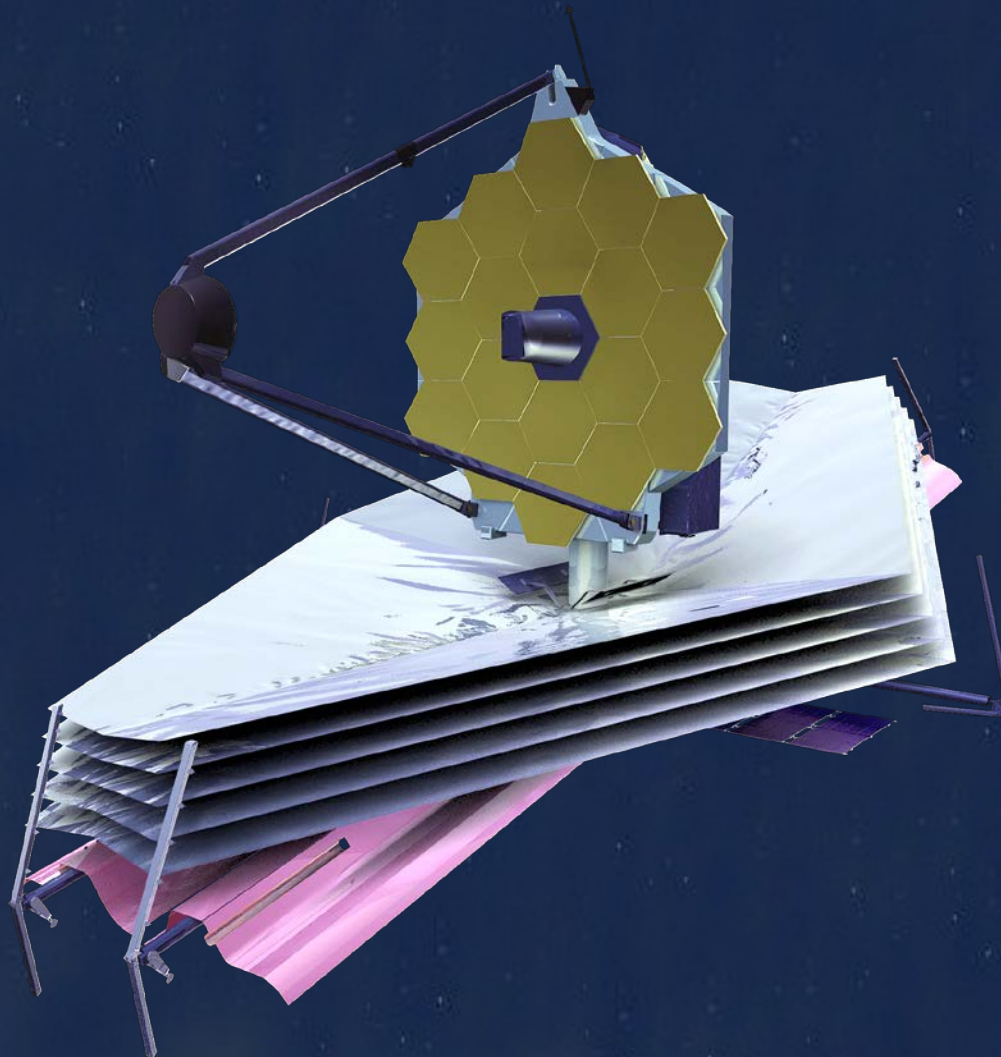


James Webb Space Telescope Optical Telescope Element Mirror Development History and Results



Lee Feinberg, GSFC
Ritva Keski Kuha, GSFC
Scott Texter, NGAS
Charlie Atkinson, NGAS
Mark Bergeland, Ball Aerospace
Ben Gallagher, Ball Aerospace



Outline



- Introduction
- As-executed roadmap
- Technology development
- Mirror Selection
- Mirror Process Flow
- As -run schedule
- Risk Management History
- Results



Mirror History



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1996

1998

2000

2002

2004

2006

2008

2010

2012

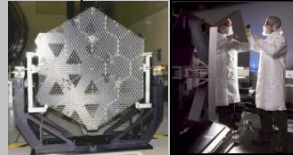
2014

Advanced Mirror System Demonstrator (AMSD)

Collaboration among 3 government agencies
15Kg/m², 1.2M diameter segments



Medium Authority Glass (ULE)



Low Authority Beryllium

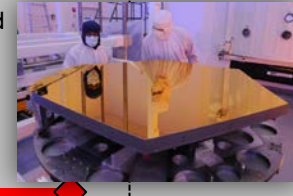
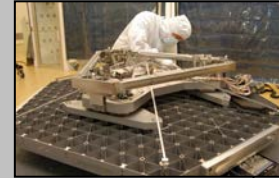
AMSD Phase 1:
8 Mirror Designs

AMSD Phase 2:
3 mirrors developed

AMSD Phase 3/Six Sigma Study
Be manuf. and process improvements

Technology Readiness

◆ **Level-6 Demonstrated:**
All key requirements and environments demonstrated



Onset of James Webb Space Telescope



Subscale Beryllium Mirror Demonstrator (SBMD):
.5 meter diameter,

OTE Optics Review (OOR):
Beryllium Selected

Engineering Design Unit.

PM Manufacturing of 18 segments



◆ **Axsys Machining Facility Complete**

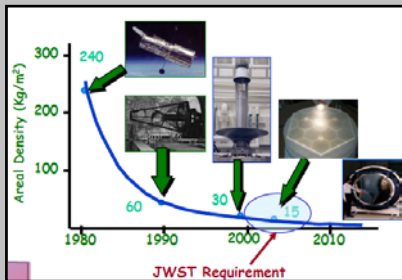
◆ **Tinsley Polishing Facility Complete**



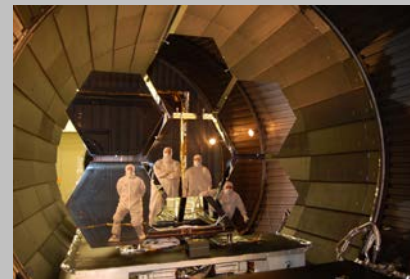
Low Areal Density Mirrors Identified as Key Enabling Technology for 25 Square Meter Space Telescope

Next Gen. Space Telescope (NGST) Mirror System Demonstrator (NMSD):

Other architectures that were not pursued



Cryo Testing



◆ ◆ ◆ **MIRRORS COMPLETE**



Mirror System Design Parameters Studied



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Wide Variety of Mirror System Design Parameters Studied

Item	SBMD (Ball)	NMSD	AMSD
Substrate Material	Be	Glass/Composite Hybrid (COI) Glass (UA)	Be (Ball) ULE (Kodak) SiO ₂ (Goodrich)
Reaction Structure	Be	Composite (both)	Composite (all)
Control Authority	Low (Focus Only)	Low (COI) High (UA)	Low (Ball) Medium (Kodak) High (Goodrich)
Mounting	Linear Flexure	Bipods (COI) 166 Hard (UA)	9 Bi-Flex (Ball) 16 Force (Kodak) 67 Bi/Ax-Flex (Goodrich)
Diameter	0.53 m	2 m (COI) 1.6 m (UA)	1.38 m (Ball) 1.4 m (Kodak) 1.3 m (Goodrich)
Areal Density	9.8 kg/m ² (mirror only)	13 kg/m ²	15 kg/m ²



Technology Development Specs



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Mirror Technology Development Specifications				
Item	SBMD	NMSD	AMSD	Units
Form	Circle with Flat	Hex	Hex	
Prescription	Sphere	Sphere	Off-Axis Parabola	
Diameter	> 0.5	1.5 to 2.0	1.2 to 1.5	meter
Areal Density	<12	< 15	< 15	kg/m ²
Radius	20	15	10	meter
PV Figure	160	160	250	nm
RMS Figure	---	---	50	nm
PV Mid (1-10 cm ⁻¹)	63	63	---	nm
RMS Finish	3	2	4	nm
Stiffness (1 st Mode)	---	---	150	HZ



Incremental TRL-6



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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	JWST PMSA's are manufactured using the exact 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



Advanced Mirror System Demonstrator (AMSD)



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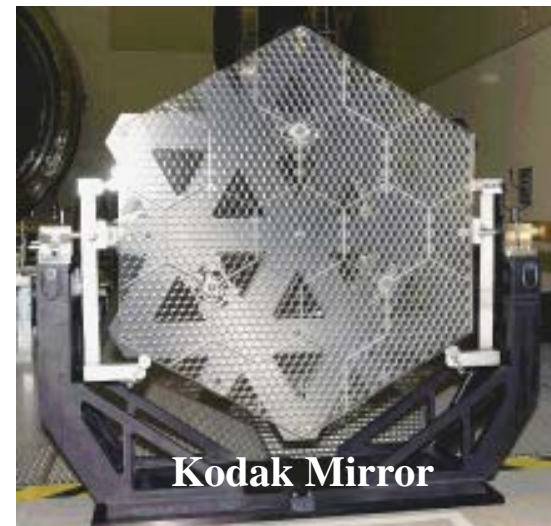
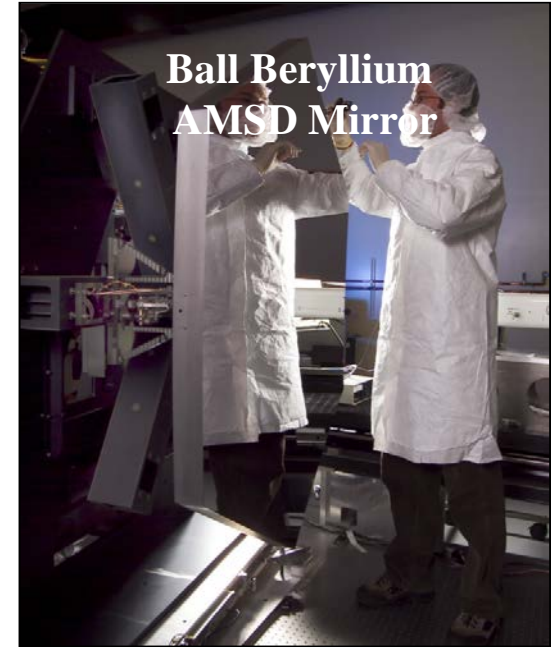


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ALLIANT TECHSYSTEMS

- NASA, DOD, NRO \$50M partnership funded 3 lightweight mirror technologies shown on the right
- Ball beryllium mirror technology completed and baselined for JWST in 2003
 - Ball beryllium mirror demonstrated all key aspects of JWST technology except for demonstration of vibro-acoustics survival which will be demonstrated this June on the Engineering Design Unit mirror
- Mirror manufacturing of flight mirrors started in September 2003





Mirror Technology Choices



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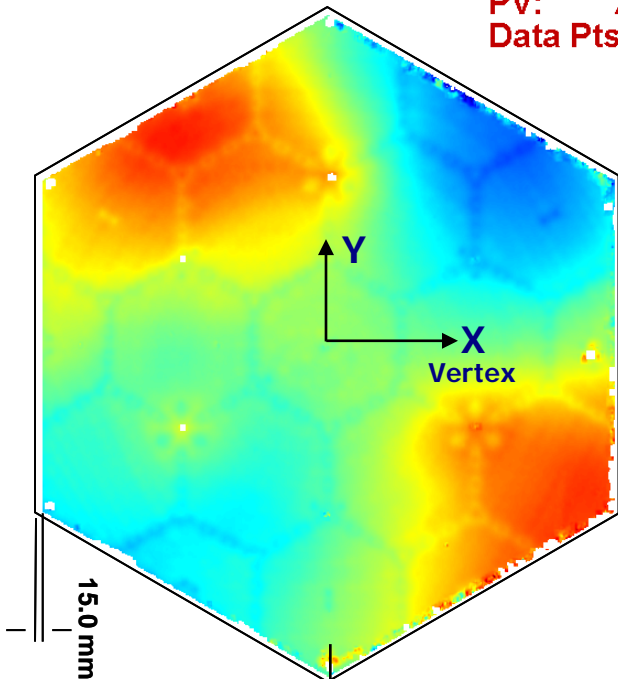
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~30 K minus Ambient

RMS: 0.3979 μm
PV: 2.8872 μm
Data Pts: 154545

Full 15mm
=155572



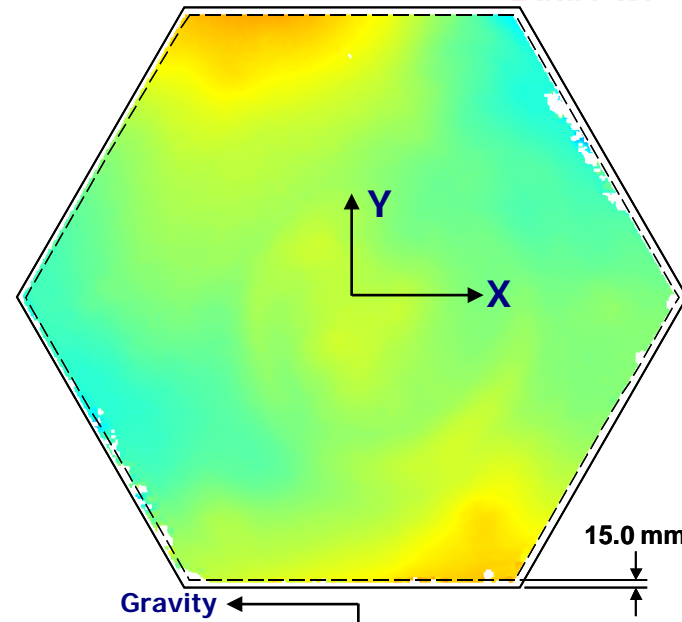
Filename: C:\My Documents\jwst\ULE_data\v30293c4_ntr.gnt

Gravity

ULE

RMS: 0.1705 μm
PV: 1.3630 μm
Data Pts: 151087

Full 15mm
=152064



Filename: C:\My Documents\jwst\Be_data\29a-294a_ntr.gnt

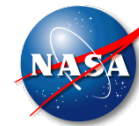
Vertex

Be

Beryllium Mirror Had Superior Cryogenic Properties



Mirror Selection Process and Results



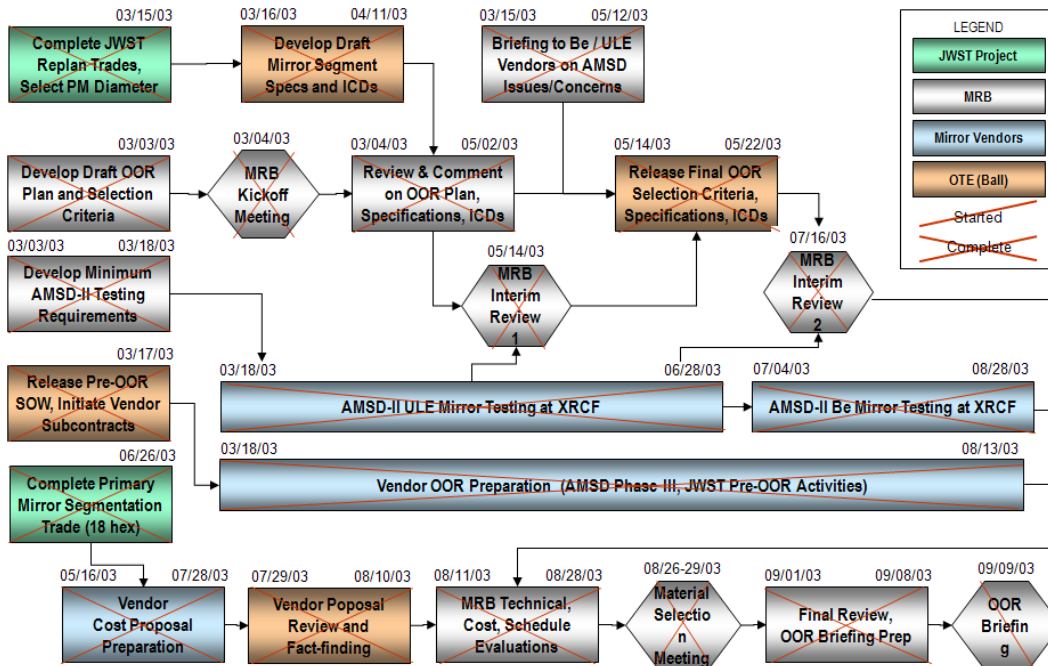
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- Beryllium was rated as the highest performing, lowest technical risk solution
 - Material has superior cryo CTE and conductivity, only technical issue was managing surface stresses to achieve final convergences
 - Provided best potential science performance, had significant margins on thermal performance and stiffness/mass
 - Key concerns were schedule and staffing at Tinsley
 - Material and manufacturing cost deltas between ULE and Beryllium were small when compared to the potential schedule deltas



■ Mirror Recommendation Board (MRB)

- > Lee Feinberg GSFC, OTE Manager, MRB Co-Chair
- > Ritva Keski-Kuha GSFC, OTE Deputy Manager
- > Mark Clampin GSFC, JWST Observatory Scientist
- > Phil Stahl MSFC, JWST Mirror Technology Lead
- > Kevin Russell MSFC, AMSD Program Manager
- > Scott Texter NGST, OTE Manager, MRB Co-Chair
- > Charlie Atkinson NGST, OTE Deputy Manager
- > Gary Rosiak NGST, Former NGST Phase 1 Program Manager
- > Beth Barinek NGST, Ball Subcontract Technical Manager
- > Doug Neam BATC, Vice President of Operations
- > Mark Bergeland BATC, JWST Program Manager
- > Gary Matthews EKC, Manager of Image Collection Systems

■ MRB Technical Consultants

- > Lester Cohen SAO, Chief Engineer
- > Matt Mountain Gemini Director and JWST SWG Representative
- > John Hraba MSFC
- > Gary Golnik Schafer Corporation
- > Paul Lightsey BATC, OTE Systems Engineer
- > James Hadaway University of Alabama, Huntsville



Mirror Assembly Configurations



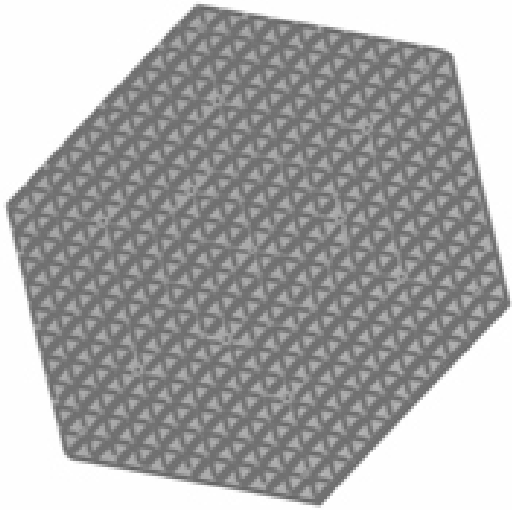
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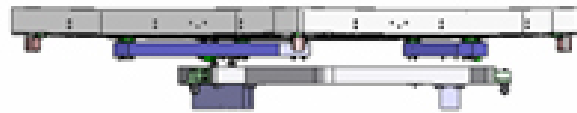
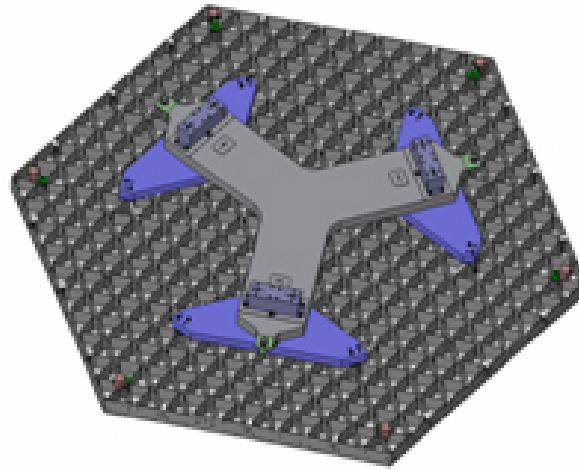


Configuration 1



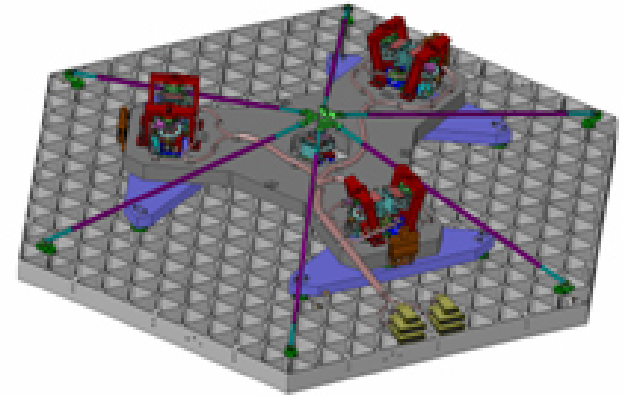
Mirror Substrate Only

Configuration 2



Mirror Substrate with Flexures, Whiffles and Surrogate Delta Frame

Configuration 3



Fully Assembled PSMA with Hexapod Assembly and ROC Actuator

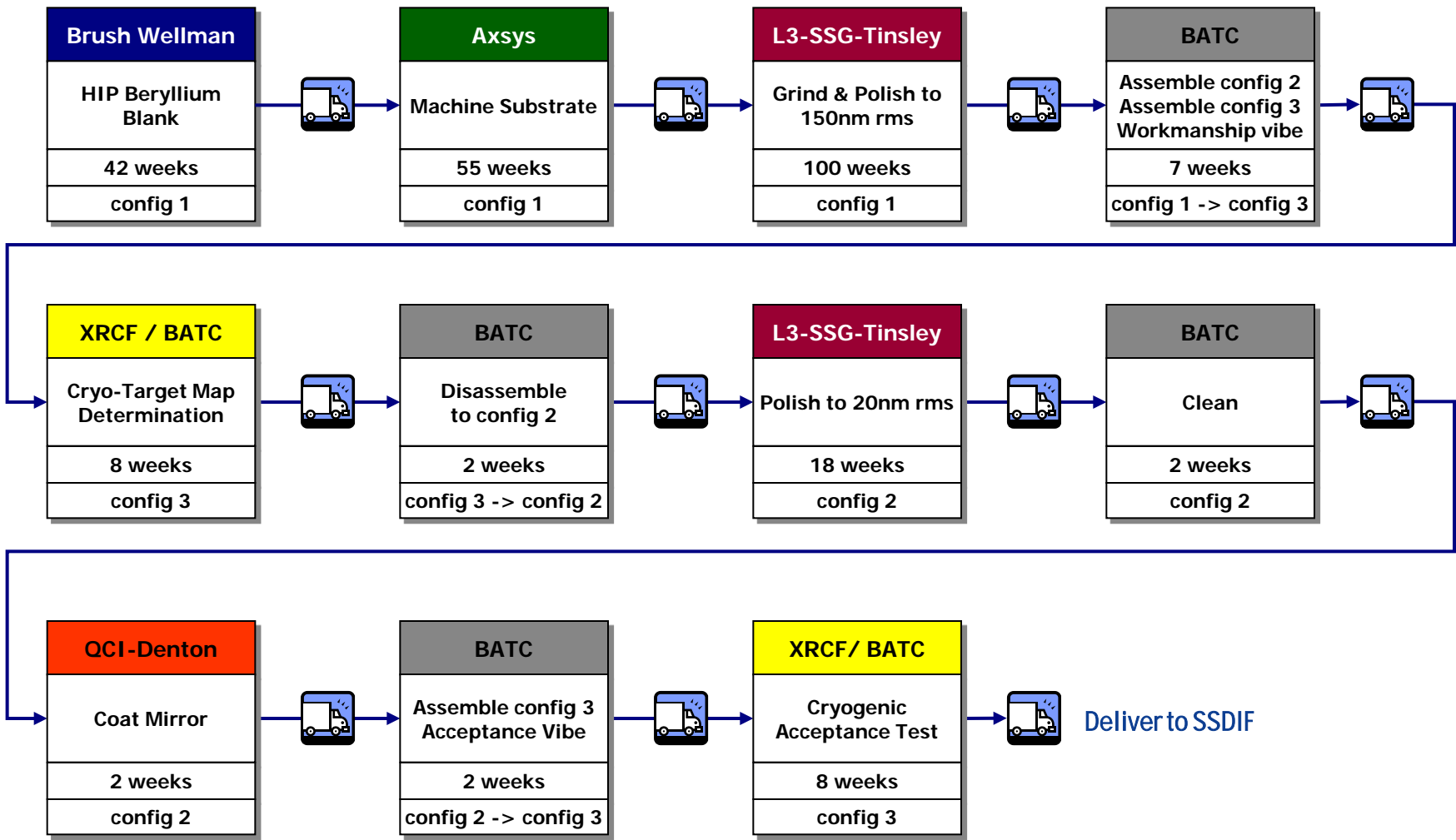
All JWST mirrors utilize similar support and actuation subsystems (PMSA, SMA, TM, FSM)



PMSA Processing Flow



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Mirror production and testing involves a series of handoffs between several suppliers



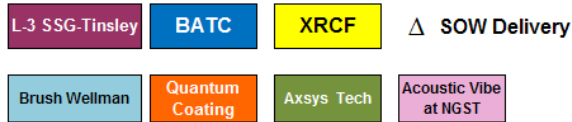
Mirror Fabrication and Test Now Complete (As Run Schedule)



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Sample of Mirror Risk Management History



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RISK Title	Likelihood	Impact	Exposure	Asignee	Dates	RISK	MITIGATION
Beryllium Mirror Optical Spec	Moderate	High	Moderate	Feinberg, Lee	Open 3/17/03 Closed 10/19/05	IF Lightweight mirrors do not meet optical spec at the segment level; THEN OTE will not meet level 2 image requirement at 2 microns	Completed fabrication of AMSD-2 mirrors 20 nm convergence task performed by Ball/Tinsley Additional AMSD-3 tasks and EDU
Beryllium mirror grinding/polishing stress characterization	Very Low	Low	Low	Feinberg, Lee	Open 4/4/03 Closed-Mitigated 3/1/11	IF the parameters that affect the residual stress created during grinding and polishing are not well understood; THEN the schedule for manufacturing the beryllium optics can easily exceed program requirements	Demonstrate Stress Controls on EDU and A1. Closed after second cryo test confirmed that cryo polishing successful.
Beryllium Mirror Performance	Low	Moderate	Low	Feinberg, Lee	Open-9/8/03 Closed-Mitigated 3/1/11	IF "Be" mirror do not converge to 20nm; THEN OTE will not meet final level 2 spec	Mitigated through additional AMSD-3 tasks and EDU, including 20nm demonstration (completing AMSD to 20nm's ambient)
PMSA Edges	Moderate	Very Low	Low	Feinberg, Lee	Open-1/23/04 Closed-Mitigated 3/1/11	IF the straylight effects of PMSA edges are not quantified and the edges processed to insure the straylight is within the acceptable limits ; THEN the level 2 encircled energy requirement may not be met and/or significant schedule slippages and cost overruns may occur.	Reviewed EDU, A1 edges, modelling of results. Metrology equipment added: Scanning Shack Hartman A1 edges met spec. EDU completed.



Environmental Testing



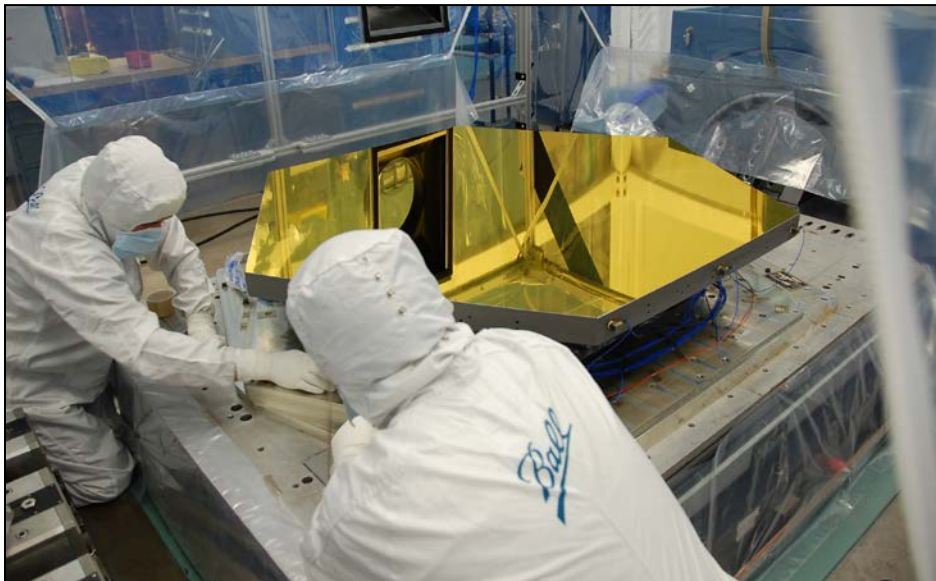
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Acoustics



Vibe



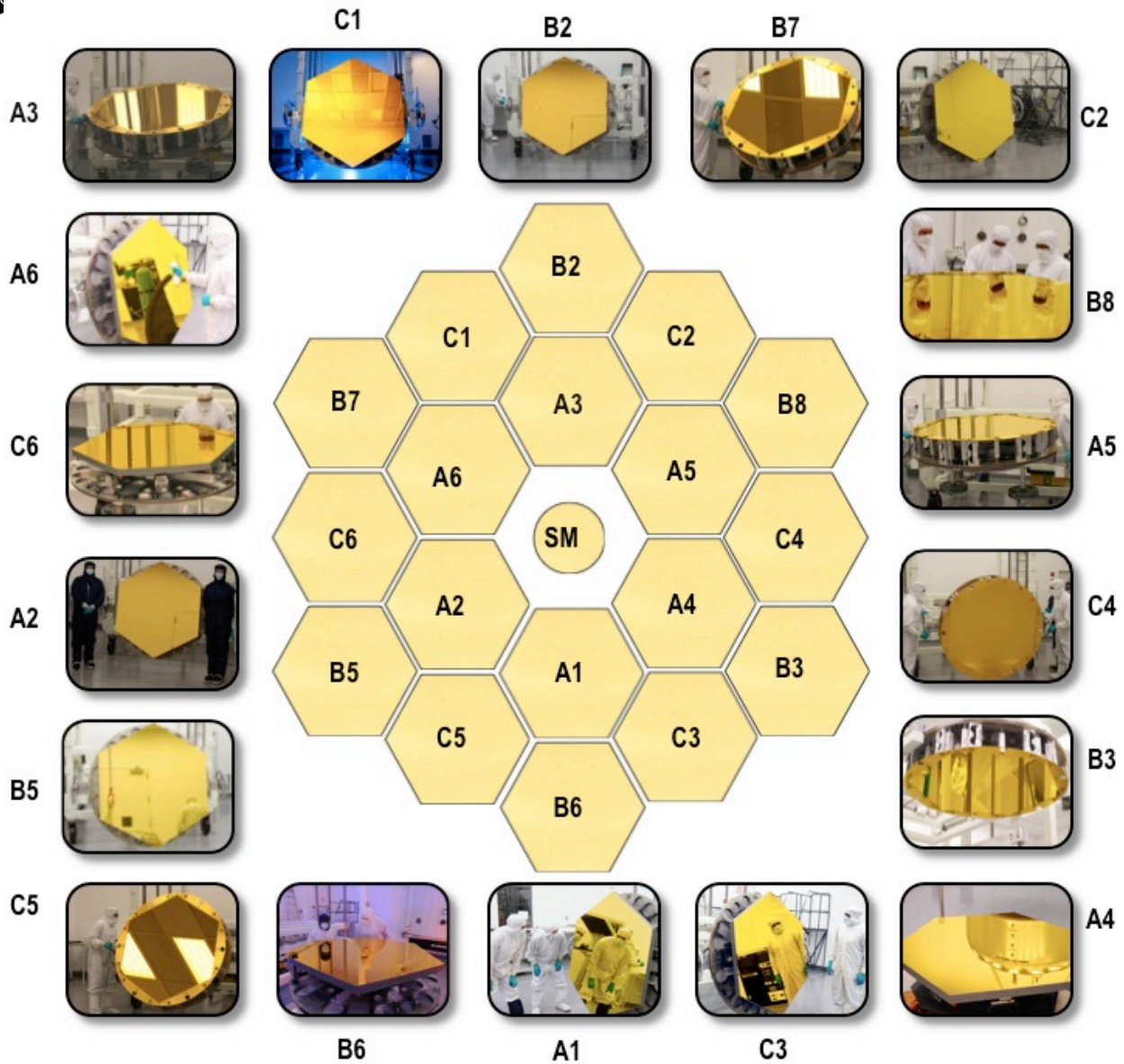
Cryo



Mirror Results



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Secondary



Tertiary



Fine Steering



JWST Mirrors Completed in 2011



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Mirror	Measured (nm rms SFE)	Uncertainty (nm rms SFE)	Total (nm rms SFE)	Req (nm rms SFE)	Margin (nm rms SFE)
Primary Mirror (18 mirror composite)	23.6	8.1	25.0	25.8	6.4
Secondary Mirror	14.7	13.2	19.8	23.5	12.7
Tertiary Mirror	18.1	9.5	20.5	23.2	10.9
Fine Steering Mirror	13.9	4.9	14.7	18.7	11.6

Primary Mirror

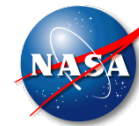
Secondary Mirror

Tertiary Mirror

Fine Steering Mirror



Mirror Results



	SFE total measured	hi freq measured	XRCF tot measured	XRCF hi measured	Tinsley sub aperture very hi measured	SFE metrology uncertainty tot	SFE metrology uncertainty hi									
	(nm rms)	(nm rms)	(nm rms)	(nm rms)	(nm rms)	(nm rms)	(nm rms)		SFE total measure d	hi freq measure d	XRCF tot measure d	XRCF hi measure d	Tinsley sub aperture very hi measure d	SFE metrology uncertainty tot	SFE metrology uncertainty hi	
	(nm rms)	(nm rms)	(nm rms)	(nm rms)	(nm rms)	(nm rms)	(nm rms)		(nm rms)	(nm rms)	(nm rms)	(nm rms)	(nm rms)	(nm rms)	(nm rms)	(nm rms)
allocation	23.6	12.2														
max	44.2	12.5	44.0	11.7	5.8	8.2	2.3									
min	16.5	8.1	15.7	7.1	2.9	8.0	2.3									
rms	23.6	10.0	23.1	8.9	4.5	8.1	2.3									
mean	22.4	9.9	21.9	8.8	4.4	8.1	2.3									
std	7.5	1.4	7.6	1.4	0.9	0.1	0.0									
cum																
A1	17.9	9.5	17.7	9.0	2.9	8.0	2.3	B5	18.4	9	18.0	8.1	3.9	8.2	2.3	
A2	22.2	11.2	21.9	10.7	3.4	8.0	2.3	B6	17.5	10.2	17.0	9.4	4.0	8.2	2.3	
A3	21.8	12.3	21.0	10.8	5.8	8.0	2.3	B7	22.6	8.9	22.2	7.8	4.3	8.2	2.3	
A4	17.1	8.2	16.8	7.5	3.2	8.0	2.3	B8	23.7	9.6	23.3	8.4	4.6	8.2	2.3	
A5	16.5	10.1	15.7	8.8	5.0	8.0	2.3	C1	22.1	9	21.5	7.4	5.1	8.2	2.3	
A6	44.2	12.5	44.0	11.7	4.5	8.0	2.3	C2	20.1	8.7	19.5	7.1	5.0	8.2	2.3	
B2	18.7	9.2	17.8	7.2	5.7	8.2	2.3	C3	18.1	8.1	17.8	7.4	3.2	8.2	2.3	
B3	18.7	9.1	18.2	8.1	4.2	8.2	2.3	C4	39.5	12.3	39.2	11.2	5.0	8.2	2.3	
								C5	20.5	10.2	20.1	9.3	4.2	8.2	2.3	
								C6	23.9	10	23.3	8.4	5.4	8.2	2.3	

Surface Area Requirement: >1.4746 m2 per segment

Surface Area: 1.47533 m2 mean

Total PM Surface Area =26.55m2

See paper by
Paul Lightsey for
More details



The Team



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Brush Wellman



Ball



XRCF



OTE



Tinsley



Metrology



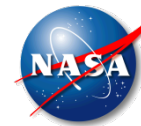
QCI



Axsys Technologies



Summary



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- In 8.5 years, 21 flight lightweighted, cryogenic beryllium mirrors were developed
- The original technology effort benefitted from a collaboration between NASA and other government agencies
- The development effort was led by Ball Aerospace with collaboration and input by NGAS, NASA and Academia
- The mirrors meet their top level specifications
- We overcame many technical challenges through aggressive risk management
- Our focus now is on finishing the rest of the telescope and performing system level testing