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

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ABSTRACT

In a little under a decade, the James Webb Space Telescope (JWST) program has designed, manufactured, assembled and tested 21 flight beryllium mirrors for the James Webb Space Telescope Optical Telescope Element. This paper will summarize the mirror development history starting with the selection of beryllium as the mirror material and ending with the final test results. It will provide an overview of the technological roadmap and schedules and the key challenges that were overcome. It will also provide a summary of the key tests that were performed and the results of these tests.

Key words: James Webb Space Telescope, Mirrors, Optical Telescope Element, OTE

1. INTRODUCTION

The James Webb Space Telescope (JWST) Optical Telescope Element includes 21 light-weighted, cryogenic beryllium primary mirror segments.[1] The full set includes eighteen 1.52m point to point hexagonal primary mirror segments along with a Secondary Mirror (SM), Tertiary Mirror (TM) and Fine Steering Mirror (FSM). The mirrors for JWST required a technology development program, a competitive mirror selection process, a facilitization effort, an aggressive risk management program, a full scale production effort, and a thorough test program. As this effort is now complete, all of the JWST mirrors are finished and available to the program.

2. TECHNOLOGY DEVELOPMENT

The technology development process for JWST started with the recognition that the cryogenic mirror technology used on the Spitzer Space Telescope was not sufficient for JWST. In fact, as shown in Figure 1, the JWST program identified the need for and began development of lower areal density mirrors soon after the 1996 inception of the program. While several mirror technology development paths were followed during those very early days, the most important ones were the Subscale Beryllium Mirror Demonstrator (SBMD), the Advanced Mirror Systems Demonstrator (AMSD) and the NGST Mirror System Demonstrator (NMSD).[2] The SBMD and AMSD[3] programs ultimately provided the key technology pathway for JWST while NMSD helped educate the program on options that were not pursued. The various mirror architectures and specifications developed in the three programs are shown on the top of Figure 2. The SBMD was a Ball Aerospace Internal Research And Development (IRAD) effort to make a .5 meter highly lightweighted berrylium mirror (sphere) using the new isotropic O-30 Beryllium powder developed by Brush Wellman. Soon thereafter, a multi-agency collaboration between NASA, DoD and NRO was formed to develop 15 kg/m2 lightweight mirrors. In its initial phase, the program selected the 8 architectures shown on the left of Figure 2 for study. Three of the mirror architectures were down-selected for Phase 2 AMSD efforts to actually fabricate the 1.2m flat to flat 15Kg/m2 mirrors studied in Phase 1. Of the three architectures, a Ball Beryllium mirror, a Hughes Danbury High Authority Mirror, and a Kodak (now ITT Exelis) ULE mirror, the Ball and Kodak mirrors were continued and finished after the JWST prime contractor was selected.

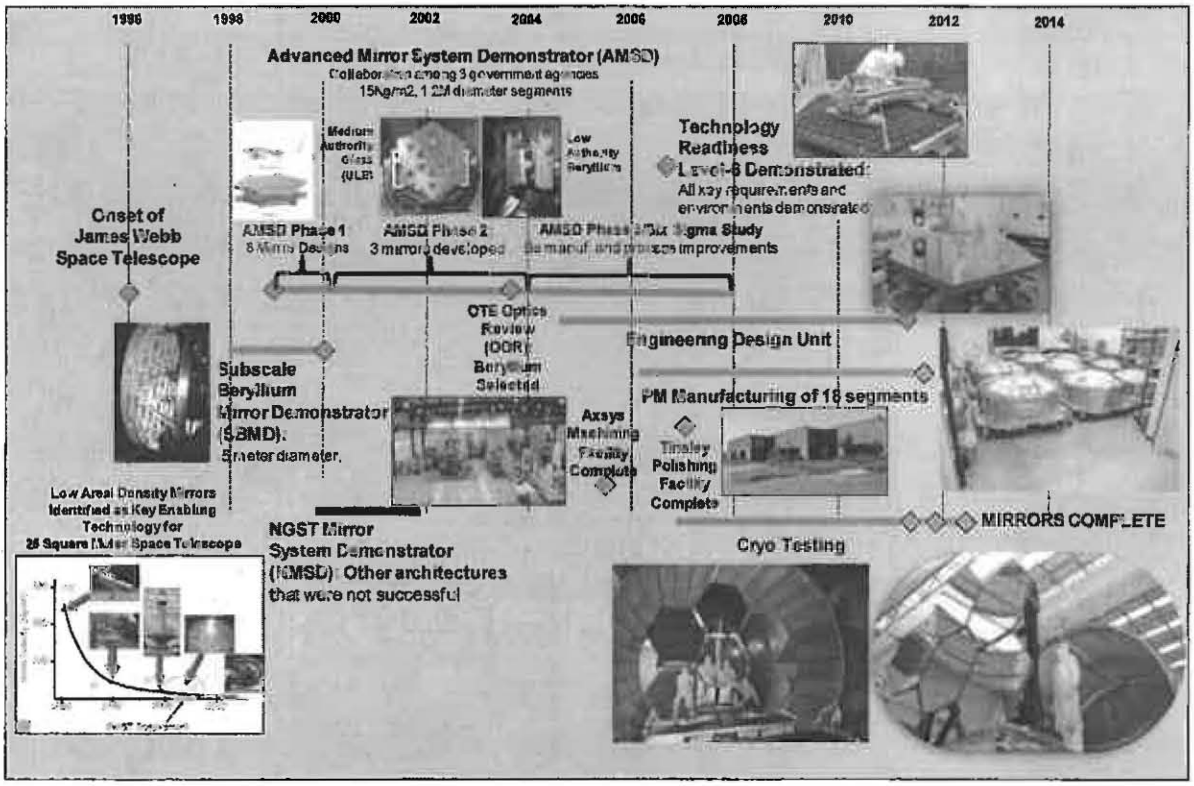


Figure 1. Roadmap

While the SBMD and AMSD programs were very instructive and achieved much of the technology demonstration needed, achieving full Technology Readiness Level-6 (TRL-6)[4] was a requirement by the program Technology Non-Advocate Review and AMSD and SBMD did not sufficiently demonstrate both flight survivability (acoustics and vibe) and stress issues of fabrication. Therefore, as shown in the lower right of Figure 2, the stress demonstration and flight survivability efforts were added to the program to achieve TRL-6. This included adding an AMSD Phase 3 which involved demonstrating the control of beryllium fabrication stresses via stress coupons. In addition, the demonstration of mirror acoustics and vibration survival was done with a partially finished flight mirror (using an electronic speckle pattern interferometer for pre and post optical measurements) and the demonstration of the actuation was done using the Engineering Design Unit. As will be shown later, many of the technology items were funded through the JWST risk management and mitigation process.

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) SiO2 (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/m2 (mirror only)	13 kg/m2	15 kg/m2

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 (1st Mode)	---	---	150	HZ

Demonstrator	Technology	Validity to JWST
SBMD	Cryogenic Coating Cryo-Null Figuring	SBMD [illegible] application [illegible] be applied to [illegible] beryllium mirror. [illegible] of large [illegible] (like JWST) is [illegible] has been developed on other flight programs.
AMSD Mirror	Figuring Cryogenic performance Actuation capability	All differences between the JWST PM [illegible] and the AMSD mirror [illegible] cryogenic performance, and provides more actuation degrees of freedom
AMSD Stress Coupons	Long term material stability	JWST PMSA [illegible] processing developed on AMSD [illegible]
JWST EDU & Flight Segment	Launch [illegible] Actuation Capability	JWST flight [illegible]

Figure 2: Mirror Technologies Summary

3. MIRROR SELECTION

Once the prime contractor was brought on board, a Mirror Recommendation Board consisting of experts from both the prime contractor team and the government worked collaboratively to select the mirror architecture. Many of these experts carried over from the technology phase. The team evaluated the two mirror options that the prime contractor proposed, one that used Beryllium and one that used ULE. The key data used to assess the cryogenic performance was the cryogenic test results of the AMSD-2 data. The decision process and dates and the team involved in this activity are shown in Figure 4.[5]

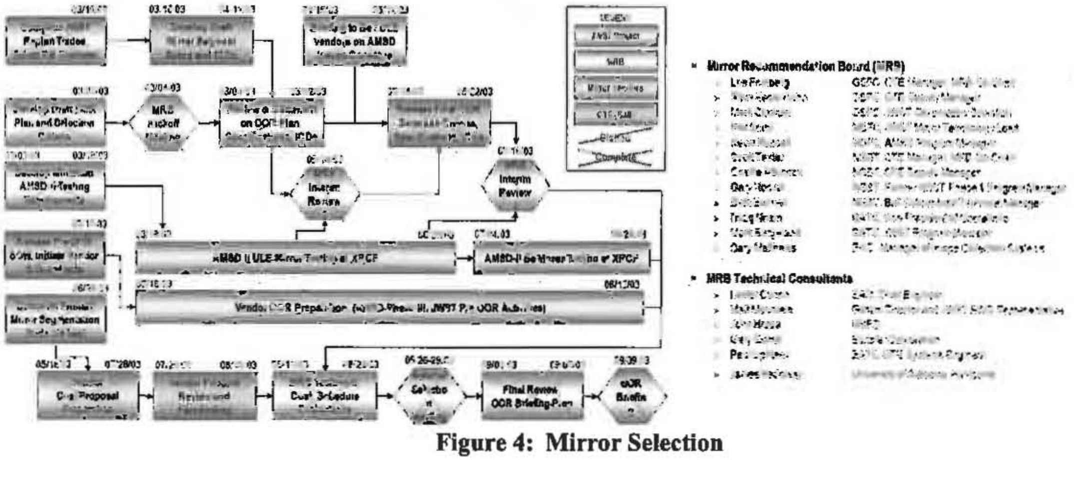
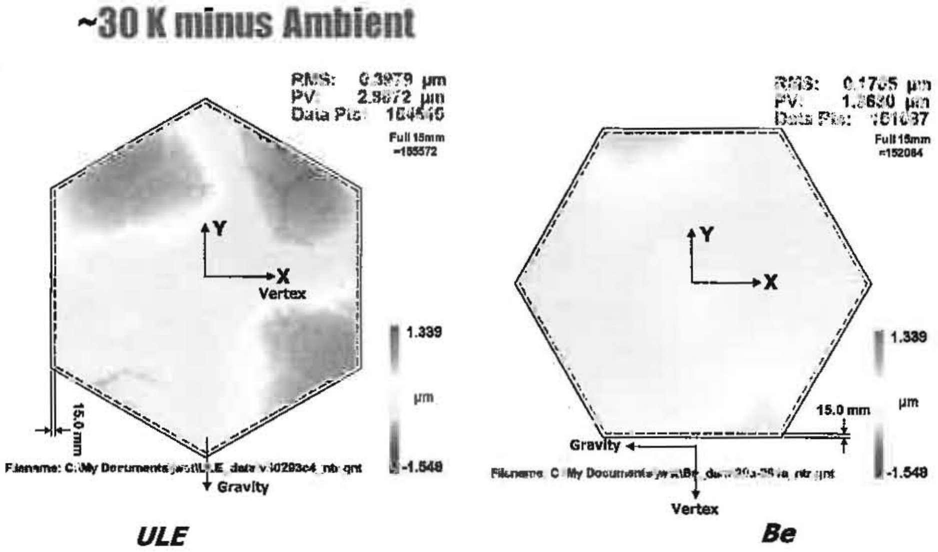


Figure 4: Mirror Selection

The results of the AMSD-2 cryogenic testing results for the ULE and Beryllium mirror are shown in Figure 5. The results substantiated the key technical advantage of Beryllium: its thermal conductivity and CTE at cryogenic temperatures. In the end, Beryllium was selected on this technical basis which was perceived to hold system advantages (for example, active thermal control was not needed). Beryllium also had another system advantage in that it could be lighter weight for the architectures proposed. The AMSD-2 data was the primary factor in the mirror selection and the main data used to plan the fabrication efforts.



ULE *Be*

Beryllium Mirror Selected Because of Superior Cryogenic Properties

Figure 5: AMSD-2 Cryogenic Data

4. RISK MANAGEMENT

Even before the mirror was selected, JWST initiated risk management processes to mitigate risks associated with its development.[6] In many ways the early adoption of risk management and the early prioritization of mirror risk management funding helped lead to the success of the mirror program. As can be seen in Figure 6, many risks were identified, entered and mitigated through the life of the mirror development program. The risks themselves chronologically track the phase of the program in which they were entered. For example, early in the program the key risks were early fabrication (especially beryllium stress issues) and design issues (for example, large vibro-acoustics loads). As the mirror development progressed, the risks transitioned to specific fabrication issues (eg, edges), testing and spares. As a result of the risk process, an engineering design unit was added for both the primary mirror segment and the secondary and both were extremely valuable and later converted to spares.

Responsible Group	Number	Title	Likelihood Meaning	Impact Meaning	Exposure Meaning	Assigned To	Status	Statement	Mitigation
OTE Mirror Technology	OTEMIR-25	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 of 2 microns	Completed fabrication of AMSD-2 mirrors 20 nm convergence task performed by Ball/Tinsley Additional AMSD 3 tasks and EDU
OTE Mirror Technology	OTEMIR-33	Beryllium mirror grinding/polishing stress characterization	Very Low	Low	Low	Feinberg, Lee	Open 4/[illegible]/03 Closed-Mitigated [illegible]/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 several cryo test confirmed that cryo polishing successful
OTE Mirror Technology	OTEMIR-34	ULE mirror face sheet to core fused joints	Undefined	Undefined	Undefined	Hayden, Bill	Open- 4/[illegible]/03 Closed-Withdrawn 5/12/04	IF the Kodak ULE Low Temperature Fusion (LTF) process cannot be shown to reliably procure face sheet to core fused joints that can withstand the magnitude and duration of all environmental loads, THEN the mirror technology has not attained the minimum TRL level needed for JWST	This risk was retired as the ULE was not used
OTE	OTE-[illegible]6	Independent Secondary Mirror Cryo Testing	Very Low	Low	Low	Feinberg, Lee	[illegible]/9/03 Open-Accept	IF The SM is not independently tested at the component level at cryo, a surface error may go undetected. SM component testing is used to build the final verification model so SM component test anomaly may cause final verification issues., THEN a SM figure error may go undetected and reduce the on-orbit optical performance.	Implemented independent crosschecks of ambient data, external reviews of cryogenic results including demonstration that low frequency errors are correctable. Subaperture crosschecks at system level.
Launch Vehicle	LV-[illegible]	40-g launch load	Undefined	Undefined	Undefined	Feinberg, Lee	Open- 4/11/03 Closed-Mitigated 1[illegible]/03	IF the mirror loads are not reduced below 40 g's THEN it may not be possible to design the PM mirror segments to survive the launch environment within the current mass allocation.	Mitigated through a combination of re-evaluation of the design loads and material allowable stress levels, revising the mirror design to accommodate these loads and allowable stresses, and allocating additional mass to the mirror segments for increasing mirror strength.
OTE	OTE-[illegible]4	Beryllium Mirror Performance	Low	Moderate	Low	Feinberg, Lee	Open-[illegible]/03 Closed-Mitigated 3/1/11	IF "Be" mirror do not converge to 2[illegible] nm; THEN OTE will not meet final level 2 spec	Mitigated through additional AMSD-3 tasks and EDU, including 20nm demonstration (completing AMSD [illegible] 2[illegible] nm [illegible]).
OTE	OTE-[illegible]5	Beryllium mirror fabrication schedule	Moderate	Moderate	Moderate	Feinberg, Lee	Open-[illegible]/03 3/1/11Closed-Mitigated	IF "Be" mirrors cannot meet schedule, THEN entire OTE will be delayed	AMSD 3 Acid etching test to demonstrate feasibility of using acid etching steps. AMSD-3 stress testing. Perform 6-Sigma mirror production process evaluation project.
OTE	OTE-[illegible]1	Cryo- Null Figure Demonstration	Low	High	Moderate	Feinberg, Lee	Open- 12/8/03 Closed-Mitigated- 3/1/11	IF a JWST mirror segment cannot be cryo-null figured to specification or can not be cryo figured to specification in one cycle THEN the level 2 requirements may not be meet and/or significant schedule slippages and cost overruns will occur.	SAT recommendations closed requirements Completed EDU cryo finish in Dec, [illegible]9 Completed EDU in Jan, 1[illegible].
OTE	OTE-98	PMSA Edges	Moderate	Very Low	Low	Feinberg, Lee	Open-1/[illegible]/04 Closed-Mitigated 2/1/11	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.
OTE Mirror Technology	OTEMIR-[illegible]7	[illegible] Segment Catastrophic Damage / Spares	Very Low	Moderate	Low	Feinberg, Lee	Open-Mitigate-2/19/04	IF JWST mirror segment is damaged beyond recovery during manufacturing, integration or test THEN significant schedule slippages and cost overruns may occur and/or the level two requirements may not be met.	Spares made for A,B,C prescription. B, C are partially finished Implementing A,B,C spares. EDU is completed and an A spare. 'B' and 'C' spares taken to 1[illegible] nm RMS.

Figure 6: Mirror Risk History

5. MIRROR FABRICATION

The mirror fabrication involved a large effort that was managed by Ball Aerospace and which included several contractors and facilities around the county. The basic flow and typical durations of the fabrication effort is shown below in Figure 7.

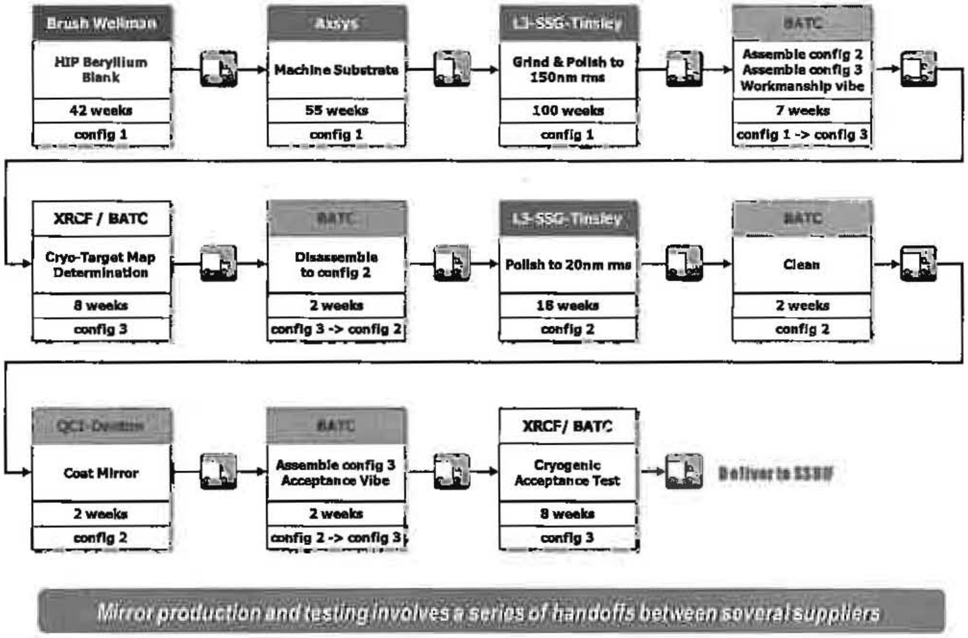


Figure 7: Mirror Fabrication Flow

The actual as-run schedule for the entire mirror fabrication effort can be seen below in Figure 8. The end to end effort lasted approximately 8.5 years.

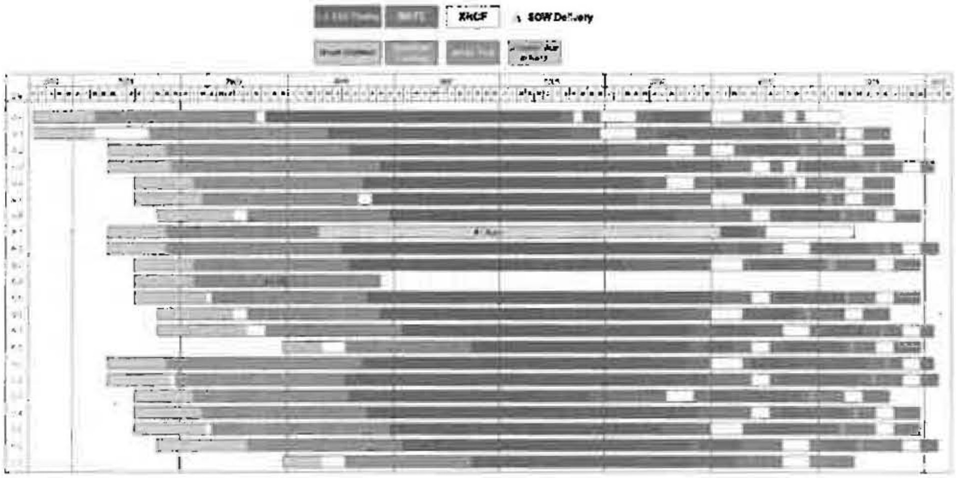


Figure 8: Mirror As-run Schedule

6. RESULTS

The fabrication of all flight mirrors including coating and testing completed in December, 2011. The mirror themselves can be seen in Figure 9. The top level RMS results for each of the mirrors can be seen in Figure 10. All mirrors meet their RMS specification which is the critical driver for telescope performance. More detailed results for the primary mirror segments can be seen after ambient testing in Figure 11. More detailed final cryogenic testing results can be seen in Figures 12 and 13. Although there were a few segment level allocations not met, the primary mirror requirements overall were met with margin.

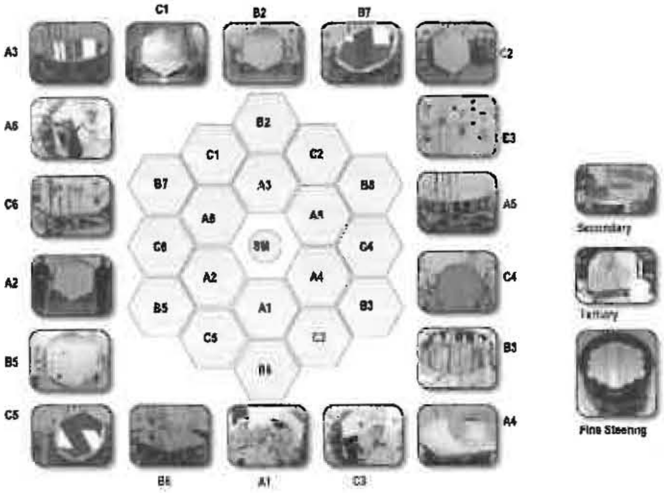


Figure 9: Flight Mirrors

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

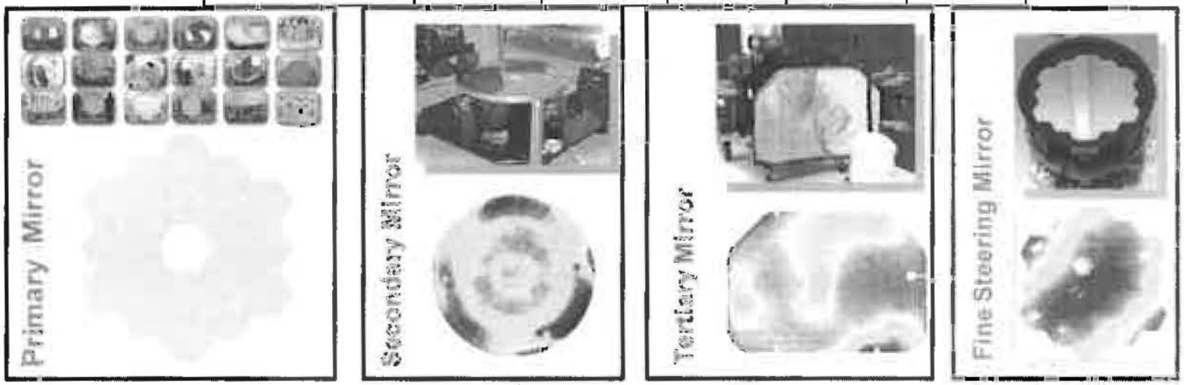


Figure 10: Flight Mirror Top-level Performance

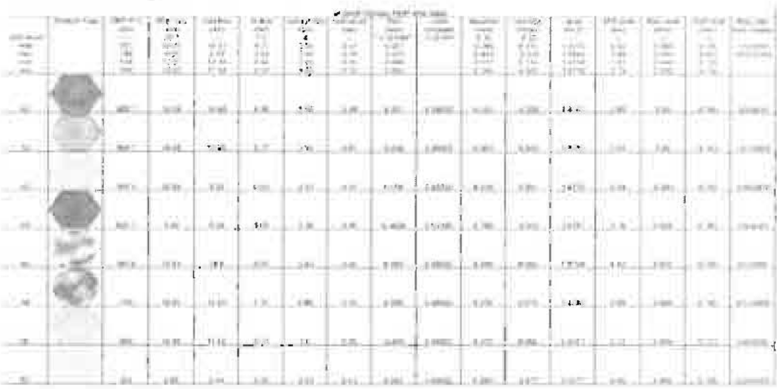


Figure 11: Primary Mirror Segment Performance after Polishing

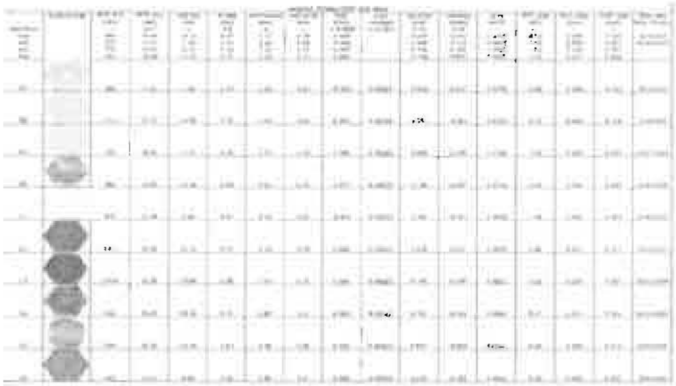


Figure 12: Primary Mirror Segment Performance after Polishing

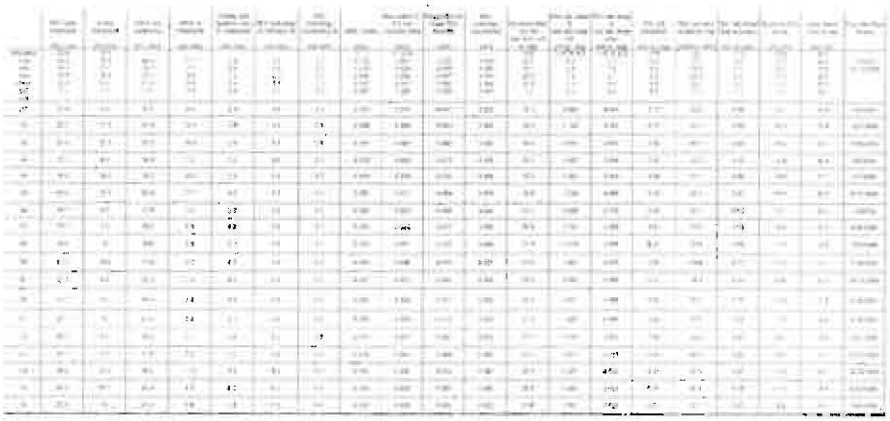


Figure 13: Primary Mirror Segment Cryogenic Performance

8. SUMMARY

The development of the mirrors for JWST was a major undertaking. The team involved included engineers, managers and technicians from several companies and organizations, many of whom are shown on Figure 14. In under a decade, 21 flight mirrors including the >25 square meters of lightweighted, cryogenic beryllium mirrors were designed and fabricated. While the original technology effort benefitted from a collaboration between NASA and other government agencies, the development effort was primarily a collaboration between NASA, industry and academia. The mirrors meet their top level specification and many technical challenges were overcome. The focus now is on finishing the rest of the telescope and performing system level testing

Figure 14: Mirror Teams

9. ACKNOWLEDGEMENTS

The authors would like to thank the hundreds of engineers, technicians and scientists around the country who helped make the mirror production a success. The list of names is too numerous to include but includes Brush Wellman, Axsys Technologies, L3-Communications SSG-Tinsley, Ball Aerospace, QCI, NGAS, SAO, MSFC, GSFC, StScI, CDA, ATK, 4D Technologies, and Wavefront Sciences . With respect to this particular paper, the authors would like to thank Paul Lightsey for providing the tabulated mirror performance data and Ratna Sengupta for the risk data. The authors would also like to call out Lester Cohen of SAO, James Hadaway of UAH and Bob Brown, Dave Chaney and Koby Smith of Ball Aerospace for their major contributions to the success. The authors would like to thank Phil Sabelhaus, John Decker and Martin Mohan for the vision to prioritize funding of the JWST mirrors early in the program.

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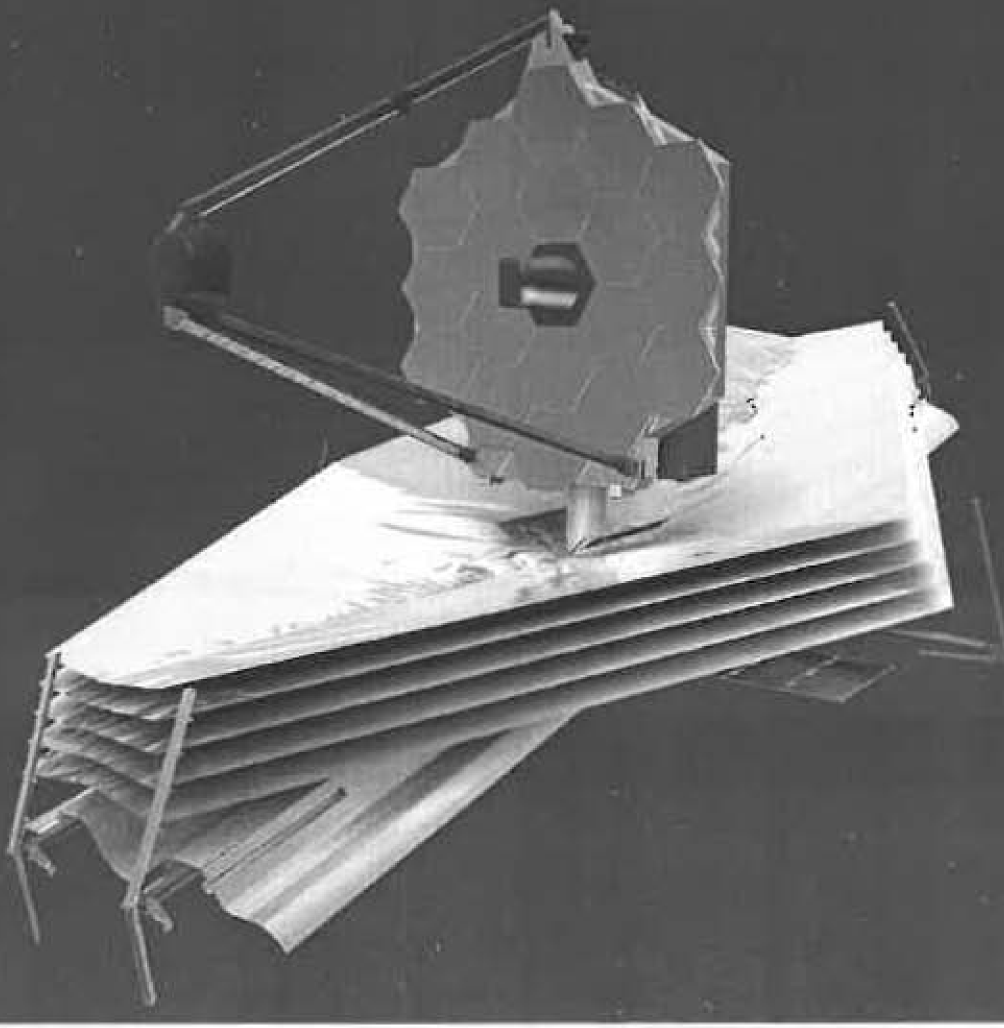

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Charlie Atkinson, NGAS
Mark Bergeland, Ball Aerospace
Ben Gallagher, Ball Aerospace

Outline

- Introduction
- Overall roadmap
- Technology development
- Mirror Selection/OOR Results and Findings
- Risk Management History
- Team – MST
- Results
  - Tinsley
  - Final

Mirror History

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

Onset of James Webb Space Telescope

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

OTE Optics Review (OOR): Beryllium Selected

Axsys Machining Facility Complete

Technology Readiness Level-6 Demonstrated:
All key requirements and environments demonstrated

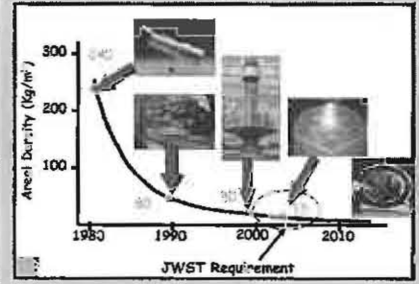
Engineering Design Unit

PM Manufacturing of 18 segments

Tinsley Polishing Facility Complete

MIRRORS COMPLETE

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



NGST Mirror System Demonstrator (NMSD): Other architectures that were not successful

Cryo Testing

Technology Development History

Wide Variety of Mirror System Design Parameters Studied			
Item	SBMD (Ball)	NMSD	AMSD
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Radius	20	15	10	meter
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RMS Figure	---	---	50	nm
PV Mid (1-10 cm^{-1})	63	63	---	nm
RMS Finish	3	2	4	nm
Stiffness (1st Mode)	---	---	150	HZ

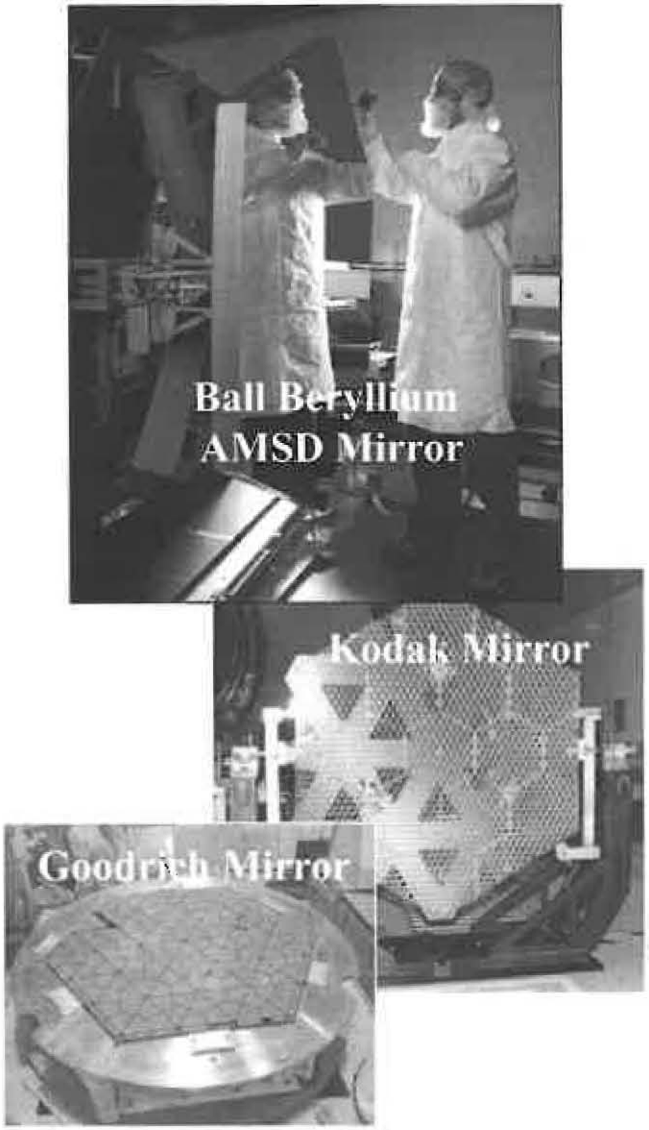
Demonstrator	Technology	Validity to JWST
SBMD	Cryogenic Coating Cryo-Null Figuring	SBMD developed a low stress gold coating application that can be applied to any beryllium mirror. Coating of large mirrors (like JWST) is not material specific and has been developed on other flight programs.
AMSD Mirror	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

Incremental 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	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

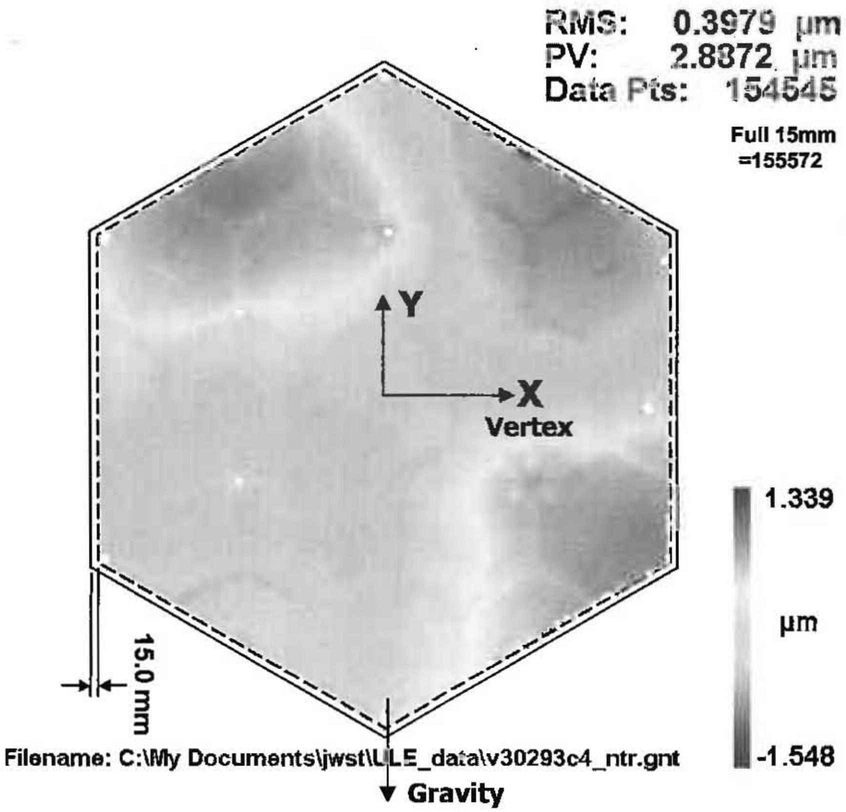
Advanced Mirror System Demonstrator (AMSD)

- **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**

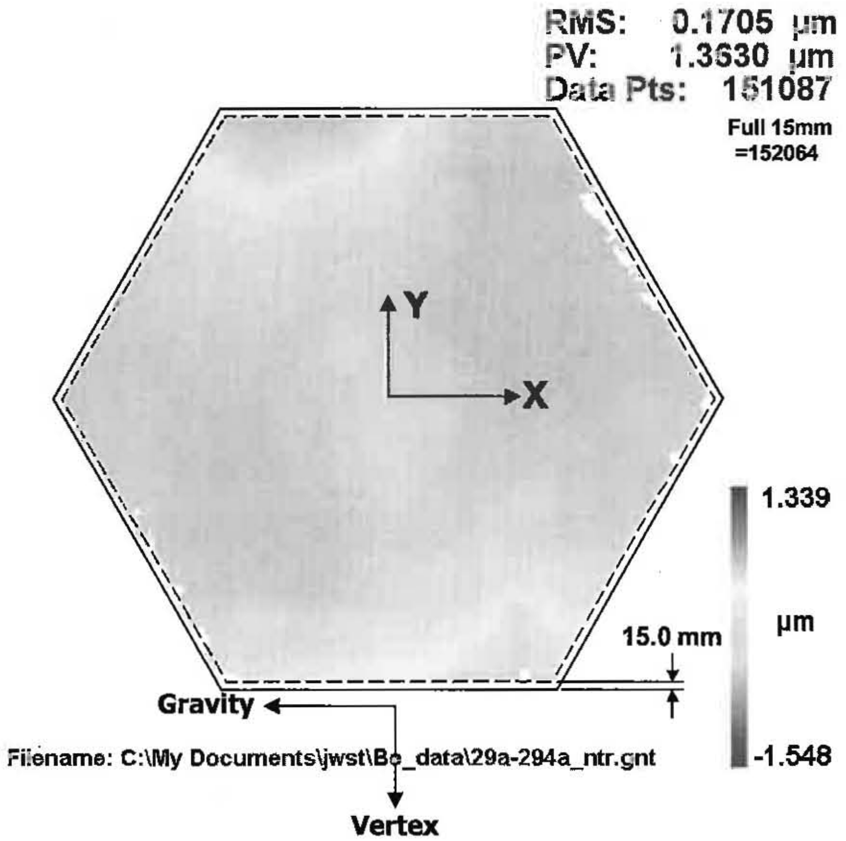


Mirror Technology Choices

~30 K minus Ambient



ULE

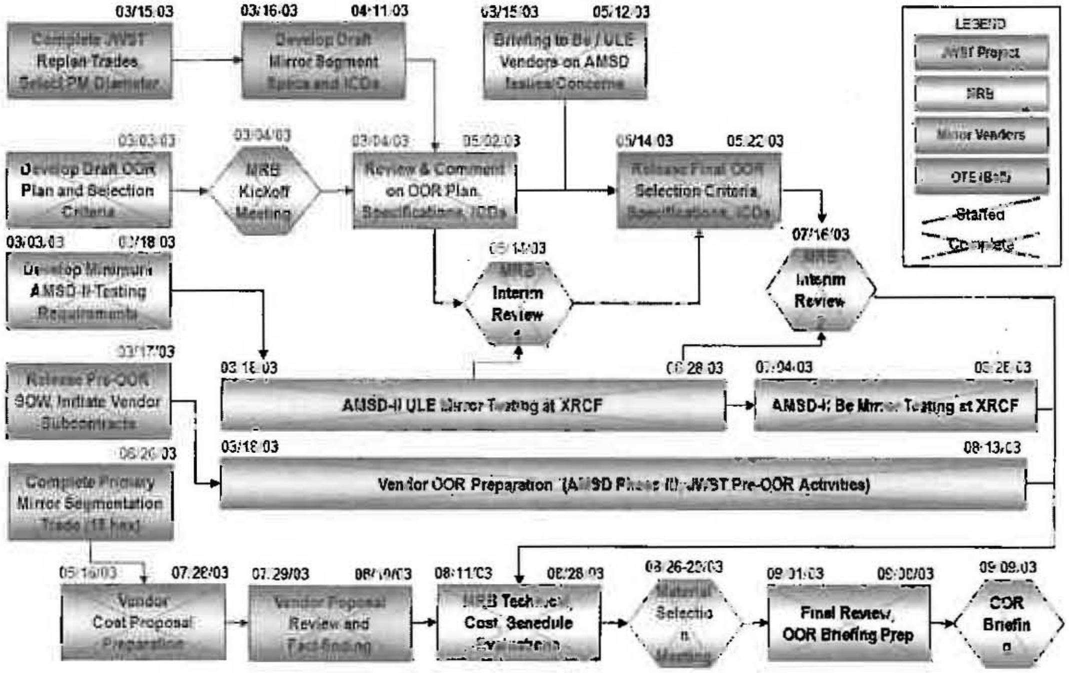


Be

Beryllium Mirror Had Superior Cryogenic Properties

Mirror Selection Process and Results

- **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 Barthek	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**

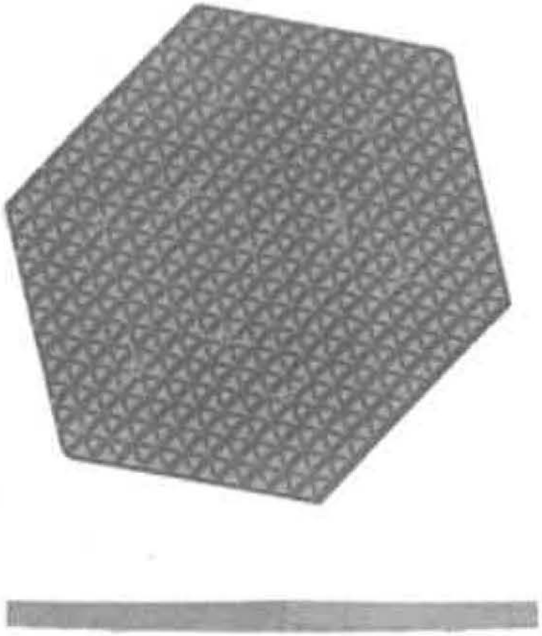
Lester Cohen	SAO, Chief Engineer
Matt Mountain	Gemini Director and JWST SWG Representative
John Hraba	MSFC
Gary Golnik	Schafer Corporation
Paul Lightsey	BATC, OTE Systems Engineer
James Hadaway	University of Alabama, Huntsville

Program Level Risk Management History

Responsible Group	Number	Title	Likelihood Meaning	Impact Meaning	Exposure Meaning	Assigned To	Status	Statement	Mitigation
OTE Mirror Technology	OTEMIR-26	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
OTE Mirror Technology	OTEMIR-33	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.
OTE Mirror Technology	OTEMIR-34	ULE mirror face sheet to core fused jounts	Undefined	Undefined	Undefined	Hayden, Bill	Open- 4/4/03 Closed-Withdrawn 5/12/04	IF the Kodak ULE Low Temperature Fusion (LTF) process cannot be shown to reliably procude face sheet to core fused joints that can withstand the magnitude and duration of all environmental loads; THEN the mirror technology has not attained the minimum TRL level needed for JWST	This risk was retired as the ULE was not used.
OTE	OTE-36	Independent Secondary Mirror Cryo Testing	Very Low	Low	Low	Feinberg, Lee	4/9/03 Open-Accept	IF The SM is not independently tested at the component level at cryo, a surface error may go undedected. SM component testing is used to build the final varfication model so SM component test errors may cause final varification issues.; THEN a SM figure error may go undetected and reduce the on-orbit optical performance.	Implemented independent crosschecks of ambient data, external reviews of cryogenic results including demonstration that low frequencies errors are correctable. Subaparture crosschecks at system level.
Launch Vehicle	LV-37	40-g launch load	Undefined	Undefined	Undefined	Feinberg, Lee	Open- 4/11/03 Closed-Mitigated 11/20/03	IF the mirror loads are not reduced below 40 g's ; THEN it may not be possible to design the PM mirror segments to survive the launch environment within the current mass allocation.	Mitigated through a combination of re-evaluation of the design loads and material allowable stress levels, revising the mirror design to accommodate these loads and allowable stresses, and allocating additional mass to the mirror segments for increasing mirror strength.
OTE	OTE-84	Beryllium Mirror Performance	Low	Moderate	Low	Feinberg, Lee	Open-9/6/03 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)
OTE	OTE-85	Beryllium mirror fabrication schedule	Moderate	Moderate	Moderate	Feinberg, Lee	Open-9/8/03 3/1/11Closed-Mitigated	IF "Be" mirrors cannot meet schedule; THEN entire OTE will be delayed	AMSD-3 Acid etching task to demonstrate feasibility of using acid etching steps. AMSD 3 stress tasks. Perform 6-Sigma mirror production process evaluation project.
OTE	OTE-91	Cryo-Null Figure Demonstration	Low	High	Moderate	Feinberg, Lee	Open- 12/8/03 Closed-Mitigated-3/1/11	IF a JWST mirror segment cannot be cryo-null figured to specification or can not be cryo figured to specification in one cycle: THEN the level 2 requirements may not be meet and/or significant schedule slippages and cost overruns will occur.	SAT recommendations eased requirements. Completed EDU cryo polish in Dec 09 Completed EDU in Jan. 11
OTE	OTE-98	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.
OTE Mirror Technology	OTEMIR-147	PM Segment Catastrophic Damage / Spares	Very Low	Moderate	Low	Feinberg, Lee	Open-Mitigate-8/19/04	IF JWST mirror segment is damaged beyond recovery during manufacturing, integration or test ; THEN significant schedule slippages and cost overruns may occur and/or the level two requirements may not be met.	Spares made for A,B,C prescription. B, C are partially finished. Implementing A,B,C spares. EDU is completed and an 'A' spare. 'B' and 'C' spares taken to 150 nm RMS.

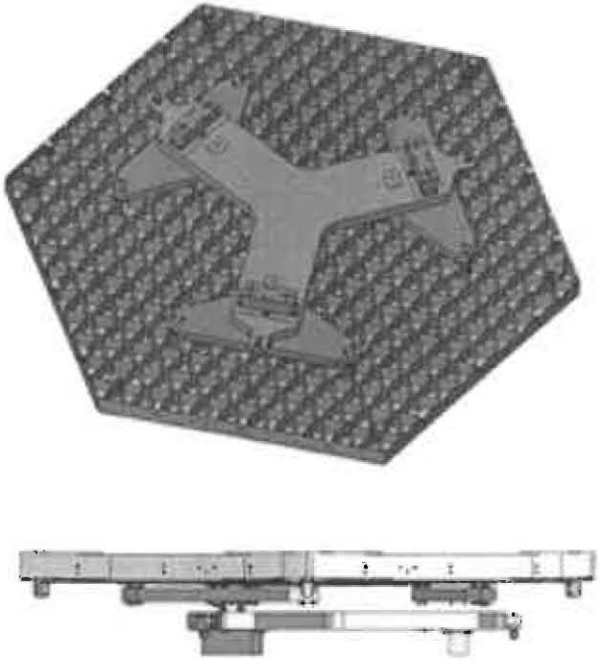
Mirror Assembly Configurations

Configuration 1



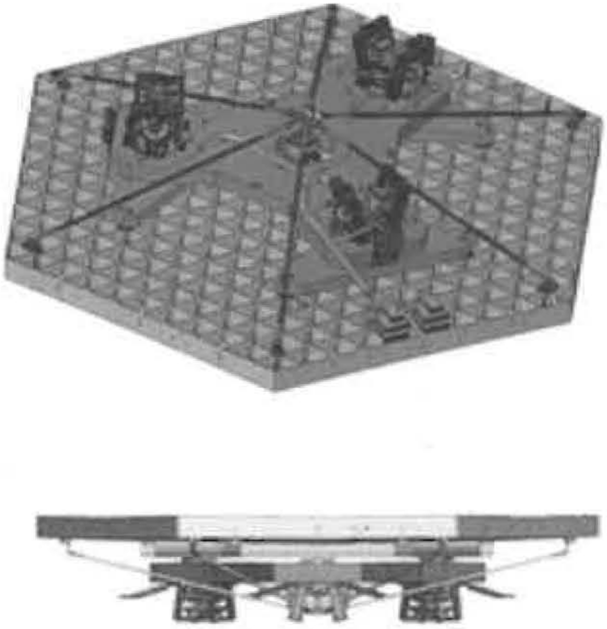
Mirror Substrate Only

Configuration 2



Mirror Substrate with Flexures, Whiffles and Surrogate Delta Frame

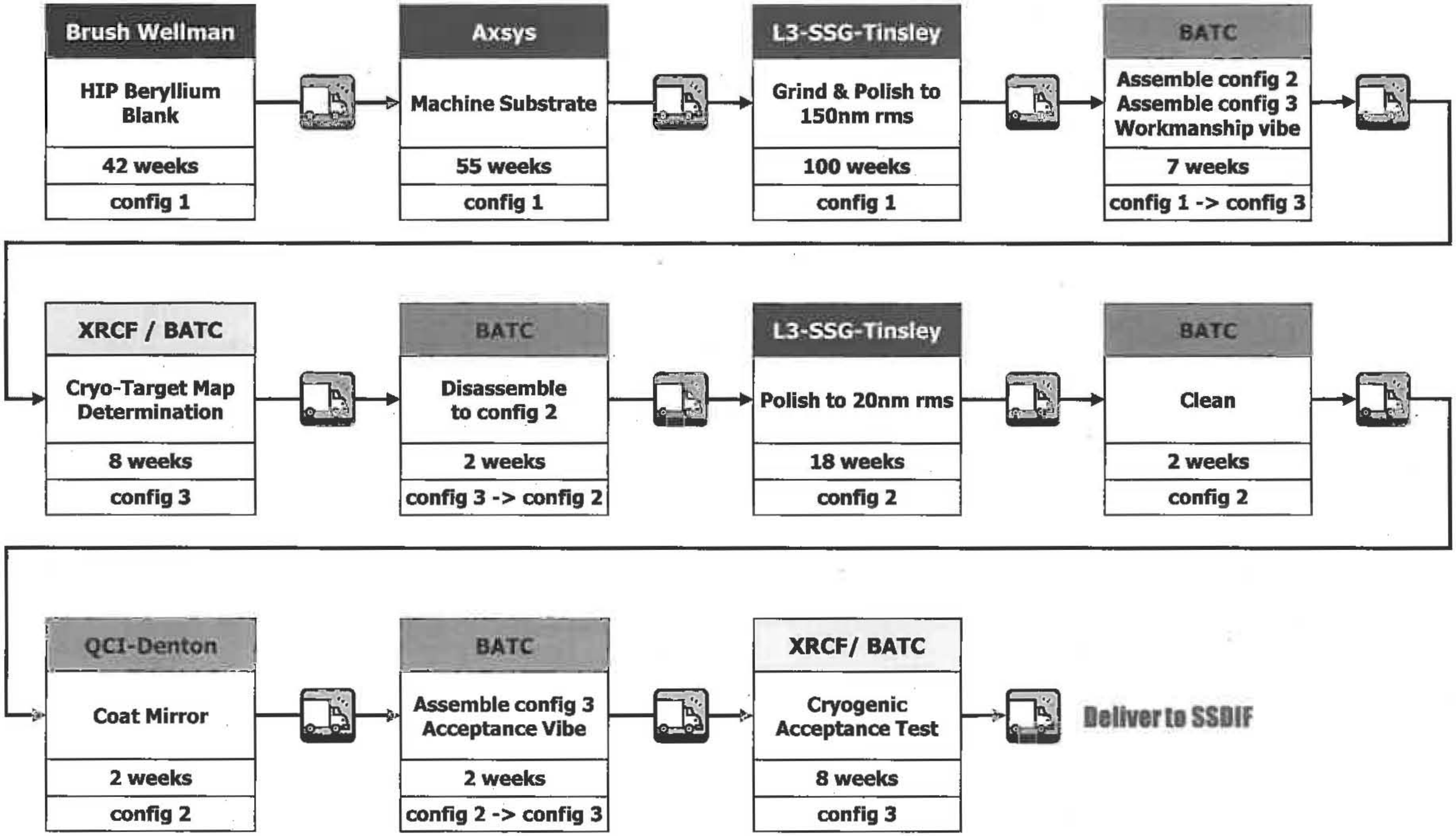
Configuration 3



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



Brush Wellman
HIP Beryllium Blank
42 weeks
config 1

Axsys
Machine Substrate
55 weeks
config 1

L3-SSG-Tinsley
Grind & Polish to 150nm rms
100 weeks
config 1

BATC
Assemble config 2
Assemble config 3
Workmanship vibe
7 weeks
config 1 -> config 3

XRCF / BATC
Cryo-Target Map Determination
8 weeks
config 3

BATC
Disassemble to config 2
2 weeks
config 3 -> config 2

L3-SSG-Tinsley
Polish to 20nm rms
18 weeks
config 2

BATC
Clean
2 weeks
config 2

QCI-Denton
Coat Mirror
2 weeks
config 2

BATC
Assemble config 3
Acceptance Vibe
2 weeks
config 2 -> config 3

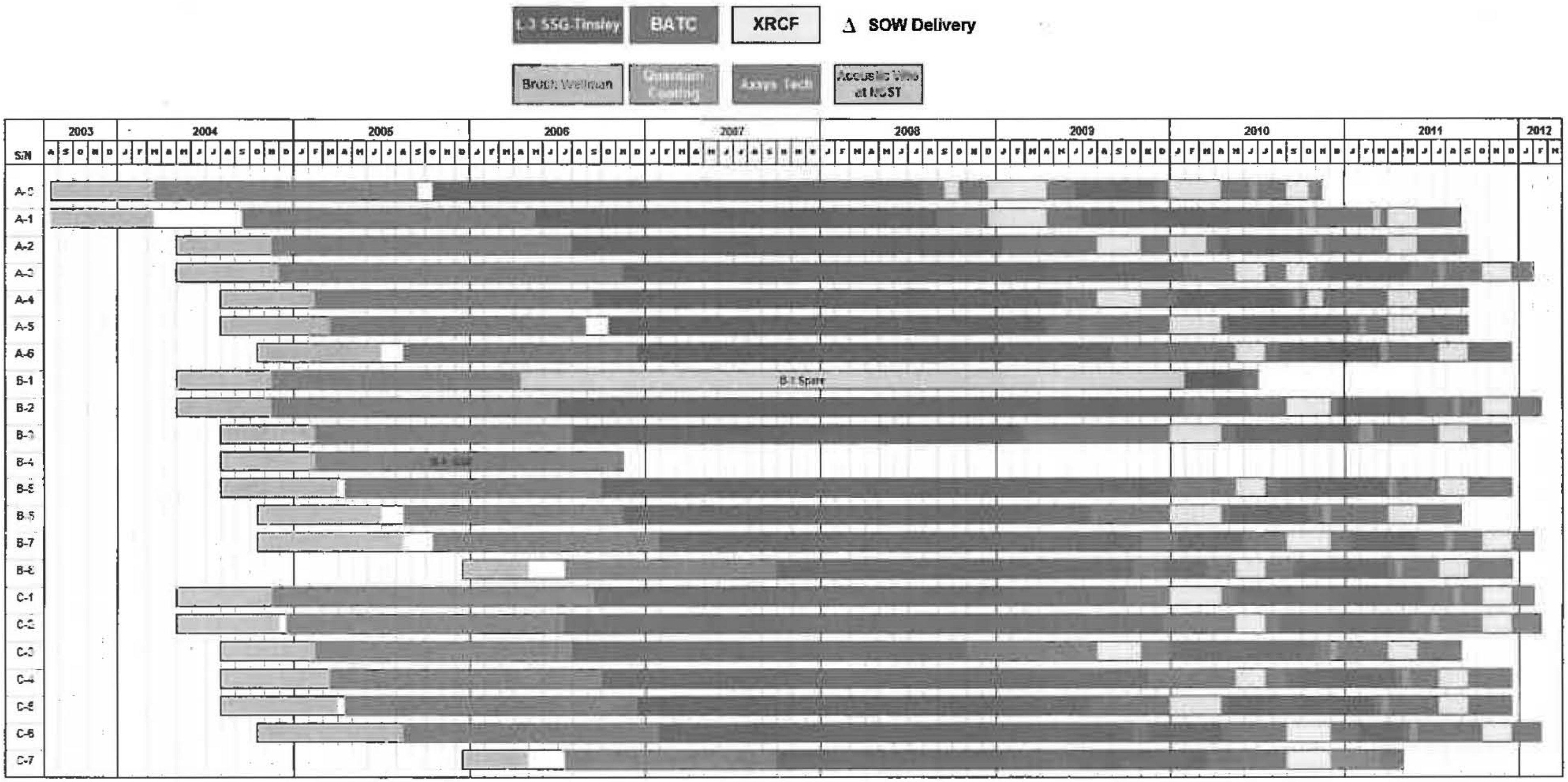
XRCF/ BATC
Cryogenic Acceptance Test
8 weeks
config 3

Deliver to SSDIF

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

Environmental Testing

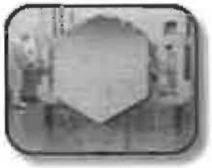
Mirror Fabrication and Test Now Complete (As Run Schedule)



Mirror Results


A3

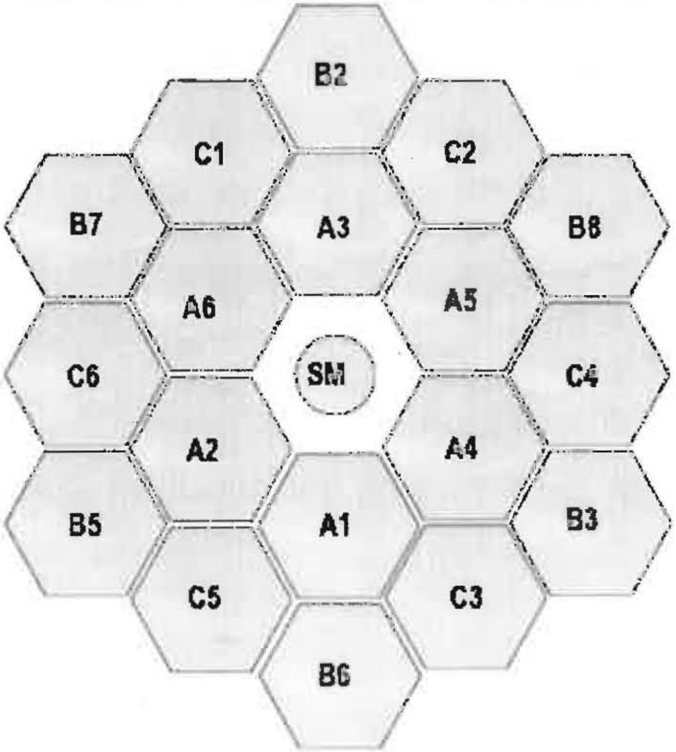

C1


B2

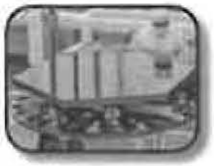

B7


C2


A6




B8

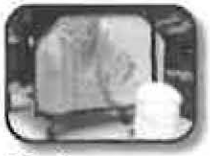

C6


A5


Secondary


A2


C4


Tertiary


B5

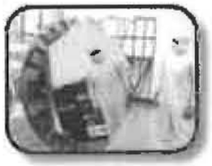

B3


Fine Steering


C5


B6

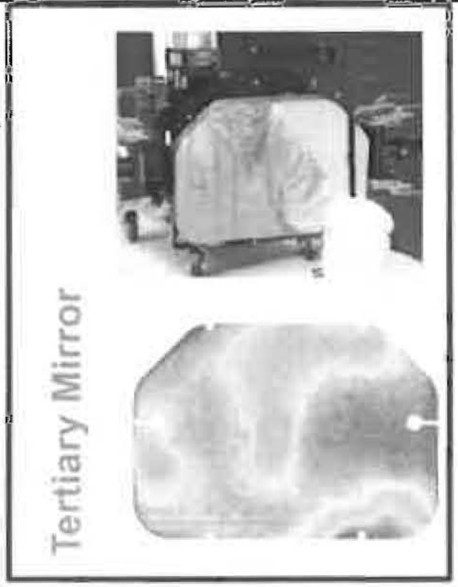

A1


C3


A4

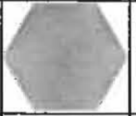
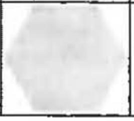
JWST Mirrors Completed in 2011

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



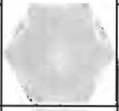
Tinsley Results Summary (p.1)

ambient (Tinsley EIDP ship data)

	Surface map	SFE P-V (nm)	SFE rms (nm)	mid freq (nm)	hi freq (nm)	surf ruf rms (nm)	surf ruf sd (nm)	RoC (mm)	conic constant	decenter (mm)	clocking (mrad)	area (m^2)	SFE stab (nm)	RoC stab (mm)	OAD stab (mm)	Ship date from Tinsley
allocation		—	23.1	—	9.5	4	—	"+/-0.028"	"+/-0.001"	0.35	0.35	—	—	—	—	
max		957	18.00	16.53	9.37	3.60	0.67	0.027		0.280	0.215	1.4775	4.82	0.084	0.165	3/9/2010
min		186	8.65	6.49	4.69	2.89	0.19	-0.015		0.043	-0.232	1.4644	1.99	-0.081	0.027	10/23/2008
rms		634	13.83	12.35	6.45	3.25	0.35	0.008		0.173	0.110	1.4718	3.81	0.048	0.125	
ave		585	13.56	11.84	6.34	3.26	0.33	0.004		0.160	0.003	1.4718	3.72	0.030	0.110	
A1		826.1	15.58	14.62	5.38	3.39	0.29	0.027	0.00022	0.153	-0.232	1.4747	2.80	0.02	0.165	3/9/2010
A2		956.7	16.69	15.80	5.37	3.16	0.67	0.016	0.00022	0.043	0.042	1.4747	3.54	0.05	0.151	12/1/2008
A3		349.5	10.65	8.35	6.61	3.27	0.31	0.008	0.00022	0.210	0.021	1.4775	3.54	-0.081	0.142	1/20/2010
A4		605.7	9.45	8.20	4.69	3.16	0.30	0.0038	0.00022	0.164	-0.076	1.4747	4.16	0.039	0.163	5/6/2009
A5		185.8	15.81	14.6	6.07	3.60	0.42	0.002	0.00022	0.280	0.040	1.4754	4.82	0.032	0.146	4/7/2009
A6		770	18.00	16.53	7.13	2.96	0.19	0.003	0.00022	0.210	0.210	1.4745	2.88	0.080	0.122	8/17/2009
B2		940	14.08	10.50	9.37	3.6	0.28	-0.015	0.00022	0.210	0.046	1.4747	3.12	0.022	0.133	1/9/2010
B3		321	8.65	6.49	5.72	3.33	0.43	0.003	0.00022	0.228	-0.017	1.4771	4.66	0.008	0.160	6/24/2009

Tinsley Results Summary (p.2)

ambient (Tinsley EIDP ship data)

	Surface map	SFE P-V (nm)	SFE rms (nm)	mid freq (nm)	hi freq (nm)	surf ruf rms (nm)	surf ruf sd (nm)	RoC (mm)	conic constant	decenter (mm)	clocking (mrad)	area (m^2)	SFE stab (nm)	RoC stab (mm)	OAD stab (mm)	Ship date from Tinsley
allocation		---	23.1	---	9.5	4	---	"+/-0.028"	"+/-0.001"	0.35	0.35	---	---	---	---	
max		864	16.46	15.12	8.75	3.47	0.46	0.006		0.215	0.215	1.4766	4.82	0.084	0.150	12/4/2009
min		275	9.34	7.90	4.60	2.89	0.20	-0.004		0.046	-0.134	1.4644	1.99	0.004	0.027	10/23/2008
rms		595	13.87	12.27	6.45	3.20	0.32	0.005		0.150	0.104	1.4689	2.94	0.045	0.104	
ave		557	13.65	11.93	6.37	3.20	0.31	0.002		0.136	0.002	1.4686	3.75	0.037	0.095	
B5		292	9.34	7.90	4.99	3.25	0.31	-0.003	0.00022	0.092	0.017	1.4748	3.88	0.084	0.143	12/3/2009
B6		413	15.97	14.90	5.76	3.04	0.46	0.005	0.00022	0.087	-0.043	1.4754	4.20	0.020	0.132	7/10/2009
B7		337	12.81	11.2	6.28	3.31	0.32	0.006	0.00022	0.046	0.038	1.4766	3.36	0.006	0.030	10/21/2009
B8		864	13.80	12.30	6.25	3.24	0.35	0.001	0.00022	0.190	-0.037	1.4748	3.43	0.004	0.093	9/30/2009
C1		670	11.08	8.69	6.87	3.33	0.25	-0.004	0.00022	0.105	-0.031	1.4646	1.99	0.054	0.069	8/18/2009
C2		841	16.46	15.12	6.50	3.18	0.29	0.006	0.00022	0.215	0.215	1.4646	2.84	0.071	0.121	12/4/2009
C3		274.8	14.55	13.80	4.60	3.47	0.35	0.006	0.00022	0.195	0.156	1.4652	4.82	0.029	0.107	10/23/2008
C4		555	16.26	13.70	8.75	2.89	0.2	-0.003	0.00022	0.147	-0.134	1.4644	4.61	0.011	0.150	10/30/2009
C5		579	14.90	13.70	5.87	3.39	0.38	0.002	0.00022	0.087	-0.059	1.4644	4.04	0.004	0.075	6/25/2009
C6		740	11.61	8.53	7.82	2.69	0.2	0.006	0.00022	0.215	-0.103	1.4644	4.36	0.033	0.027	10/2/2009

XRCF Testing Results

	SFE total measured (nm rms)	hi freq measured (nm rms)	XRCF tot measured (nm rms)	XRCF hi measured (nm rms)	Tinsley sub aperture very hi measured (nm rms)	SFE metrology uncertainty tot (nm rms)	SFE metrology uncertainty hi (nm rms)	ΔRoC (nom) (mm)	RoC match to -0.5 mm nominal delta (mm)	RoC match to mean RoC nominal (mm)	RoC metrology uncertainty (mm)	fig distort from roc adj (nm rms / um pv sag)	RoC adj range & test adj range min (um pv sag)	RoC adj range & test adj range max (um pv sag)	RoC adj resolution (nm pv sag)	RoC actuator length/pv-sag (unitless ratio)	RoC adj single step accuracy (nm pv sag)	fig distort from rb adj (nm rms)	astig distort from rb adj (nm rms)	Ship date from Tinsley
allocation	23.6	12.2						+/- 1	+/- 0.16			<28	>=0.16 & 4	>=0.16 & 4	<=10	na	<=3	12.8	34.2	
max	44.2	12.5	44.0	11.7	5.8	8.2	2.3	-0.419	0.081	0.032	0.085	22.6	-0.6	5.5	0.4	22.5	0.4	13.3	[illegible]	3/9/2010
min	16.5	8.1	15.7	7.2	2.9	8.0	2.3	-0.539	-0.039	[illegible]	0.082	19.1	[illegible]	3.9	0.4	19.2	0.1	9.9	19.6	10/23/2008
rms	23.9	10.0	23.1	9.9	4.5	8.1	2.3	0.509	0.026	0.027	0.084	21.3	1.3	4.7	0.4	20.3	0.2	11.4	28.8	
mean	22.4	9.9	21.6	8.9	4.4	8.1	2.3	-0.507	-0.011	0.000	0.084	20.8	-1.3	4.6	0.4	20.3	0.1	11.3	28.3	
std	7.5	1.4	7.5	1.4	0.9	0.1	0.0	0.028	0.028	0.026	0.001	1.2	0.3	0.4	0.0	1.1	0.1	1.0	5.5	
cum																				
A1	17.9	9.5	17.7	9.0	2.9	8.0	2.3	-0.490	0.010	-0.017	0.085	19.3	-0.662	4.444	0.37	22.0	0.06	9.9	20.9	3/9/2010
A2	22.2	11.2	21.9	10.7	3.4	8.0	2.3	-0.504	-0.004	-0.003	0.085	19.3	-1.349	4.355	0.37	21.2	0.09	10.2	19.6	12/1/2008
A3	21.8	12.3	21.0	10.8	5.8	8.0	2.3	-0.507	-0.007	0.000	0.085	19.4	-0.911	4.875	0.38	20.7	0.03	10.4	26.3	1/20/2010
A4	17.1	8.2	16.8	7.5	3.2	8.0	2.3	-0.520	-0.020	0.013	0.085	19.1	-1.557	3.906	0.37	22.0	0.18	10.8	26.9	5/6/2009
A5	16.5	10.1	15.7	8.8	5.0	8.0	2.3	-0.539	-0.039	0.032	0.085	19.2	-1.456	4.229	0.38	21.1	0.08	10.6	31.1	4/7/2009
A6	44.2	12.5	44.0	11.7	4.5	8.0	2.3	-0.483	0.017	-0.024	0.085	19.8	-1.240	4.085	0.35	22.5	0.05	10.0	30.9	8/17/2009
B2	18.7	9.2	17.8	7.2	5.7	8.2	2.3	-0.502	-0.002	-0.005	0.084	21.1	-0.988	5.170	0.40	20.1	0.22	11.7	25.6	1/9/2010
B3	18.7	9.1	18.2	8.1	4.2	8.2	2.3	-0.524	-0.024	0.017	0.084	22.6	-1.131	4.954	0.41	19.6	0.14	12.2	25.9	6/24/2009
B5	18.4	9	18.0	8.1	3.9	8.2	2.3	-0.493	0.007	-0.014	0.084	21.8	-1.414	4.595	0.41	19.9	0.09	11.9	22.0	12/3/2009
B6	17.5	10.2	17.0	9.4	4.0	8.2	2.3	-0.496	0.004	-0.011	0.081	21.8	-1.767	4.319	0.41	19.4	0.13	11.3	[illegible]	7/10/2009
B7	22.6	8.9	22.2	7.8	4.3	8.2	2.3	-0.527	-0.027	0.020	0.084	21.8	-0.845	5.469	0.41	19.9	0.16	12.8	36.1	10/21/2009
B8	23.7	9.6	23.3	8.4	4.6	8.2	2.3	-0.524	-0.024	0.017	0.084	22.0	-1.637	4.998	0.43	19.2	0.13	13.3	27.4	9/30/2009
C1	22.1	9	21.5	7.4	5.1	8.2	2.3	-0.520	-0.020	0.013	0.082	21.9	-1.203	4.895	0.40	19.6	0.33	11.2	30.2	8/18/2009
C2	20.1	8.7	19.5	7.1	5.0	8.2	2.3	-0.531	-0.031	0.024	0.082	21.6	-1.165	4.957	0.40	19.6	[illegible]	12.1	33.4	12/4/2009
C3	18.1	8.1	17.8	7.4	3.2	8.2	2.3	-0.419	0.081	[illegible]	0.082	21.5	-1.873	4.041	0.39	20.4	0.05	10.9	31	10/23/2008
C4	39.5	12.3	39.2	11.2	5.0	8.2	2.3	-0.491	0.009	-0.016	0.082	20.3	-1.497	4.505	0.41	20.1	0.22	11.0	26.7	10/30/2009
C5	20.5	10.2	20.1	9.3	4.2	8.2	2.3	-0.532	-0.032	0.025	0.082	20.9	-1.455	4.544	0.40	20.1	0.19	11.0	29.1	6/25/2009
C6	23.9	10	23.3	8.4	5.4	8.2	2.3	-0.532	-0.032	0.025	0.082	21.4	-1.107	5.068	0.41	19.7	0.21	12.6	32.5	10/2/2009

The Team


Ball
Brush Wellman
James Webb Space Telescope
The "First Light" Machine
XRCF
OTE
Congratulations to the JWST Mirror Team
Tinsley
C1
Metrology
QCI
Axsys Technologies

Summary

- In under a decade, 21 flight mirrors including the >25 square meters of lightweighted, cryogenic beryllium mirrors were developed
- The original technology effort benefitted from a collaboration between NASA and other government agencies
- The development effort was primarily a collaboration between NASA, Industry and Academia
- The mirrors meet their top level specifications
- We overcame many technical challenges
- Our focus now is on finishing the rest of the telescope and performing system level testing