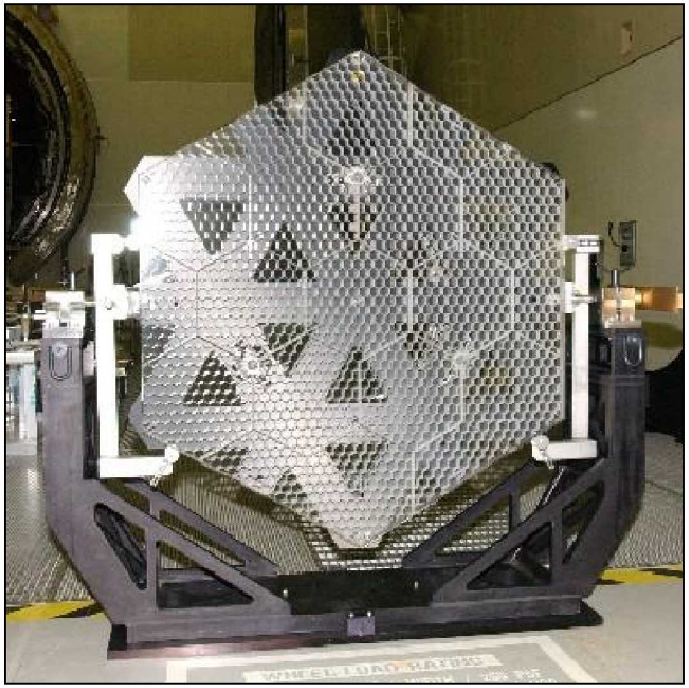
AMSD was a joint NASA, Air Force & NRO program.

AMSD developed two mirror technologies for JWST yielding data on:

- Ambient and Cryogenic Optical Performance
- Manufacturability
- Cost
- Schedule

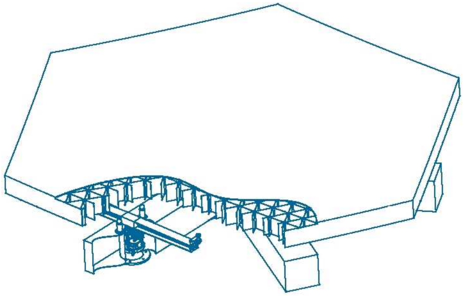


Beryllium AMSD Mirror

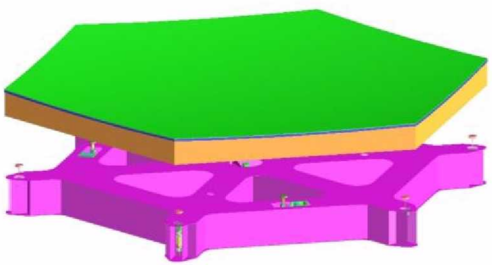


ULE Glass AMSD Mirror

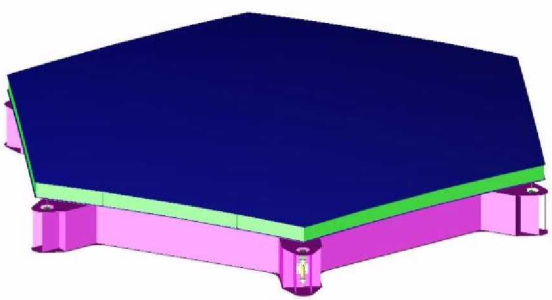
AMSD was Phased Down Select Program



Beryllium



Hybrid



Glass

AMSD PHASE I

MAY-SEPT. 1999

5 Contractors

8 Mirror Designs

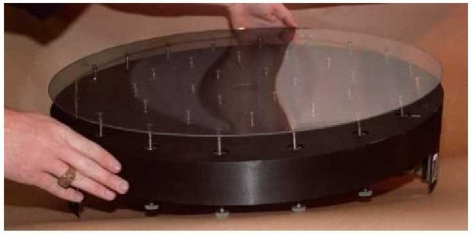
Raytheon(3)

Ball

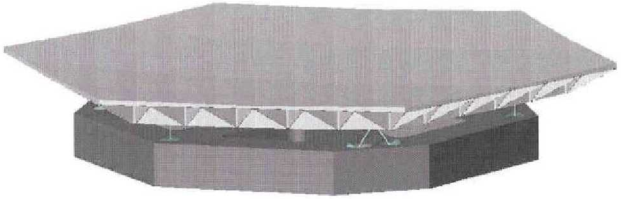
Kodak(2)

COI

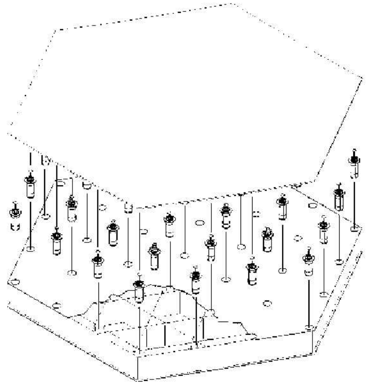
UOA



Glass Meniscus



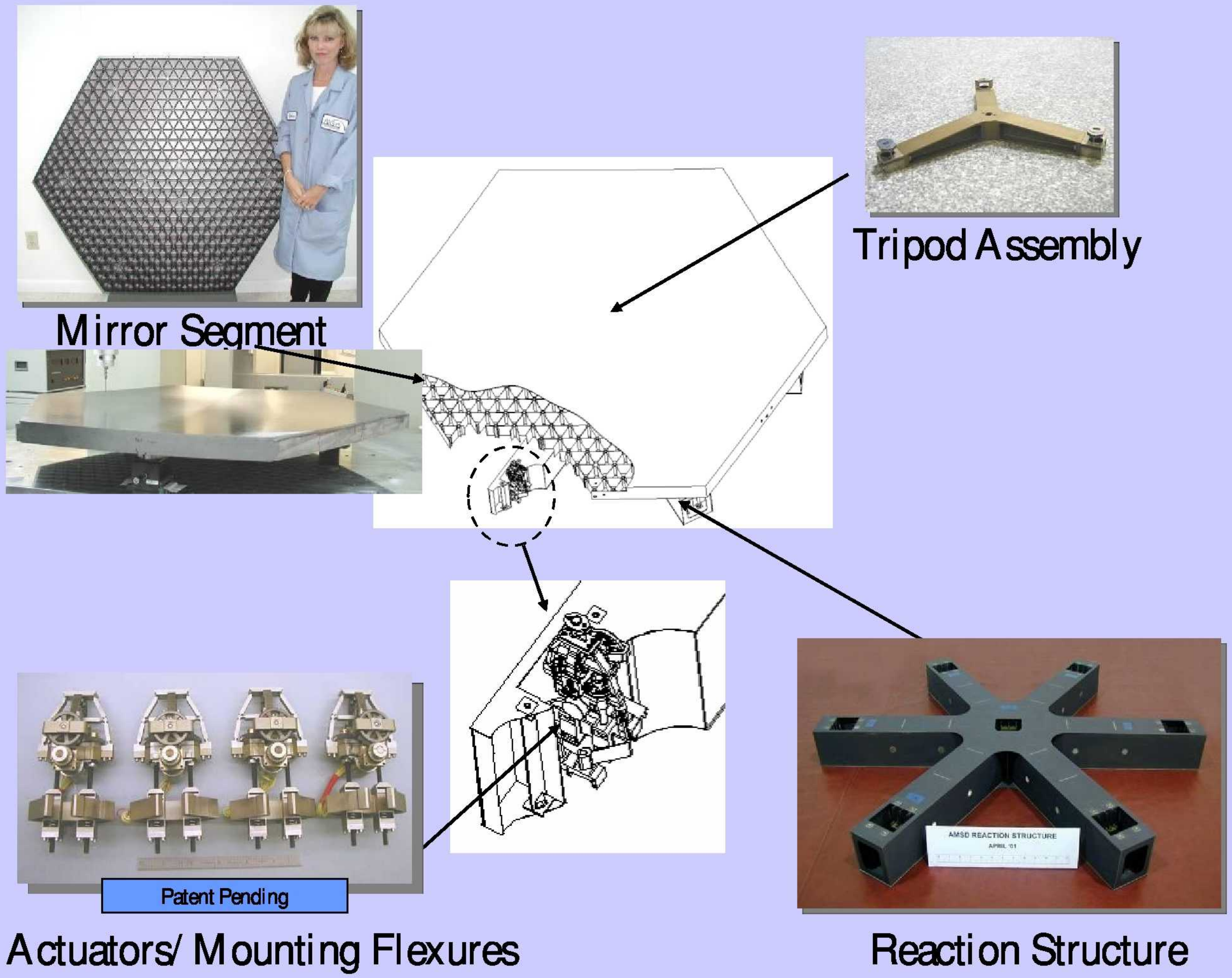
CSiC



SiC,Be,Glass Meniscus

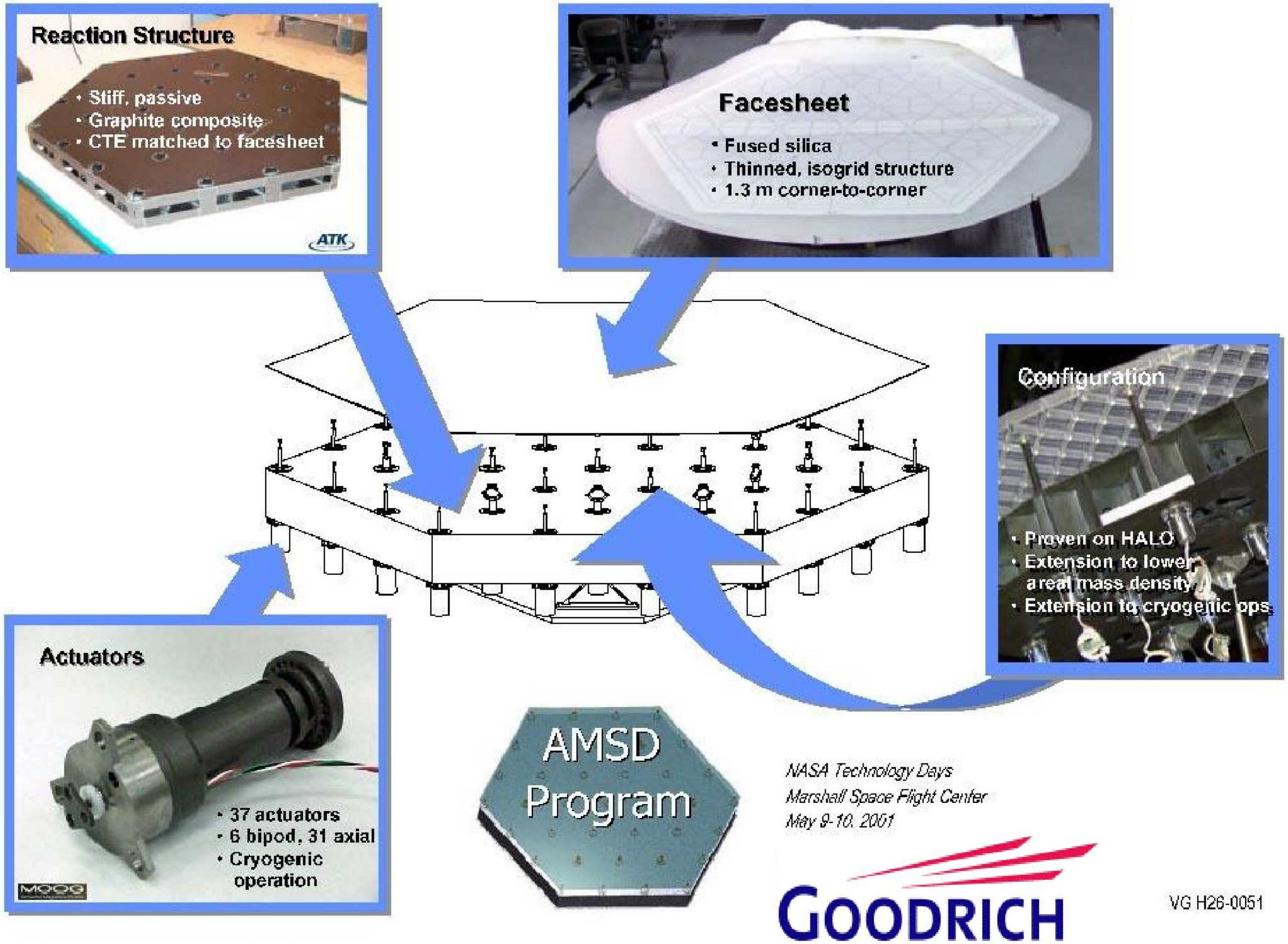
Ball AMSD Mirror

Ball's Beryllium Semi-Rigid Design for AMSD



- 1.39-m point-to-point open back light-weighted O-30 beryllium semi-rigid mirror
- < 15 kg/m^2 areal density for mirror system including mirror, reaction structure, flexures, and actuators
- Graphite Epoxy (M55J) Reaction Structure
- 4 Ball Actuators (3-rigid body and one for ROC).
- Major Subcontractors: SVG Tinsley, AXSYS, Brush-Wellman, COI

Goodrich AMSD Mirror



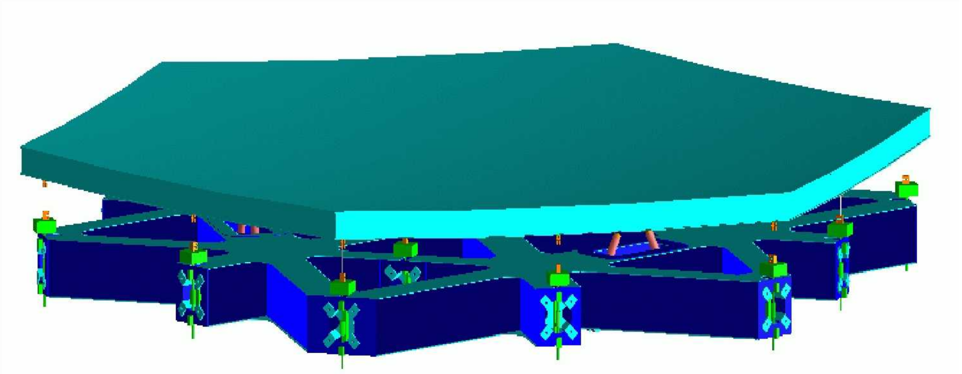
1.3 m SiO2 Iso-Grid Thin Meniscus Mirror

Graphite Composite Reaction Structure from ATK

37 Displacement Actuators from Moog

Kodak AMSD Mirror

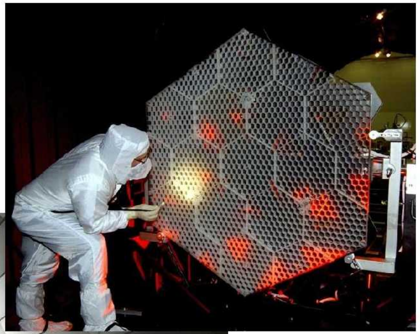
- 1.4 m Diameter Semi-Rigid ULE Closed-Back Sandwich Construction Mirror
  - **Low Temperature Fusion into a Flat Substrate**
  - **Grind Facesheets to Final Mass**
  - **Low Temperature Slump into Sphere**
- Graphite Epoxy (M55J) Reaction Structure by COI
- 16 Force Actuators by Moog
  - **7 for wavefront & radius**
  - **9 for gravity offloading**
  - **No Rigid Body Adjustments**

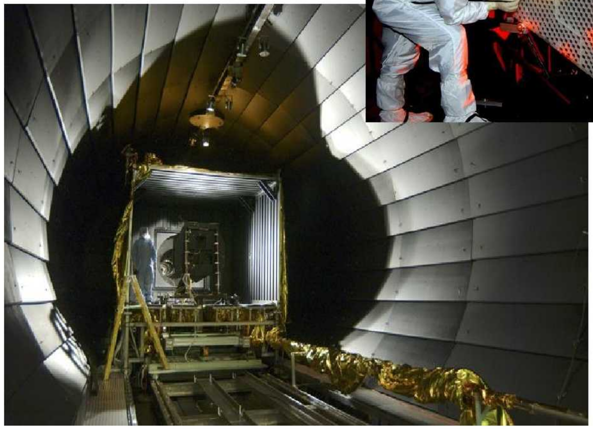


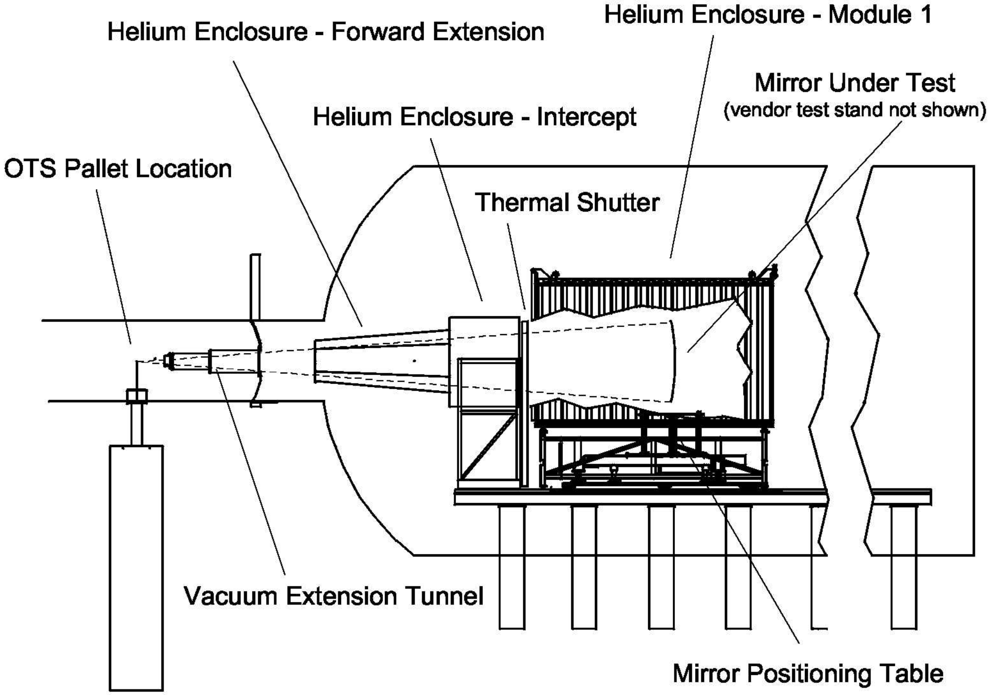
Performance Characterization

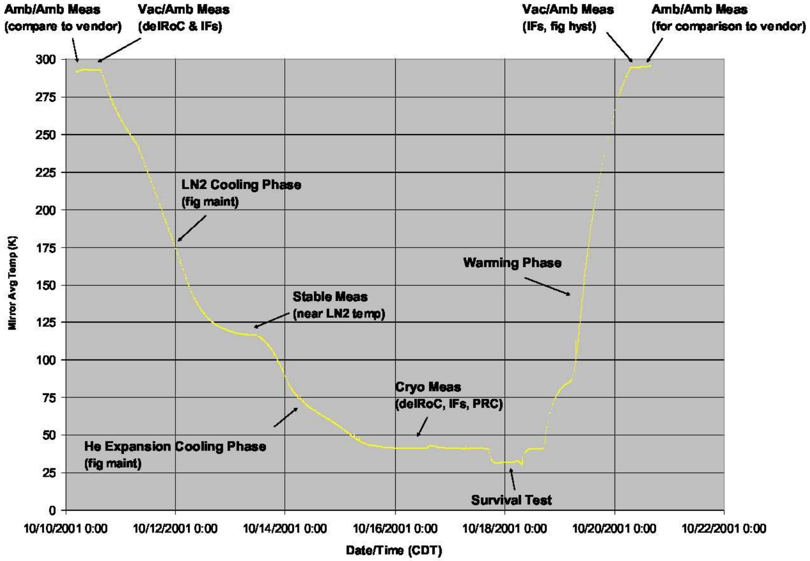
Ambient and Cryogenic Optical Performance was measured at XRCF.

Each mirror tested multiple times below 30K









AMSD ± Ball & Kodak

Specifications

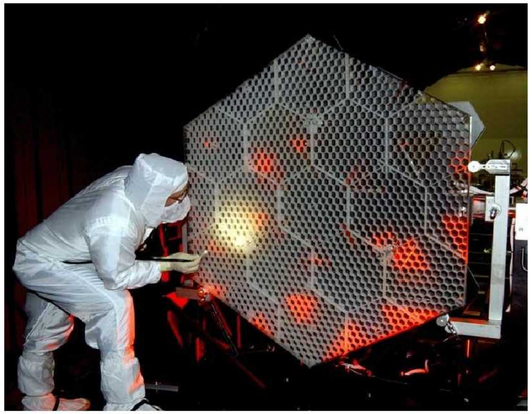
Diameter	1.4 meter point-to-point
Radius	10 meter
Areal Density	< 20 kg/m2
Areal Cost	< $4M/m2

Beryllium Optical Performance

Ambient Fig	47 nm rms (initial)
Ambient Fig	20 nm rms (final)
290K – 30K	77 nm rms
55K – 30K	7 nm rms

ULE Optical Performance

Ambient Fig	38 nm rms (initial)
290K – 30K	392 nm rms
55K – 30K	55 nm rms
290K – 30K	188 nm rms (w/ adjust)
55K – 30K	20 nm rms (w/ adjust)

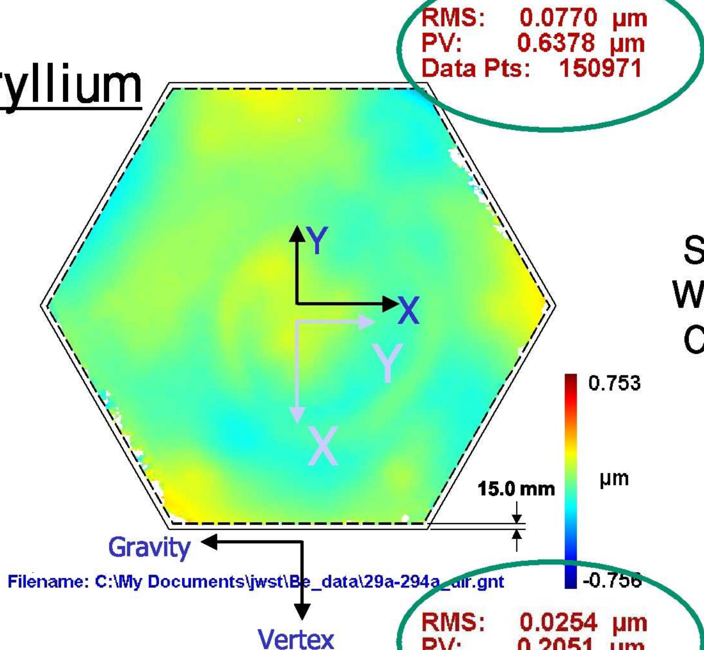


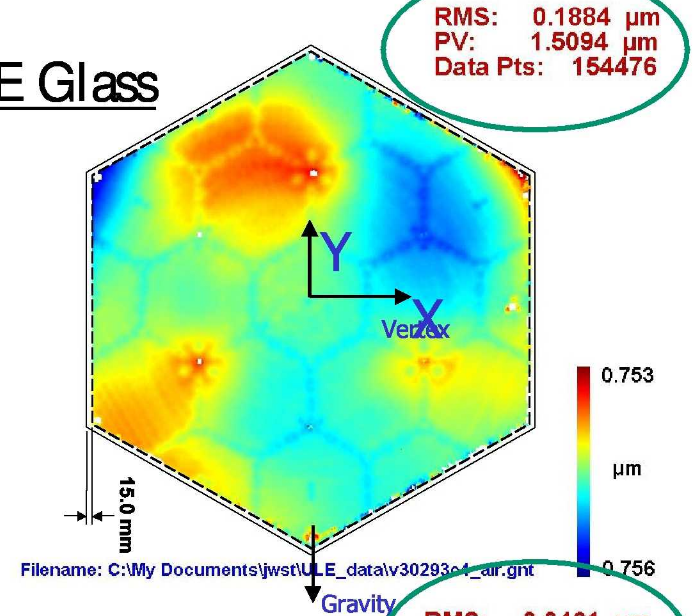
AMSD Figure Change: *Ambient-to-Cryo (30 K)*

Beryllium

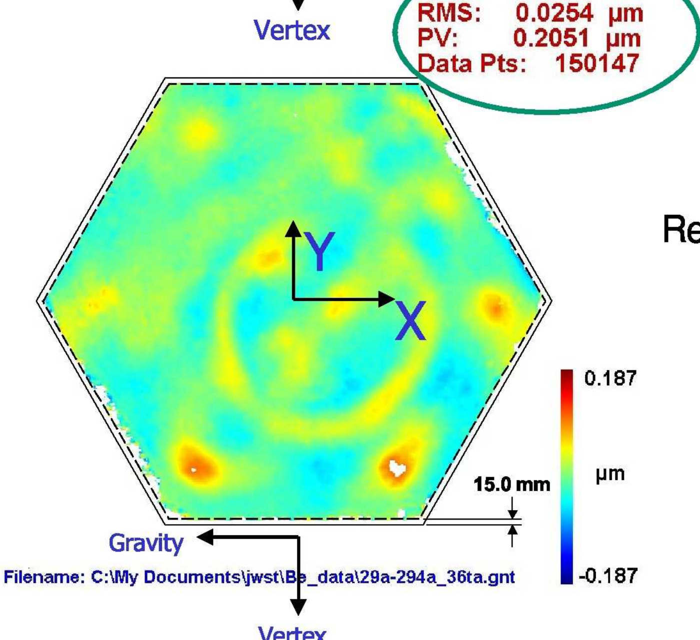
ULE Glass

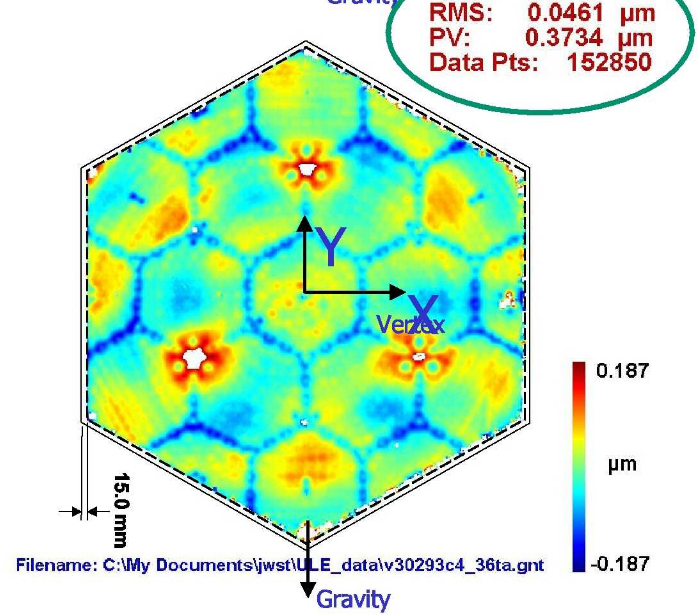
Surface Figure With Alignment Compensation





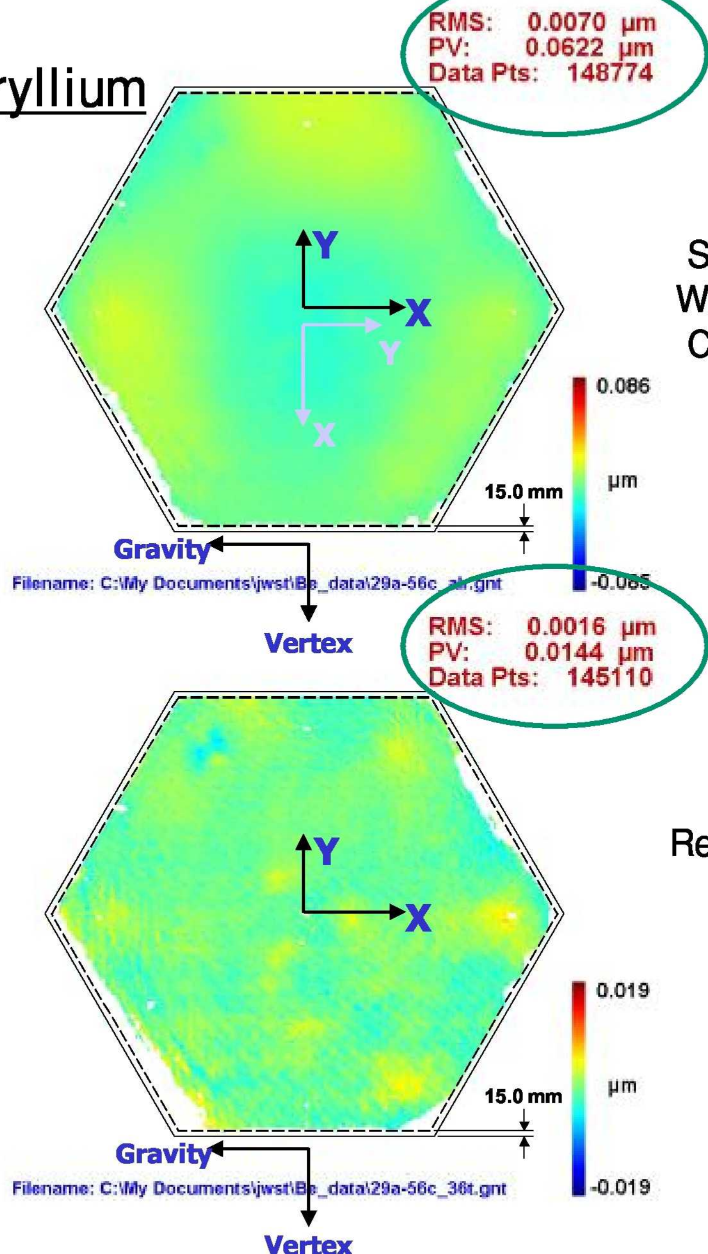
Residual with 36 Zernikes Removed



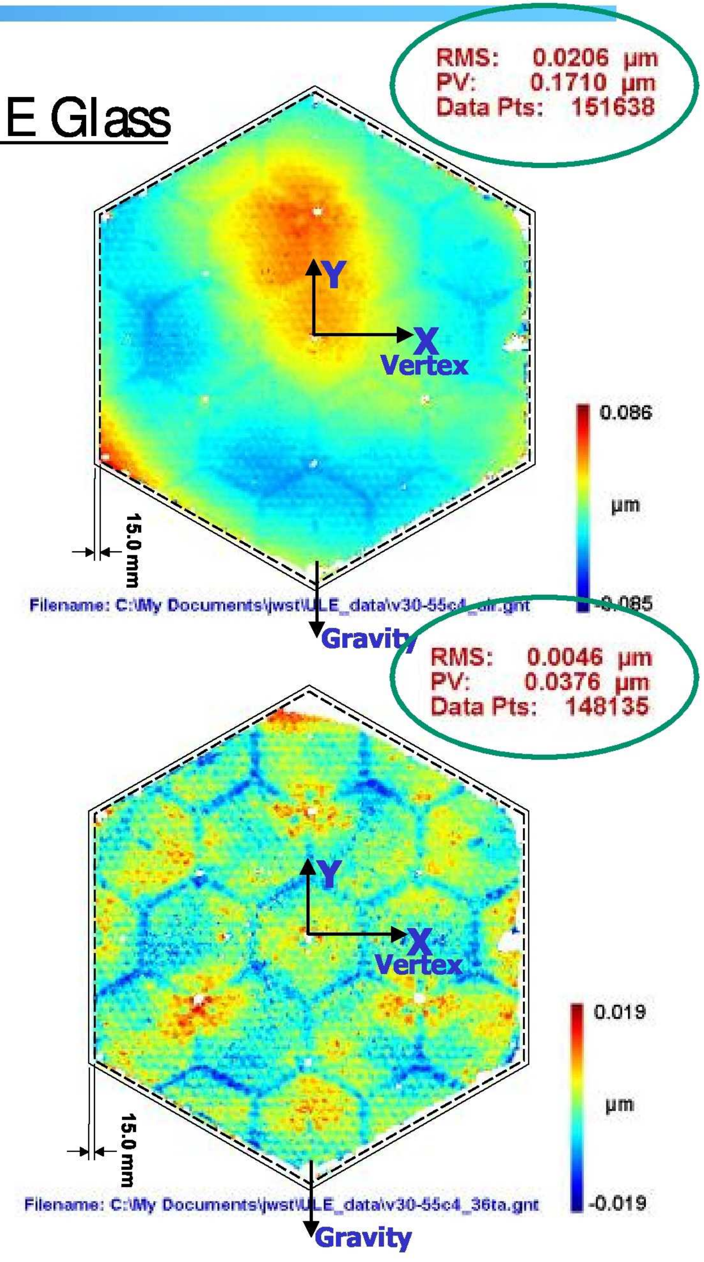


AMDS Figure Change: *30-55K Operational Range*

Beryllium



ULE Glass



Surface Figure With Alignment Compensation

Residual with 36 Zernikes Removed

Mirror Technology Development Program

NASA and DoD Partners invested $40M in mirror technology development:

- AMSD - Advanced Mirror System Demonstrator
  - Ball Semi-Rigid Low-Authority Be
  - Kodak Semi-Rigid Medium-Authority ULE Glass
  - Goodrich Iso-Grid High-Authority Fused Silica Glass
- NMSD - NGST Mirror System Demonstrator
  - Arizona Meniscus Very-High-Authority Glass
  - COI Rigid Hybrid-Glass-Composite
- SBMD - Small Beryllium Mirror Demonstrator
- SiC & C/SiC
  - IABG (ECM) 0.5 meter 7.8 kg/m2 mirror has been cryo-tested
  - Xinetics 0.5 meter 25 kg/m2 mirror has been cryo-tested
- Foam Mirrors
  - Schafer Corp Foam Si
  - MER and UltraMet Foam SiC
- JBMD - Joined Beryllium Mirror Demonstrator
- MSFC Nickel Replication

Enabling Technology

It is my personal assessment that there was 4 key Technological Breakthroughs which have enabled JWST:

- O-30 Beryllium (funded by AFRL)
- Incremental Improvements in Deterministic Optical Polishing
- Metrology Tools (funded by MSFC)
  - PhaseCAM Interferometer
  - Absolute Distance Meter
- Advanced Mirror System Demonstrator Project (AMSD)
  - funded by NASA, Air Force and NRO

AMSD Lessons Learned

Any proposal which seems overly conservative to me is probably just about right. Required cost and schedule reserve is always more than what you think it needs to be.

Standard process tooling and handling procedures are not scaleable to large aperture light-weight mirrors.

It is very hard to polish a mirror all the way to the edge.

Fiducialization is critical for knowing where you are.

Imaging Distortion through a CGH can cause edge miss-hit by as much as 50 mm

A properly designed support structure interface will not distort a light-weight substrate

A properly designed substrate does not have cryo-quilting

Substrate CTE variation drives cryo-deformation

Mirror Technology TRL-6 Certification

Technical Non-Advocate Review

Mirror Technology was required to be assessed at TRL-6 by a Technical Non-Advocate Review (T-NAR) panel before JWST Optical Telescope Assembly (OTA) could undergo its Critical Design Audit (CDA).

On 31 January 2007. the T-NAR declared that 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.

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

JWST Requirements vs pre-JWST SOA

JWST Mirror Technology vs State of Art			
PMSA Technology	**JWST Requirement**	**Hubble**	**Spitzer**
PMSA-110: Spectral Reflectance 0.6-28 µm	Gold Coating on O-30 Be with 28K Survival	UV/Visible	Uncoated
PMSA-530: Operational Temperature 28-50K			
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 PMSA-530: Operational Temperature 28-50K	Gold Coating on O-30 Be with 28K Survival	Gold Coating on O-30 Be with 28K Survival	SBMD
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

Four PMSA Technology Demonstrators for TRL-6

Demonstrator	Technology	Validity to JWST
SBMD	Cryogenic Coating Cryo-Null Figuring	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
AMSD Stress Coupons	Long term material stability	-:67□306$¶V□DUH□PDQXIDFWXUHG□XVLQJ□WKH□I processing developed on AMSD III to assure low residual surface stresses and low material creep.
JWST EDU & Flight Segment	Launch distortion Actuation Capability	JWST flight segment used to show technology readiness

Gold Coating on O-30 Be with 28K Survival

SBMD survival tested to 28K

Gold Coating provides Spectral Range

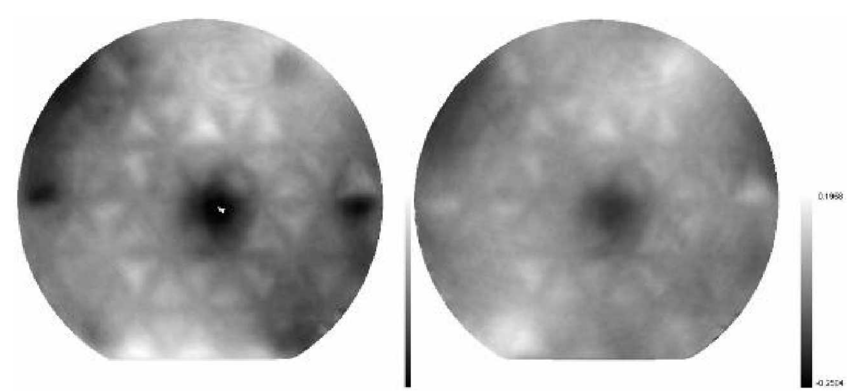
Adhesion demonstrates Operational Temperature

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

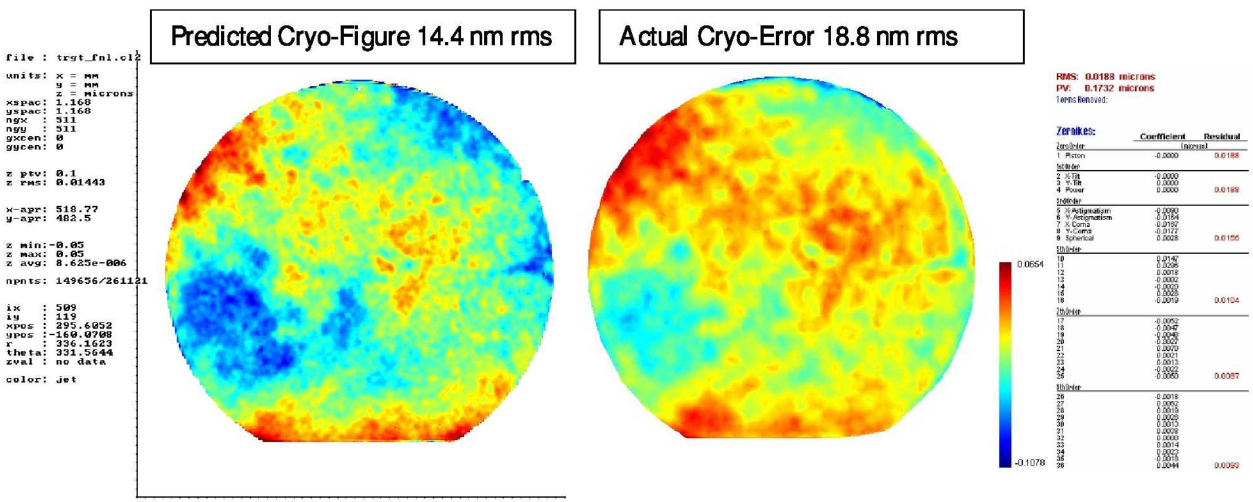
SBMD exhibited a cryo-deformation of approximately 90 nm rms.

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.



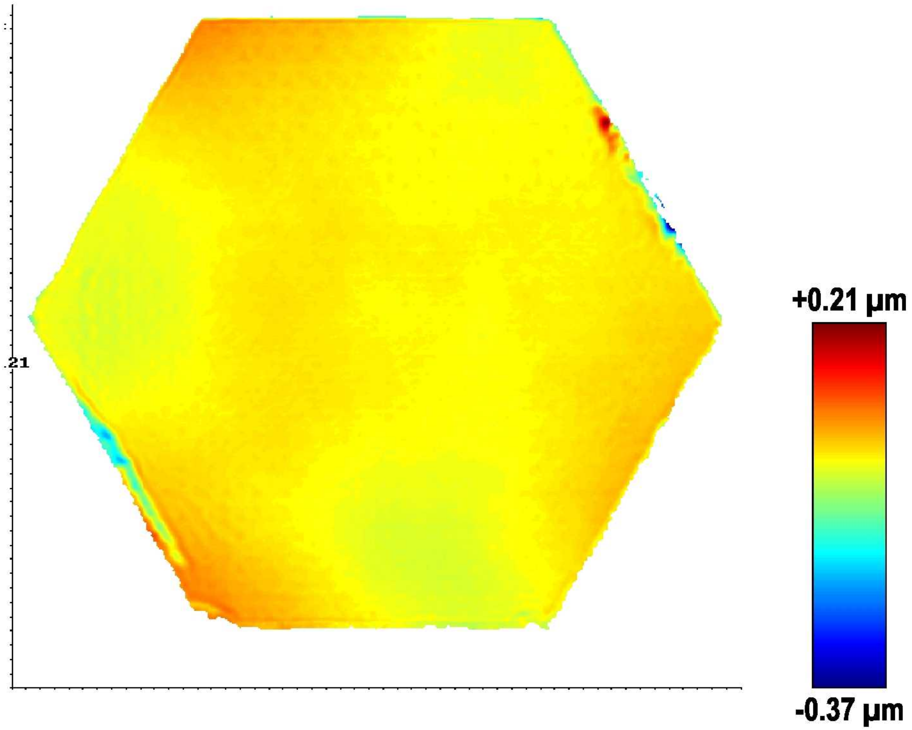
AMSD Key Technology Results

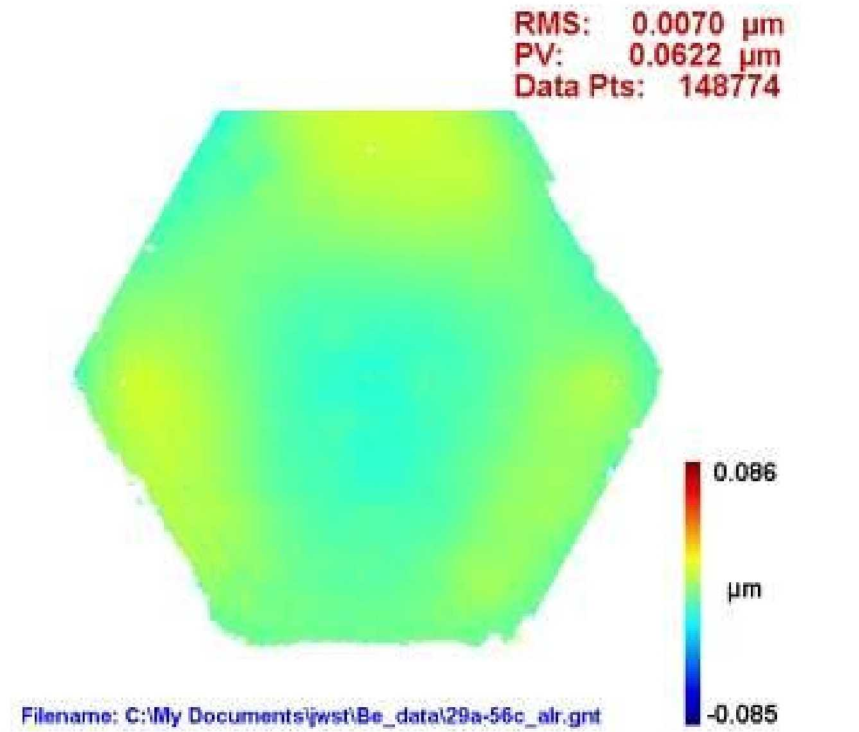
Since SBMD demonstrated the ability to cryo-null polish to 20 nm rms.

For cost and schedule reasons, AMSD demonstrated 20 nm rms at ambient.

AMSD did certify Cryo-Figure Stability over the operating range.

Results of AMSD 20 nm-rms convergence	Results of AMSD-II 30 to 55 Kelvin
RMS = 19.2 nm **Area of Mirror = 97.1%** Requirements PMSA-150 & 70	**Operational range** **Delta = 7 nm-rms (0.28 nm-rms/K)** Requirement PMSA-170





JWST Mirror Design Builds on AMSD Heritage

Specific modifications were made to the JWST flight PMSA design based on AMSD Lessons Learned to improve producibility, performance, launch survival & reduce risk

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

AMSD Mirror

Photos shown approximately to scale

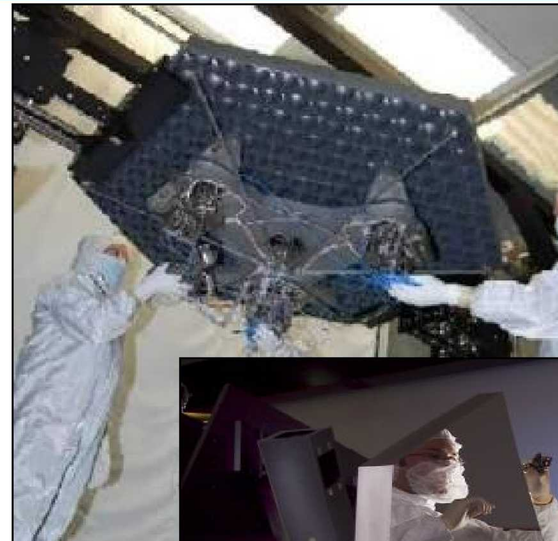
JWST Mirror

Mirror Technology has been demonstrated

time and maturity

Flight mirror demonstration

- Launch Load survival
- Acoustic tests



Advanced Mirror System Demonstrator

- Areal density, full scale asphere
- Surface figure requirements
- Radius of curvature control
- Cryo-repeatability

Subscale Beryllium Mirror Demonstrator

- Areal density
- Cryo-figuring
- Radius of curvature control
- Cryo-testing of protected gold coating

Flight PMSA Fabrication

Engineering Development Unit

an EDU is Essential

AMSD ran out of time and money.

Therefore, as discussed, TRL-6 was established via a combination of multiple mirrors: AMSD, SBMD and Flight.

TRL-6 was never established with a single mirror.

Furthermore, the flight mirror design was significantly modified as a result of AMSD lessons learned.

Thus, the EDU was necessary to verify how the new design interacted with the fabrication process.

While the JWST PMSAs have been successful, they could have been even more successful if, as suggested by the recent National Academy Report, more time had been spent during Phase A to fully demonstrate the technology.

Leaning vs Forgetting Curve

Just as there is a ‘learning’ curve, there is also a ‘forgetting’ curve

Too much time elapsed between end of AMSD and start of flight

Thus, the process had to be re-established on the EDU

The process was not stable until the 3rd or 4th PMSA

To use EDU learning, must keep a gap between EDU and Flight

No Process should ever be performed to a flight mirror until first performed on a full scale EDU

Schedule Lessons Learned

Plan for unplanned Activities

Because of unplanned activities, AMSD's actual schedule was 60% longer than its initial prediction.

At the start of JWST,

Vendor Team estimated an EDU production schedule similar to the AMSD schedule based on the assumption that lessons learned.

Review Team estimated an DEU production schedule 75% longer.

The EDU production schedule was actually 150% longer.

Delay to the EDU schedule impact every flight mirror.

Lessons Learned and Conclusions

Lessons Learned ± in no particular order

Large Mirrors are harder to make than Small Mirrors

Technology must be ‘scaled-up’ by validating increasing larger Mirrors

Technology demo-ed on Sub-Scale Mirrors does not necessarily ‘Scale-Up’

Full Scale Pathfinders are extremely valuable

Low areal density mirrors are harder to make than high areal density mirrors

Processes for high areal density do not necessary work for low areal density

Process Characterization and Control is Critical

Standard tooling and handling procedures are not scaleable to large aperture light-weight mirrors

Mirror Stiffness is at least as important as Areal Density

It is hard to polish a mirror all the way to the edge

Fiducialization is critical for knowing where you are

CGH imaging distortion can cause miss-registration of as much as 50 mm

CGH imaging distortion and depth of focus can introduce Fresnel diffraction effects which blur edges resulting in ‘rolled’ edges

Lessons Learned ± continued

Nothing behaves the same at 300K and 30K

Designing Mechanisms to operate at 30K is difficult

Validate all Components under Operational Conditions before Assembly

Your intuition about how things behave at 30K is probably wrong

Nothing works the way it is initially designed or modeled

Uniform CTE properties are essential for predictable cryo-performance

Manufacturing Production Quantities is harder than a Demo Unit

Things break and mechanisms can have infant mortality as high as 30%

Glass Mirrors will Fracture and Metal Mirrors will be Stressed

Just as there is a learning curve, there is also a forgetting curve. Don't allow too much time between the end of technology development and the start of flight fabrication.

EDUs are critical, but the schedule gap between the EDU and flight mirrors must be maintained – not too large other wise forgetting occurs, not too short otherwise lessons learned cannot be applied.

There is no substitute for Experience.

Conclusions

Starting in 1996, 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)**

The effort dramatically reduce cost, schedule, mass and risk for large-aperture space optical systems.

TRL-6 was achieved before the Technical Non-Advocate Review (T-NAR)

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 (and ~$40M) to mature mirror technology from TRL 3 to 6.

BACK-UP

Mirror Technology Development Program

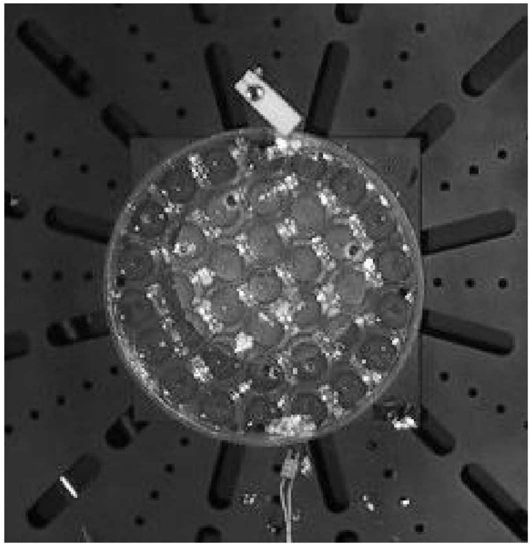
Other Mirrors Tested at MSFC

Table 1 Cryogenic Performance of Selected Mirrors (all values are approximate)				
Mirror	Material	Diameter	Areal Density	Cryo-Distortion [290K to 30K]
Beryllium Mirrors				
Ball SBMD	O-30 Be	0.5 m	10 kg/m2	17 nm rms
Ball AMSD	O-30 Be	1.4 m	16 kg/m2	77 nm rms
Glass Mirrors				
Kodak	Fused Silica	0.23 m	10 kg/m2	17 nm rms
Hextek	Borosilicate	0.25 m	14 kg/m2	25 nm rms
Kodak	ULE	0.35 m	10 kg/m2	8 nm rms
Kodak AMSD	ULE	1.4 m	18 kg/m2	188 nm rms
SiC Mirrors				
Schafer	Foam SiC	0.125 m	10 kg/m2	4 nm rms
POCO	Foam SiC	0.25 m	16 kg/m2	16 nm rms
TREX	CVD SiC	0.25m	9 kg/m2	38 nm rms
Xinetics	RB SiC	0.5 m	22 kg/m2	25 nm rms
IABG (Note 1)	C/SiC Felt	0.5 m	8 kg/m2	443 nm rms
Note 1: IABG cryo deformation aligned with the felt bias direction, it is anticipated that a mirror facesheet with more felt layers (and more mass) would have had a substantially smaller cryo-deformation.				

Hextek Gas Infusion Mirror

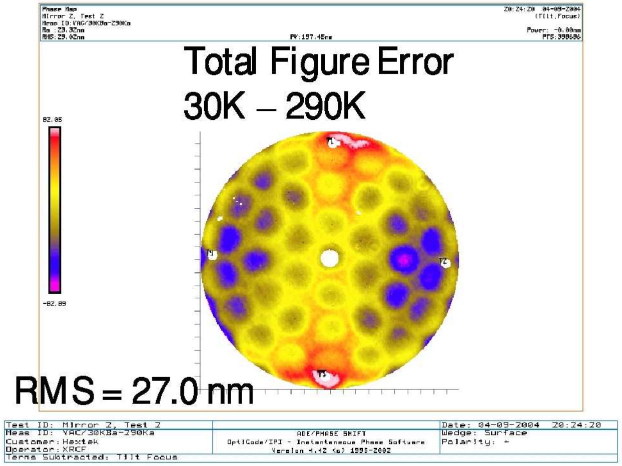
Specifications

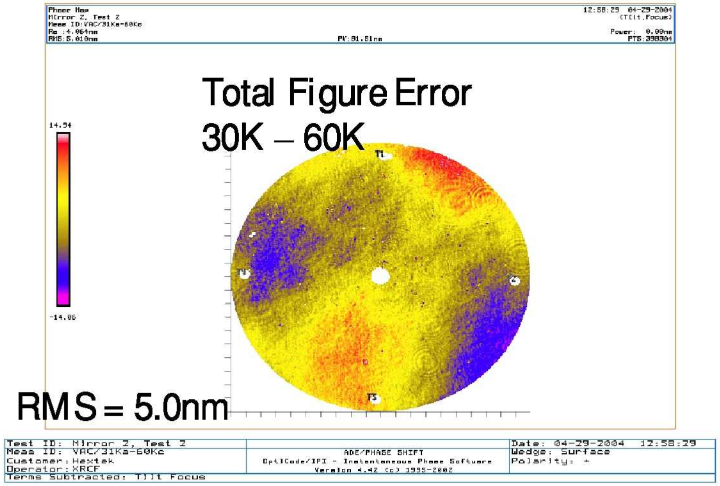
Diameter	0.25 meter
Radius	2.5 meter
Areal Density	< 10 kg/m2
Areal Cost	< $300K/m2



Polished by MSFC

Ambient Fig	23 nm rms
30K Figure	40 nm rms
30K – 290K	27 nm rms
30K – 60K	< 5 nm rms





Cryo Null Figured by QED with Residual Error of 13 nm rms

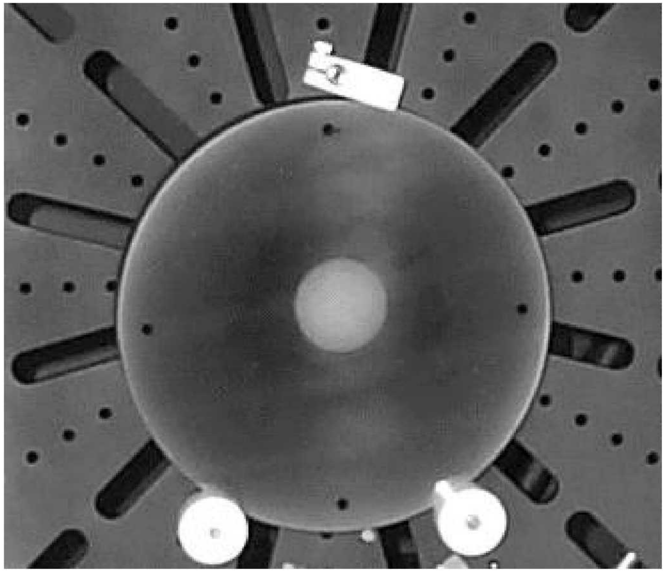
POCO SiC Mirror

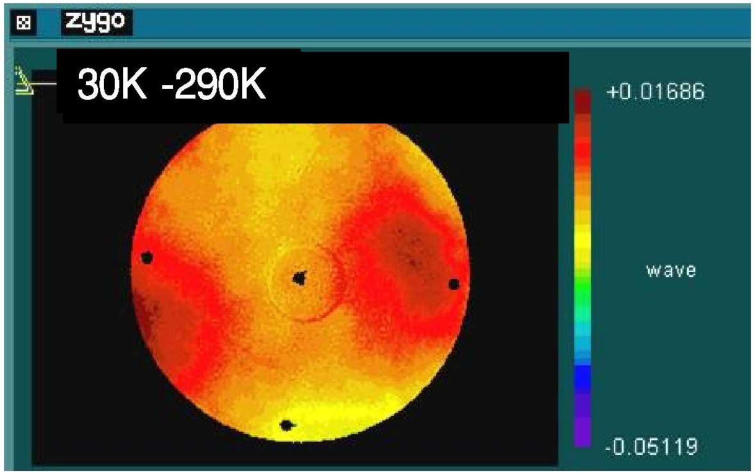
Specifications

Diameter	0.25 meter
Radius	2.5 meter
Areal Density	< 10 kg/m2
Areal Cost	< $1M/m2

Delivered Polished

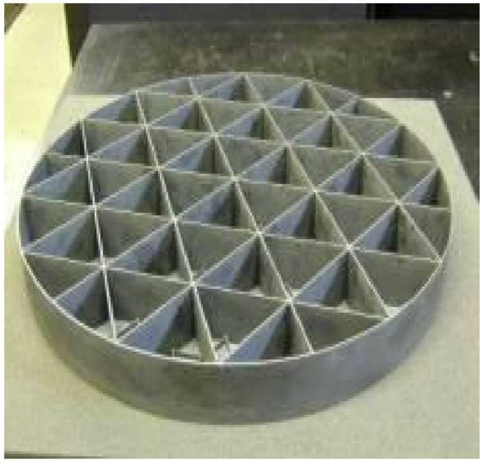
Ambient Fig	89 nm rms
30K Figure	96 nm rms
290K – 30K	16 nm rms

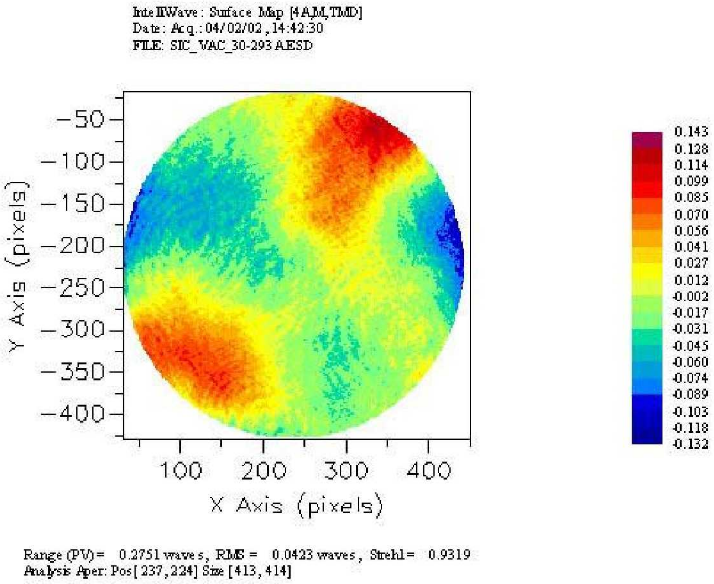




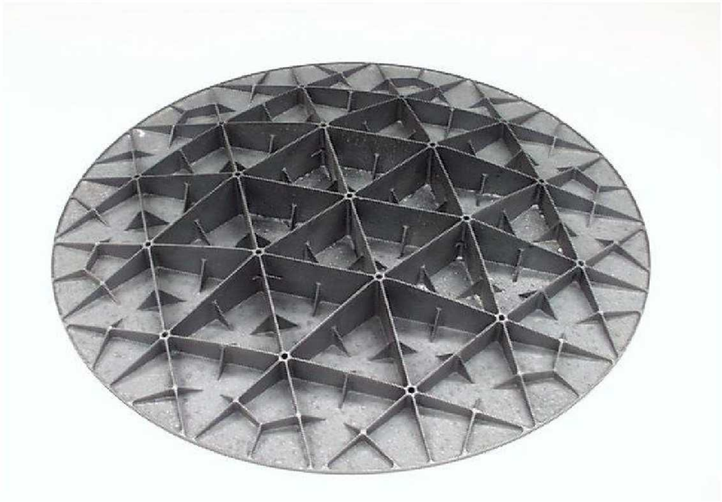
Xinetics SiC Mirror

Specifications	
Diameter	0.5 meter
Radius	20 meter
Areal Density	< 20 kg/m2
Areal Cost	< $1.5M/m2
Delivered Polished	
Ambient Fig	300 nm rms
290K – 30K	27 nm rms





IABG 0.5 m 20 m Rcv Carbon Silicon Carbide

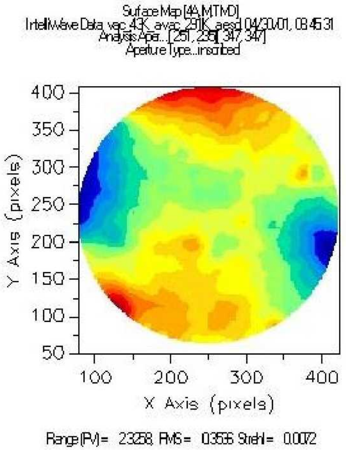


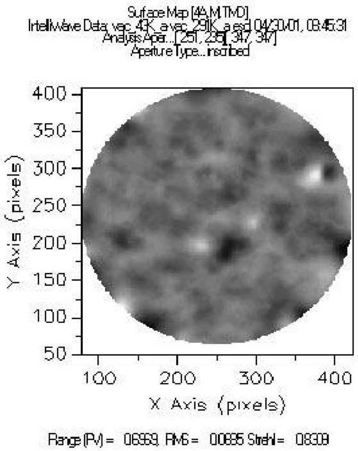
IABG Carbon Silicon Carbide Mirror C/SiC
- 0.5 m Diameter
- 20 m Rcv
- 7.8 kg/m^2 Areal density

Blank polished at General Optics
- Figure of ½ wave PV
- Finish of 100 Angstroms RMS

Mirror tested to 120K at Kodak (Sept 99)
- 280 nm RMS, 2.53 μm PV Cryo-Figure Change

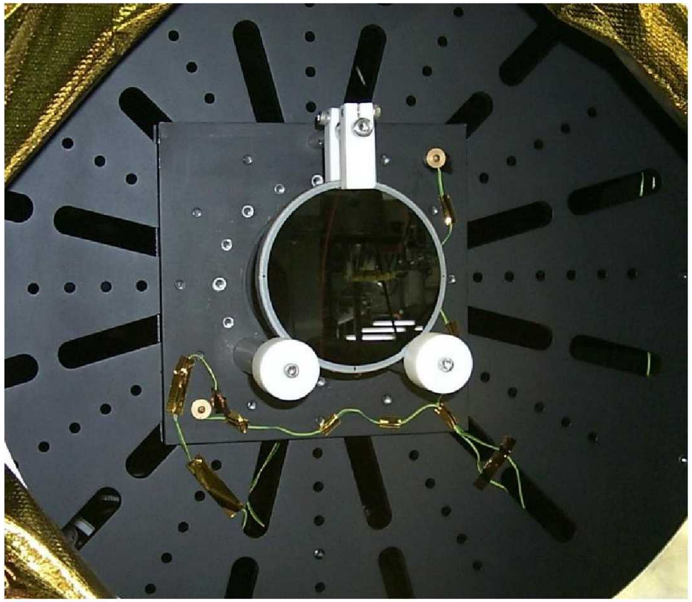
Mirror tested to 30K at MSFC (Apr 01).
- 350 nm RMS, 2.32 μm PV Cryo-Figure Change





Schafer SLIM (Si Foam) Mirror

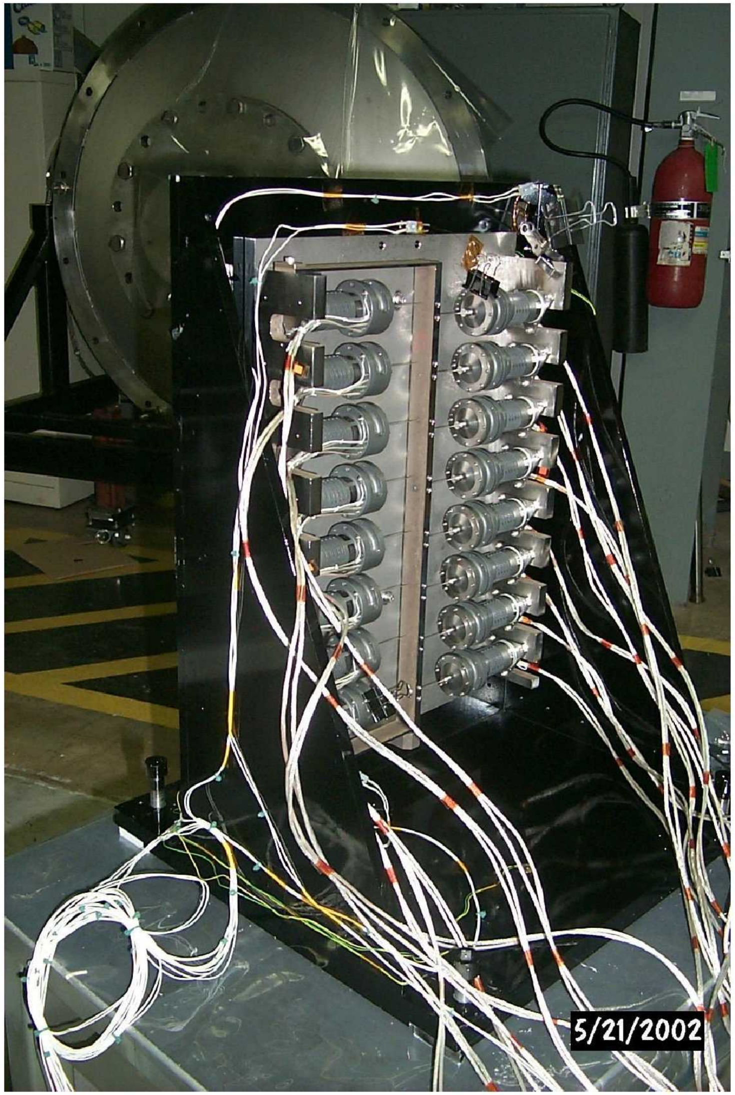
Specifications	
Diameter	0.125 meter
Radius	0.6 meter
Areal Density	< 10 kg/m2
Areal Cost	< $2.5M/m2
Delivered Polished	
Ambient Fig	29 nm rms (free)
290K – 30K	10 nm rms (free)
290K – 30K	46 nm rms (mounted)
75K – 30K	< 4 nm rms (free)



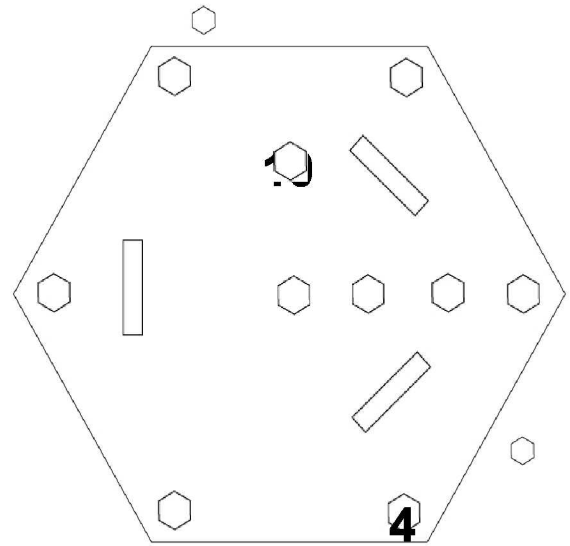
Kodak Actuator V&V at MSFC

Characterize Kodak/Moog Force Actuators at 30K in MSFC 1m Chamber.

- Step Size and Linearity
- Operation under Load

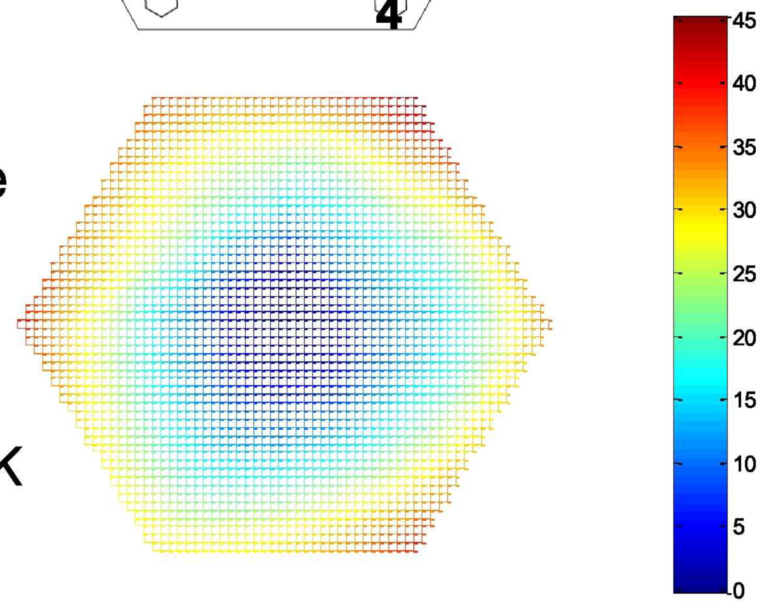


Cryo-Deformation of Goodrich reaction structure

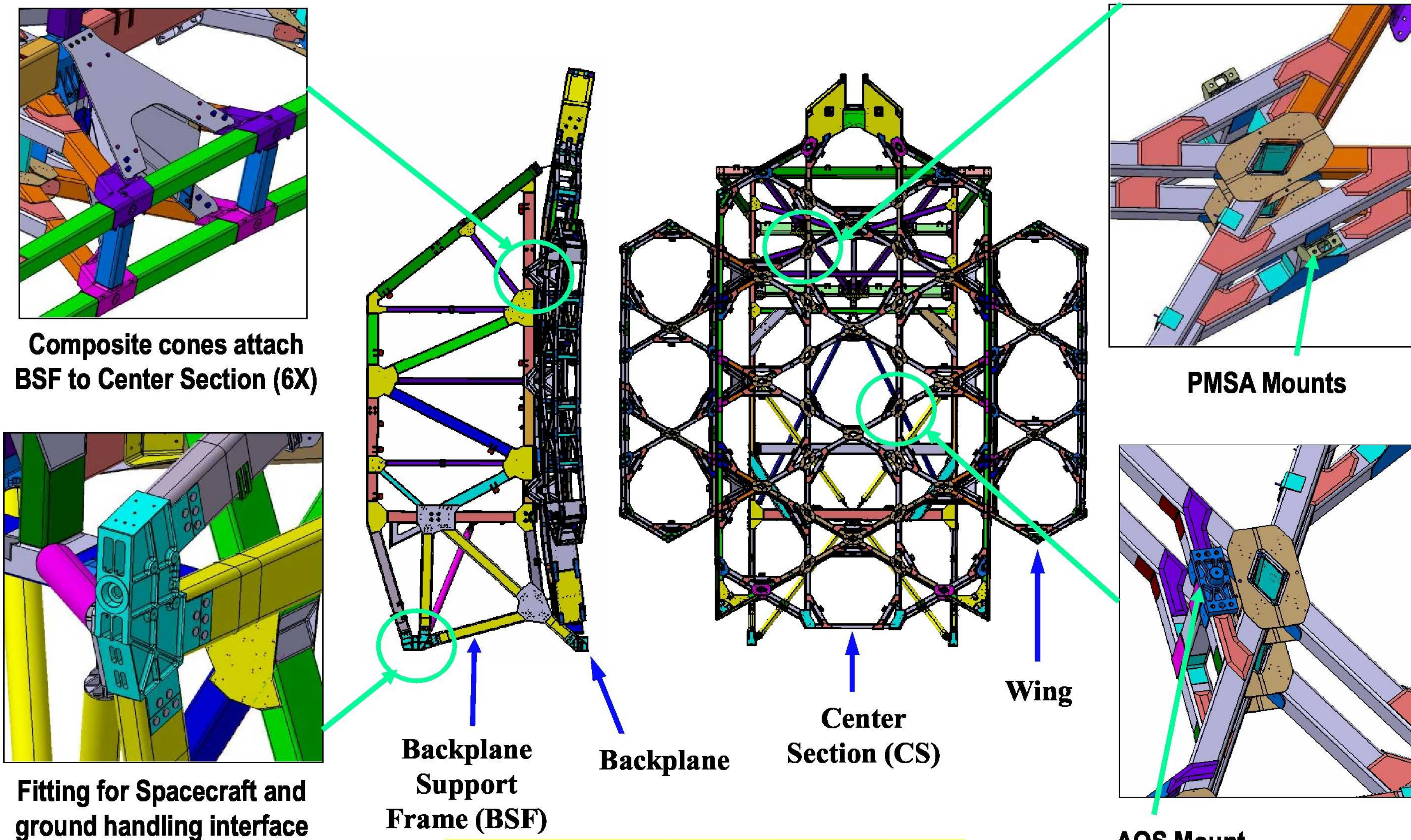


MSFC measured reaction structure cryo-change

- Instrument with corner cubes
- Characterize with Leica ADM
- 30 micrometer change from Ambient to 25K



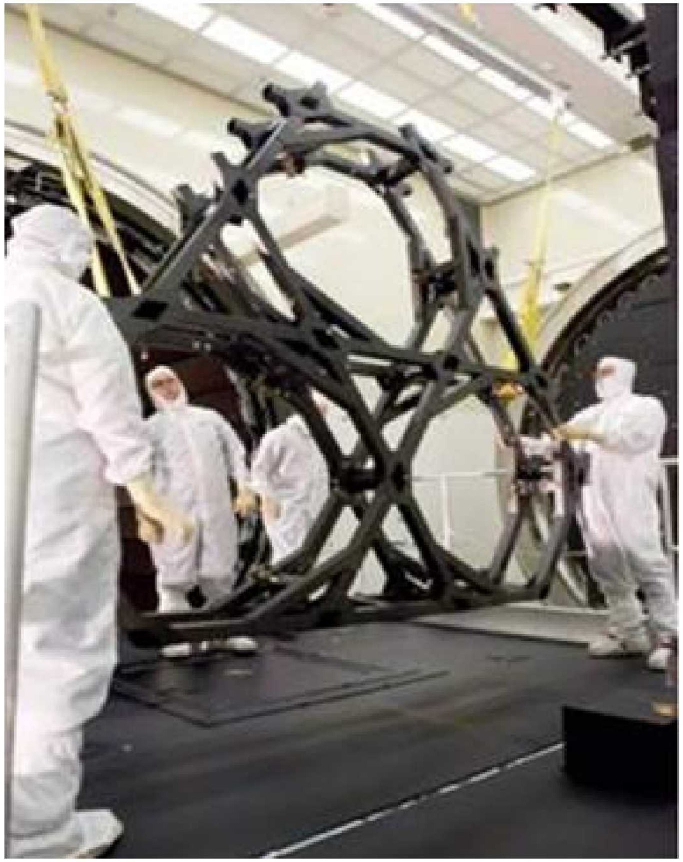
Primary Mirror Backplane Support Structure

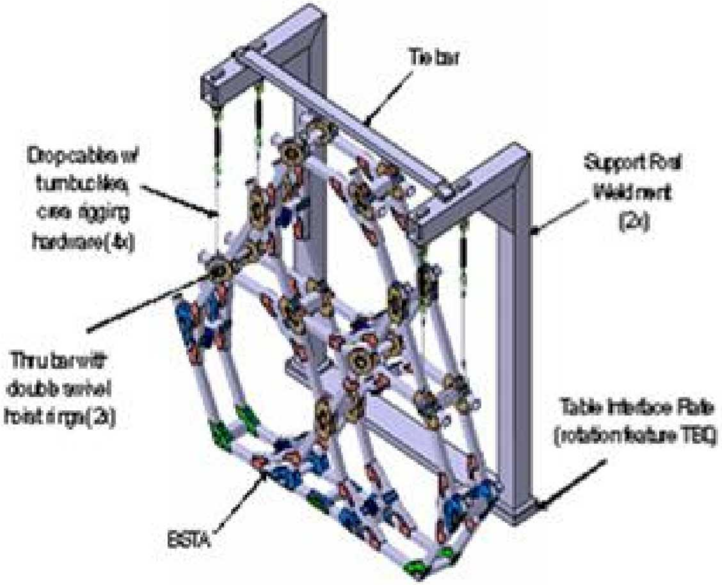


Colors indicate different laminate designs

Cryo-Tested EDU Structures

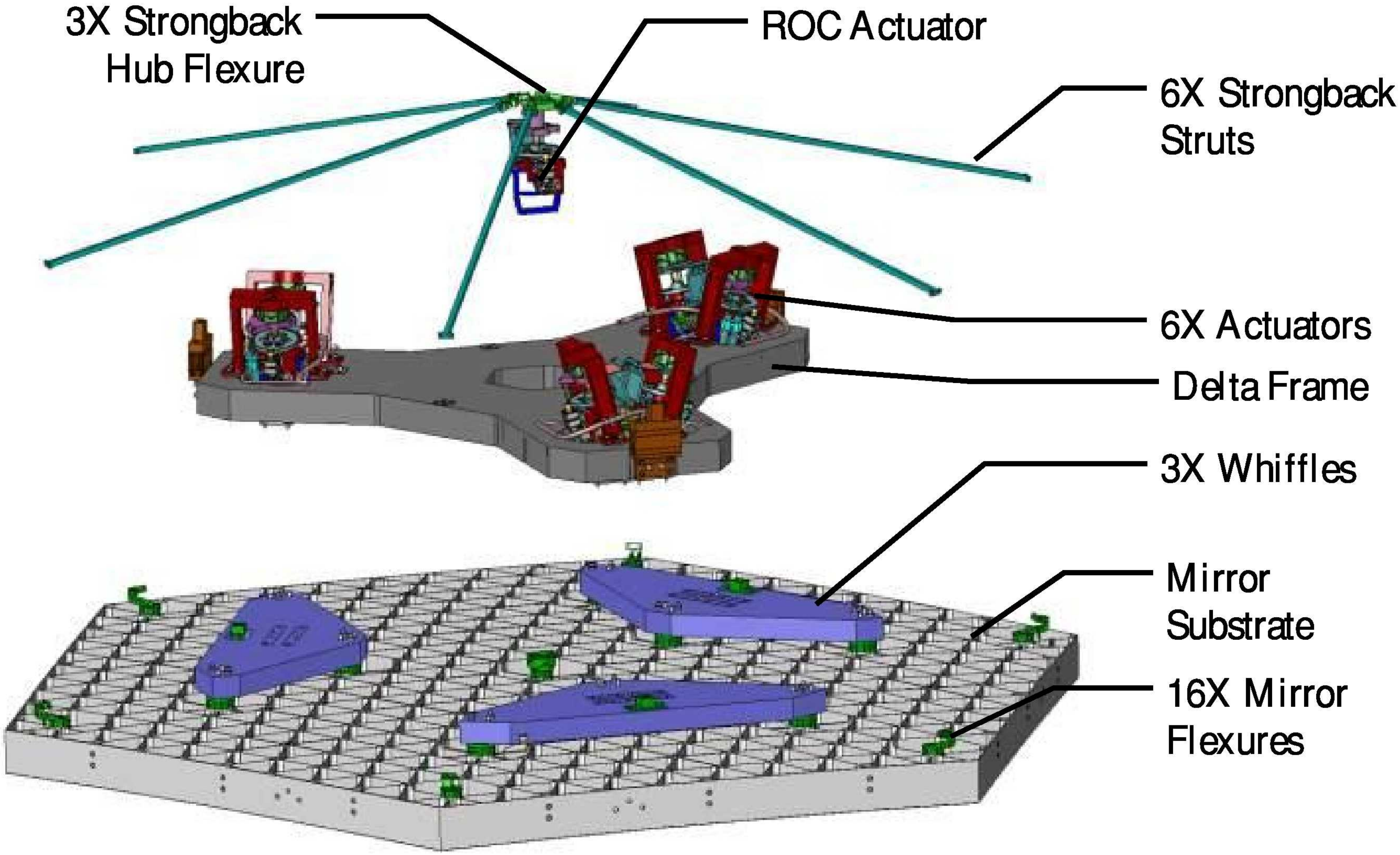
When cryo-tested to 30K, the Backplane Support Test Assembly (BSTA) demonstrated remarkable agreement with model prediction.





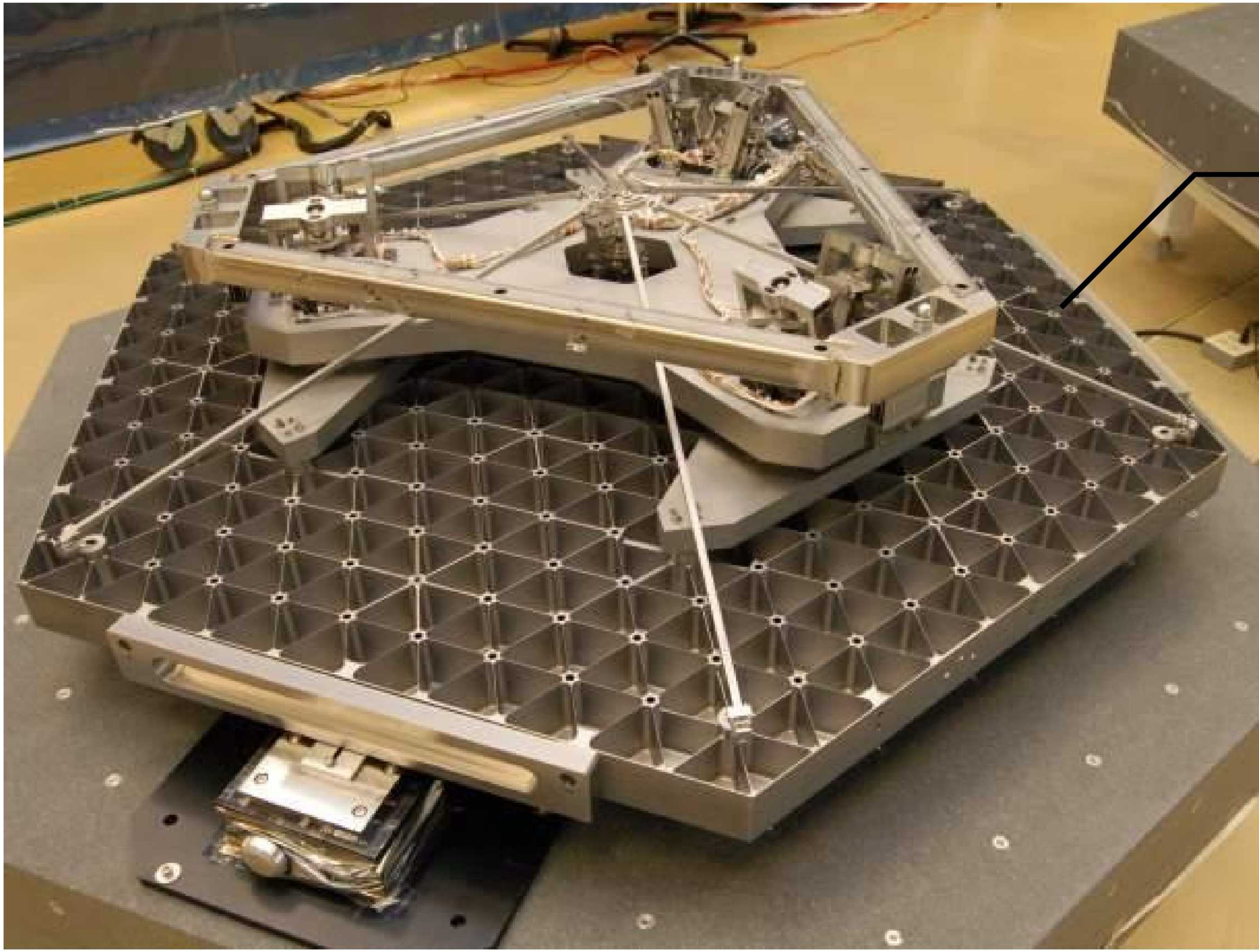
Mirror Technology TRL-6 Certification

PMSA Component Definition



Mirror Substrate focus of technological development

Mirror required Technological Development

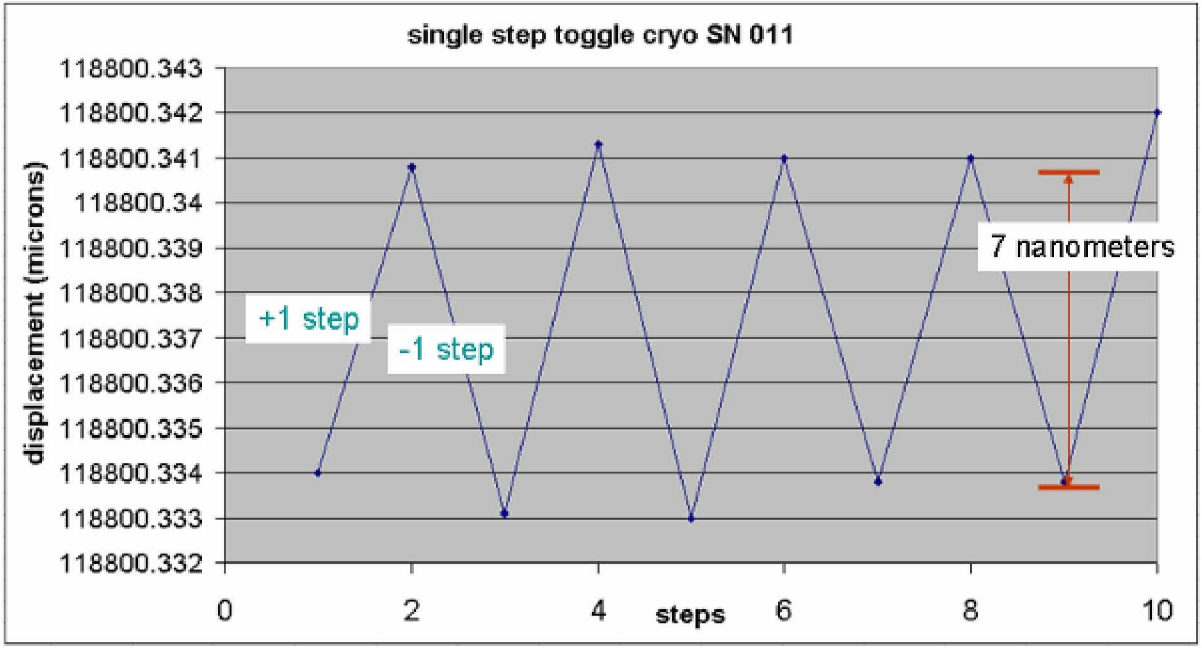


Cryogenic Actuators

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 Cryo on AMSD

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

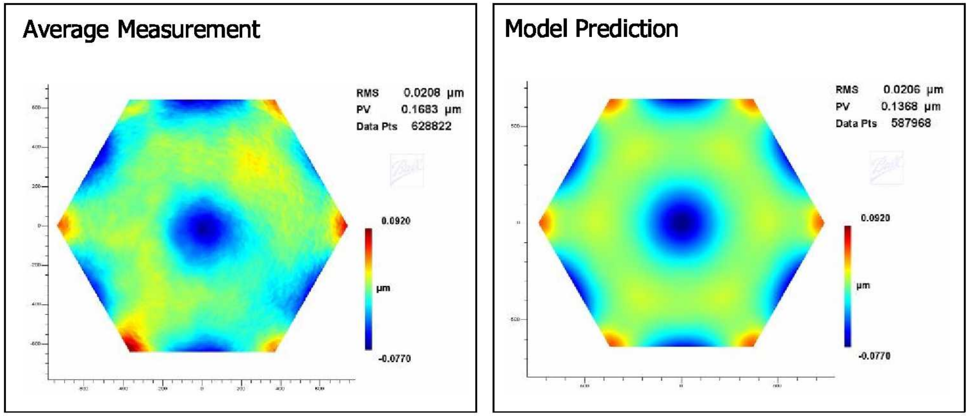
Mirror	Requirement (nm PV)	Cryo Demonstration (nm PV)	Capability (nm PV)
AMSD	50	38*	0.24
JWST	10	-	0.4

* 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)



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

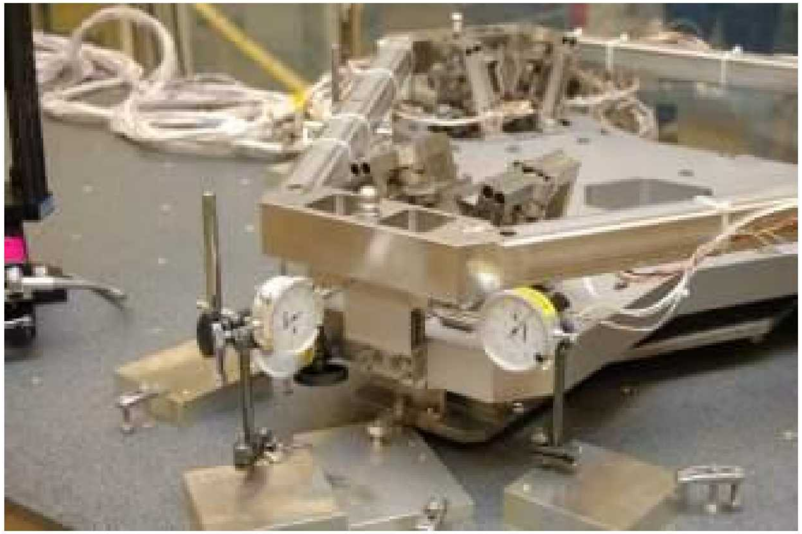
TRL-6 PMSA hexapod fully integrated & tested prior to and after environmental testing

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**



Relevant Test Environment for TRL-6 Vibro-Acoustic Demo

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

□□□*¶V□ORDG□SDUDOOHO□WR□PRXQWLQJ□VXUIDFH□□OD

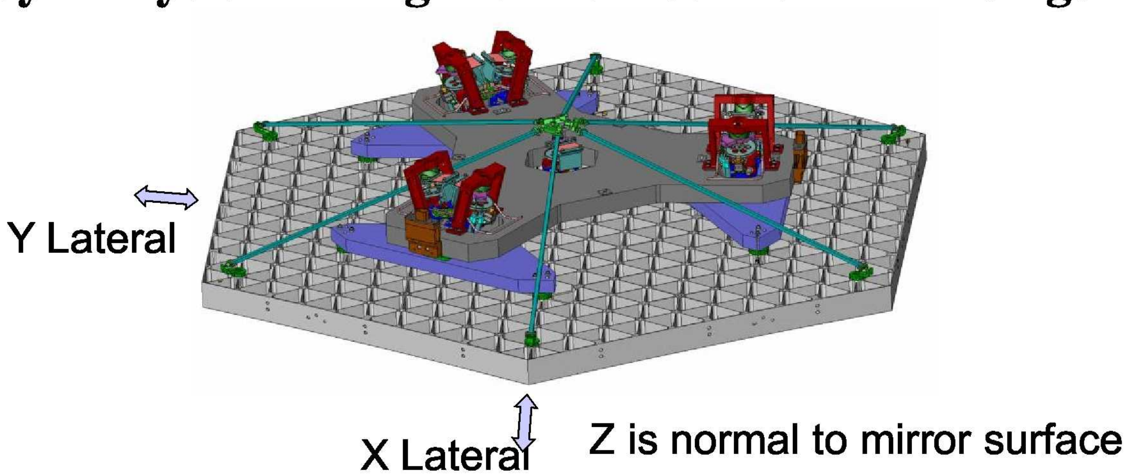
□□□□□□1□IRUFH□QRUPDO□WR□PRXQWLQJ□VXUIDFH□□D[LD

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

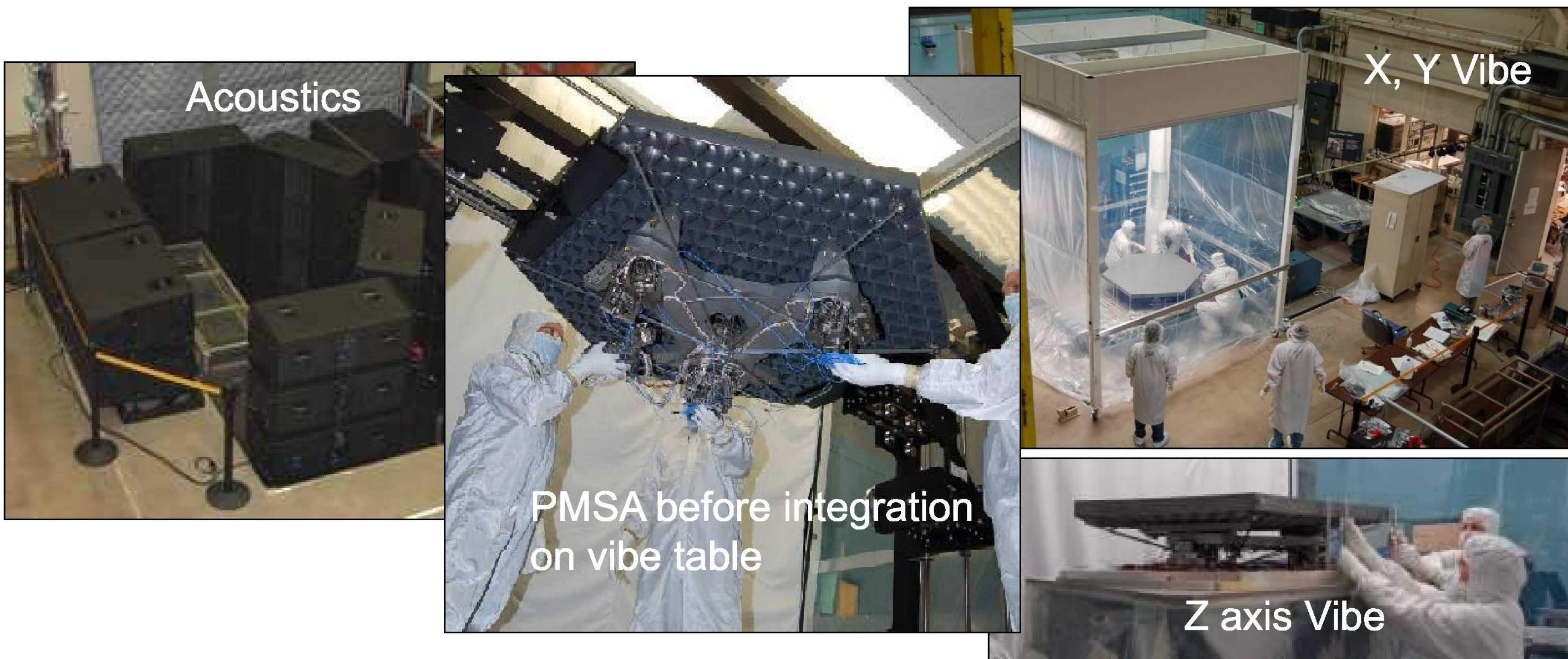


Mirror TRL-6 Load Testing

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

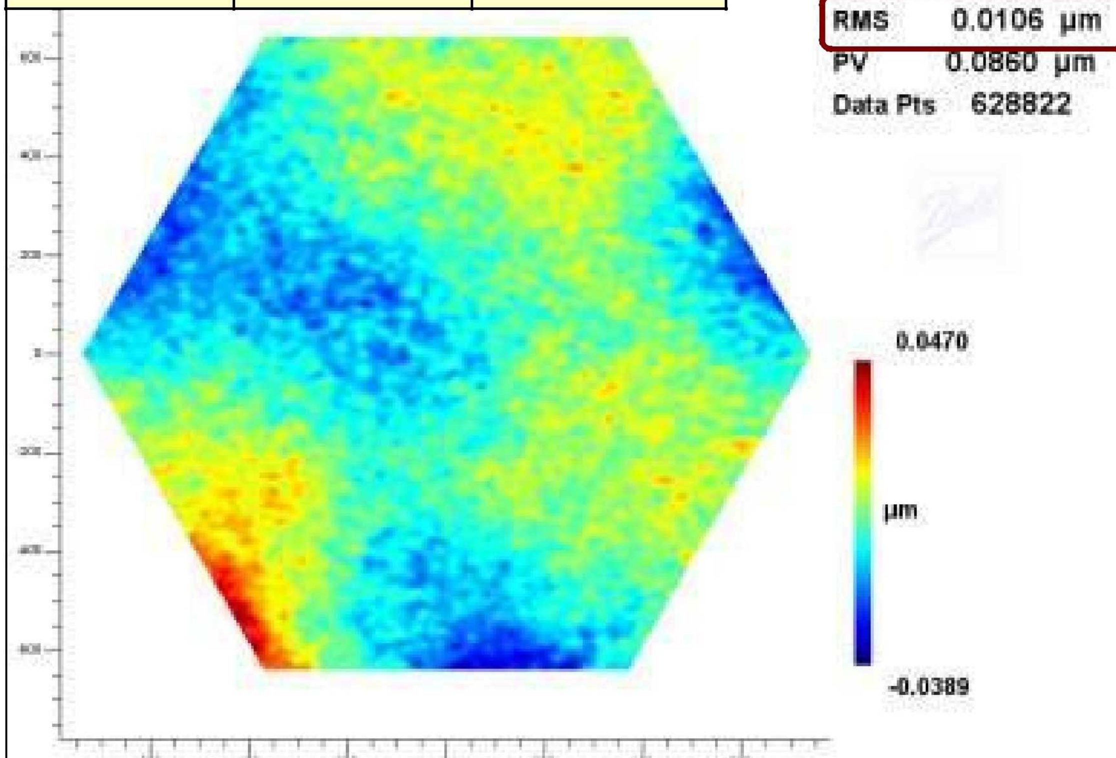
Mirror Loads:

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

Measured Figure Error is Below Metrology Uncertainty

Measured Astigmatism is Below Metrology Uncertainty

Measured Power is Below Metrology Uncertainty



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

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