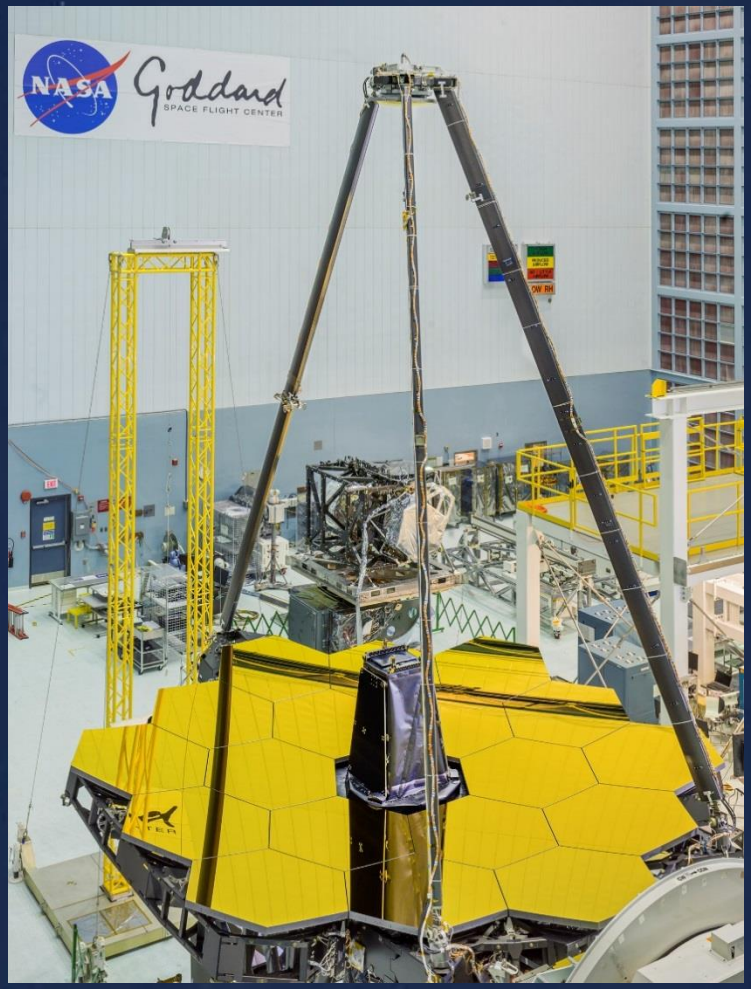


Engineering History of the James Webb Space Telescope (JWST) Optical Telescope Element

Plenary Talk
SPIE Austin, Texas

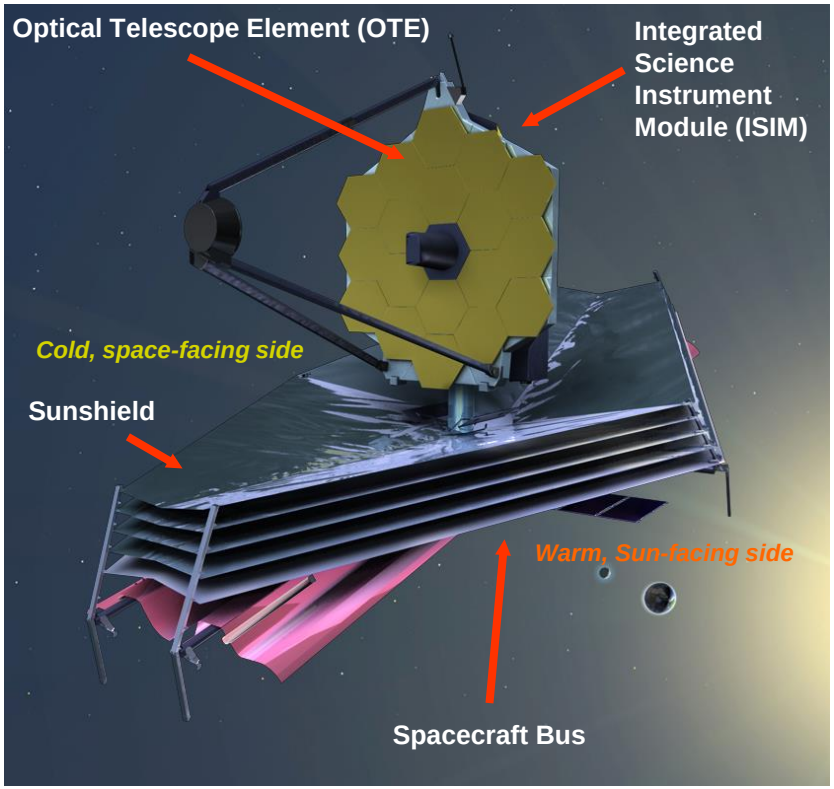
Lee Feinberg
JWST Optical Telescope Element Manager
NASA Goddard Space Flight Center

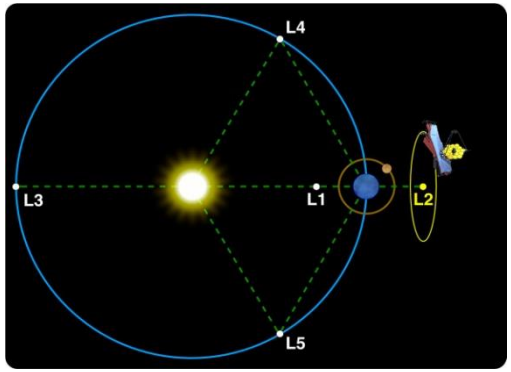
James Webb Space Telescope (JWST)

Mission Objective

- Study the origin and evolution of galaxies, stars and planetary systems
  - *Optimized for infrared observations (0.6 – 28 μm)*

- **Organization**
  - Mission Lead: Goddard Space Flight Center
  - International collaboration with ESA & CSA
  - Prime Contractor: Northrop Grumman Space Technology
    - Telescope Subs: Ball Aersopace, Harris Corp, Orbital ATK
  - Instruments:
    - Near Infrared Camera (NIRCam) – Univ. of Arizona
    - Near Infrared Spectrograph (NIRSpec) – ESA
    - Mid-Infrared Instrument (MIRI) – JPL/ESA
    - Fine Guidance Sensor (FGS) – CSA
  - Operations: Space Telescope Science Institute (STScI)

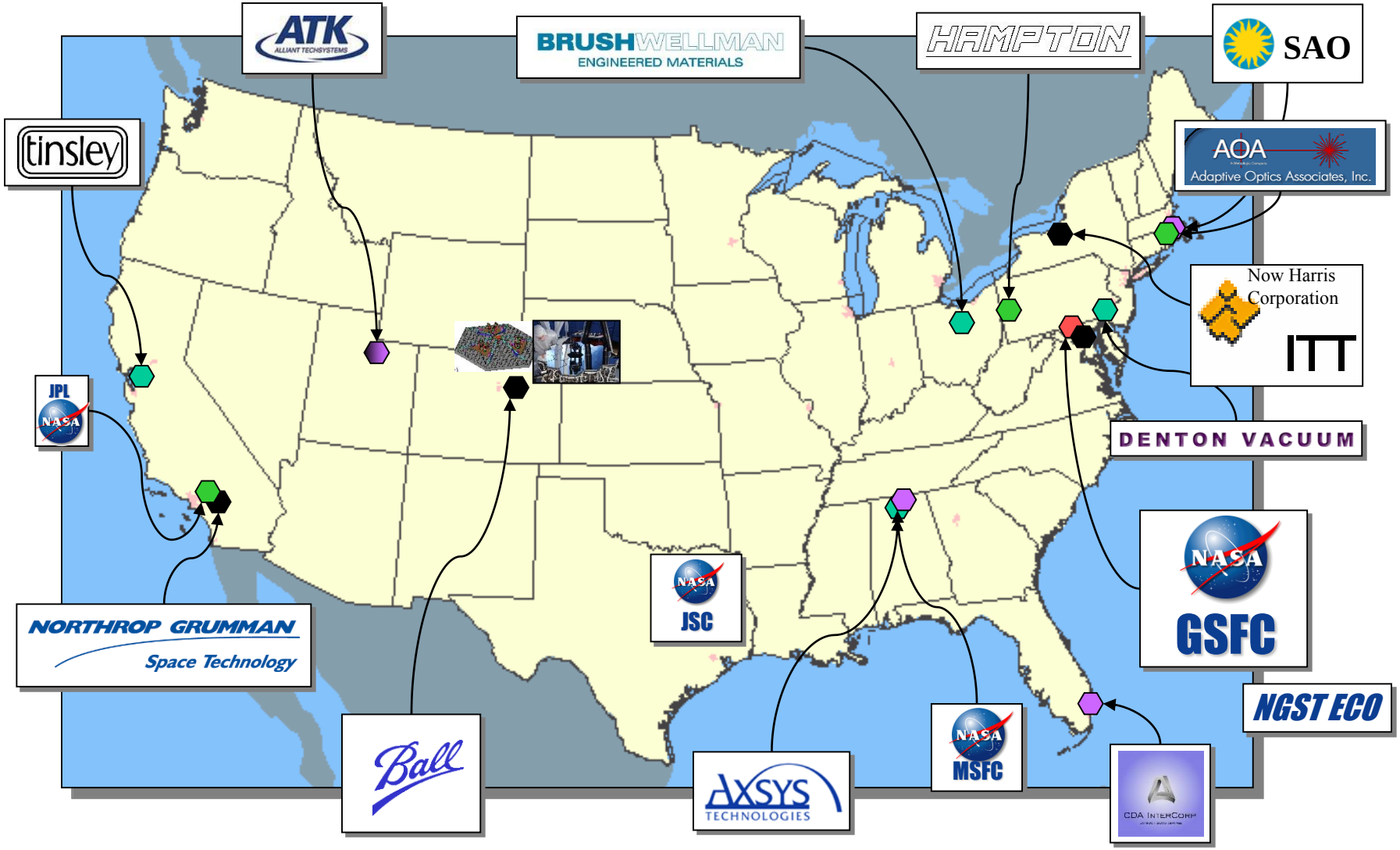




Description

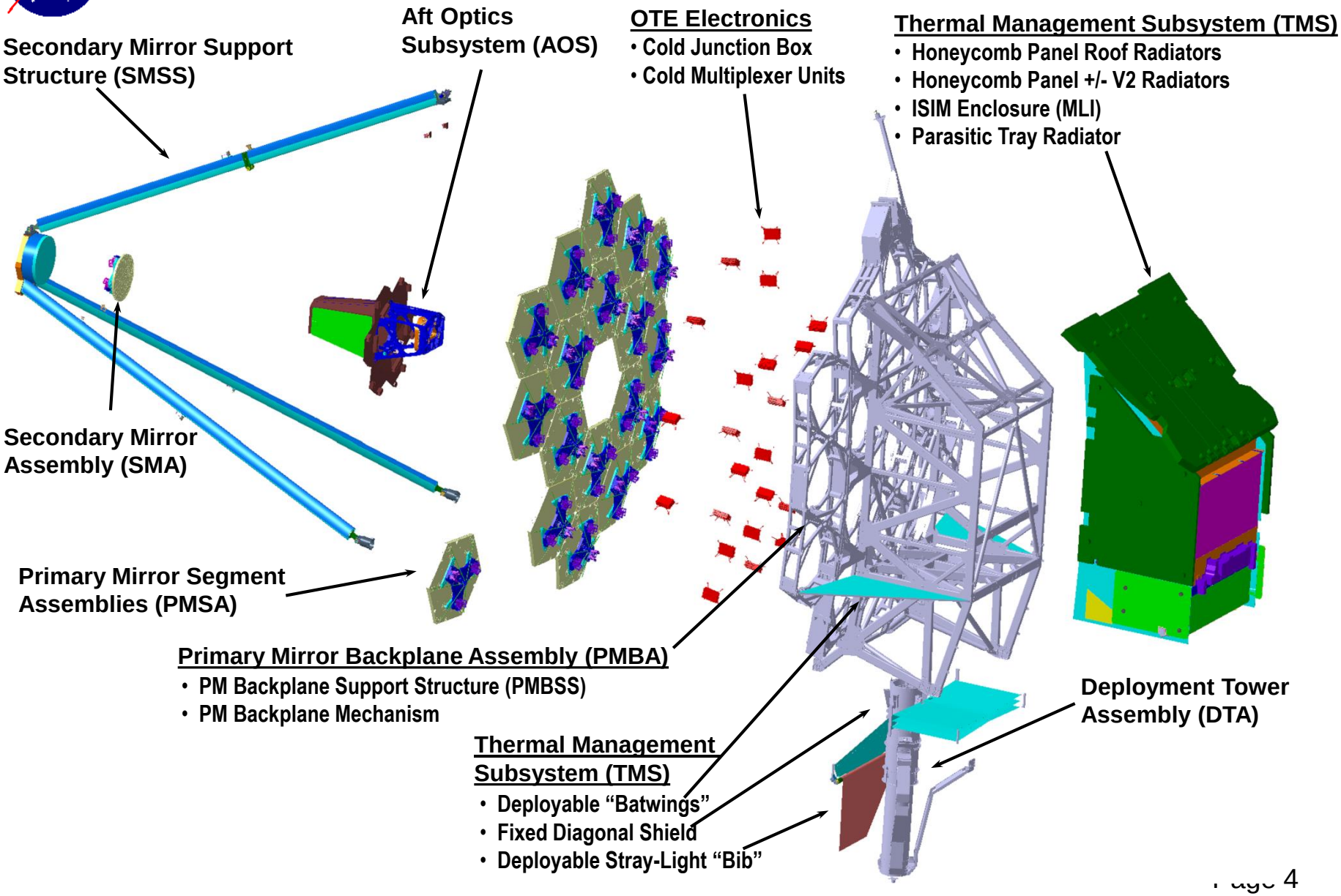
- Deployable telescope w/ 6.5m diameter segmented adjustable primary mirror
- Cryogenic temperature telescope and instruments for infrared performance
  - 50K, -370F
- Launch NET Oct 2018 on an ESA-supplied Ariane 5 rocket to Sun-Earth L2
- 5-year science mission (10-year goal)

Telescope and OTIS Team



NASA Project Office | JWST Prime Team | Beryllium Suppliers | WFS&C Suppliers/Associates | Other Suppliers/Associates

OTE Architecture Overview

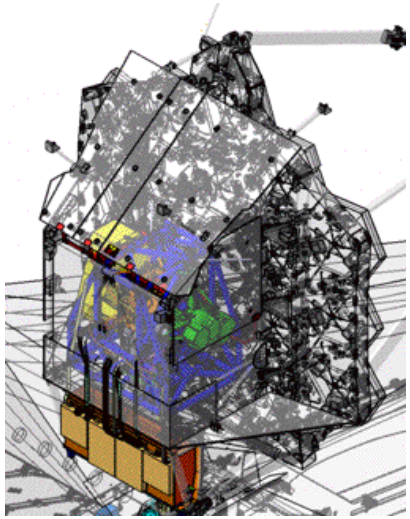


Why 18 segments?

- **Original Northrop Grumman proposal was for a 7 meter, 36 segment telescope with 4-degrees of freedom per mirror**
- **Trades were done to:**
  - Save money by reducing size slightly, enabling 18 segment option
  - Adding 6-degree of freedom of hexapods on mirrors gives us adjustability in decenter and rotation – this wound up being critical!
  - Segmentation trade of 18 vs 36
    - Larger segments had more risk of misalignment but hexapods mitigated that risk
    - Based on mirror technology developments, we learned the effort to make a mirror was not strongly influenced by size and thus making half as many would be less effort.
    - In the end, the decision to go with mirrors that had hexapods was incredibly important or our I+T program would be much more difficult and thus 18 made sense

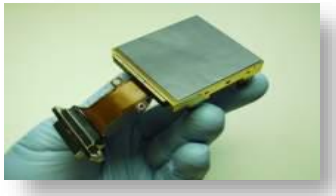
JWST Technology validated by Technology NAR 1-year in advance of the PDR/NAR

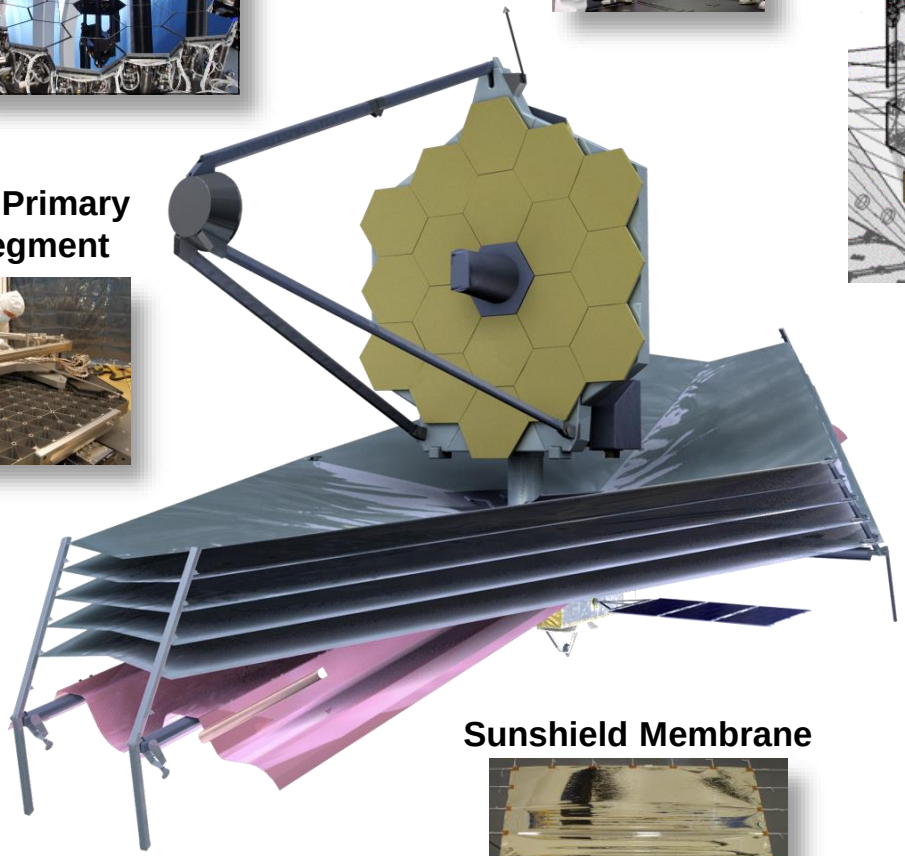
Backplane



Mirror Phasing Algorithms

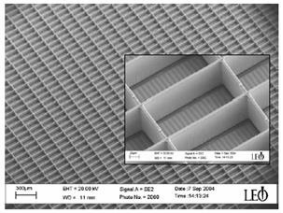
Near-Infrared Detector



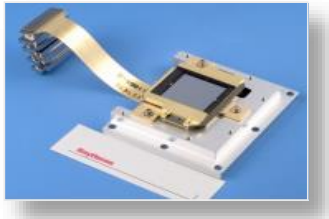


Beryllium Primary Mirror Segment

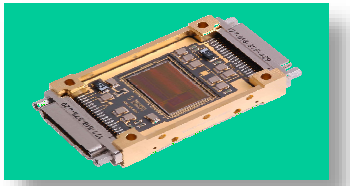
µShutters



Mid-Infrared Detector

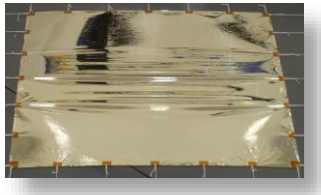


Cryogenic ASICs



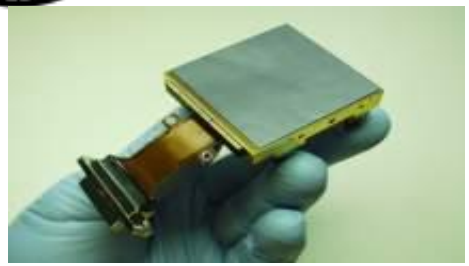
Cryocooler

Sunshield Membrane

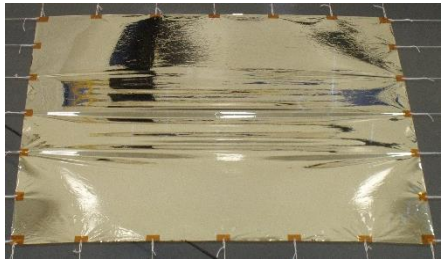


Technologies Demonstrated in 2006

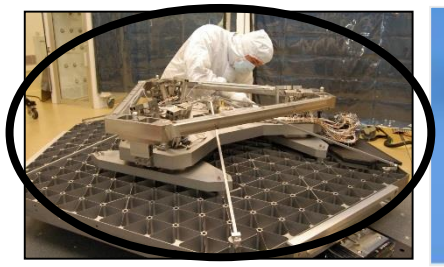
(All our mission critical technologies, OTE are circled)



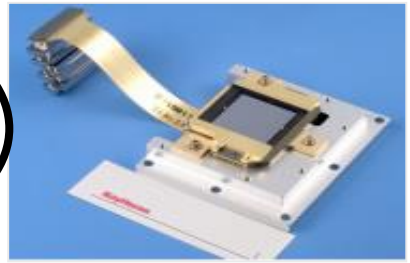
Near Infrared Detectors
April 2006



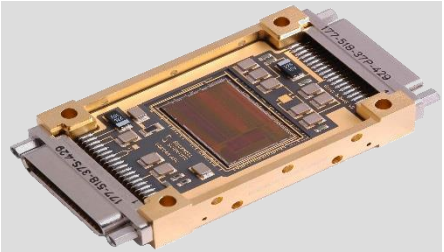
Sunshield Material
April 2006



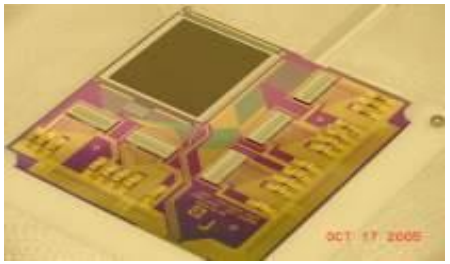
Primary Mirror Segment Assembly
June 2006



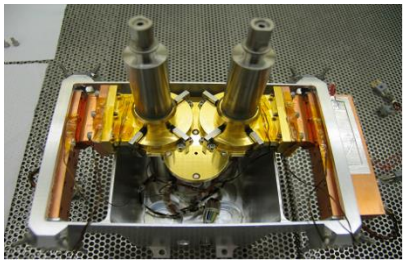
Mid Infrared Detectors
July 2006



Cryo ASICs
August 2006

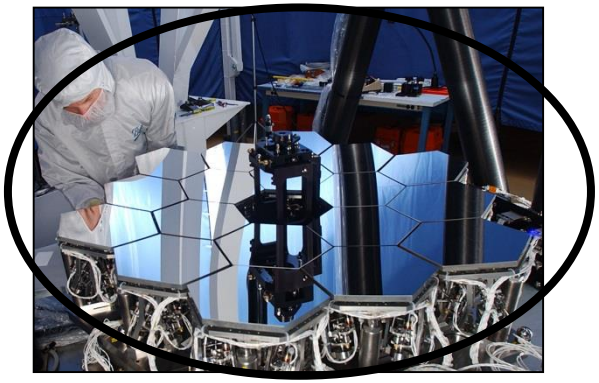


Microshutter Arrays
August 2006

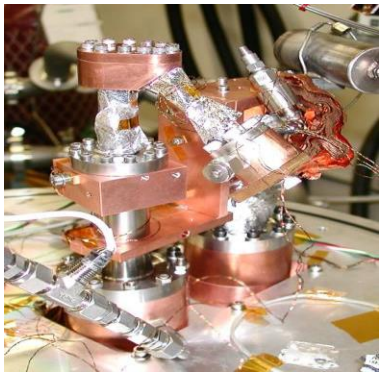


Heat Switches
September 2006

Large Precision Cryogenic Structure
November 2006



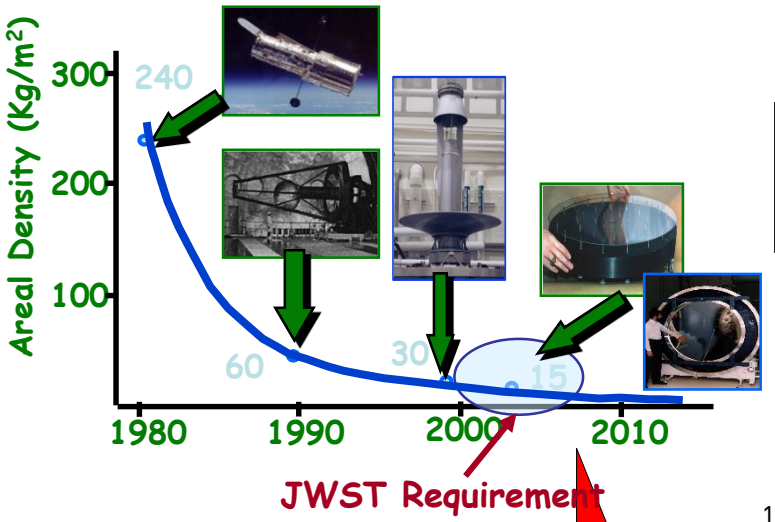
Wavefront Sensing & Control
November 2006



Cryocooler
December 2006

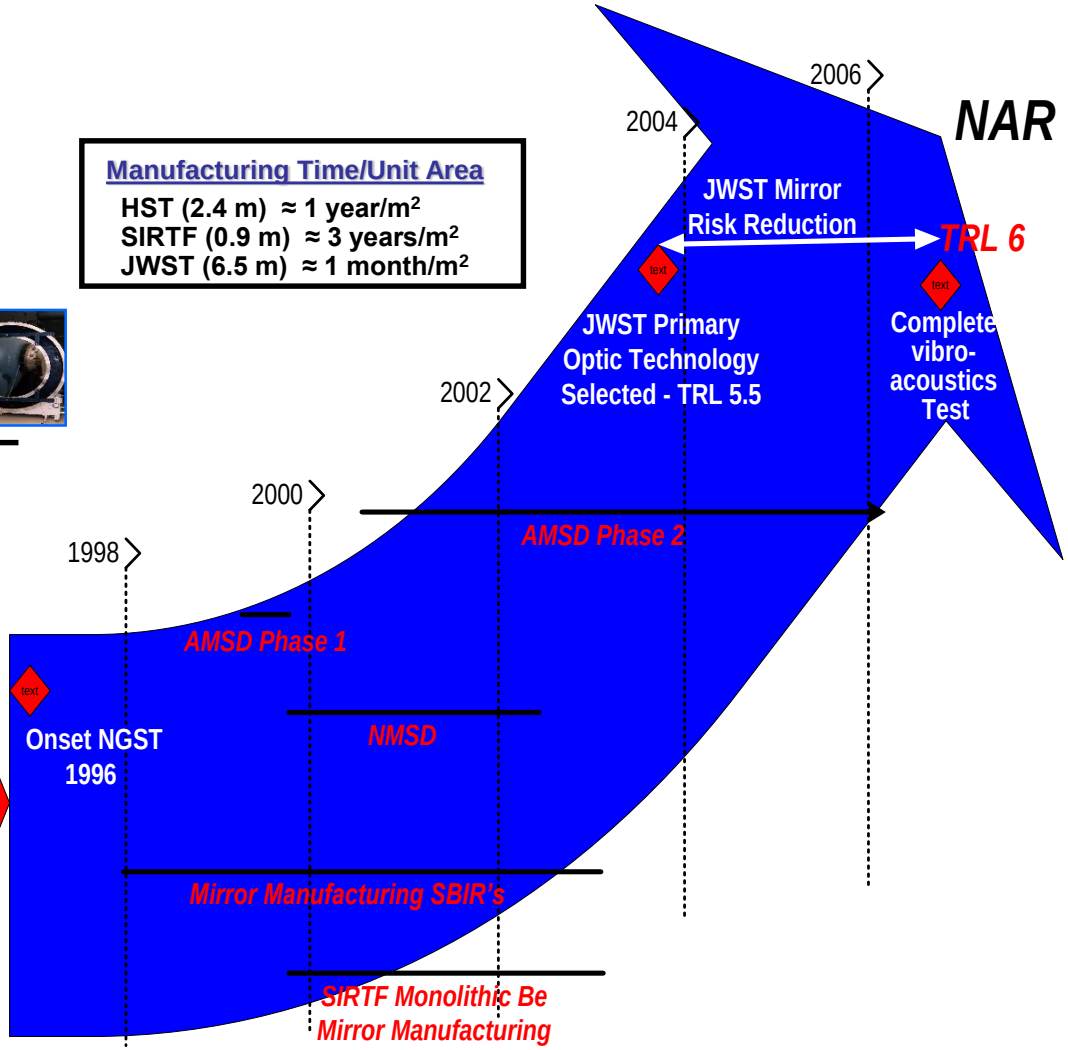
National Aeronautics and Space Administration
Goddard Space Flight Center

Early JWST Mirror Technology History



Manufacturing Time/Unit Area

HST (2.4 m) ≈ 1 year/m²
SIRTF (0.9 m) ≈ 3 years/m²
JWST (6.5 m) ≈ 1 month/m²



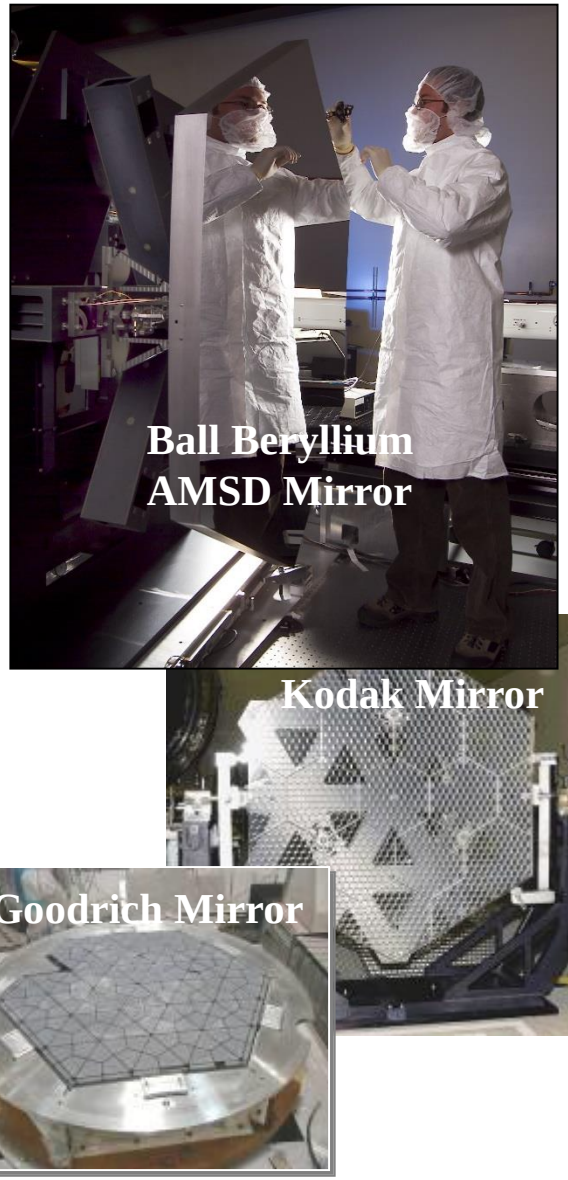
* NASA HST, Chandra, SIRTF Lessons Learned

- *TRL 6 by NAR*
- *Implement an active risk management process early in the program (Early investiment)*

Based on lessons learned, JWST invested early in mirror technology and mirror production to address lower areal densities and manufacturing time

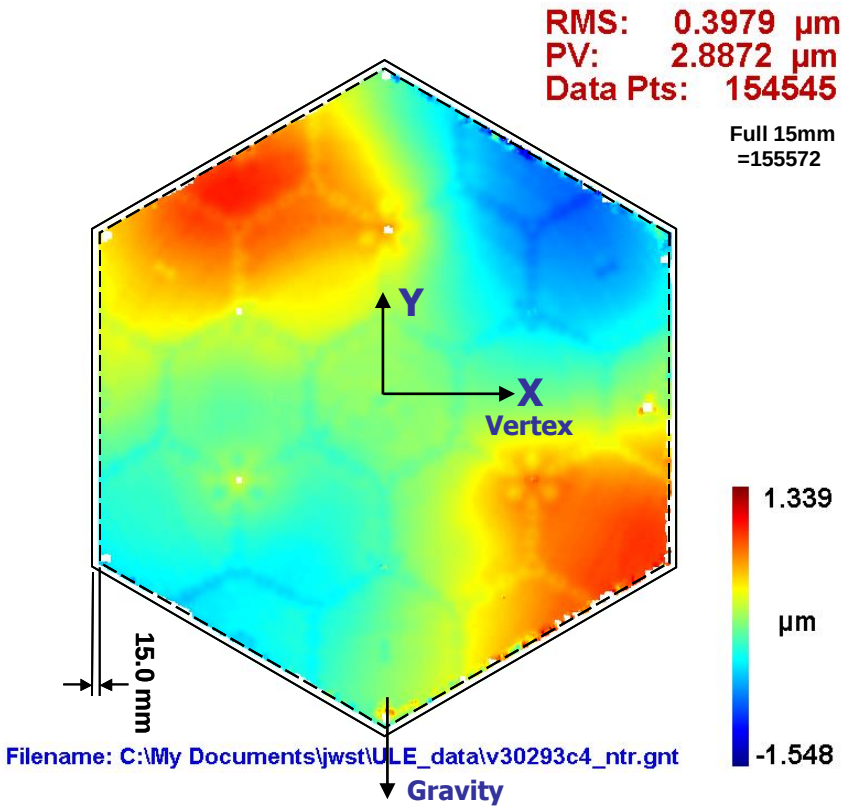
Advanced Mirror System Demonstrator (AMSD)

- 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 was demonstrated on the Engineering Design Unit mirror
- Mirror manufacturing of flight mirrors started in September 2003

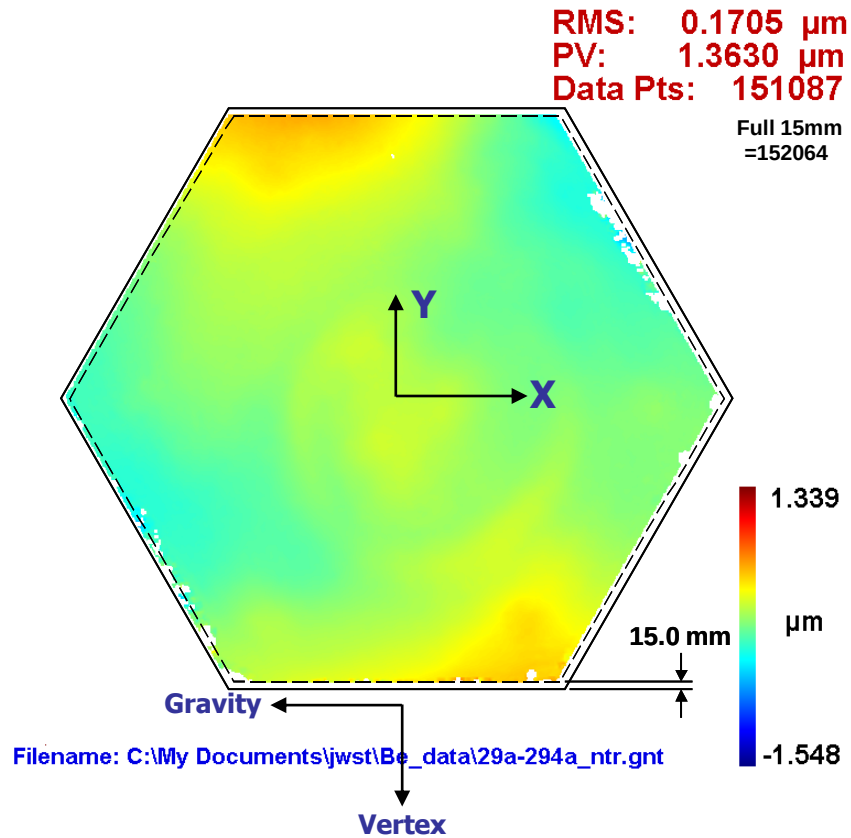


Mirror Technology Choices

~30 K minus Ambient



ULE



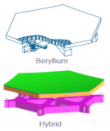
Be

Beryllium Mirror Selected Because of Superior Cryogenic Properties

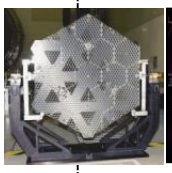
Mirror History

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**

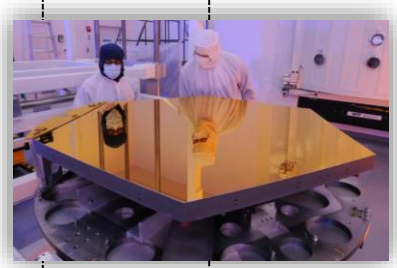
Technology Readiness Level-6 Demonstrated:
All key requirements and environments demonstrated

Onset of **James Webb Space Telescope**

AMSD Phase 1: 8 Mirror Designs

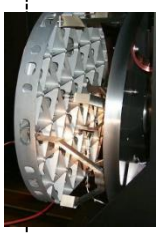
AMSD Phase 2: 3 mirrors developed

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



OTE Optics Review (OOR): Beryllium Selected

Engineering Design Unit.



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

PM Manufacturing of 18 segments

Primary Mirror Segment Assemblies Complete

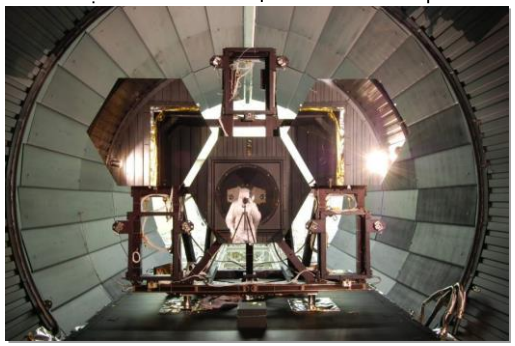
Machining Facility Complete

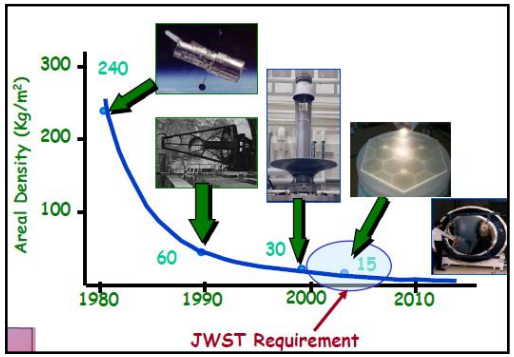
Cryo Testing

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

Polishing Facility Complete



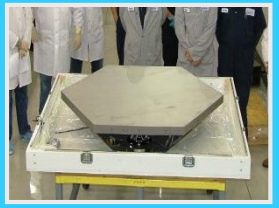


All Primary Mirror Blanks Completed

Axsys Machining Facility

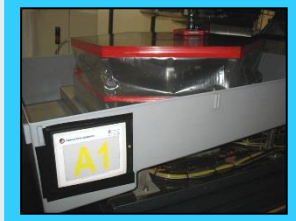
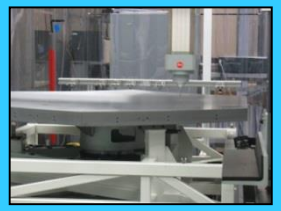
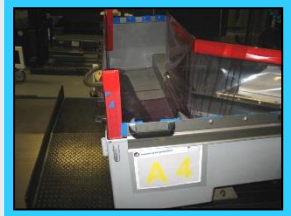
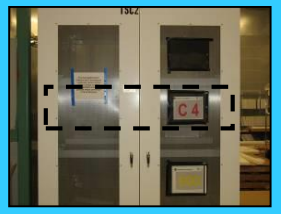
Dedicated facility and machining centers for JWST mirror production

Beryllium Flight Mirror Machining Complete at Axsys Technologies

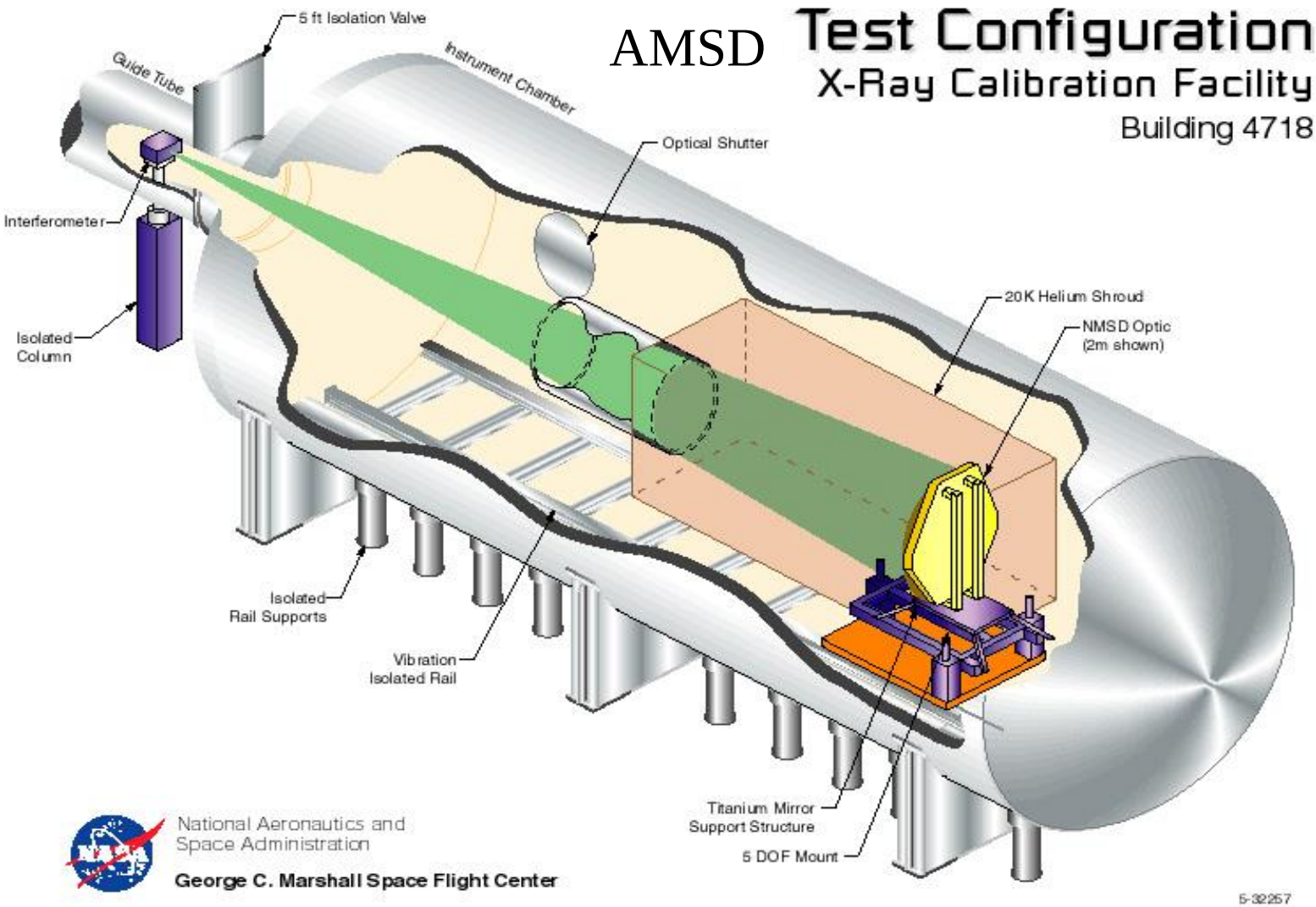
Pathfinder  ***Done at Axsys!!*** PMSA #1 (EDU-A / A1)	Pathfinder  ***Done at Axsys!!*** PMSA #2 (11 / B3)	Pathfinder  ***Done at Axsys!!*** PMSA #3 (12 / C3)	 ***Done at Axsys!!*** PMSA #4 (5 / A2)	 ***Done at Axsys!!*** PMSA #5 (6 / B2)	 ***Done at Axsys!!*** PMSA #6 (7 / C2)
 ***Done at Axsys!!*** PMSA #7 (13 / A4)	 ***Done at Axsys!!*** PMSA #8 (17 / B5)	 ***Done at Axsys!!*** PMSA #9 (4 / C1)	 ***Done at Axsys!!*** PMSA #10 (16 / A5)	 ***Done at Axsys!!*** PMSA #11 (20 / B6)	 ***Done at Axsys!!*** PMSA #12 (15 / C4)
 ***Done at Axsys!!*** PMSA #13 (8 / A3)	 ***Done at Axsys!!*** PMSA #14 (22 / B7)	 ***Done at Axsys!!*** PMSA #15 (18 / C5)	 ***Done at Axsys!!*** PMSA #16 (19 / A6)	 ***Done at Axsys!!*** PMSA #17 (3 / B1) (TRL6 PMSA)	 ***Done at Axsys!!*** PMSA #18 (21 / C6)

Tinsley Built A New Large Optics Facility To Support the JWST Program

Mirror Grinding/Polishing Status at L-3 SSG-Tinsley

Batch #1 (Pathfinder)	Batch #1 (Pathfinder)	Batch #1 (Pathfinder)	Batch #2	Batch #2	Batch #2
					
PMSA #1 (EDU-A / A1)	PMSA #2 (11 / B3)	PMSA #3 (12 / C3)	PMSA #4 (5 / A2)	PMSA #5 (6 / B2)	PMSA #6 (7 / C2)
Batch #3	Batch #3	Batch #3	Batch #4	Batch #4	Batch #4
					
PMSA #7 (13 / A4)	PMSA #8 (17 / B5)	PMSA #9 (4 / C1)	PMSA #10 (16 / A5)	PMSA #11 (20 / B6)	PMSA #12 (15 / C4)
Batch #5	Batch #5	Batch #5	Batch #6	Batch #6	Batch #6
					
PMSA #13 (8 / A3)	PMSA #14 (22 / B7)	PMSA #15 (18 / C5)	PMSA #16 (19 / A6)	PMSA #17 (3 / B1) (TRL6 PMSA)	PMSA #18 (21 / C6)

External metrology has been demonstrated as part of JWST Mirror Test Configuration



JWST Dedicated Mirror Coating Chamber at QCI/Denton

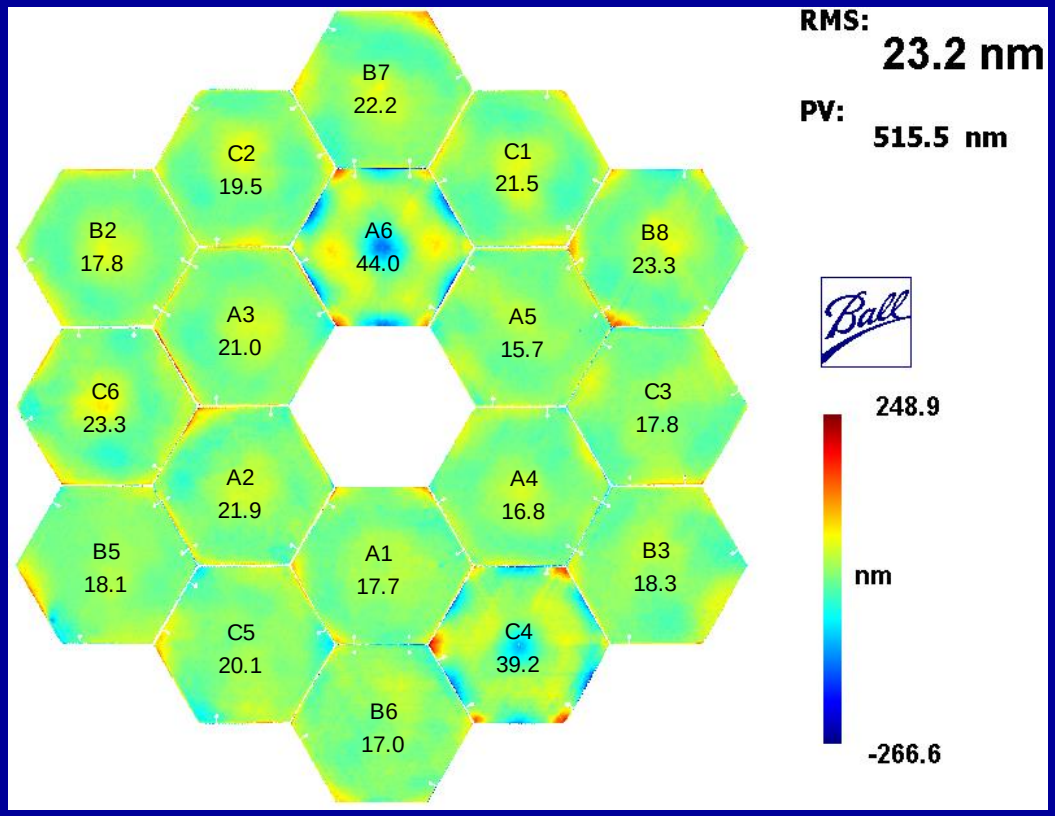
National Aeronautics and Space Administration
Goddard Space Flight Center

Coated Primary Mirror Segment Assembly

Measured Primary Mirror Cryogenic Surface Figure Error meets requirements

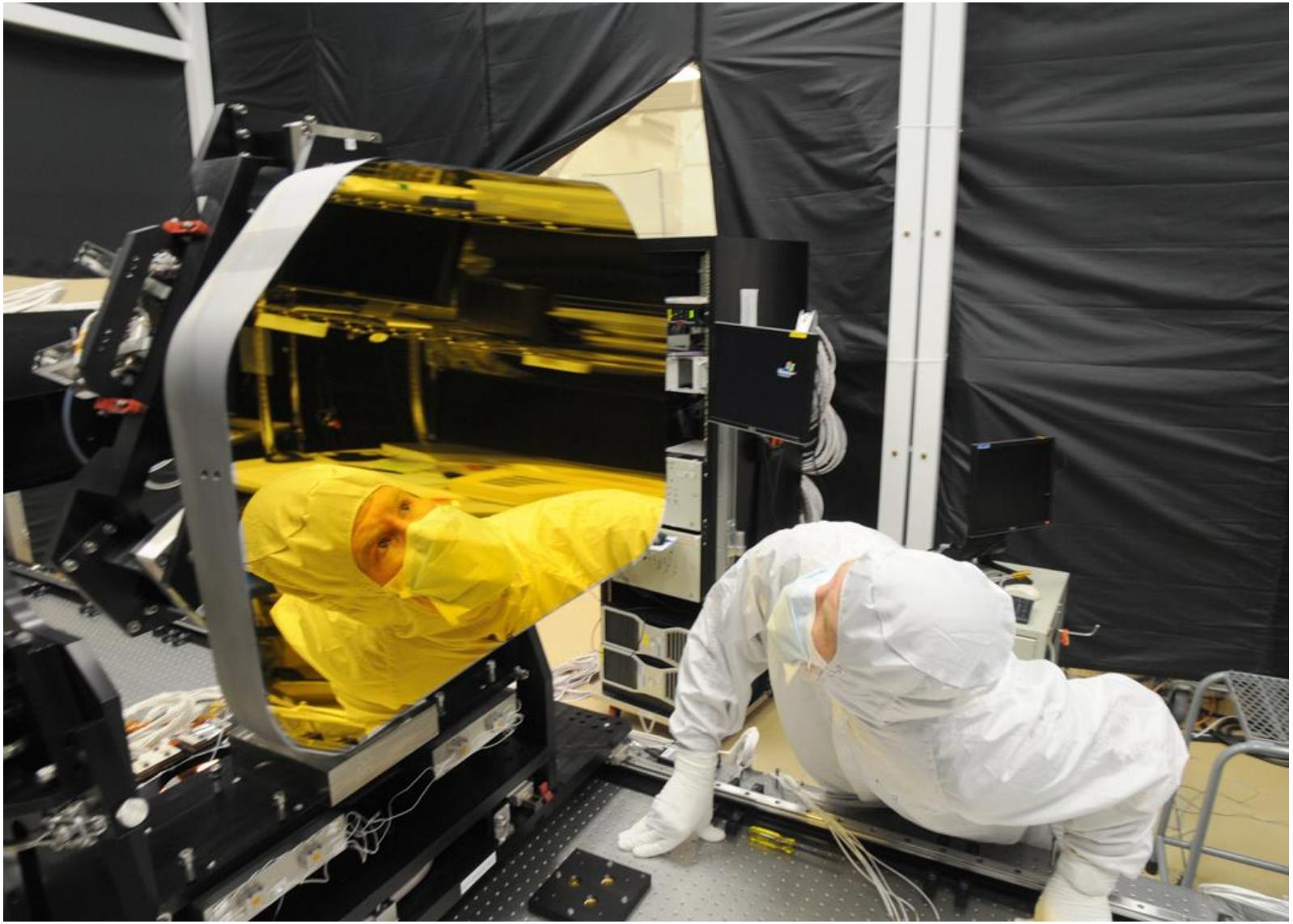
6 PMSAs ready for cryo testing

Requirement	=	25.8 nm rms
Total Measurement + Uncertainty	=	25.0 nm rms

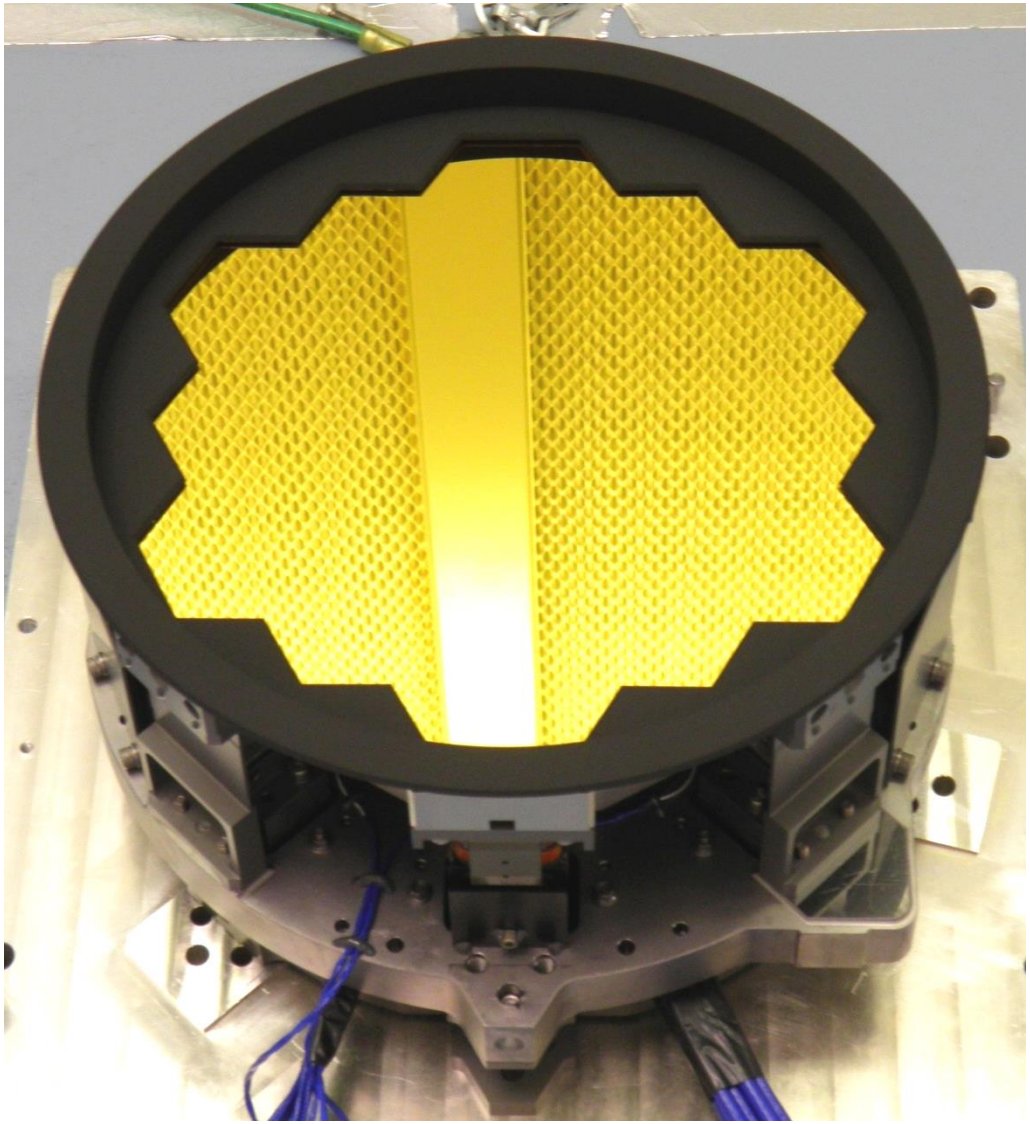


Composite Primary Mirror meets requirements

Tertiary Mirror



Fine Steering Mirror

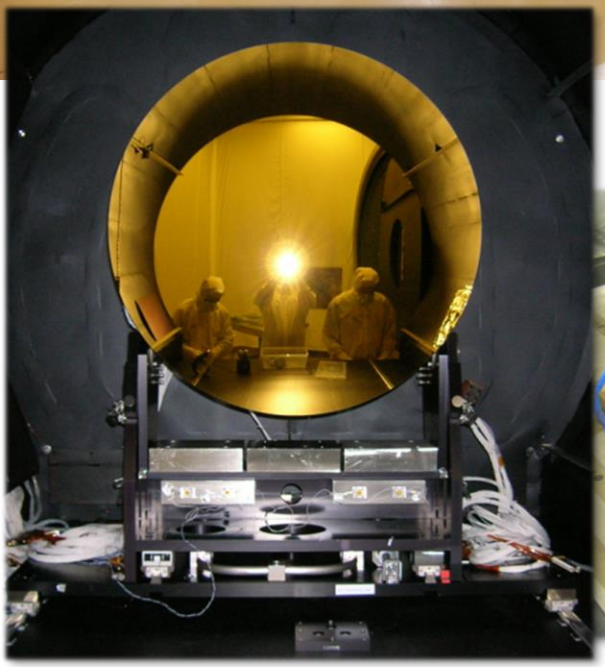


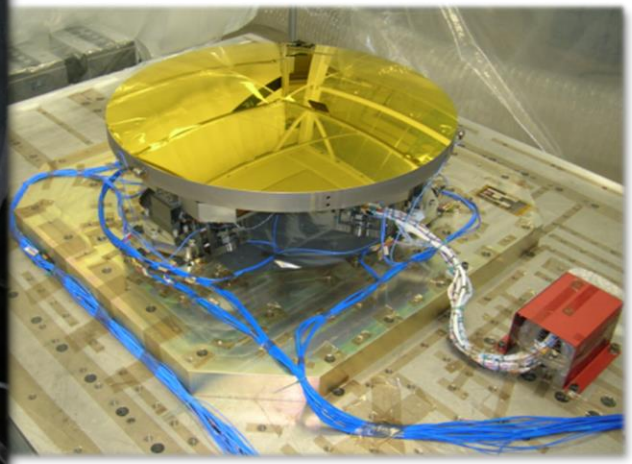
Flight SMA is Complete

SMA SFE: 19.8nm RMS SFE (including measurement uncertainty) vs. 23.5nm req't

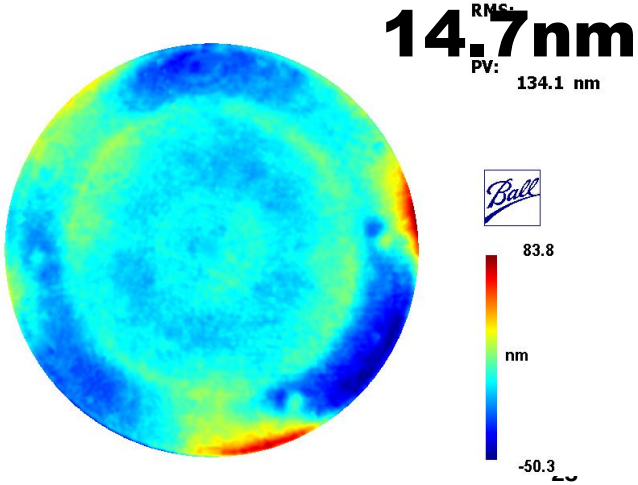
On convex mirror 0.7 meters in diameter.

One of the more challenging tasks on the program, and therefore, one of the more spectacular achievements.

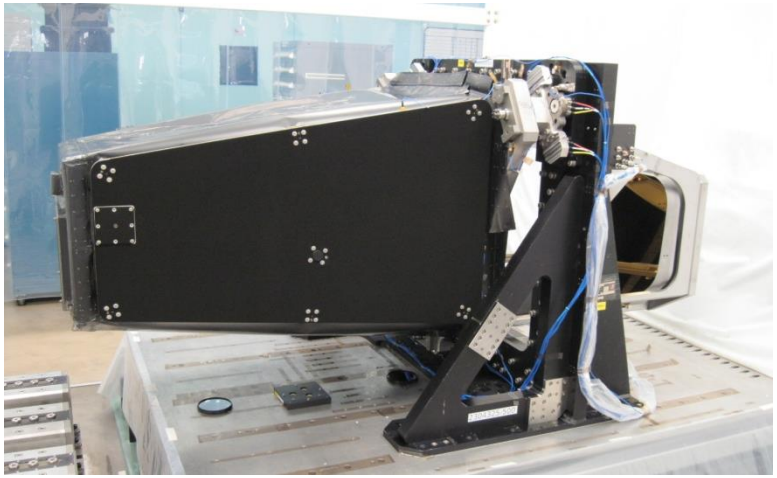


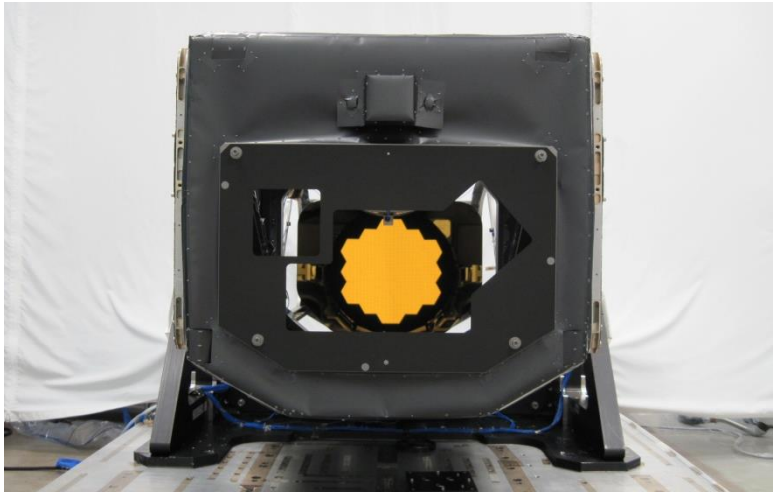


20K SMA Measured Surface Figure

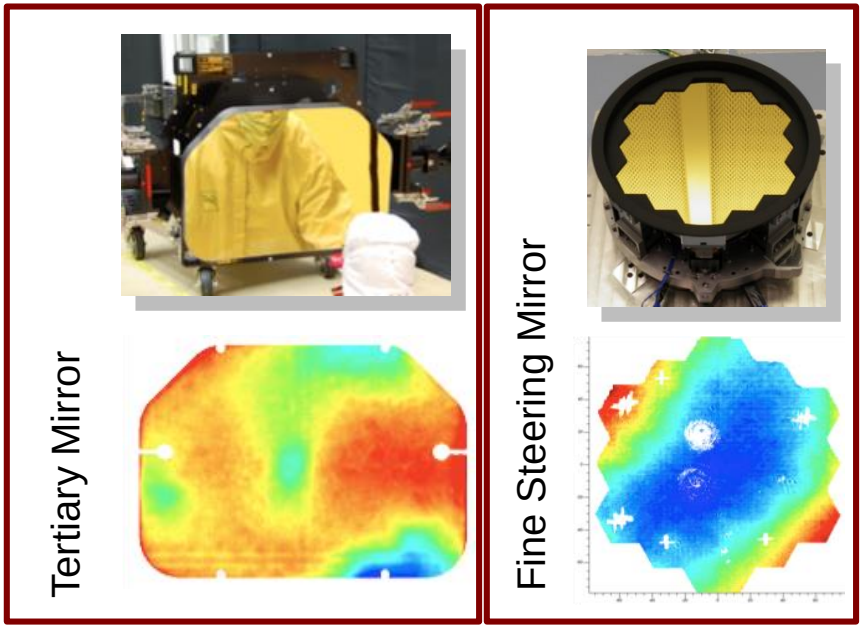


The fully integrated AOS

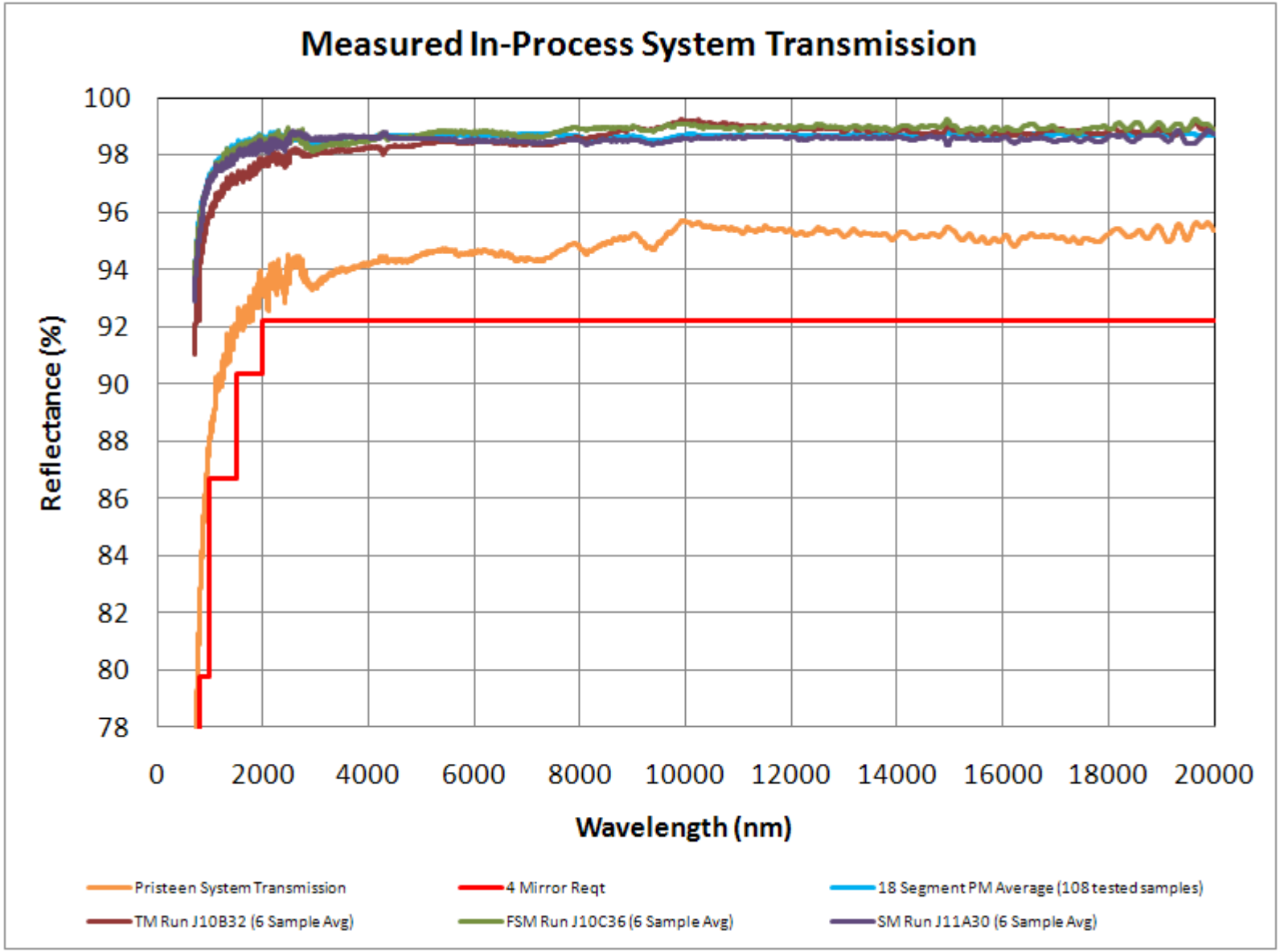




Mirror	Measured (RMS SFE)	Uncertainty (RMS SFE)	Total (RMS SFE)	Require-ment (RMS SFE)
Tertiary	18.1 nm	9.5 nm	20.5 nm	23.2 nm
Fine Steering	13.9 nm	4.9 nm	14.7 nm	18.7 nm



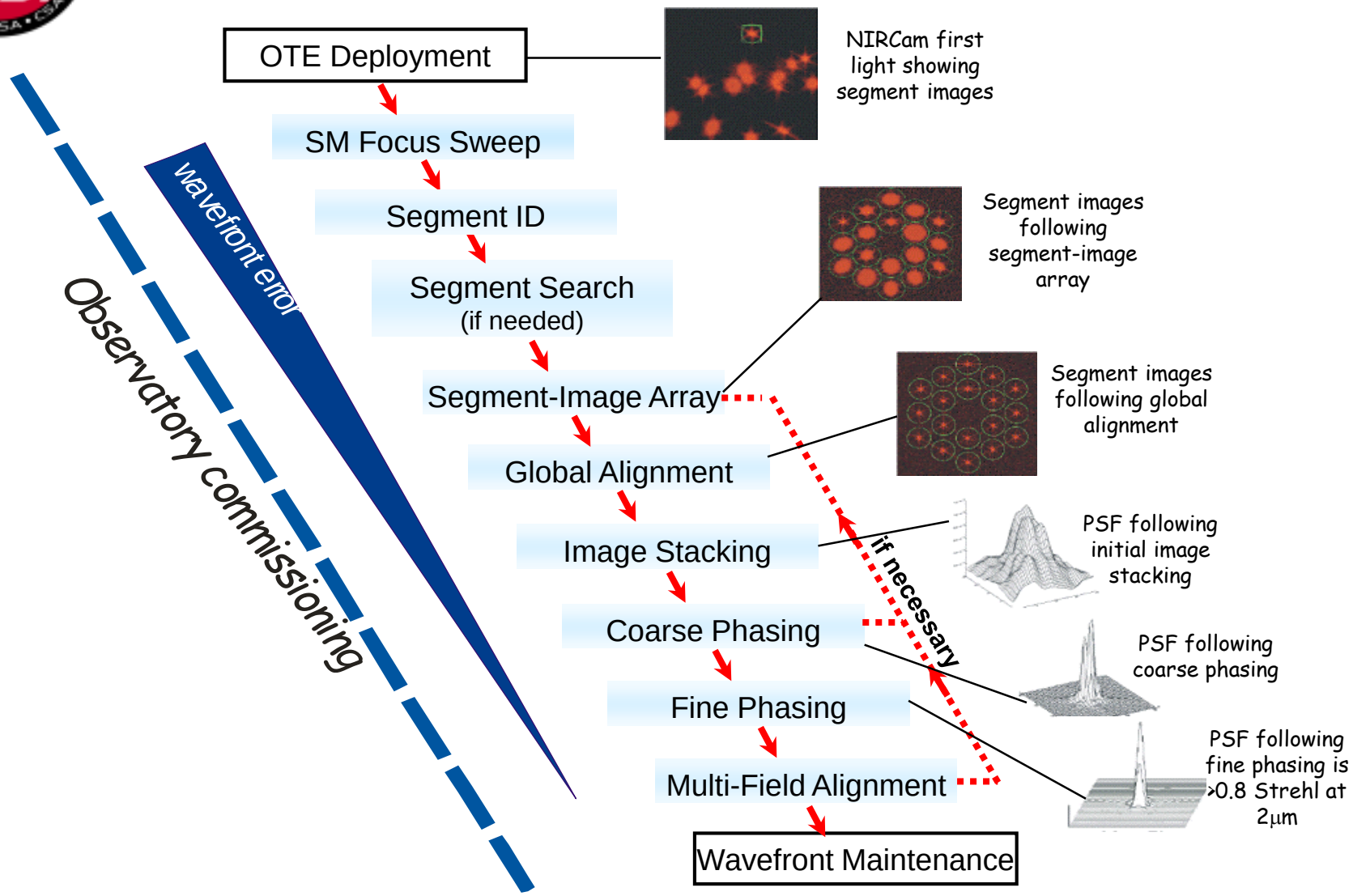
System transmission meets requirements



25

Completed Mirrors in Storage

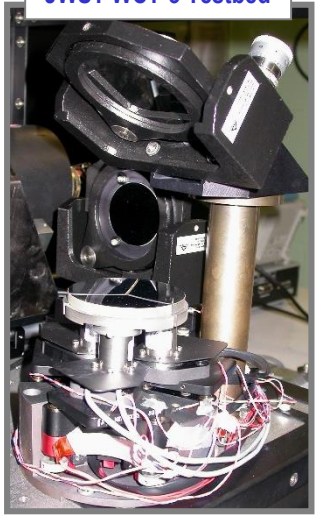
JWST Wavefront Sensing & Control Process

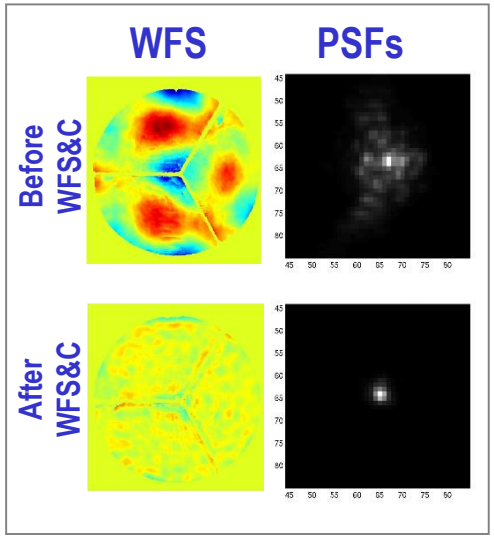


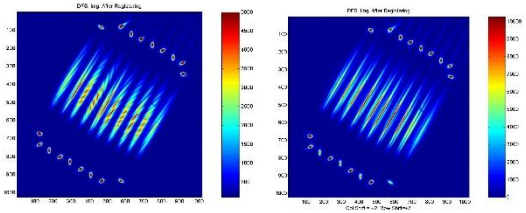
The viability of the JWST wavefront sensing and control approach was demonstrated subscale

- Wavefront Sensing and Control provides the software and algorithms used to align the telescope
- Techniques build on image based software and algorithms developed for HST Prescription Retrieval, ground telescopes, and on a large array of testbeds
- Early investments in WFSC proved the basic feasibility of the JWST segmented mirror approach through modeling and hardware demonstrations
- WFSC testbeds at the Goddard Space Flight Center (the Wavefront Control Testbed) and at Ball were used to develop JWST-specific technologies to TRL 4/5
- An experiment on the inner 18 segments of the Keck Telescope demonstrated the specific coarse phasing portion to be used on JWST

JWST WCT-3 Testbed



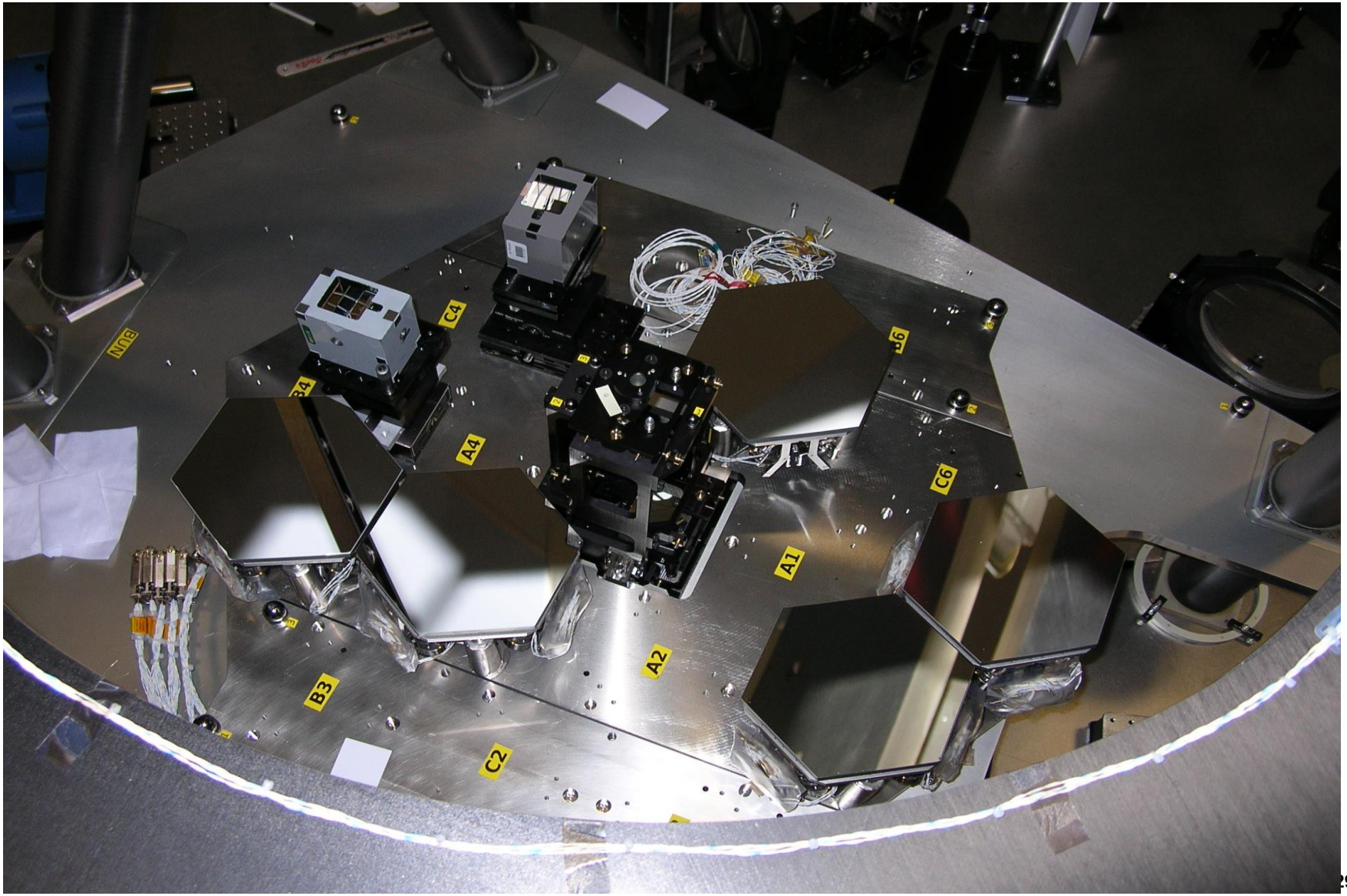




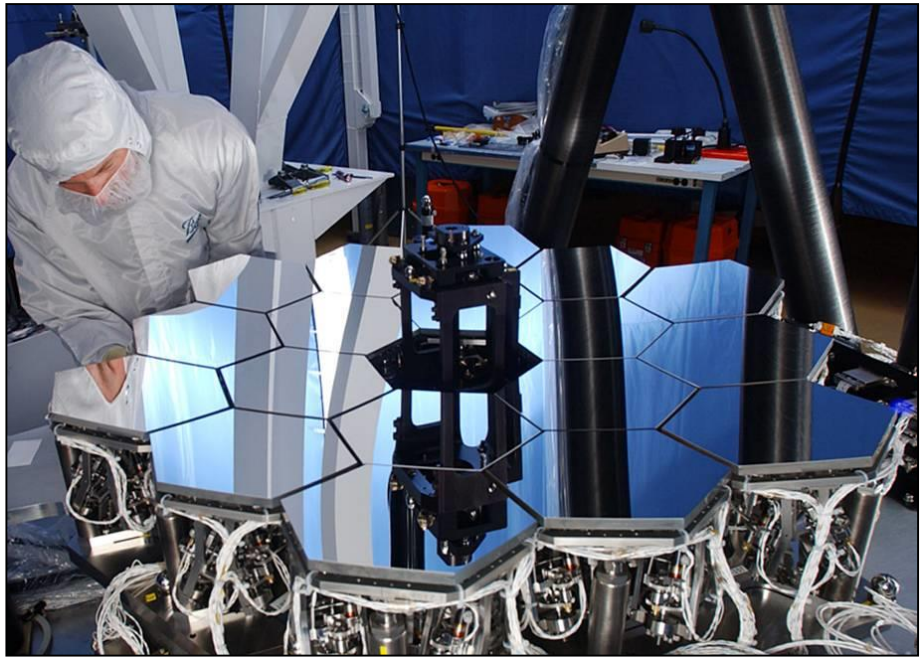
Initial errors
Max piston error=19 microns
Rms=5 microns

After correction
Max piston error=0.66 microns
Rms=0.18 microns

Ball WFSC Testbed with 5 Segments Installed



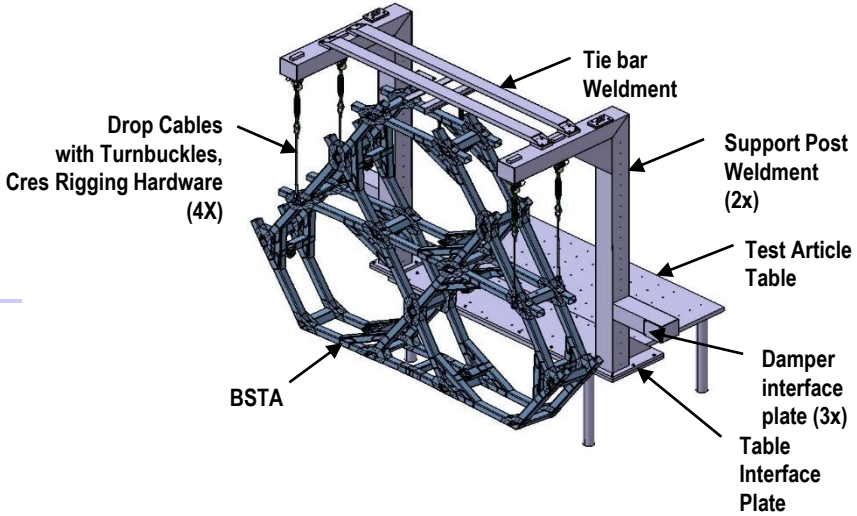
WFSC Development Plan – Testbed Telescope

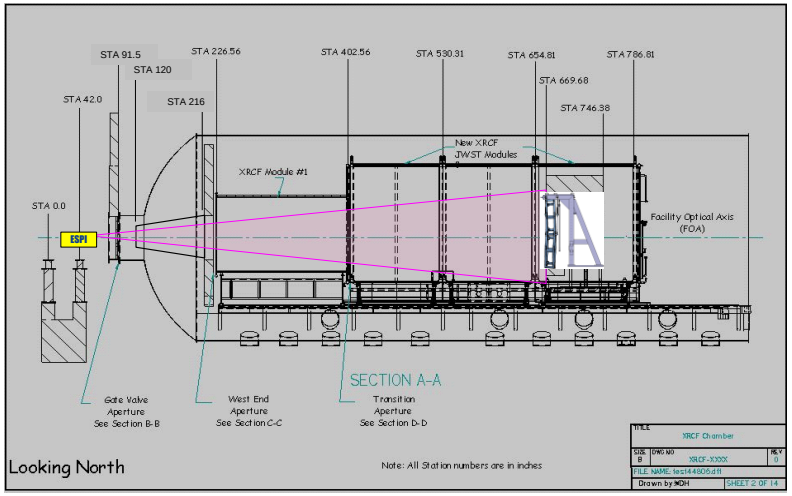


- WFSC Testbed Telescope is a 1/6th scale, fully functional model of the JWST telescope with performance traceable to JWST
- Testbed provides functionally accurate simulation platform for developing deliverable WFSC algorithms and software
- Algorithms have had initial check outs on the testbed
- Remaining WFSC TRL task is to demonstrate end-to-end wavefront sensing and control through final alignment

Backplane Stability Test Article to be used for cryo structure stability TRL-6 demonstration in the fall

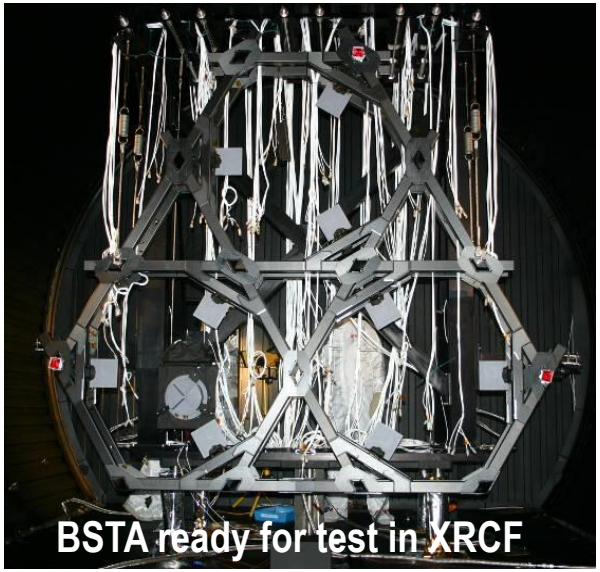
- 1/6th full-scale portion of backplane
- Underwent cryogenic testing
  - Over operational ranges (hot to cold)
- Used ESPI to measure thermal distortions
- Demonstrated modeling and CTE testing approach and thus demonstrate our ability to predict backplane thermal stability

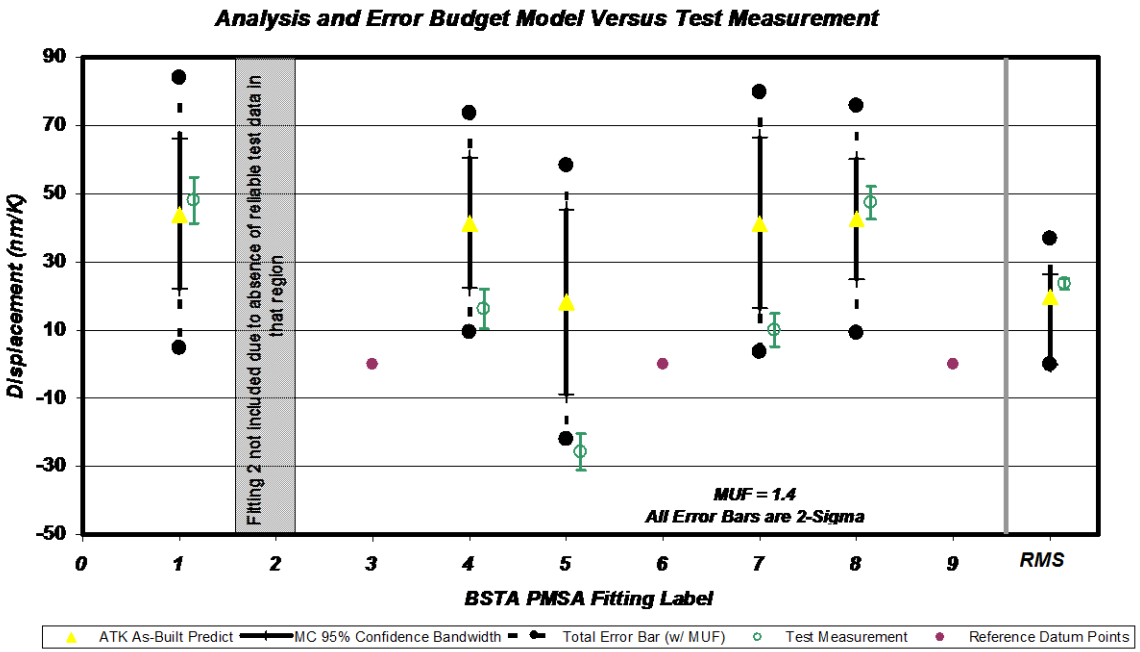


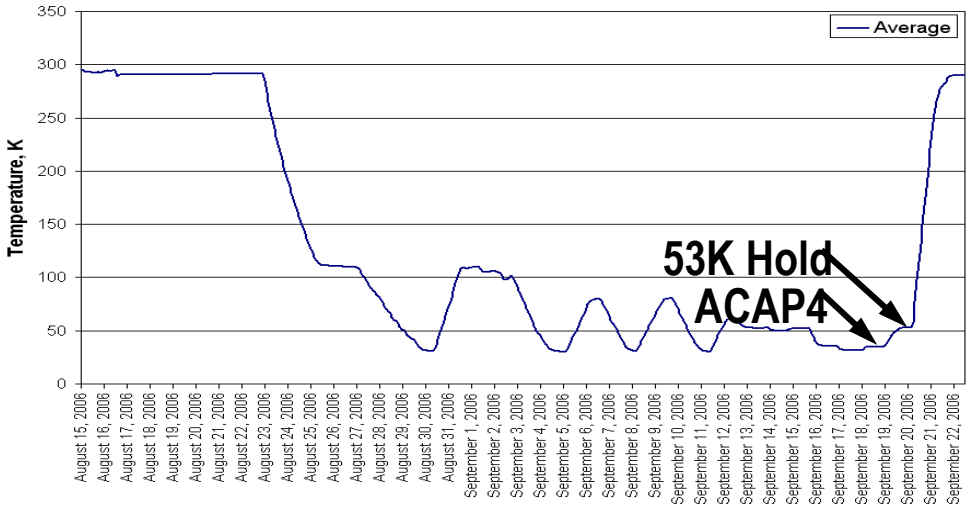


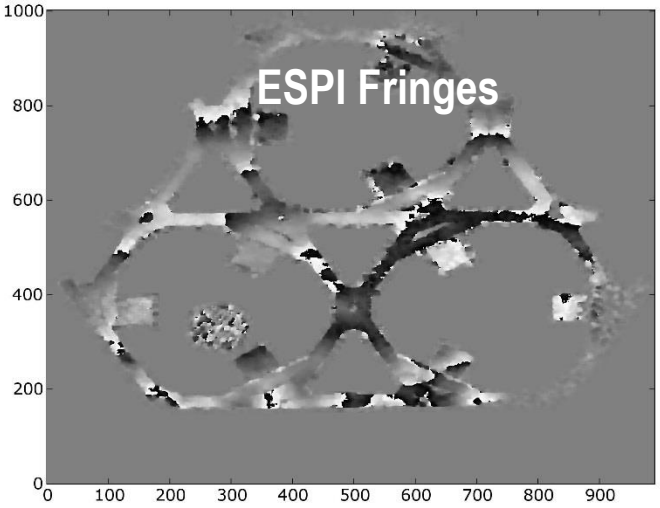
Test Configuration at XRCF

BSTA Results





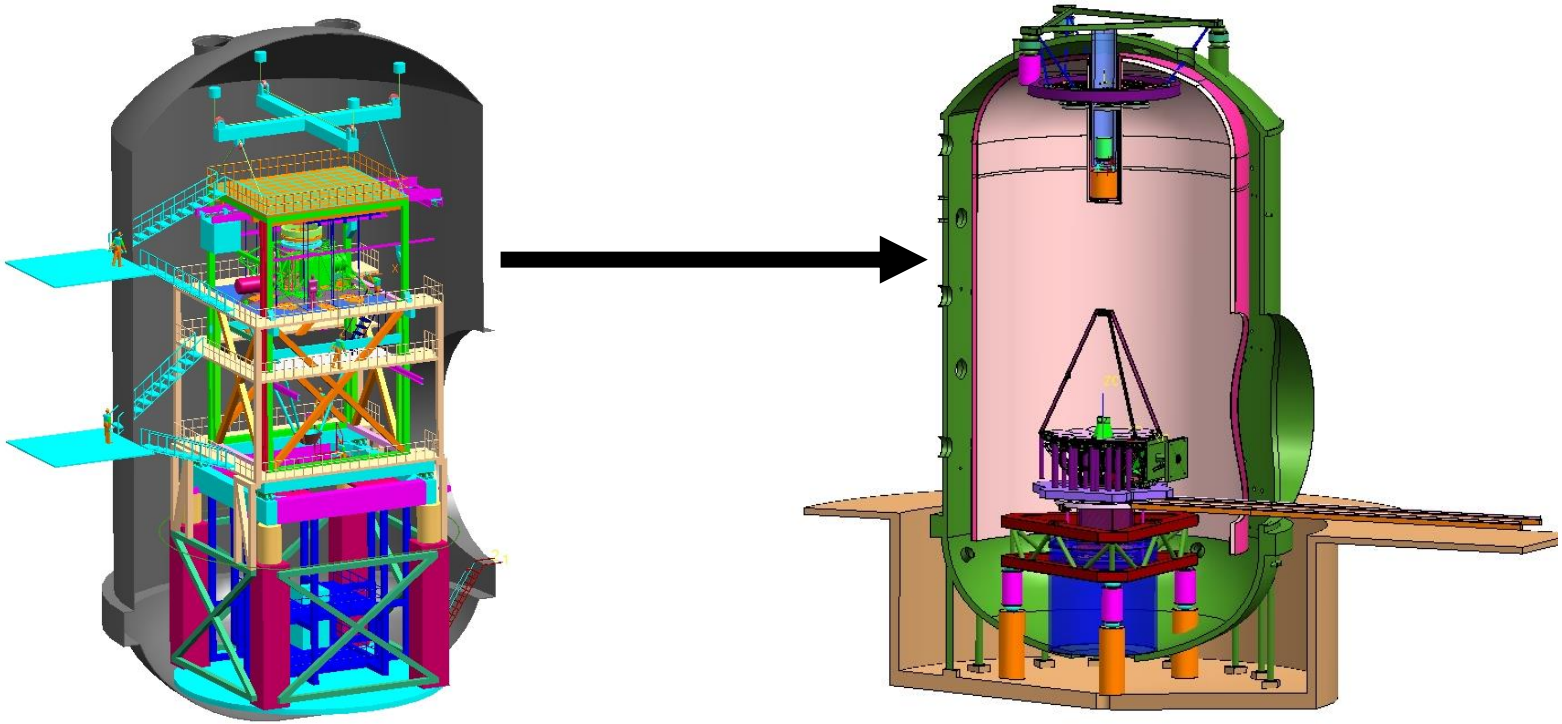




JSC Cup Up Configuration Removed Need for Expensive Metrology Tower

Old "Cup Down" Configuration Included Large Metrology Tower And Test Equipment Inside Shrouds

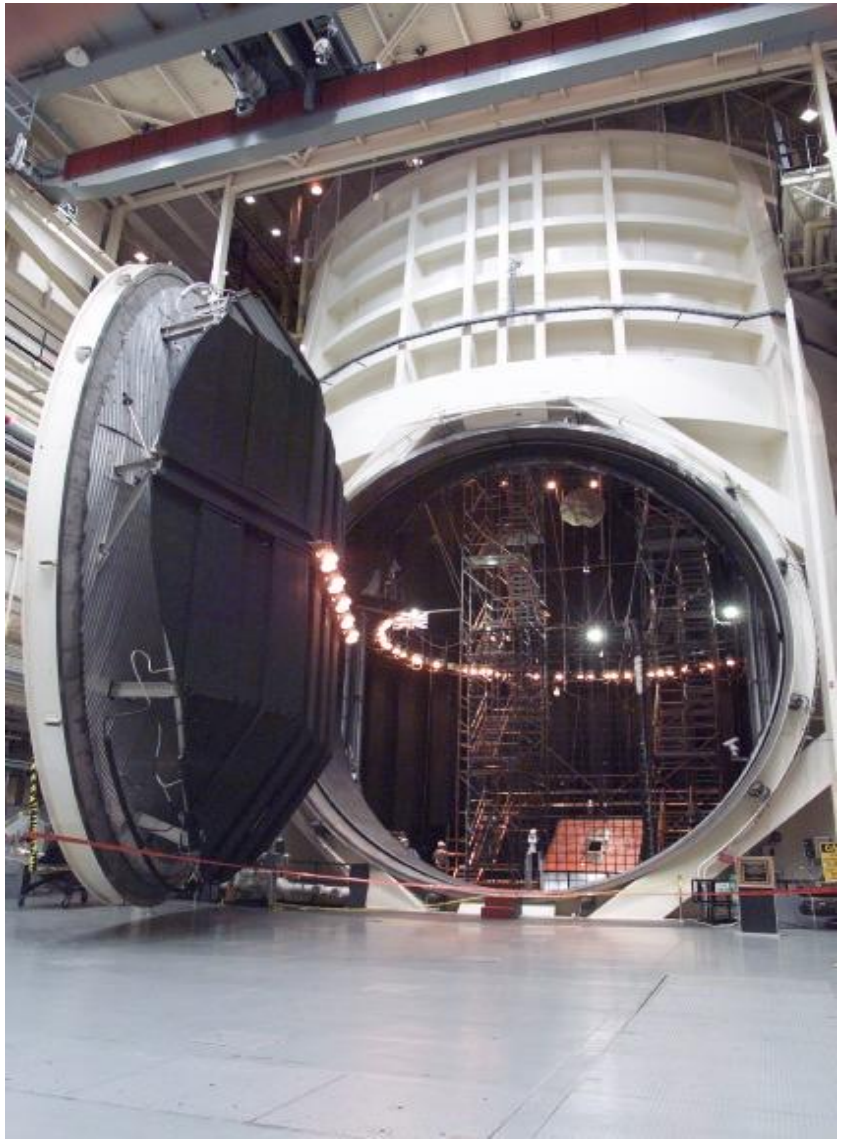
New "Cup Up" Configuration Eliminates Tower And Allows for Accessibility to Test Equipment From Top and Bottom of Chamber during testing



JSC Size, Accessibility, and Large Side Door Access Make it Well Suited for This Configuration

Cryogenic Testing Conducted in JSC Chamber A Thermal Vacuum Facility

Chamber A was used for Apollo landers and already includes Nitrogen and Helium systems. Plan is to upgrade it with a new Helium Inner Shroud.

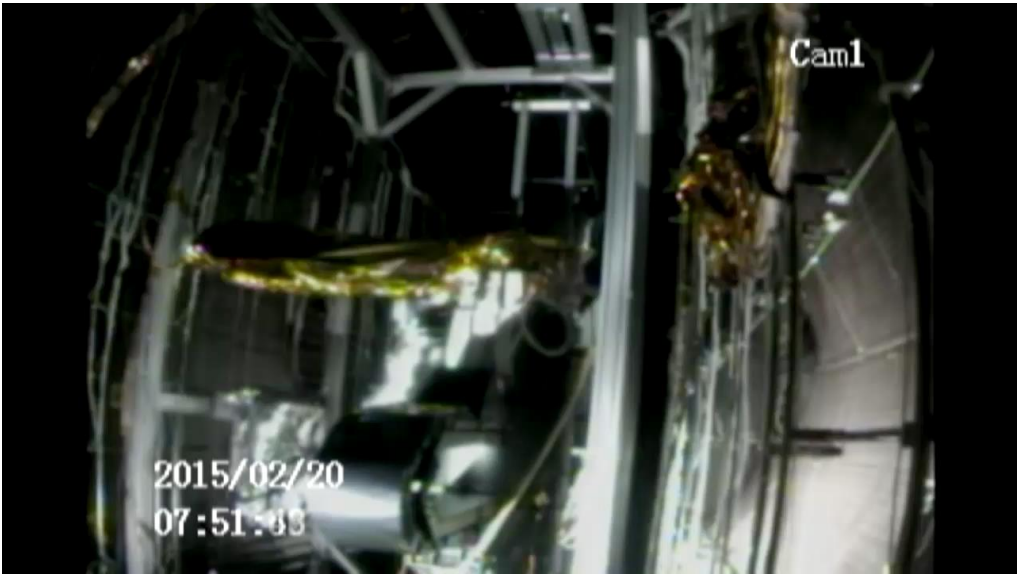


Telescope Pieces at Northrop Grumman

Backplane in Redondo Beach

DTA Deployment Test at Ambient

DTA deployment and Secondary Mirror Support Structure

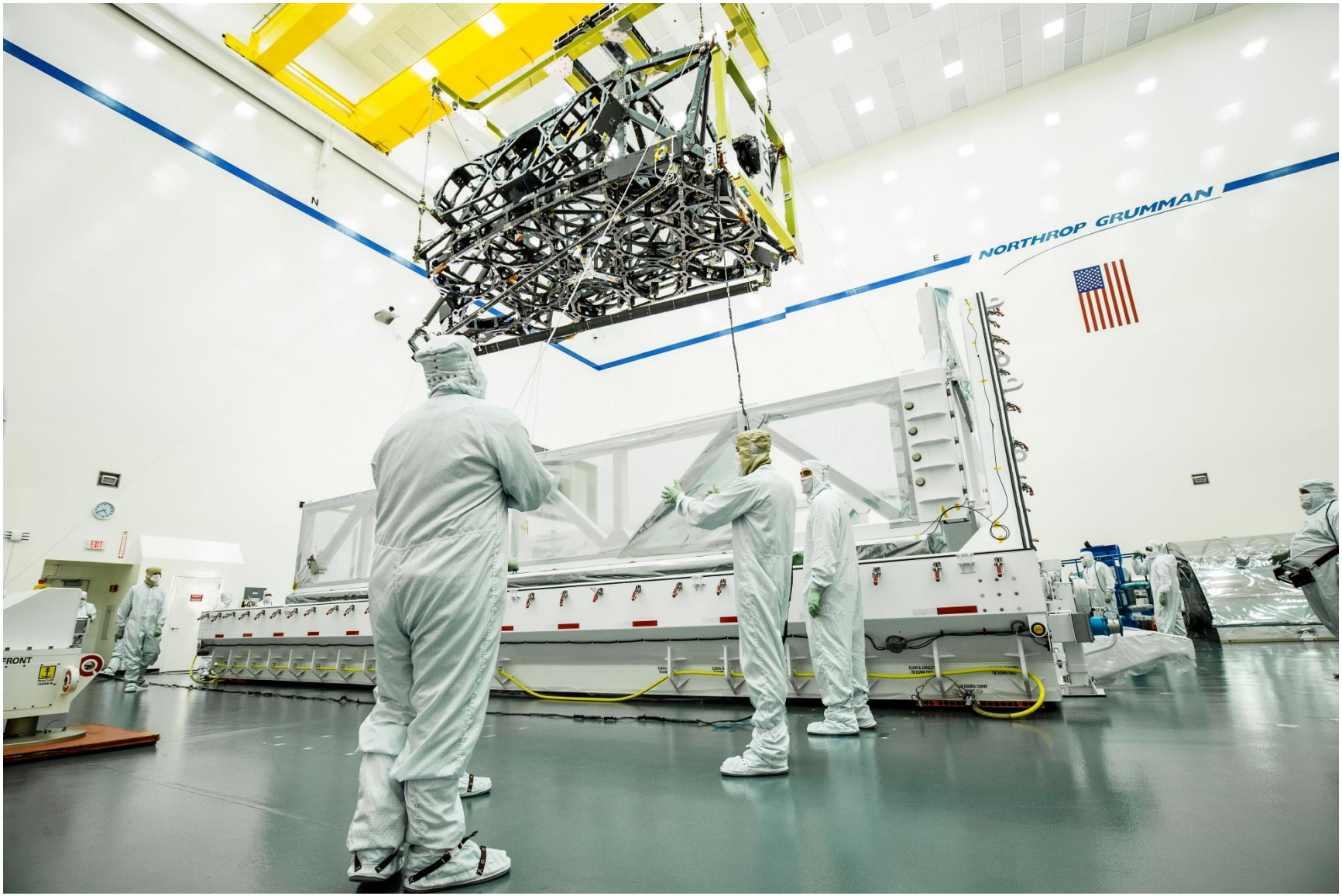


May 2015

Wing Hinge Installation in Redondo Beach

DTA Installation

OTE Structure into Shipping Container



August 2015

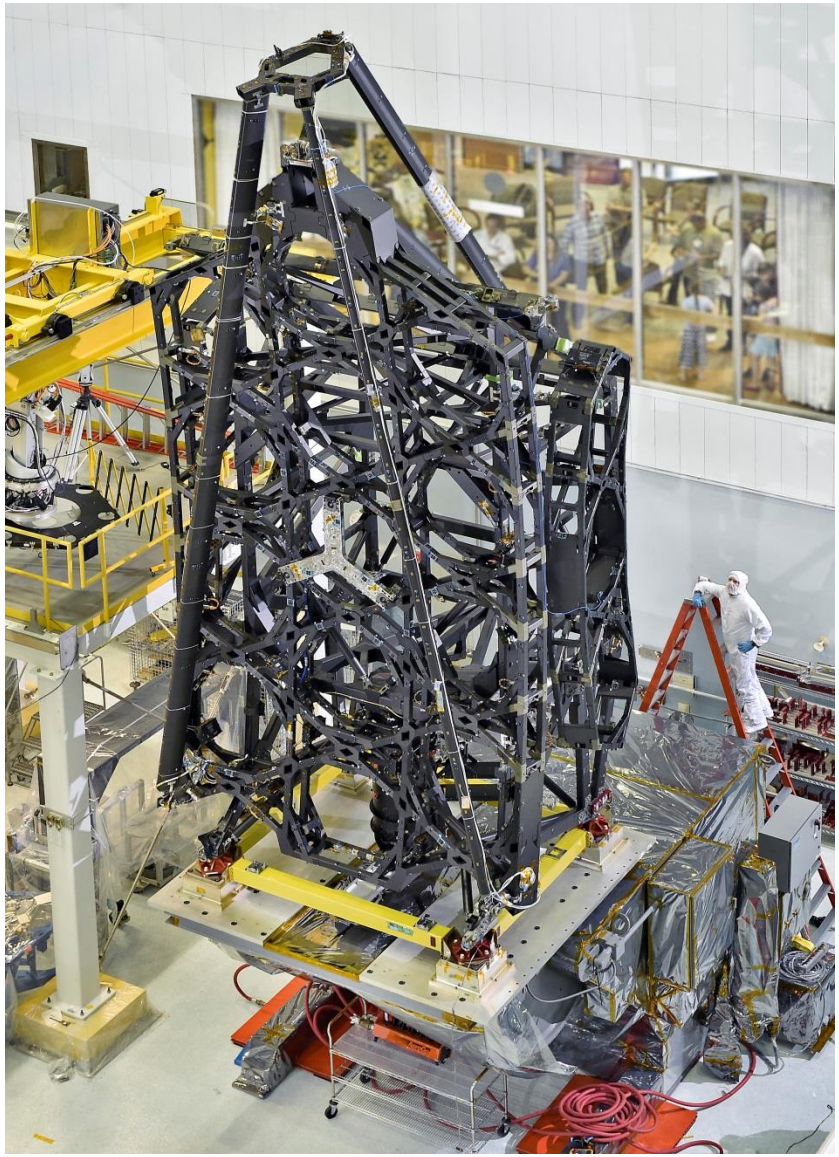
Welcome to GSFC (August 2015)

August 2015

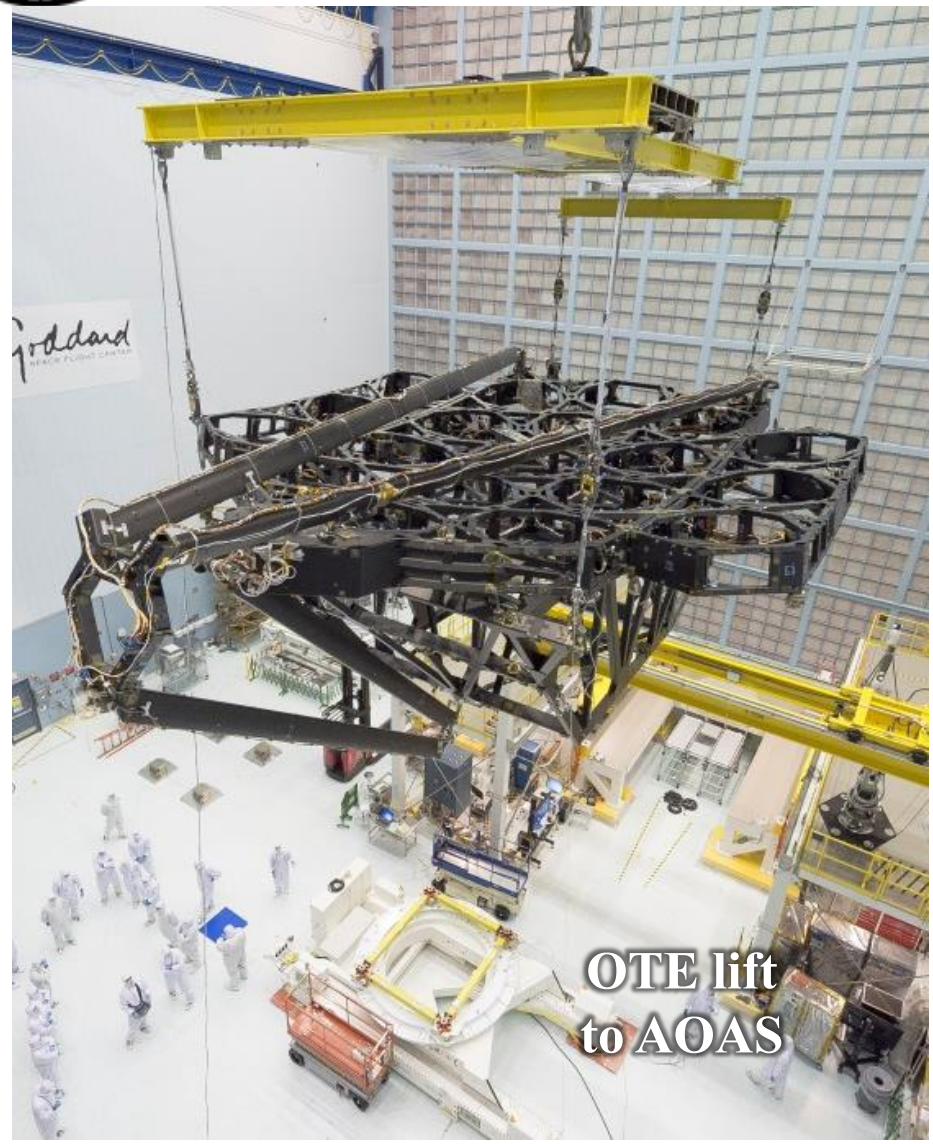

hubble.nasa.gov
OVERSIZE LOAD
NELSON
OTTAWA, OHIO
419-523-5321
KEEP CLEAR

August 2015

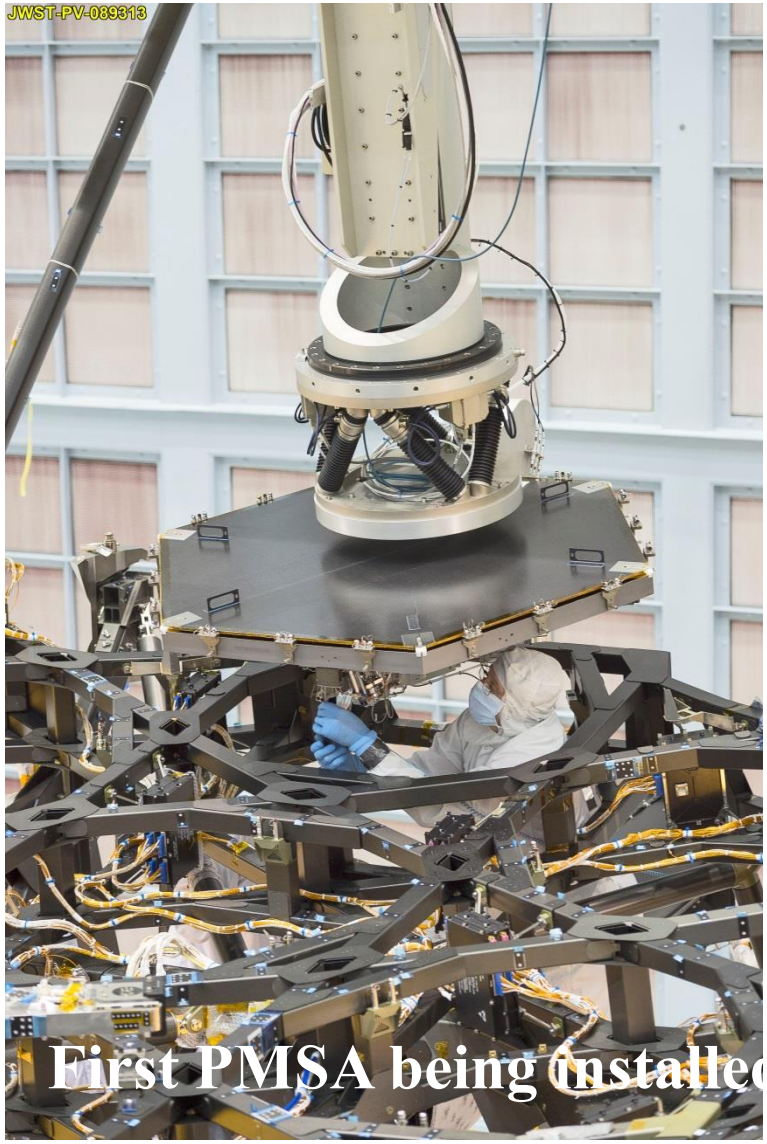
- In Cleanroom at GSFC



Mirror Installation (Nov '15 – Jan -16)

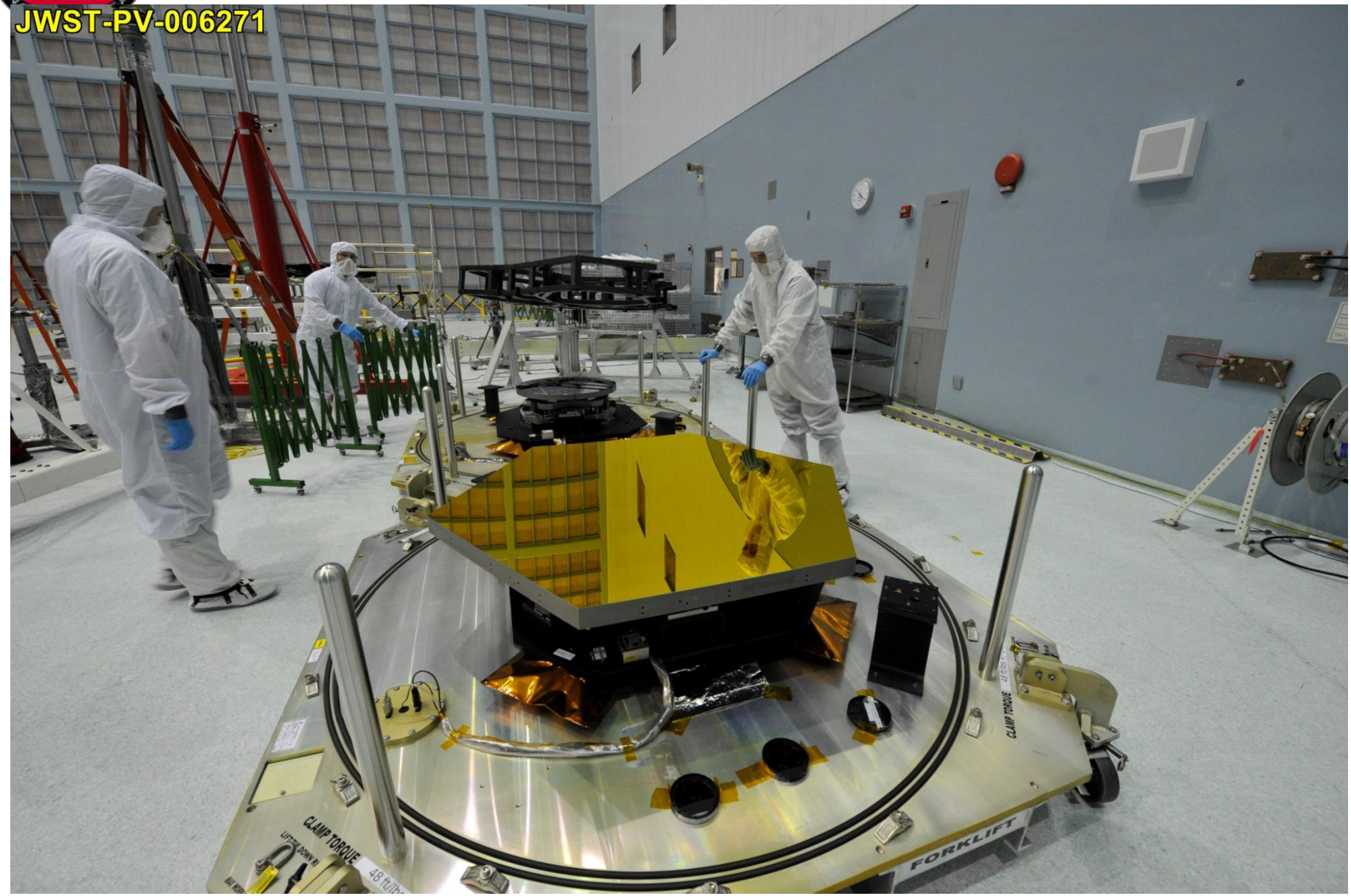


OTE lift
to AOAS



First PMSA being installed

Primary Mirror EDU and Secondary Mirror EDU in SSDIF: practice tests



PMSA Processing in the GSFC CIAF

Every mirror was sent to the CIAF for CMM measurements before and after shimming (Roughly March to July for flight)

Performed final inspections


1-TON

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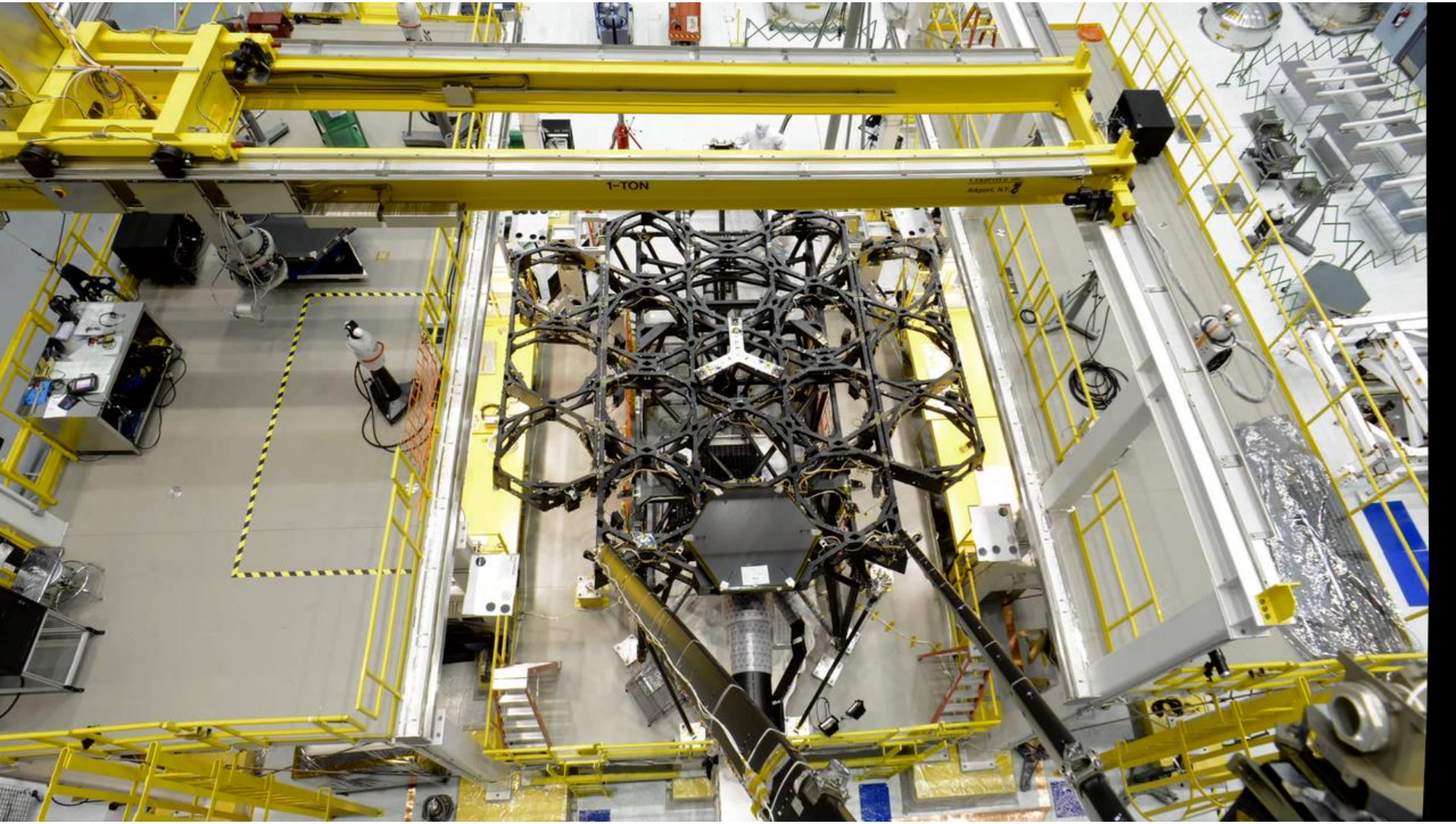
Mirror installation



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Thank you!

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OTE/ISIM Instrument Module Integration

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Goddard Space Flight Center

OTIS on its way to Vibe and Acoustics

OTIS Protoflight Vibe

OTIS I&T @ GSFC – Rotating for V1 axis testing

Rotate OTIS so the V1 axis can be tested [2017.01.24]

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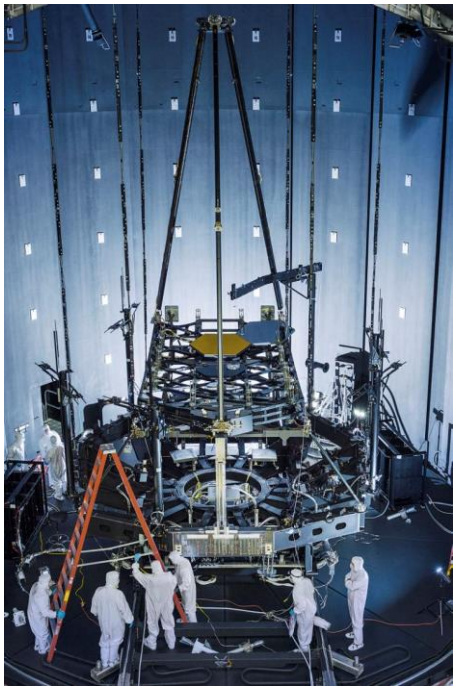
OTIS Acoustics

OTIS I&T @ GSFC – OTIS Oriented in Acoustics Chamber

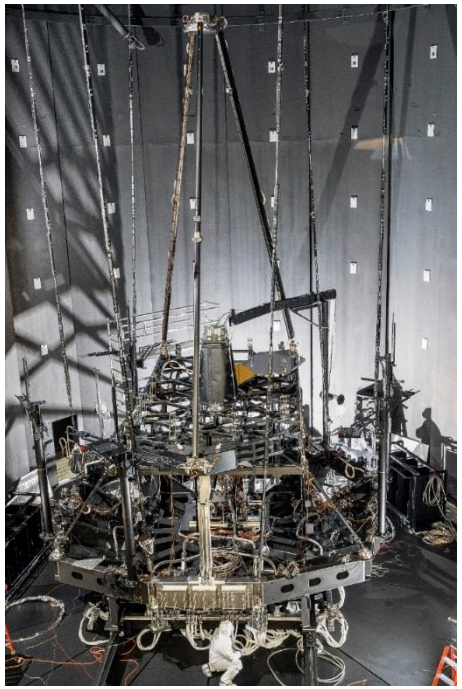
OTIS Risk Reduction at JSC

3 Pathfinder Tests/Rehearsals in JSC Chamber to test the test equipment and ready the test team

- Only thing not tested prior to OTIS testing was OTIS itself



Optical Ground Support Equipment (OGSE) #1: Prove-out optical GSE. Featured Cryo Optical Test on Pathfinder OTE w/ 2 Spare PMSA's and Spare Secondary

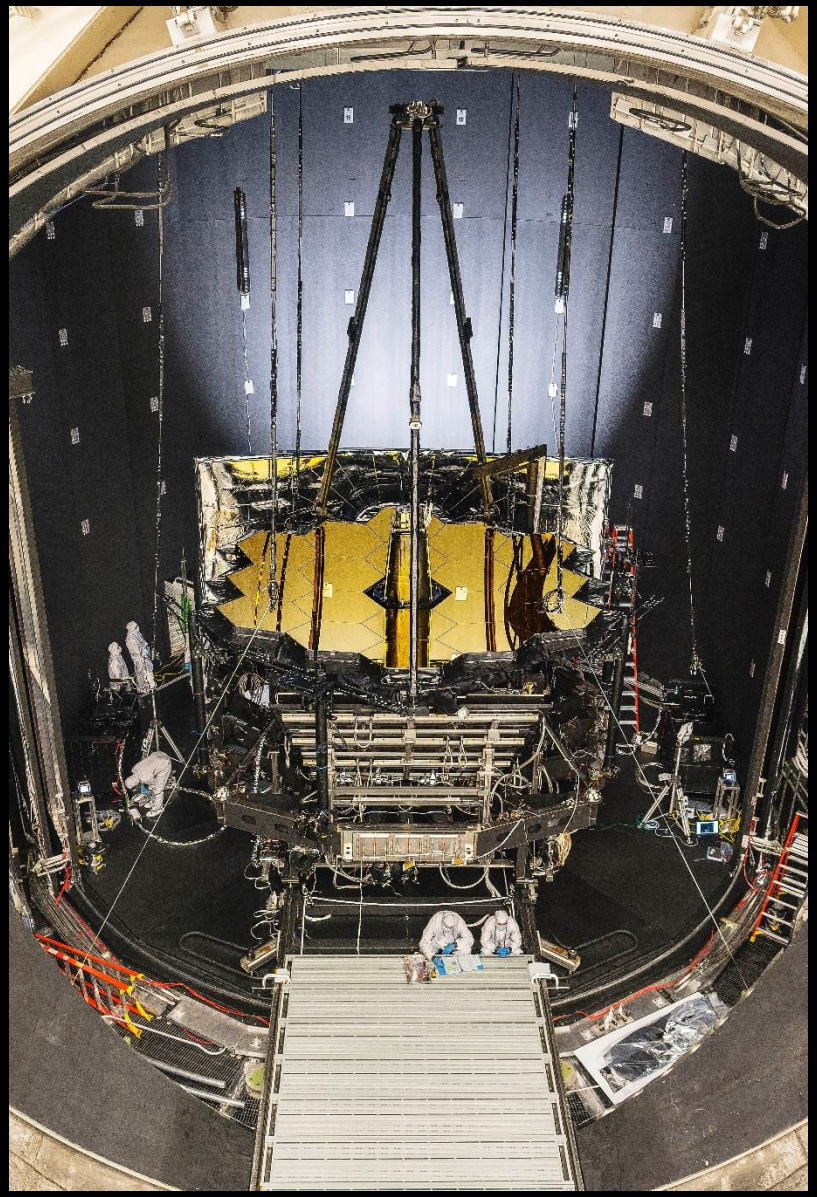


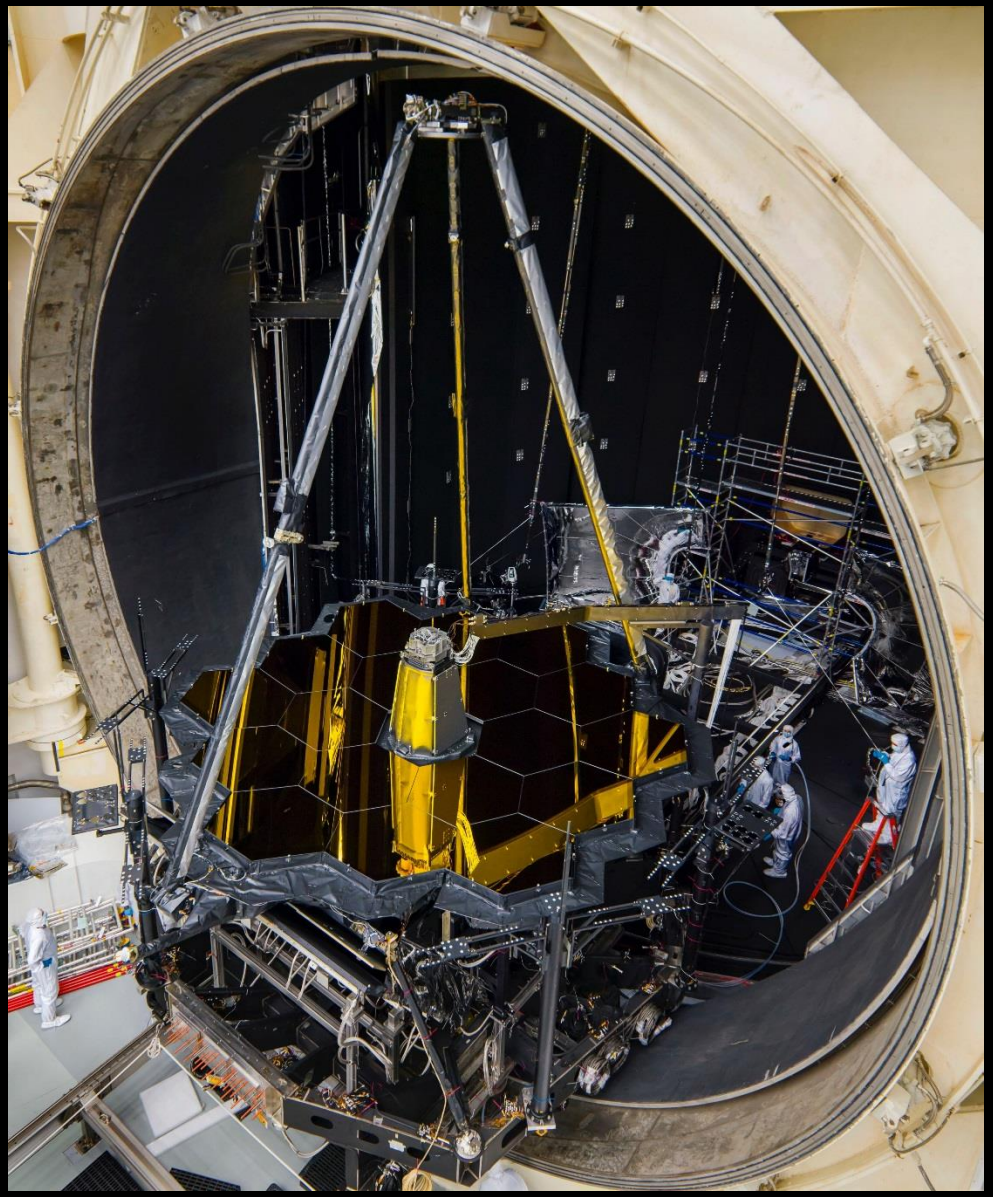
OGSE #2: 2nd Cryo Optical Test but w/ Flight Aft Optics System and AOS Source Plate Assembly. Full check-out of optical GSE and measurement schemes

Thermal Pathfinder: Verified all thermal environment/boundary conditions (e.g., sunshield layer 5 thermal simulator, ISIM radiator sinks)

- *Learned a lot about vibration isolation, facility readiness, and GSE performance*
- *Successful "Ready to Receive OTIS" review at JSC on 3/15/2017*

End-to-end optical testing in Summer 2017





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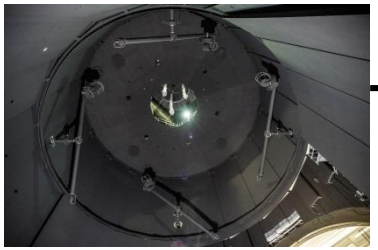
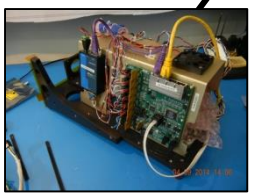
OTIS Test GSE Architecture

Chamber Isolator Units
Dynamically isolates OTIS Optical Test – 6 Passive Isolators

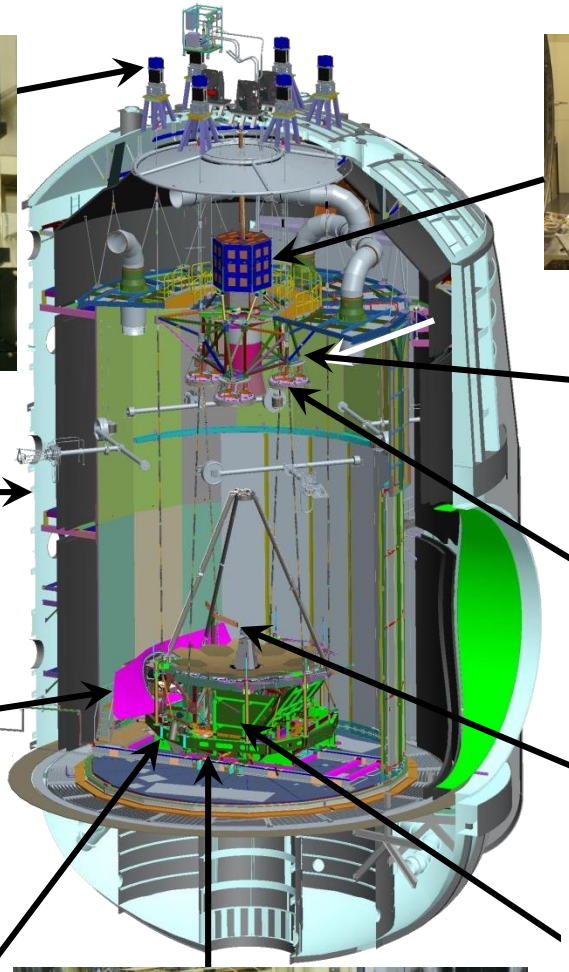
Cryo Position Metrology (CPM)
Photogrammetry System
4 Windmills with PG Cameras



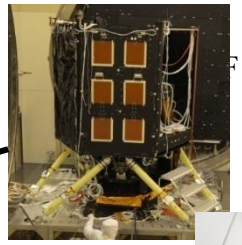
Space Vehicle Thermal Simulator (SVTS)
and Sunshield Simulator



Absolute Distance Measuring Interferometer



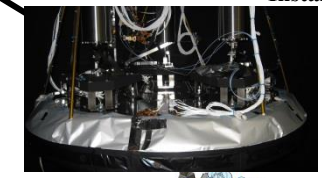
HOSS – Hardpoint Offloader Support Structure
In integration in Clean Room



Center of Curvature Optical Assembly (COCOA)

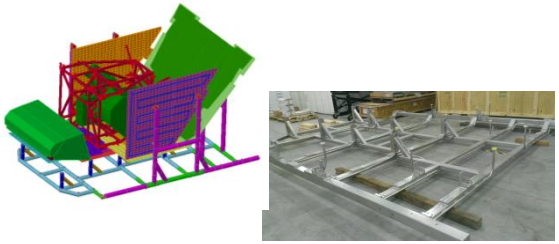
- **Multiwavelength interferometer (MWIF), null, calibration CGH, coarse/fine PM phasing tools, Displacement Measuring Interferometer**

USF Structural Frame – supports Metrology Installed in Chamber



3 Auto collimating Flat Mirrors (ACFs)
1.5 M Plano for Pass and Half Testing
ACF 1 installed in Chamber A, ACF 4 and ACF 5 are complete,

AOS Source Plate Assembly (ASPA)
Over 50 cryo fiber infrared sources



Deep Space Edge Radiation Sink (DSERS)

Cryo Mag Dampers

OTIS Cryo Vac Test Statistics

- **The JSC Cryogenic Test was a huge success**
  - All test objectives met (>100 sub-procedures used)
  - All 30+ tests on the optical test matrix completed
  - Overall optical and thermal performance is excellent
    - » *Measurements match Predictions (see subsequent slides)*
- **OTIS CV Test Duration: 100.2 days (Original plan was 93.5 days)**
- **Start: July 13, 2017, 0108 CDT**
- **End: October 21, 2017, 0540 CDT**
  - Hurricane Harvey:
    - » Rain: 51 inches
    - » Lasted about 6 days

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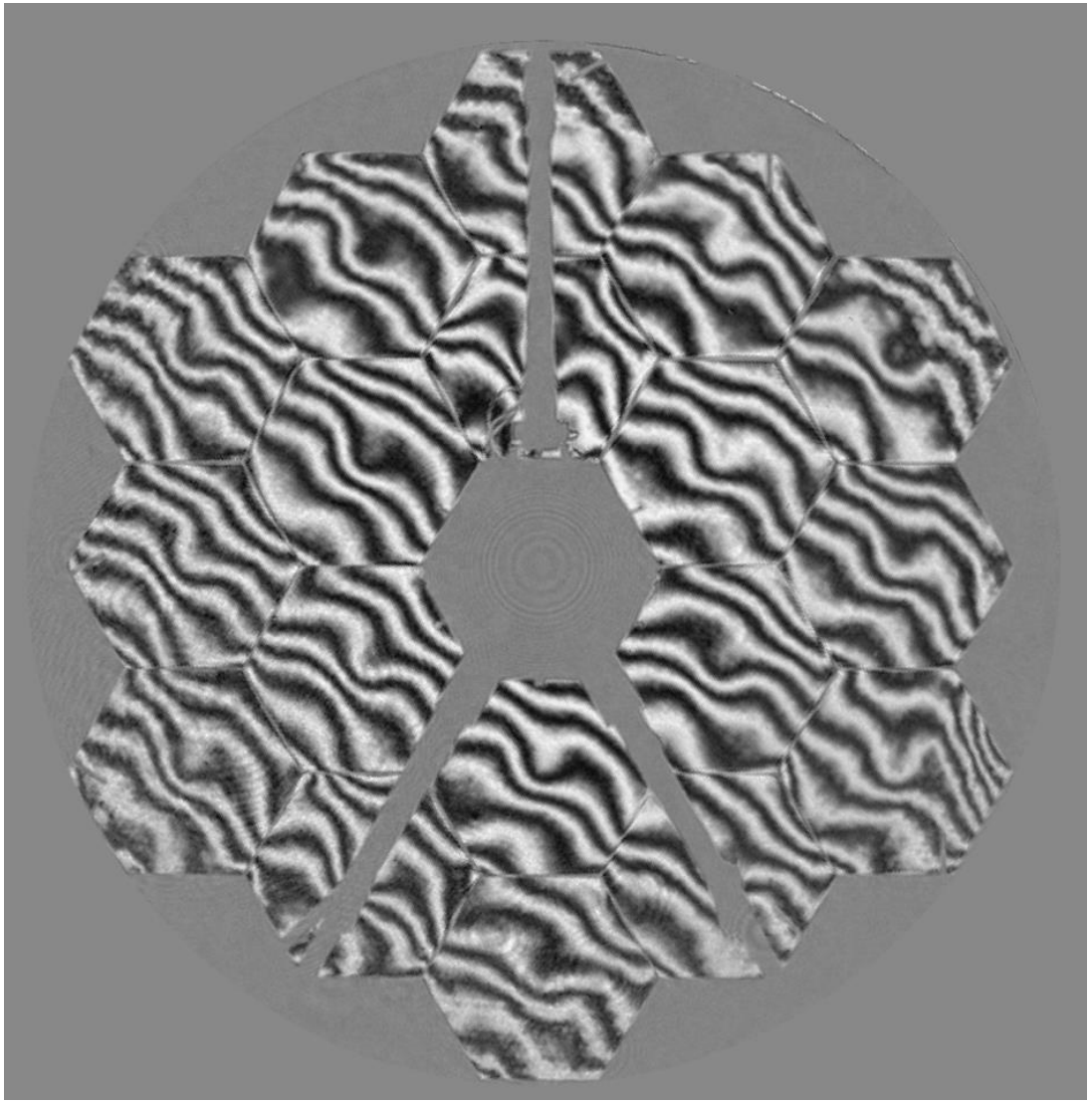
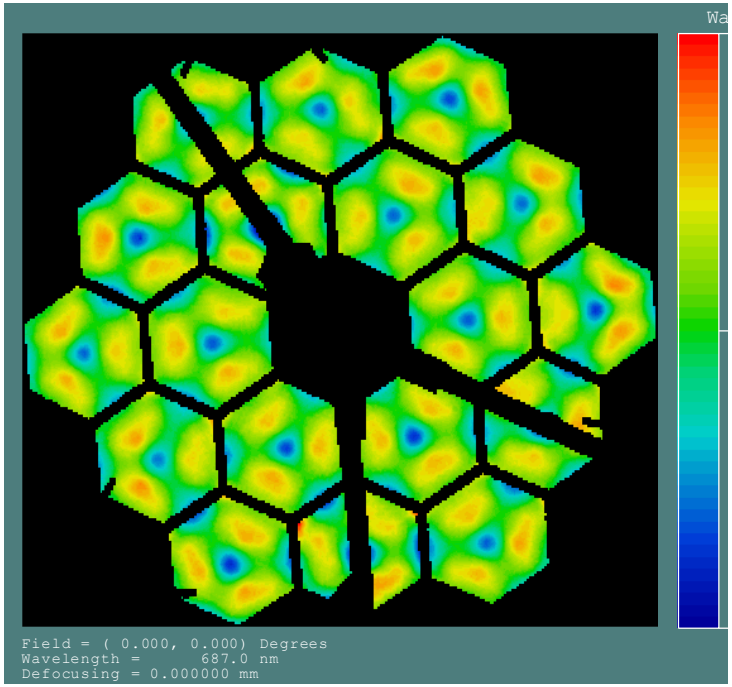
Primary Mirror Interferogram



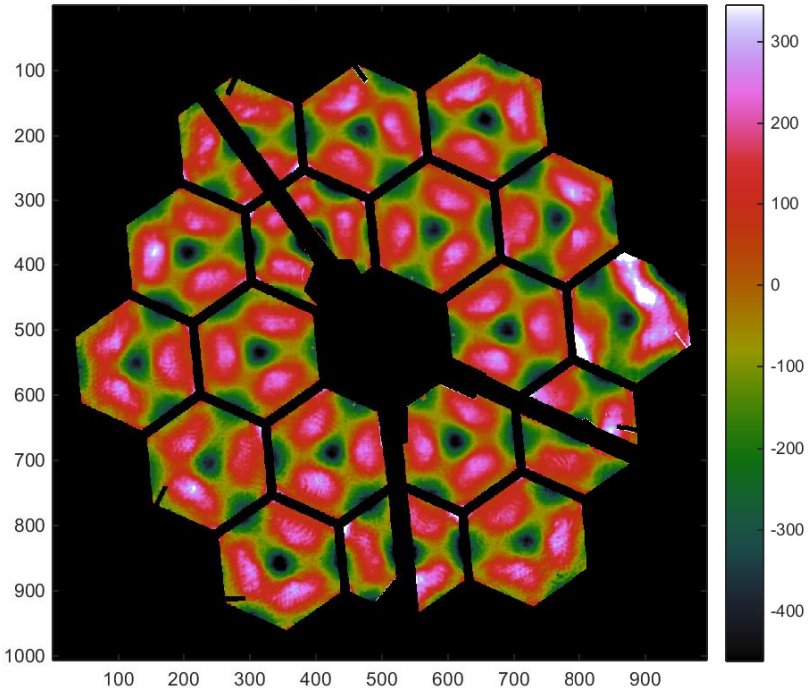
PM phasing demonstrated

Measured vs Predicted 1g PM WFE

Model Prediction (Rev H)
158 nm-rms



Measurement (Run 517)
156 nm-rms

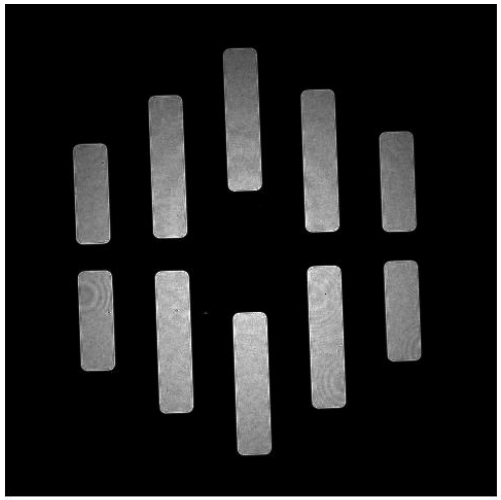


Both WFE maps have same masking and PMSA misalignment removed.
Excellent visual & magnitude correlation, with exception of known B3 issue .

NIRCam B Pupil Images – TIS 317 and 326

Direct imaging of NIRCam B pupil

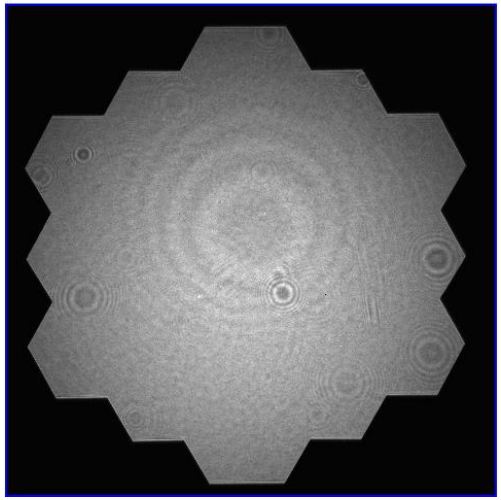
GDHS0
1.4 µm



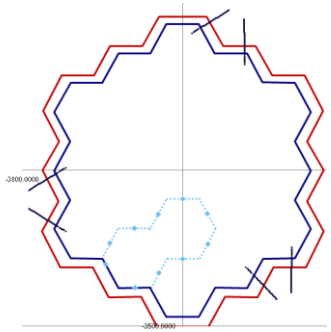
GDHS60
1.4 µm

Direct imaging of FSM

CLEAR
1.4 µm



FLABs used to infer PM location



V2
at FSM
V3

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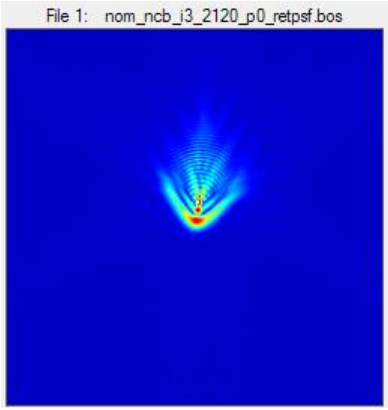
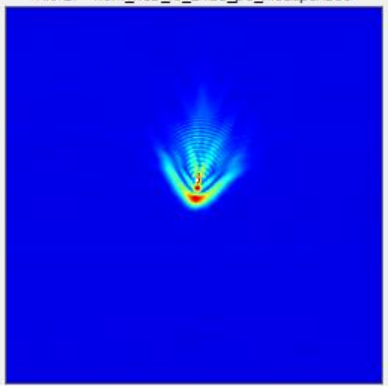
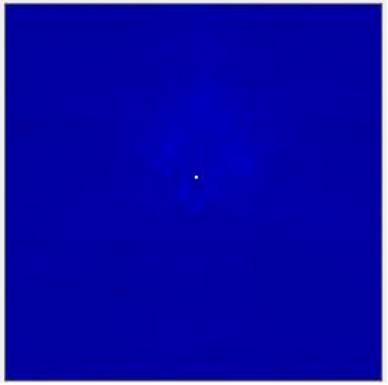
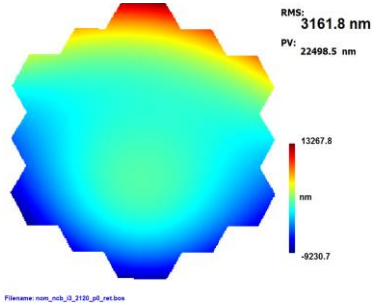
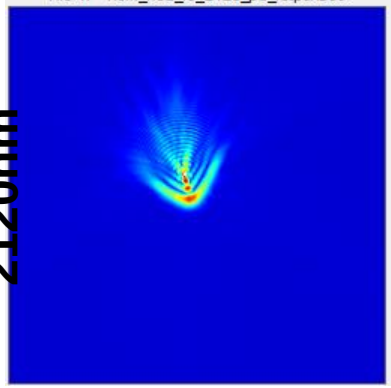
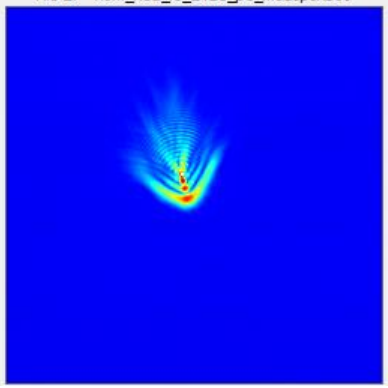
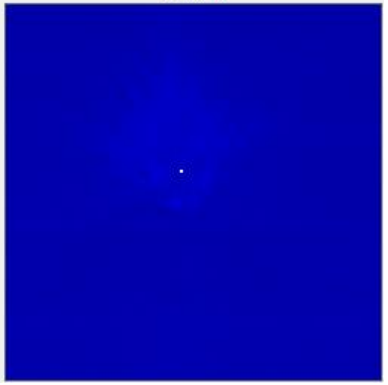
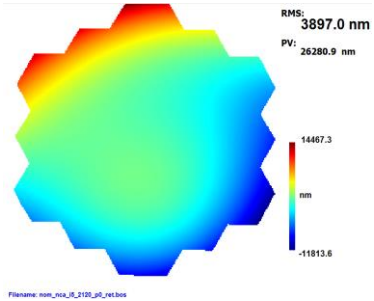
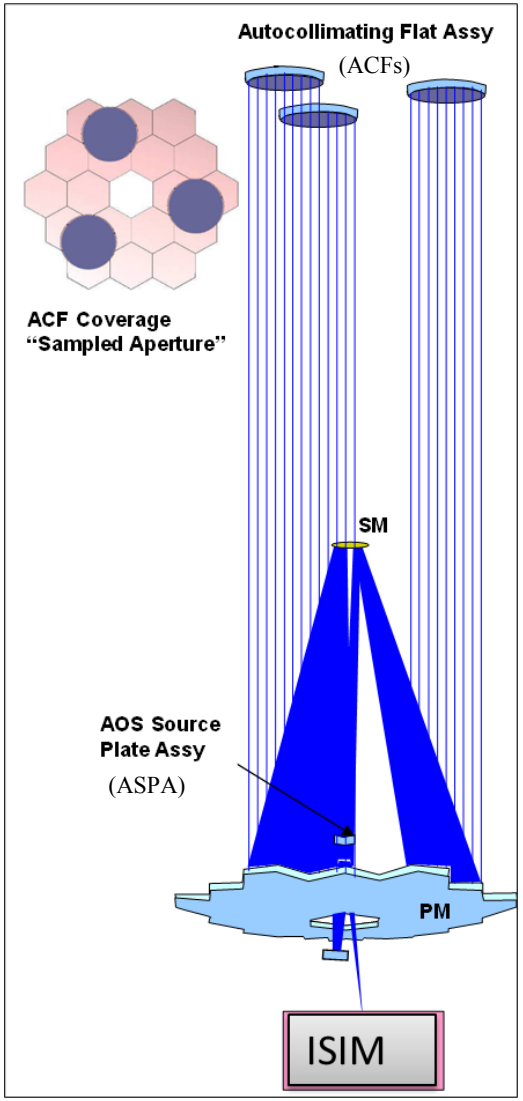
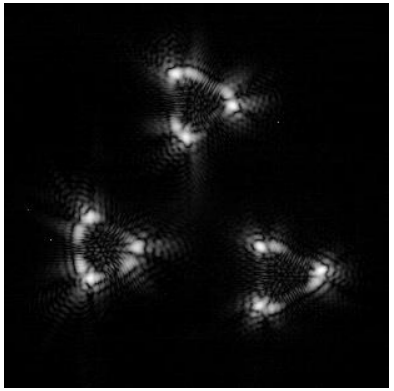
Half-Pass PSF Image Phase Retrieval Results
NIRCamA & NIRCamB

	Modeled/Retrieved PSF	Measured PSF	Difference	Modeled/ Retrieved Wavefront
NIRCamB I-3, 2120nm				
NIRCamA I-5, 2120nm				

End-To-End test crosschecked the system



Pass-and-a-Half Layout

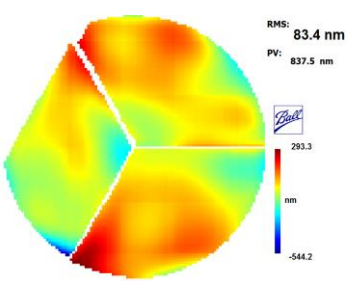


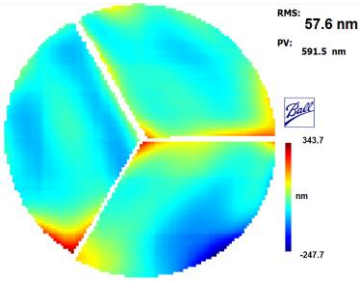
NCA, SM=-0.486

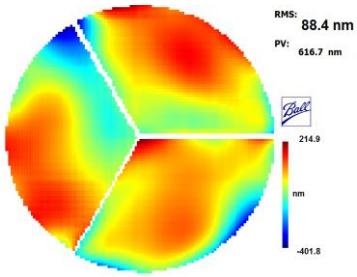
NCA, SM=+0.486

Hartmann spots used to measure focus/alignment
Successfully crosschecked Primary Mirror to Aft Optics System (AOS) alignment and crosschecked Secondary Mirror Alignment

End to End wavefront crosschecks meet 92nm RMS Requirement (including uncertainty)







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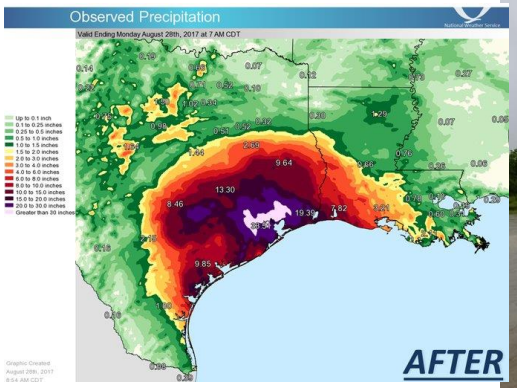
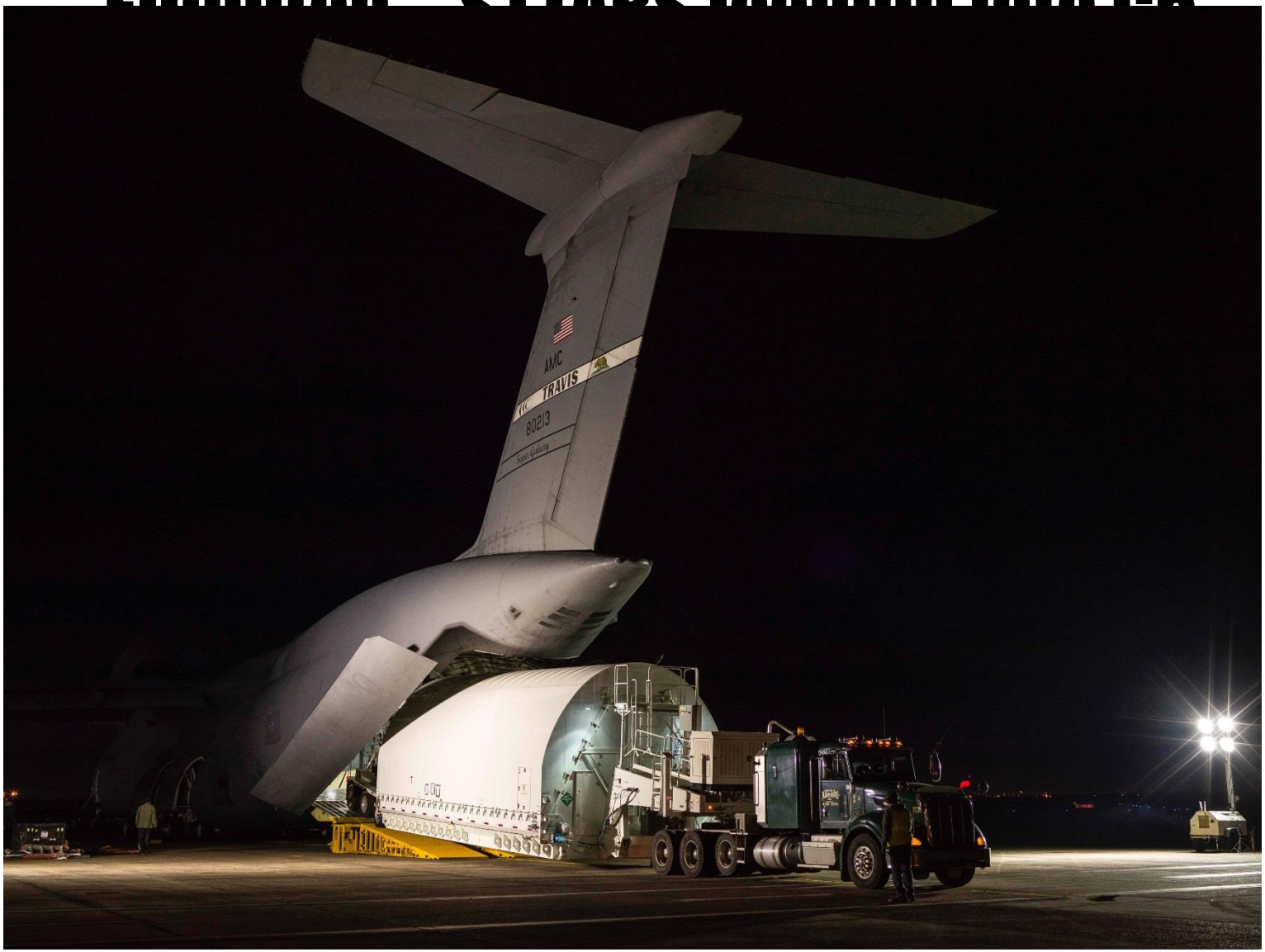


STARS leaving JWST Cleanroom at JSC

Ellington – STTARS loading into C5



STTARS Arrival at NGAS

Picture of telescope and Spacecraft at NGAS

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Goddard Space Flight Center

OTE management team stable for 14 years!

National Aeronautics and Space Administration
Goddard Space Flight Center

Looking Back: THANK YOU to the Incredibly Skilled and Dedicated Teams

Brush Wellman/Materuion

Ball

NGAS OTE I+T

Tinsley

XRCF

OTE

Metrology

QCI

Axsys Technologies

Product Integrity Team