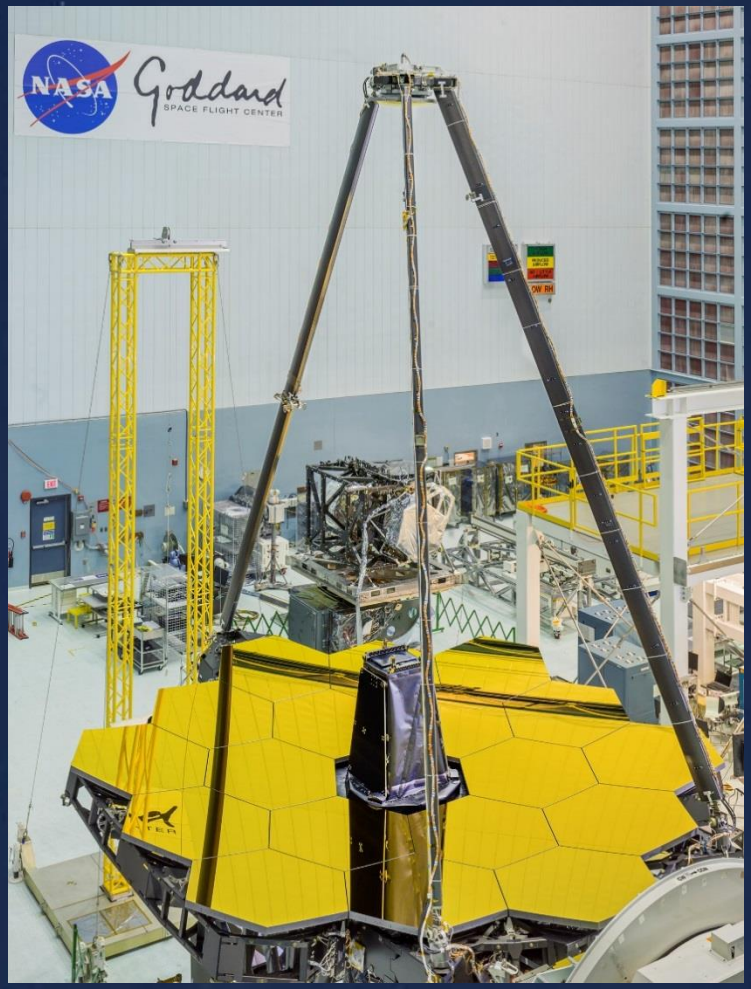


Optical Engineering History of the James Webb Space Telescope (JWST)

OSA Student Leadership Conference
September 15, 2019

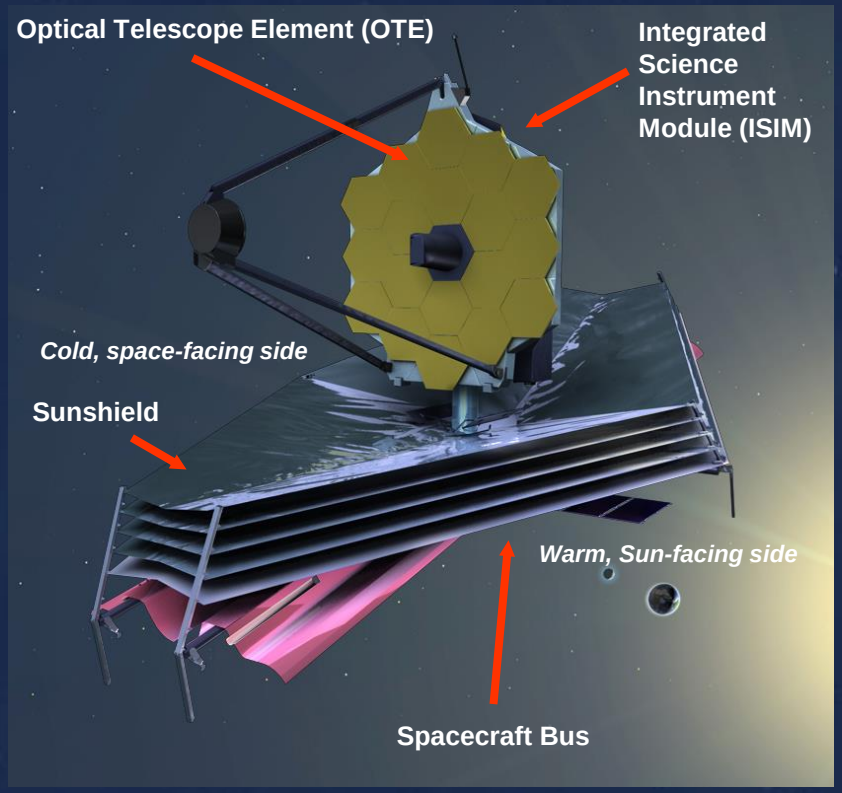
Lee Feinberg
JWST Optical Telescope Element Manager
NASA Goddard Space Flight Center

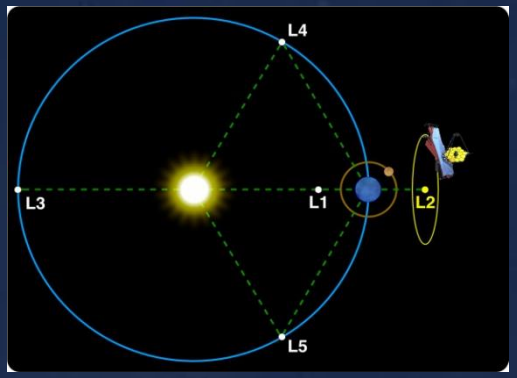
James Webb Space Telescope (JWST)

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 Aerospace Systems
    - 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)

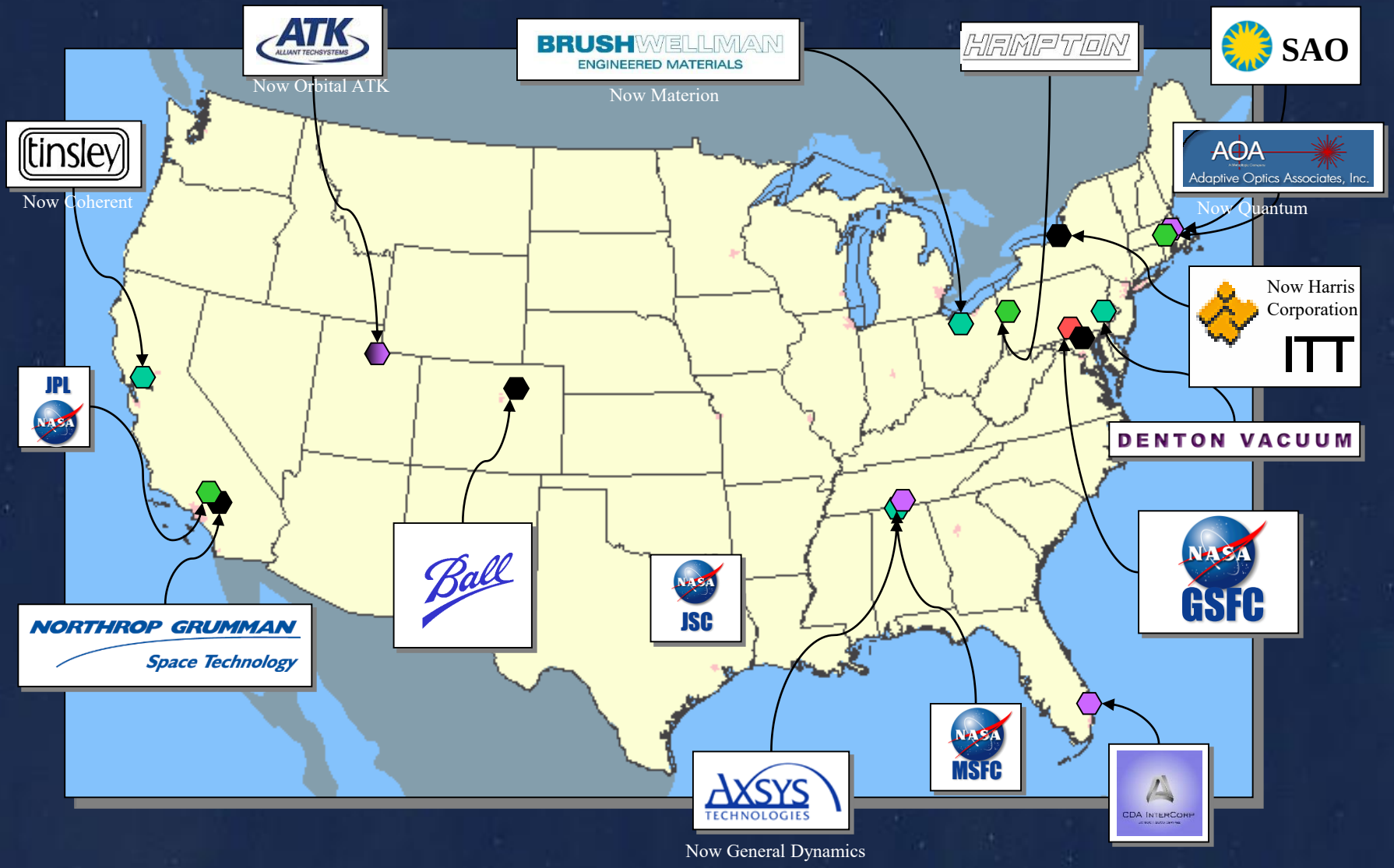




Description

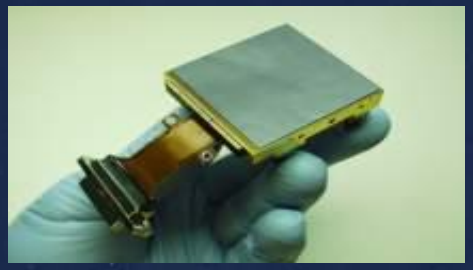
- Deployable telescope w/ 6.5m diameter segmented adjustable primary mirror
- Cryogenic temperature telescope and instruments for infrared performance
  - 50K, -370F
- 5-year science mission (10-year goal)

Optical Telescope Element Teams

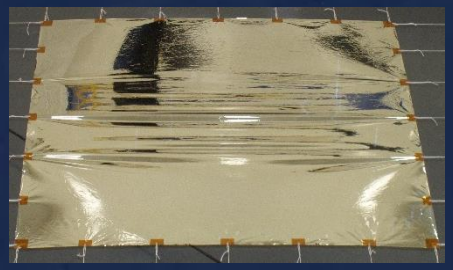


Technologies Demonstrated in 2006

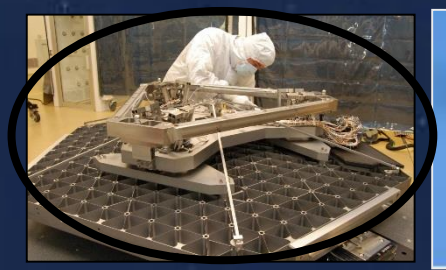
(All our mission critical technologies, OTE are circled)



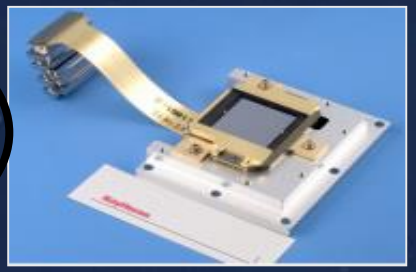
Near Infrared Detectors
April 2006



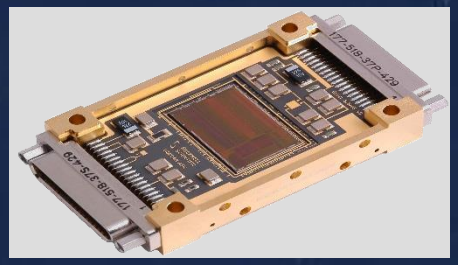
Sunshield Material
April 2006



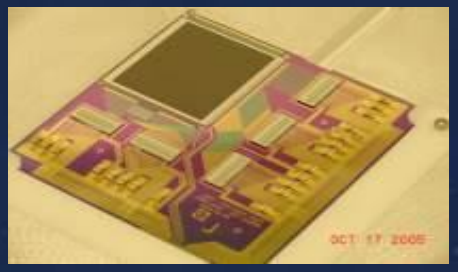
Primary Mirror Segment Assembly
June 2006



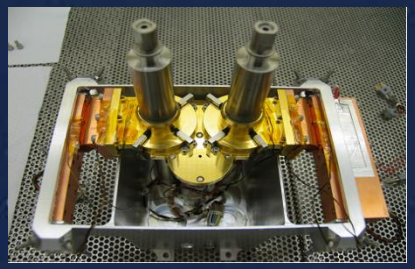
Mid Infrared Detectors
July 2006



Cryo ASICs
August 2006



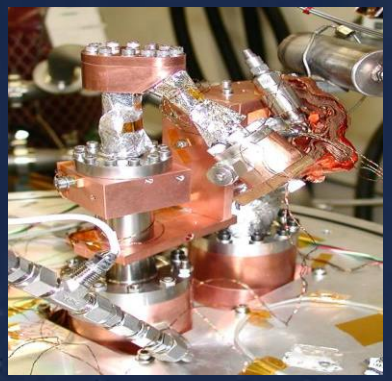
Microshutter Arrays
August 2006



Heat Switches
September 2006

Large Precision Cryogenic Structure
November 2006

Wavefront Sensing & Control
November 2006



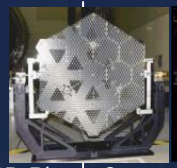
Cryocooler
December 2006

Mirror History

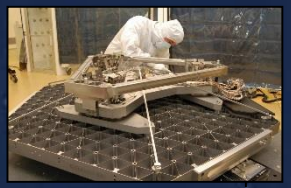
1996 1998 2000 2002 2004 2006 2008 2010 2012 2014

Advanced Mirror System Demonstrator (AMSD)
Collaboration among 3 government agencies
15Kg/m2, 1.2M diameter segments

Medium **Authority** Glass (ULE)



Low Authority **Beryllium**



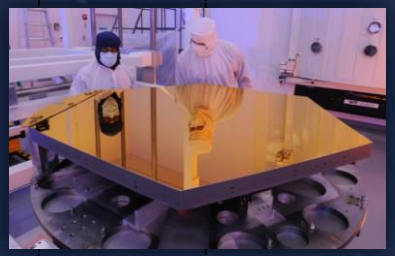
Technology Readiness Level-6 Demonstrated:
All key requirements and environments demonstrated

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 (COR): Beryllium Selected

Engineering Design Unit.

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

PM Manufacturing of 18 segments

Primary Mirror Segment Assemblies Complete

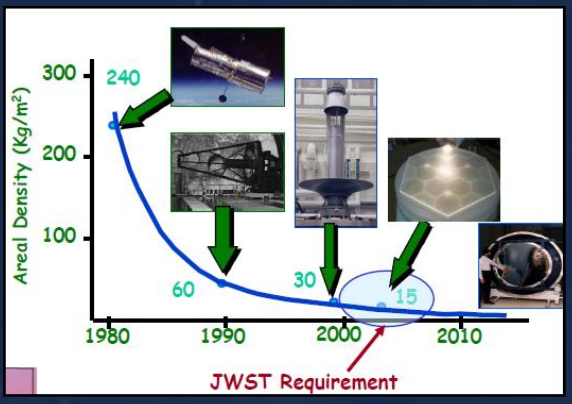
Machining Facility Complete

Cryo Testing

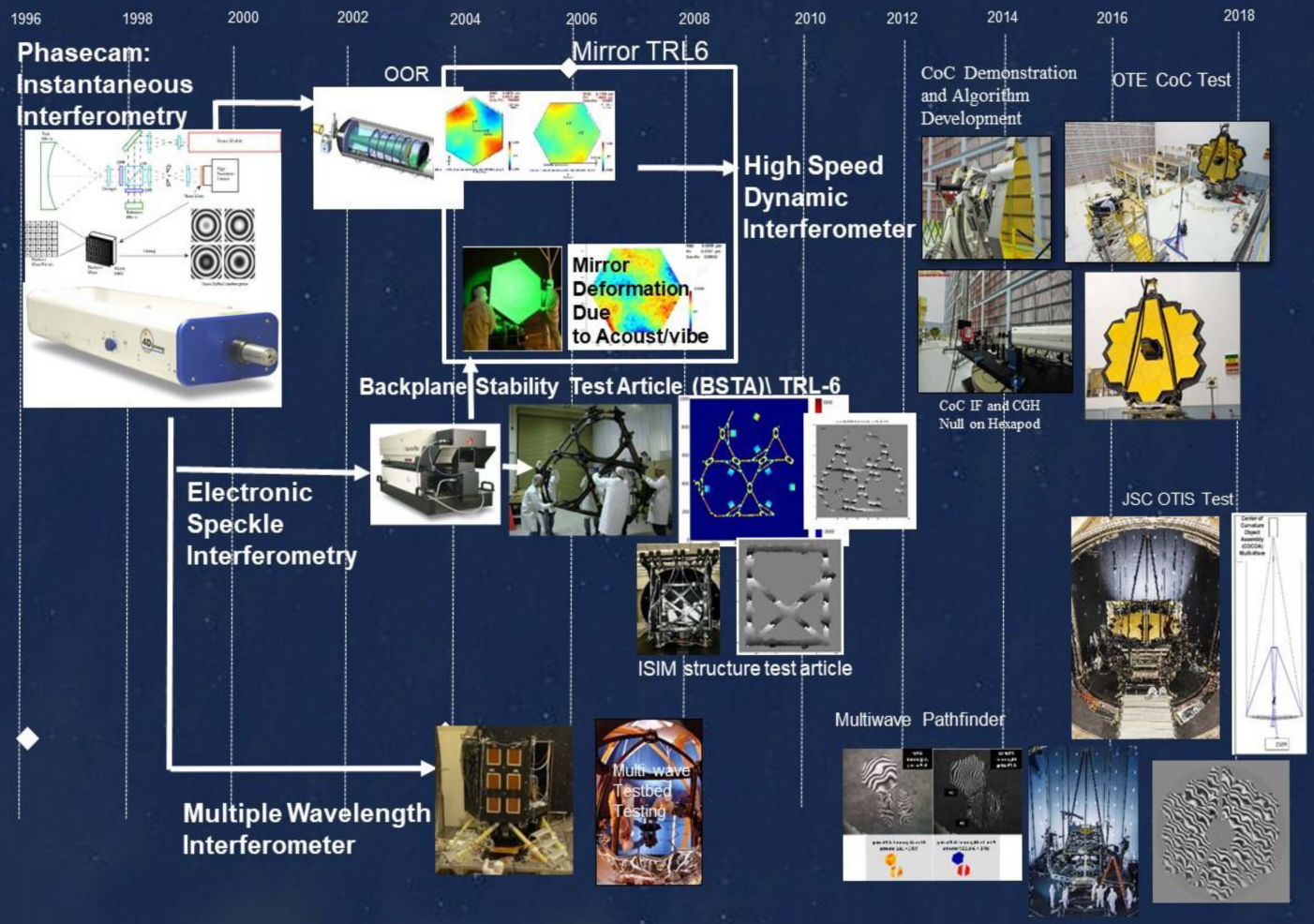
Low Areal Density Mirrors Identified as Key Enabling Technology for 25 Square Meter Space Telescope

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

Polishing Facility Complete



Webb Interferometry History



Primary Mirror Architecture Trade History

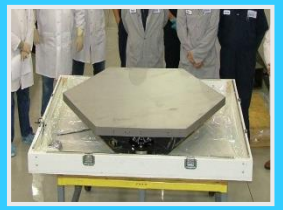
- **Original prime contractor design was for a 7 meter, 36 segment telescope with 4-degrees of freedom per mirror**
- **Trades were done to:**
  - Save money by reducing size slightly, enabling 18 segment option
  - Adding 6-degree of freedom of hexapods on mirrors gives us adjustability in decenter and rotation – this wound up being critical!
  - Segmentation trade of 18 vs 36
    - 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 18 mirrors that had hexapods was important or our I+T program

All Primary Mirror Blanks Completed

Axsys Machining Facility

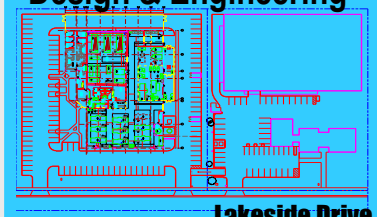
Dedicated facility and machining centers for JWST mirror production

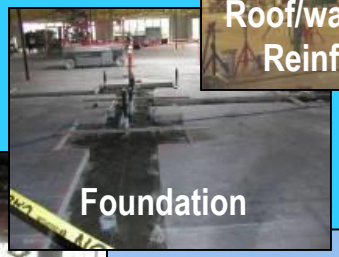
Beryllium Flight Mirror Machining Complete at Axsys Technologies

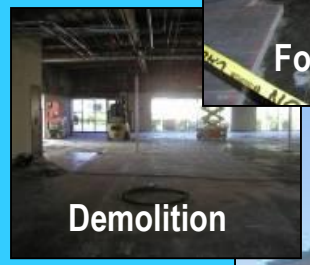
Pathfinder  ***Done at Axsys!!*** PMSA #1 (EDU-A / A1)	Pathfinder  ***Done at Axsys!!*** PMSA #2 (11 / B3)	Pathfinder  ***Done at Axsys!!*** PMSA #3 (12 / C3)	 ***Done at Axsys!!*** PMSA #4 (5 / A2)	 ***Done at Axsys!!*** PMSA #5 (6 / B2)	 ***Done at Axsys!!*** PMSA #6 (7 / C2)
 ***Done at Axsys!!*** 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

Design & Engineering







JWST Dedicated Mirror Coating Chamber at QCI/Denton

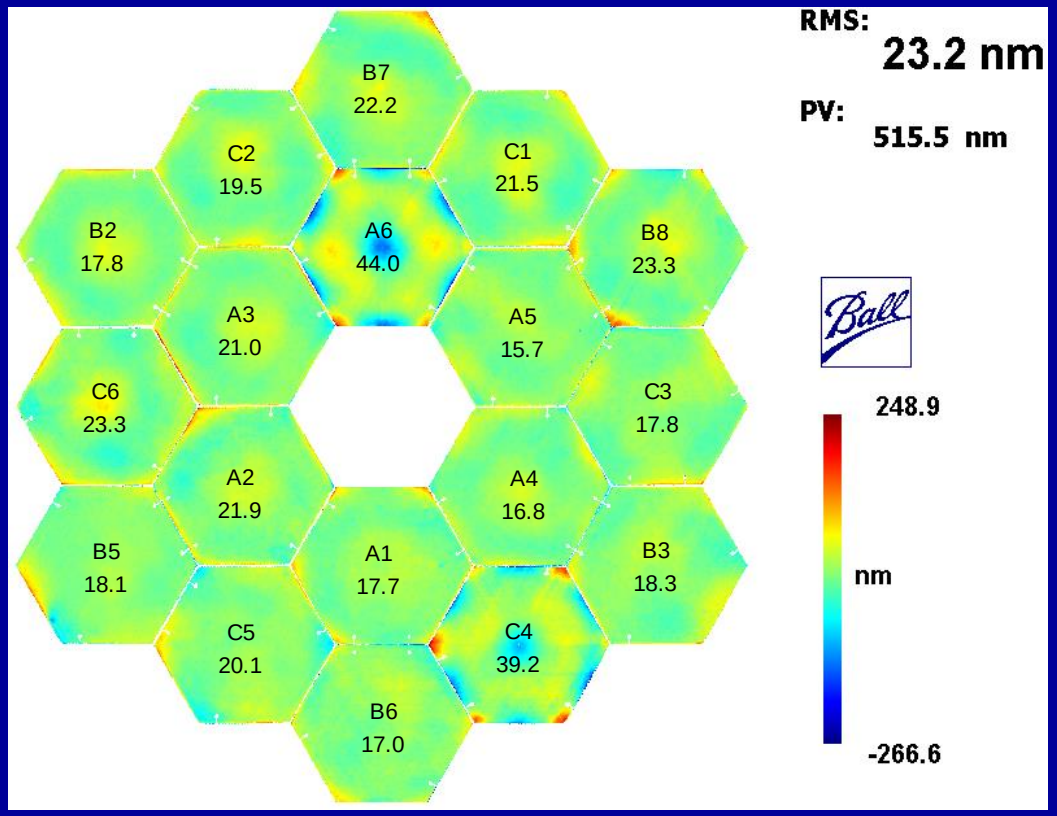
National Aeronautics and Space Administration
Goddard Space Flight Center

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



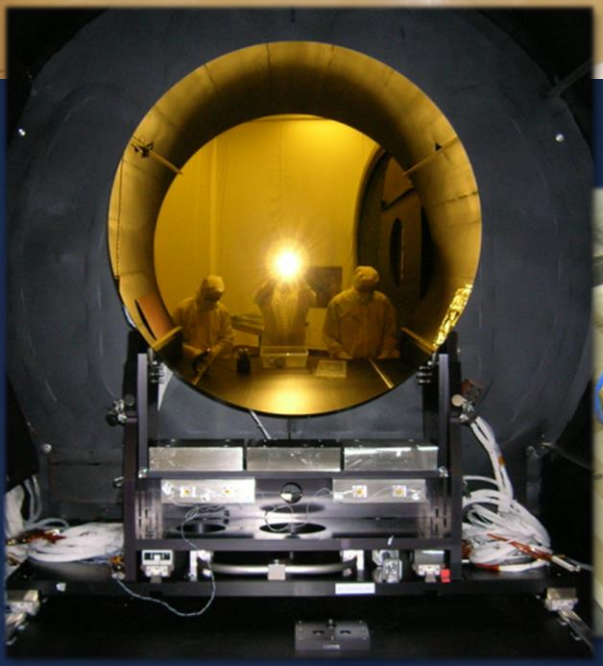
Composite Primary Mirror meets requirements

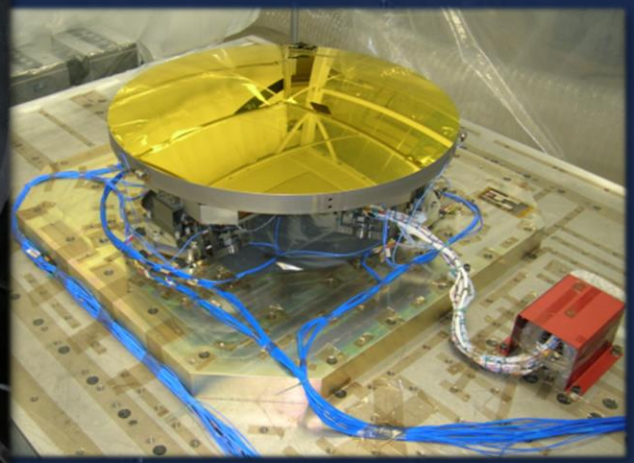
Flight Secondary Mirror

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

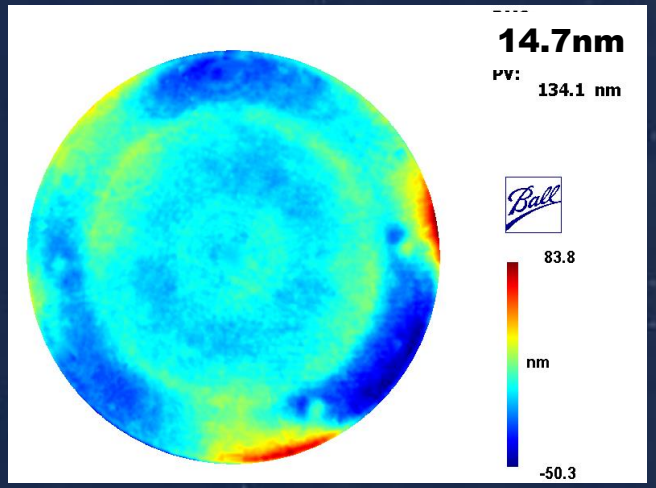
On convex mirror 0.7 meters in diameter.

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

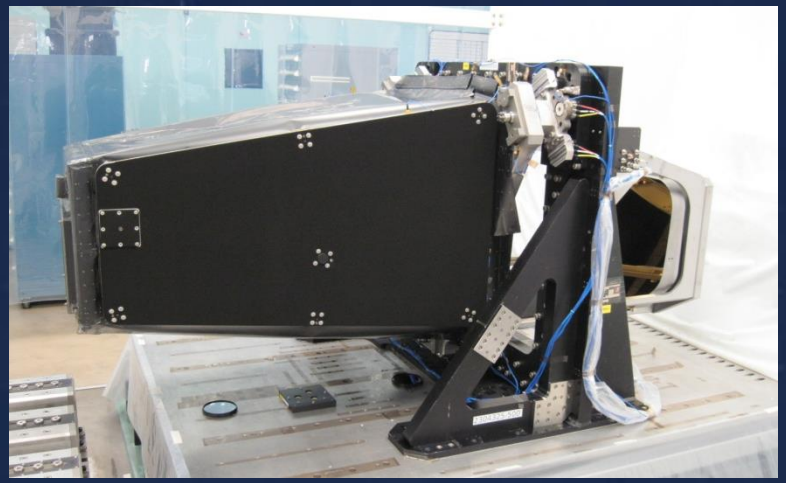




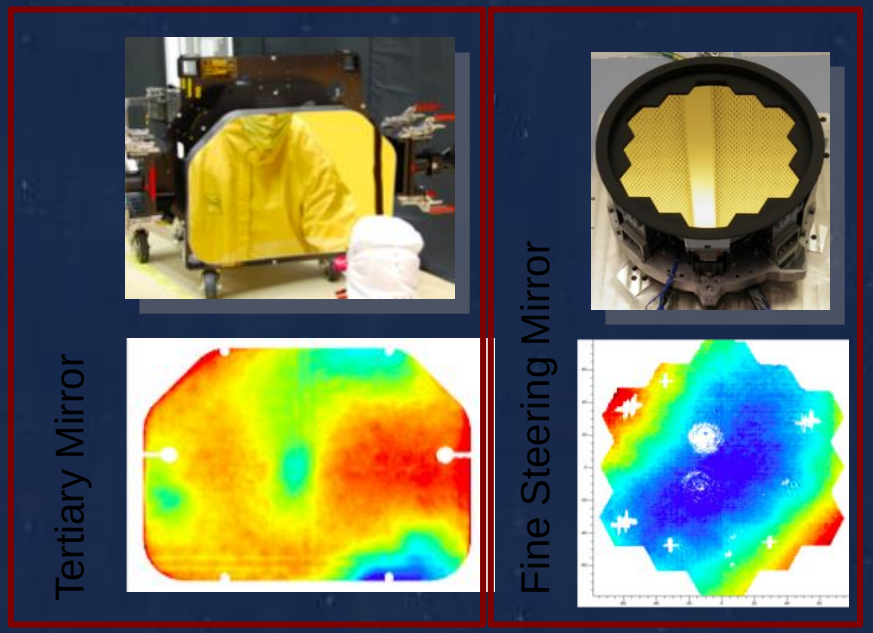
20K SMA Measured Surface Figure



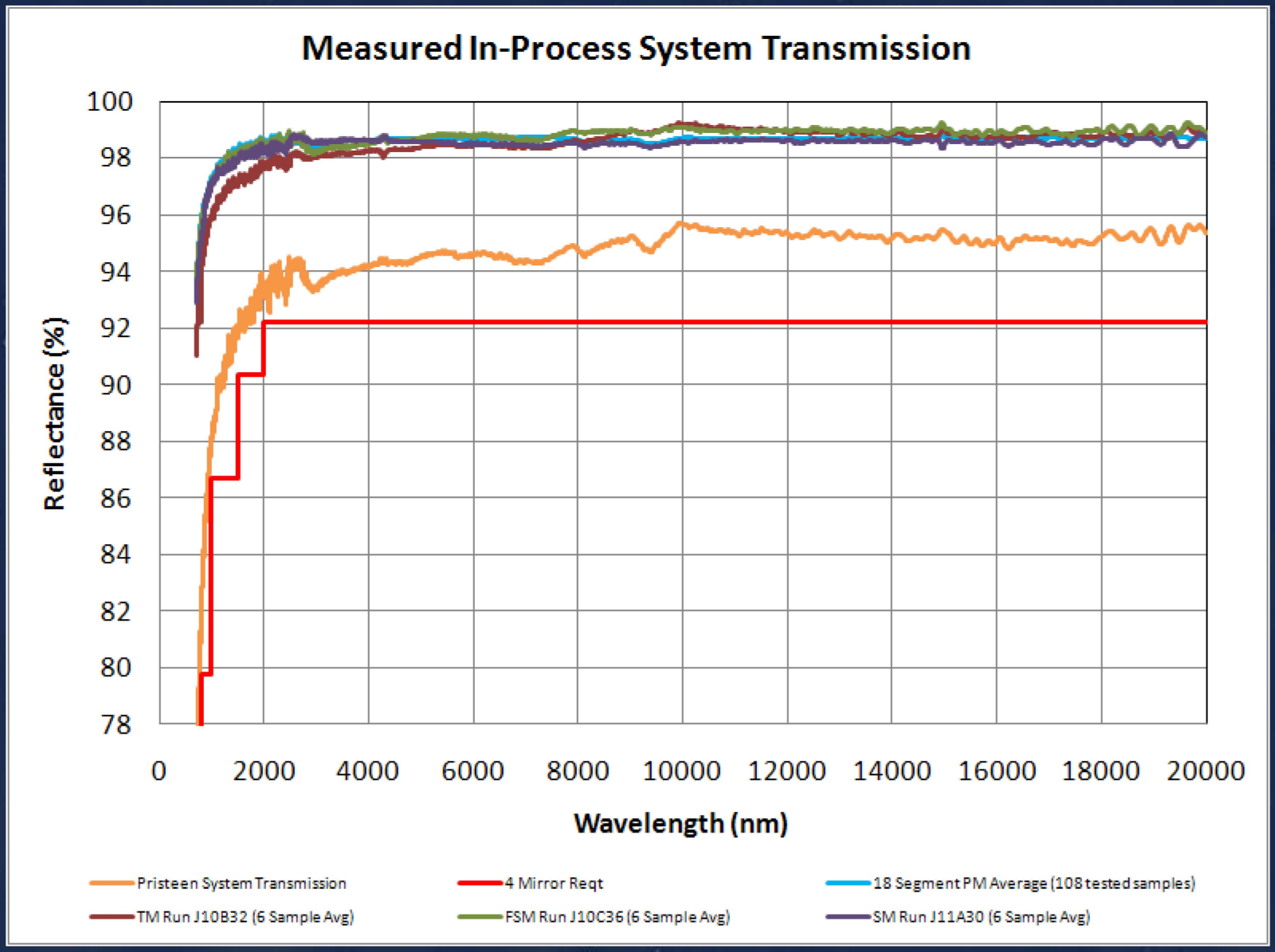
The fully integrated Aft Optics Systems (AOS)



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

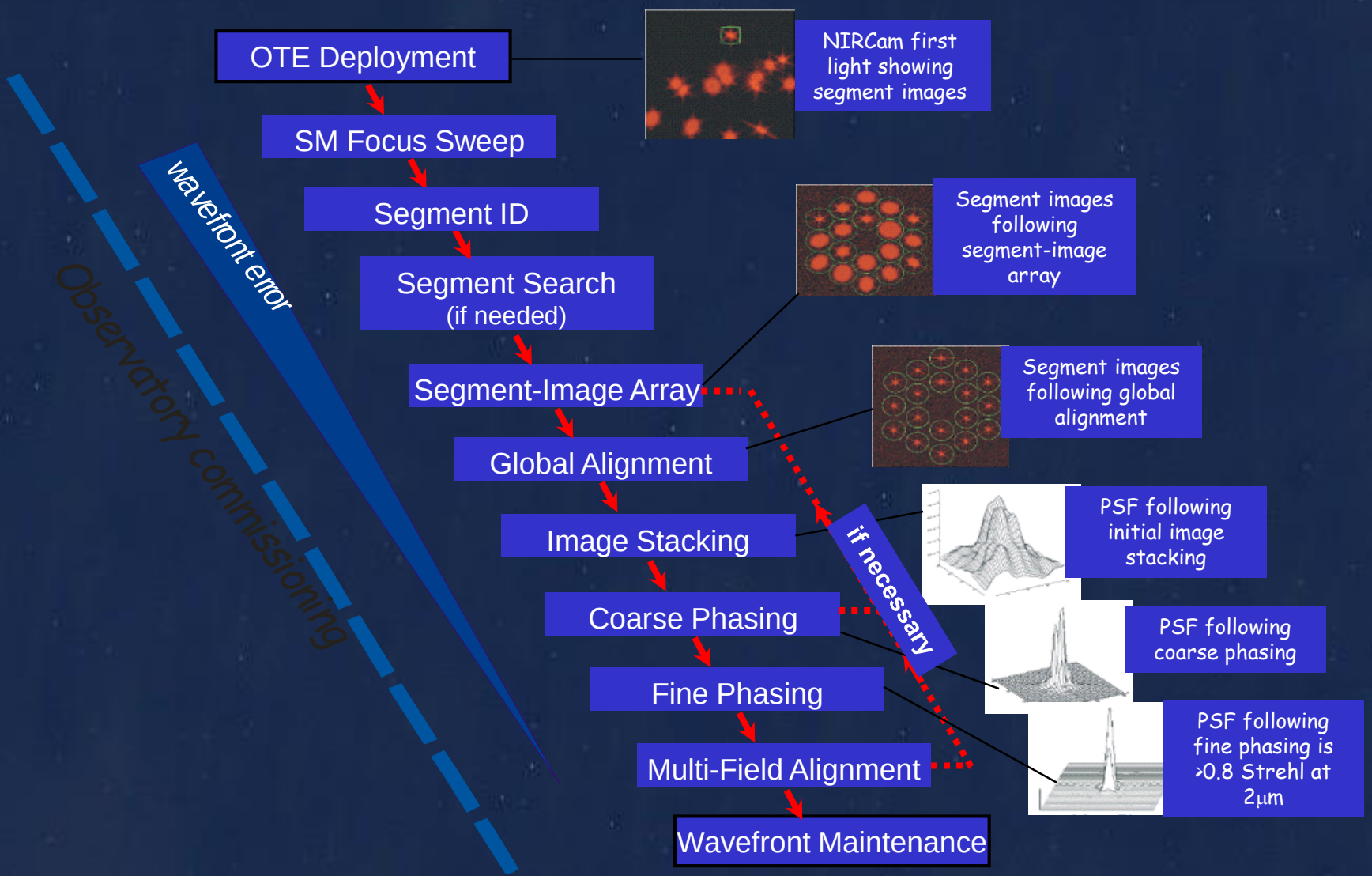


System transmission meets requirements



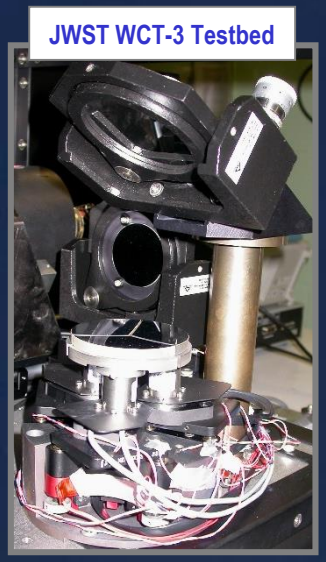
17

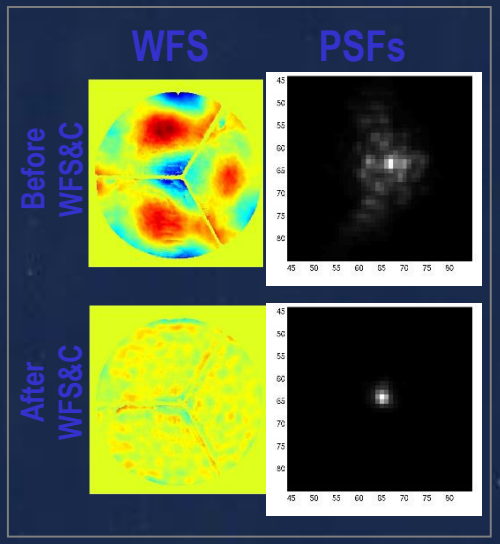
JWST Wavefront Sensing & Control Process

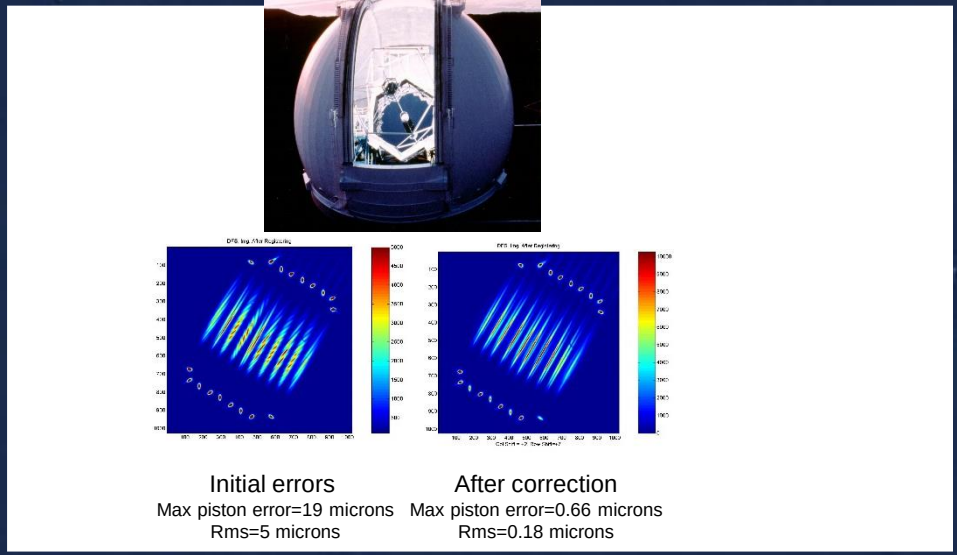


The viability of the JWST wavefront sensing and control approach was demonstrated subscale

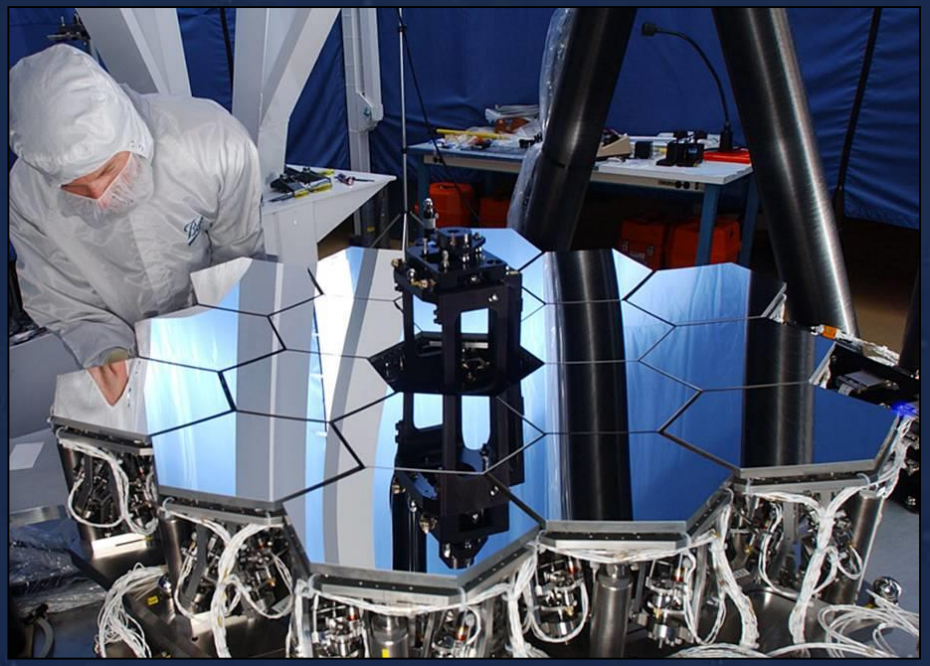
- Early investments in WFSC proved the basic feasibility of the JWST segmented mirror approach through modeling and hardware demonstrations
- WFSC testbeds at the Goddard Space Flight Center (the Wavefront Control Testbed) and at Ball were used to develop JWST-specific technologies
- An experiment on the inner 18 segments of the Keck Telescope demonstrated the specific coarse phasing portion to be used on JWST





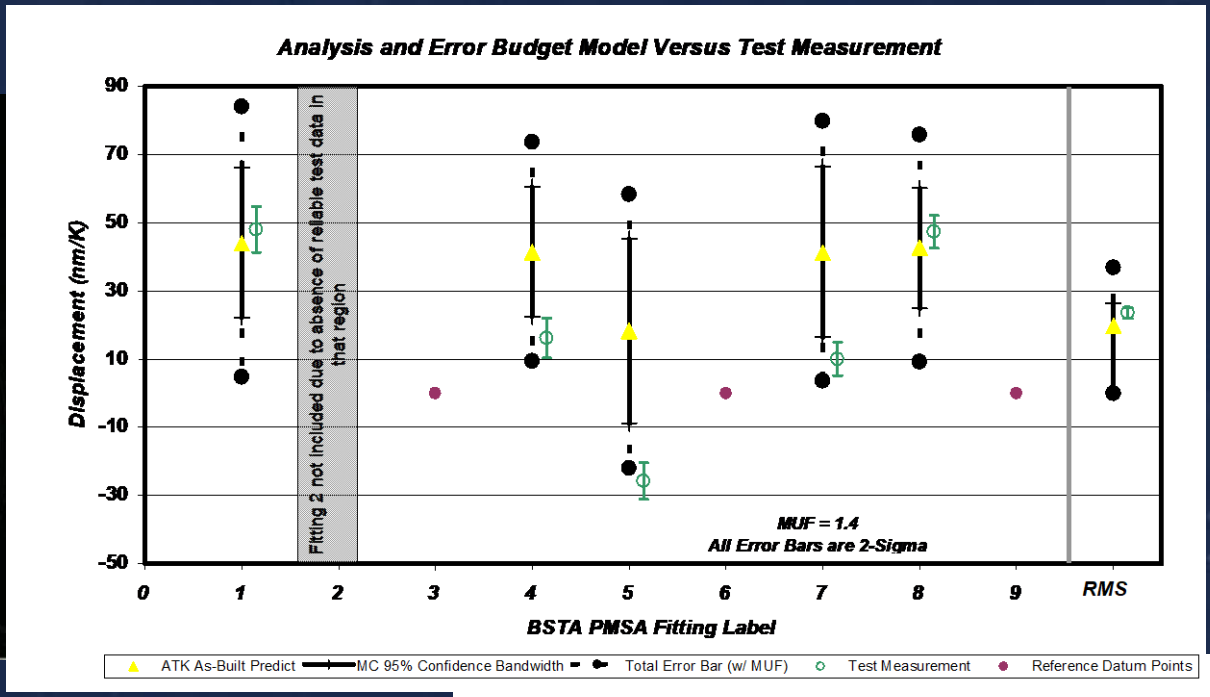


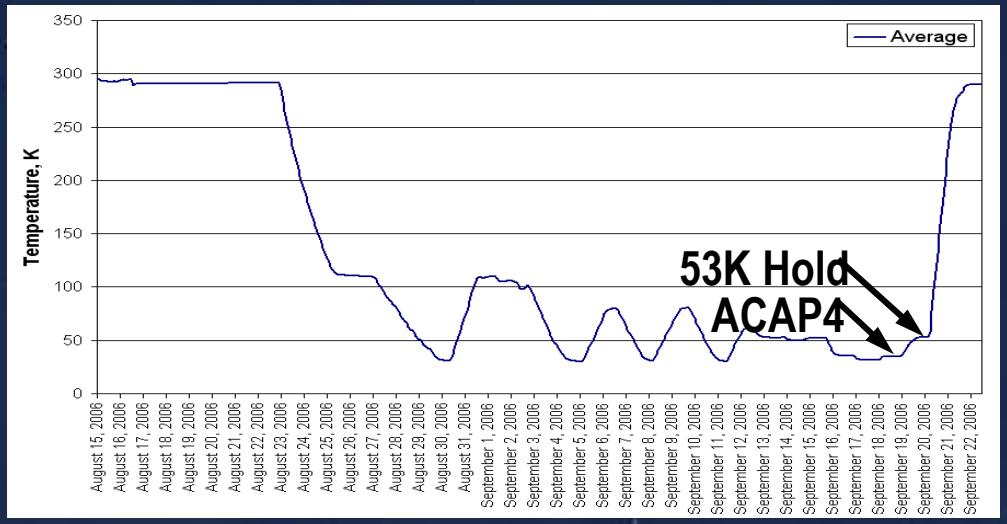
Wavefront Sensing and Control
Testbed Telescope at Ball Aerospace

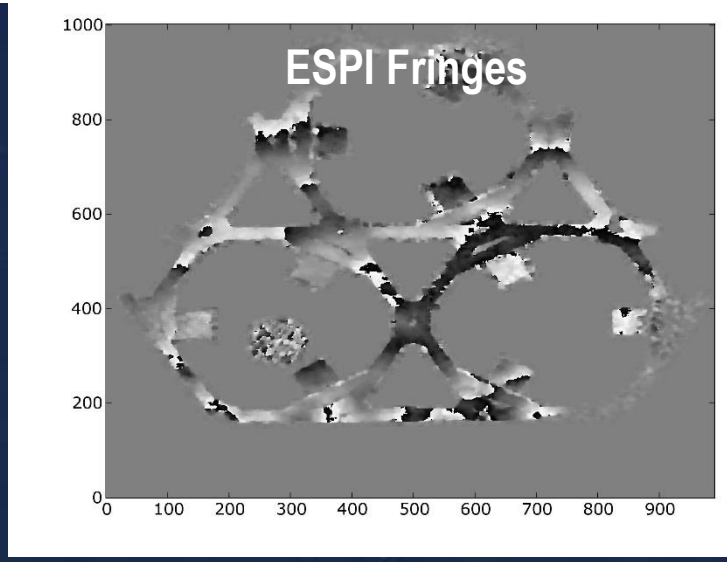


- WFSC Testbed Telescope is a 1/6th scale, fully functional model of the JWST telescope with performance traceable to JWST
- Testbed provides functionally accurate simulation platform for developing deliverable WFSC algorithms and software

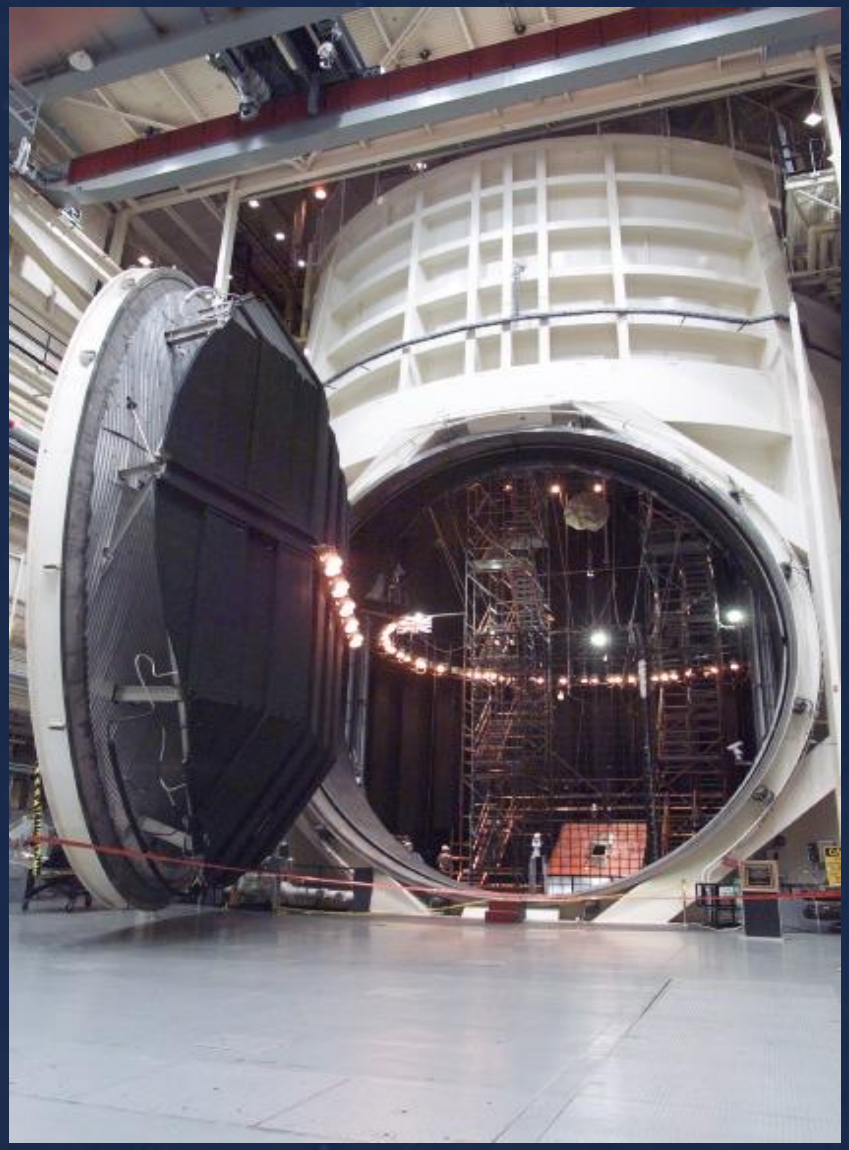
Backplane Stability Test Article Results







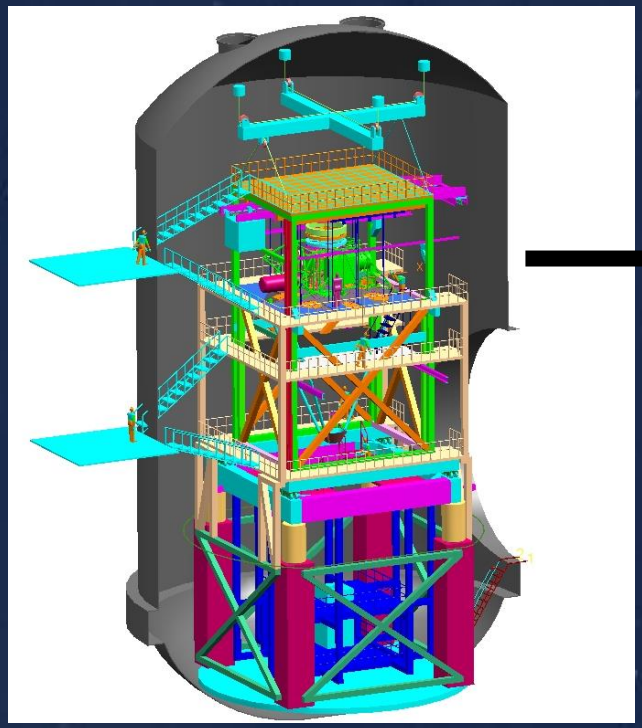
Cryogenic Testing Conducted in Historic JSC Chamber A Thermal Vacuum Facility

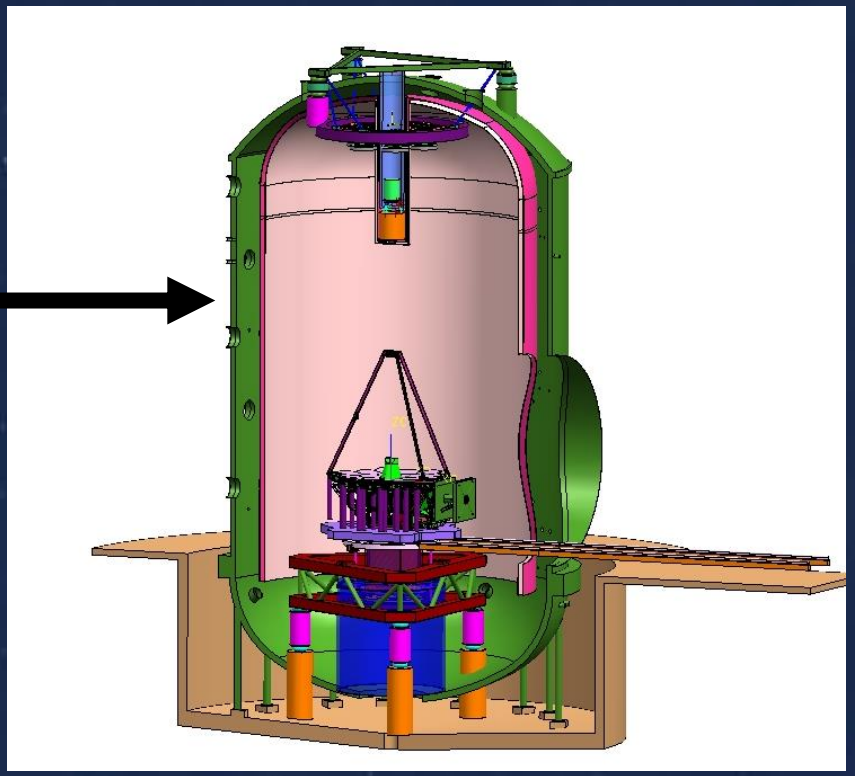


JSC Cup Up Configuration Removed Need for Expensive Metrology Tower

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





Telescope Structure

Composite Backplane built at ATK and tested at NGAS

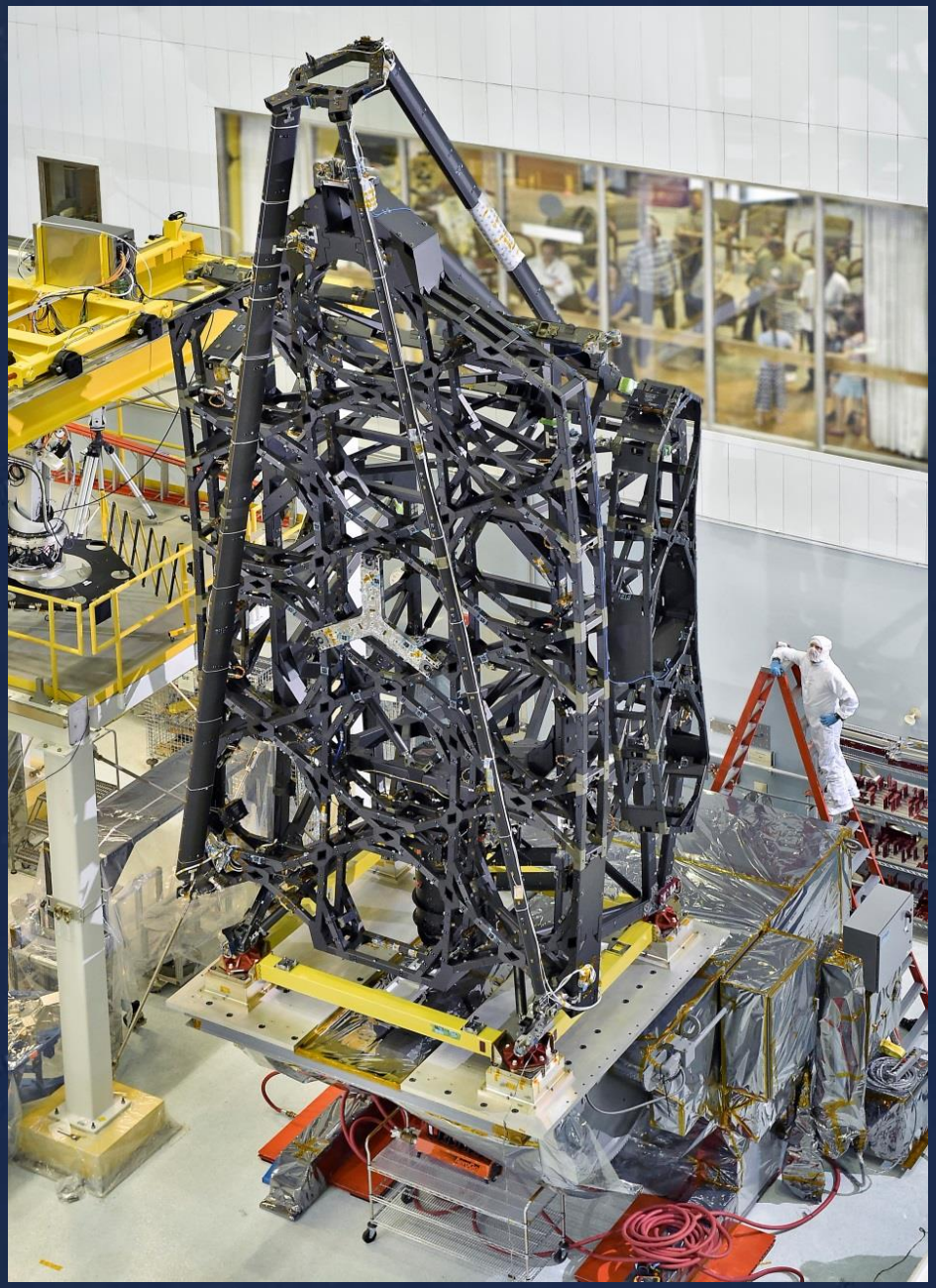
DTA Deployment Test at Ambient (built at Astro)

OTE Structure into Shipping Container

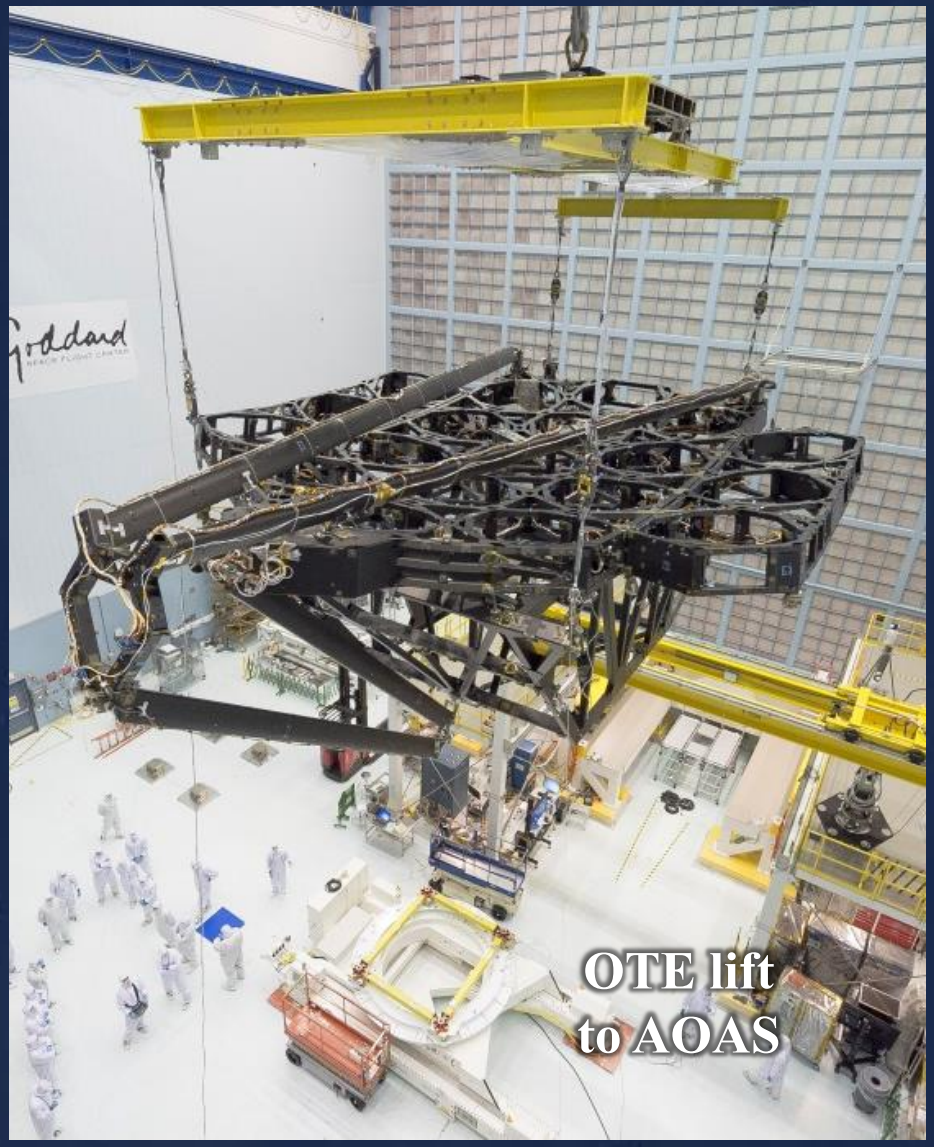
Welcome to GSFC (August 2015)

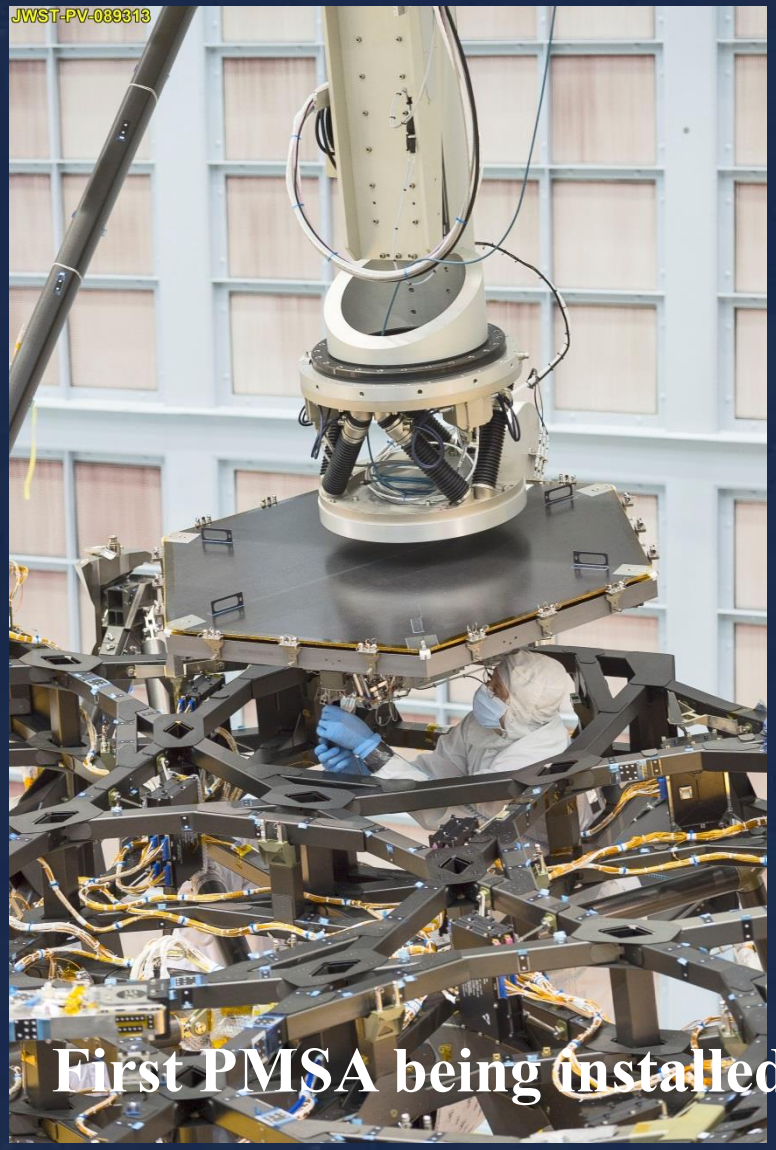
August 2015

- In Cleanroom at GSFC

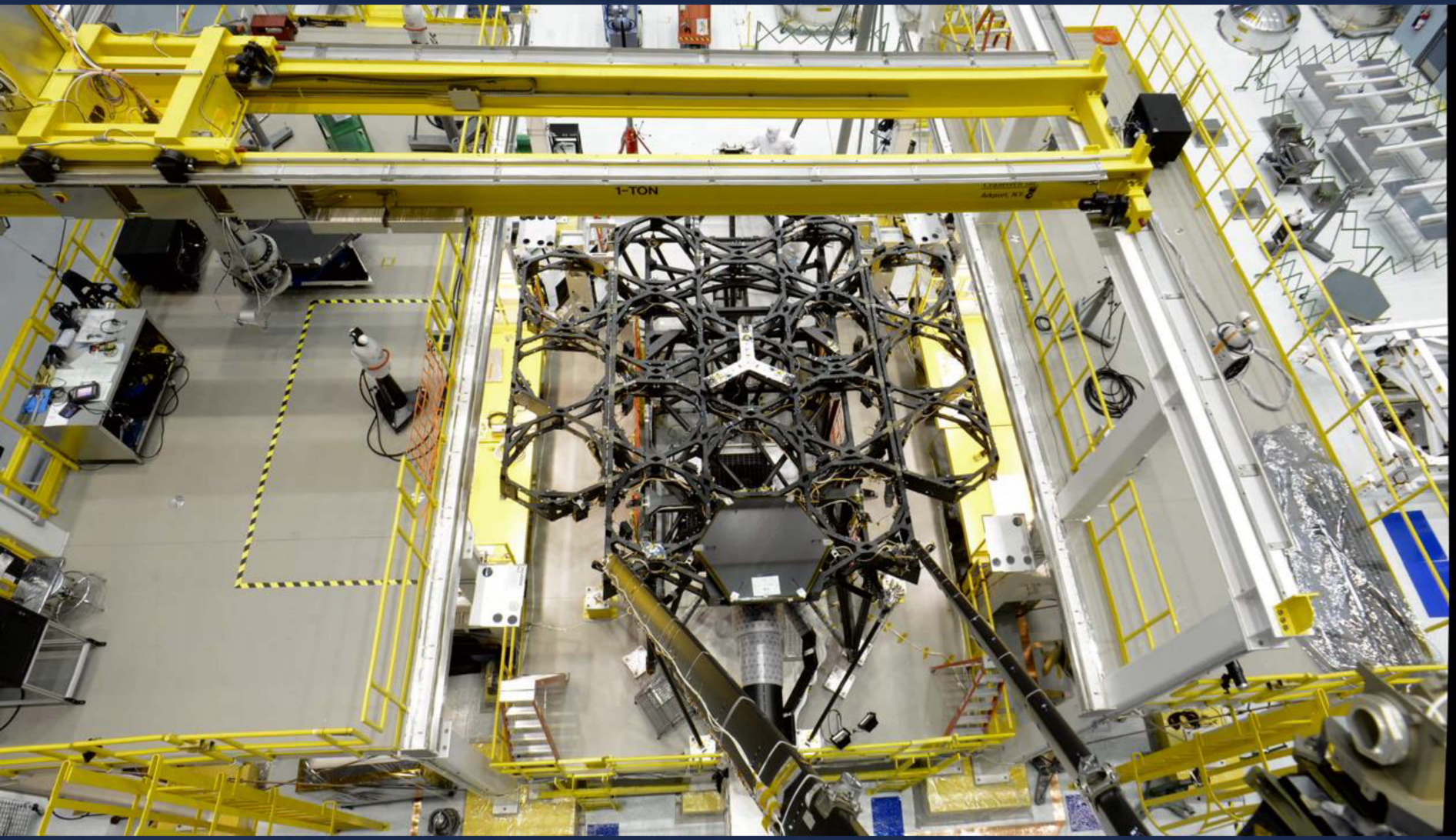


Mirror Installation (Nov ‘15 – Jan -16)

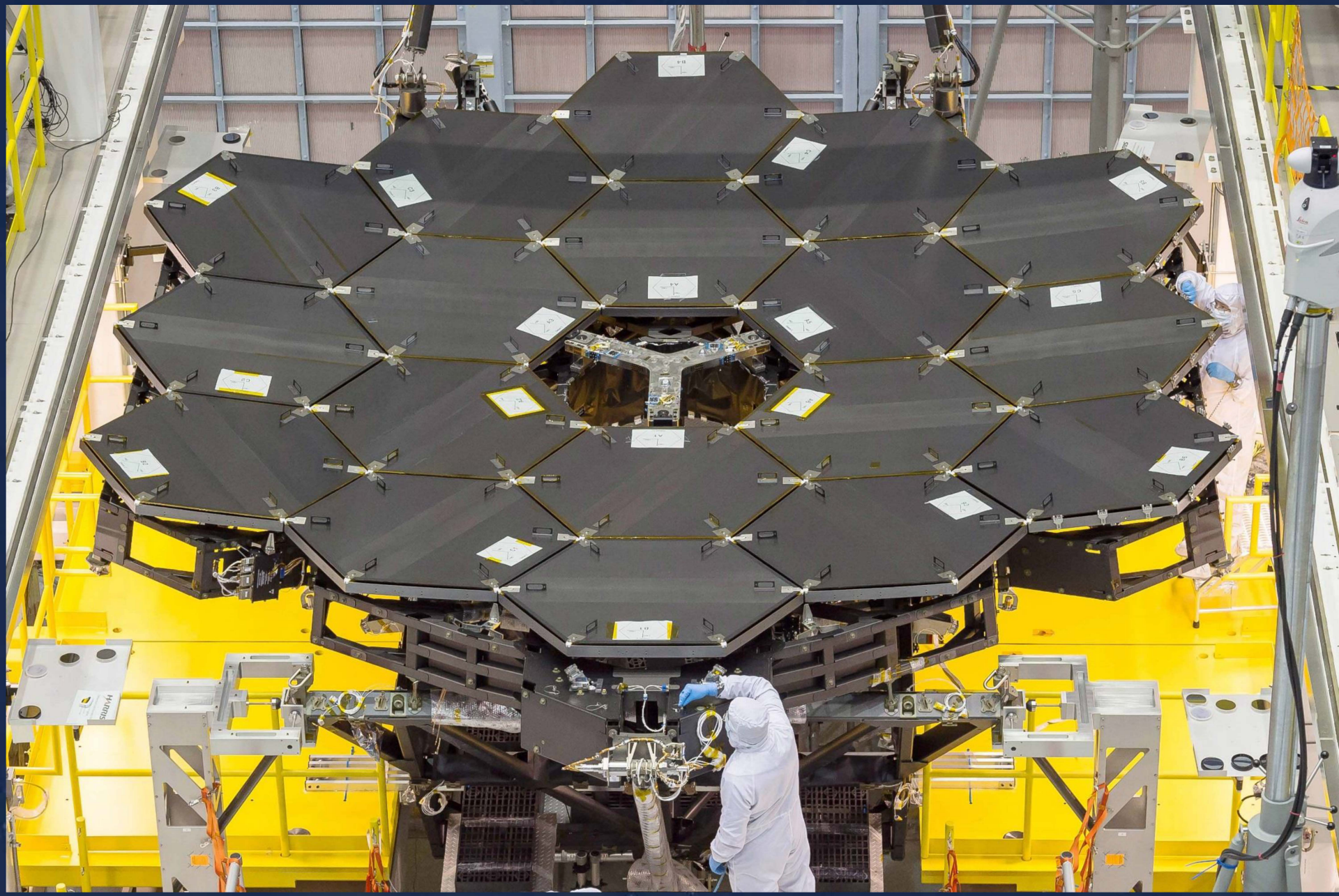




Mirror installation

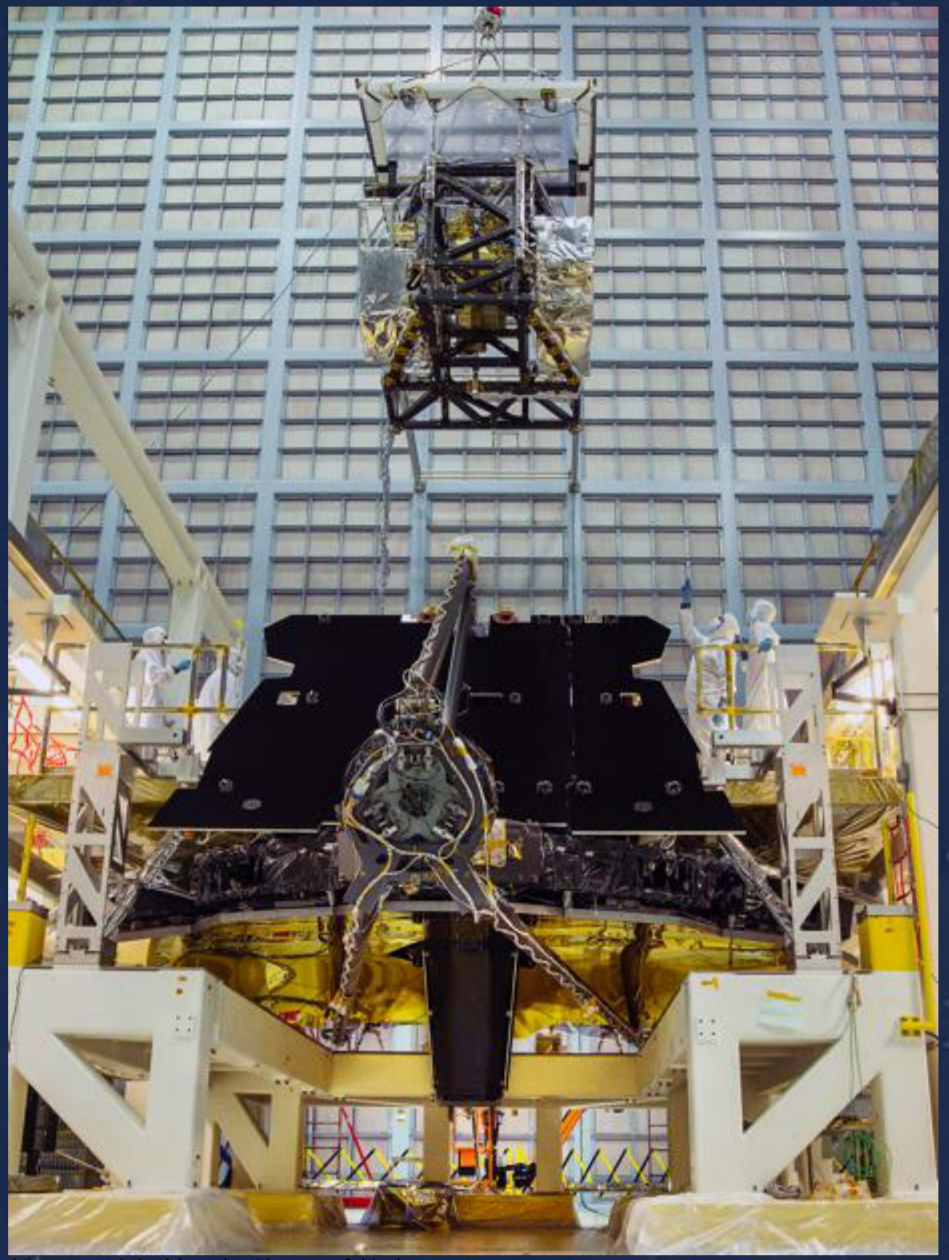


National Aeronautics and Space Administration
Goddard Space Flight Center



National Aeronautics and Space Administration
Goddard Space Flight Center

OTE/ISIM (OTIS) Instrument Module Integration



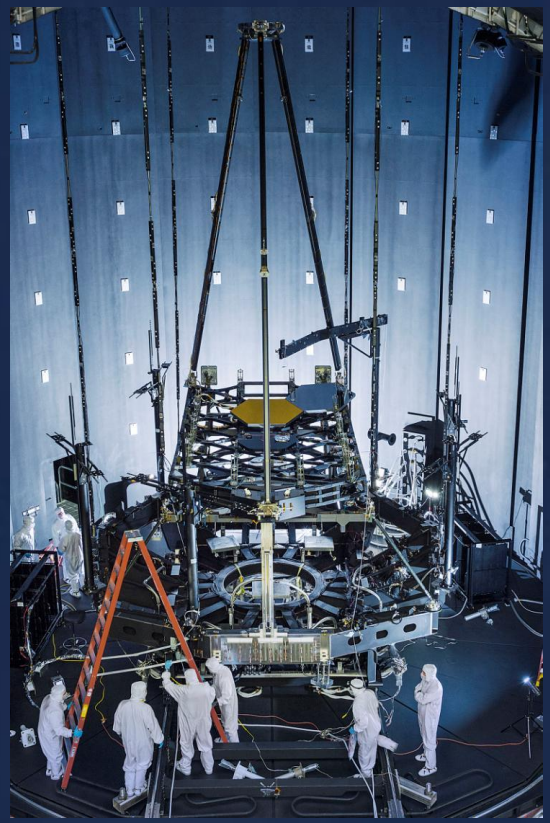
OTIS on its way to Vibe and Acoustics

Ambient Integration at Goddard Practiced on Pathfinder

Hugely Successful 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

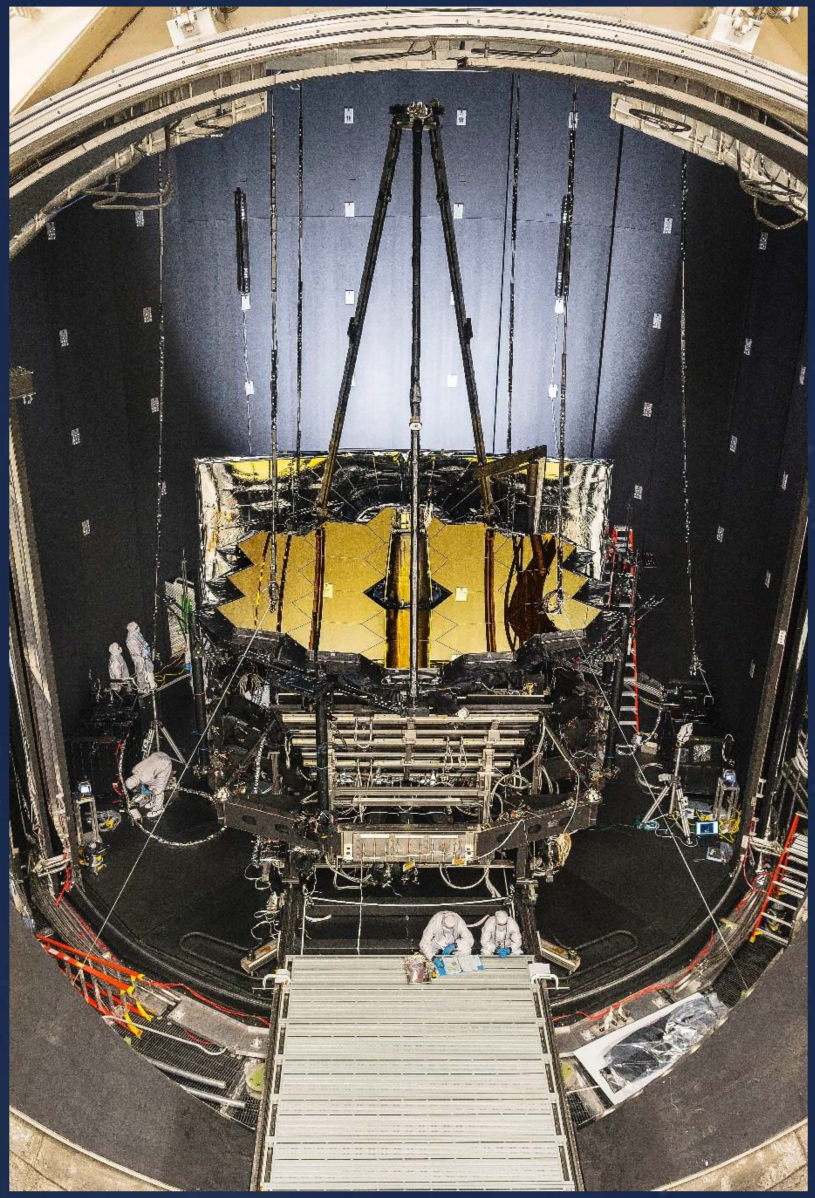


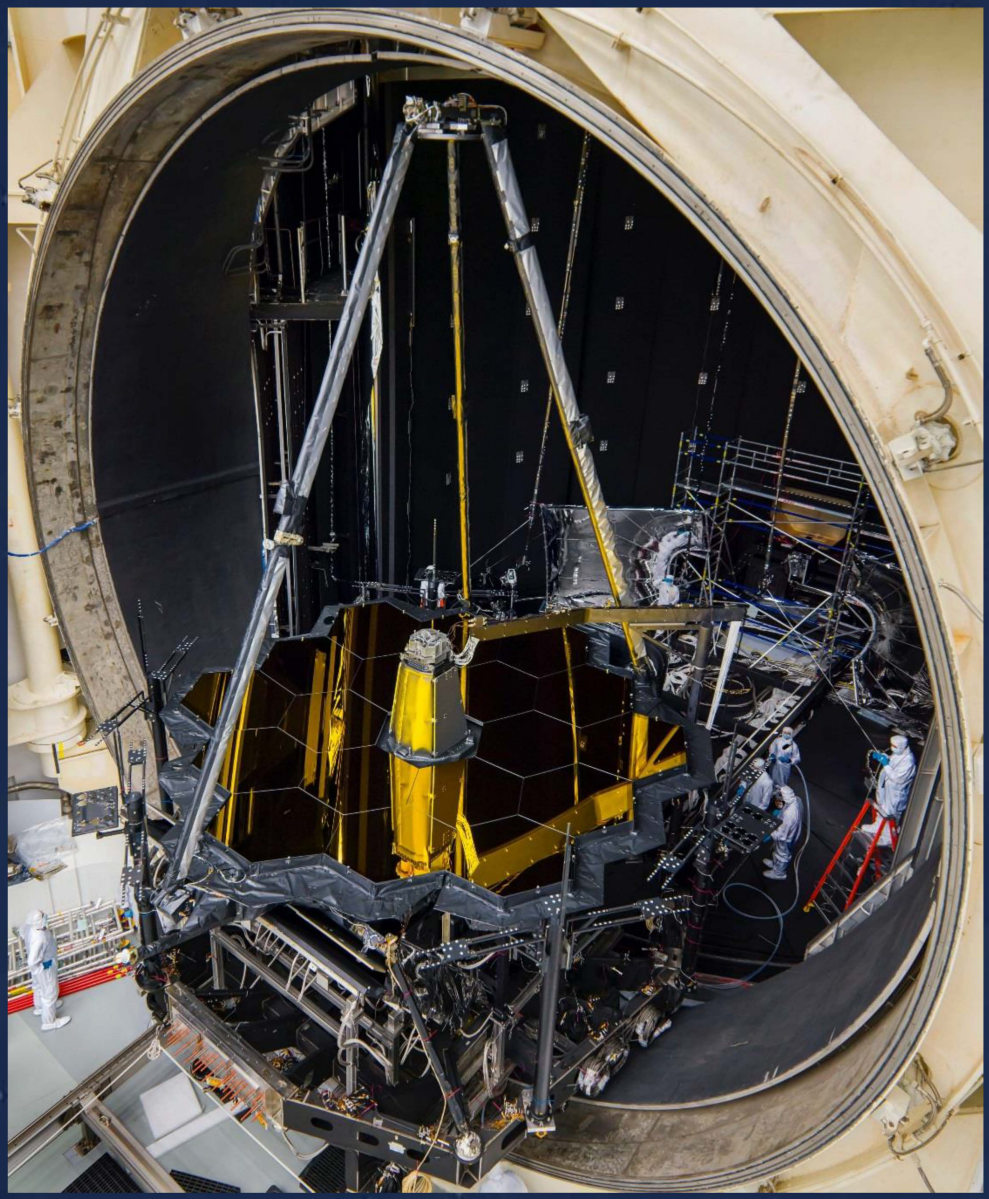
Optical Ground Support Equipment (OGSE) #1

OGSE #2

Thermal Pathfinder

End-to-end optical testing in Summer 2017





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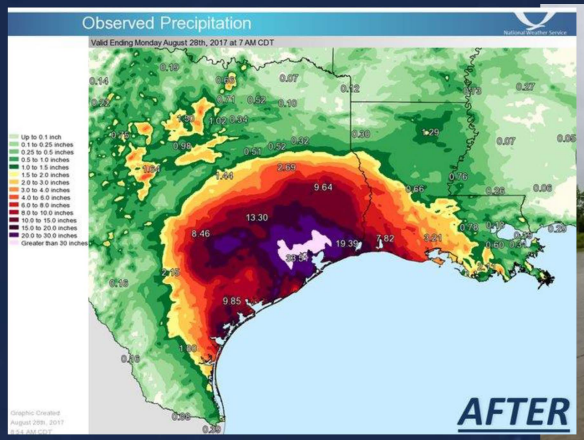
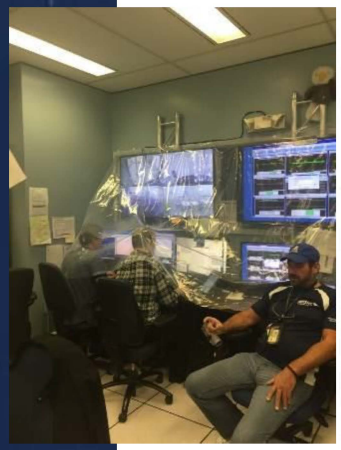
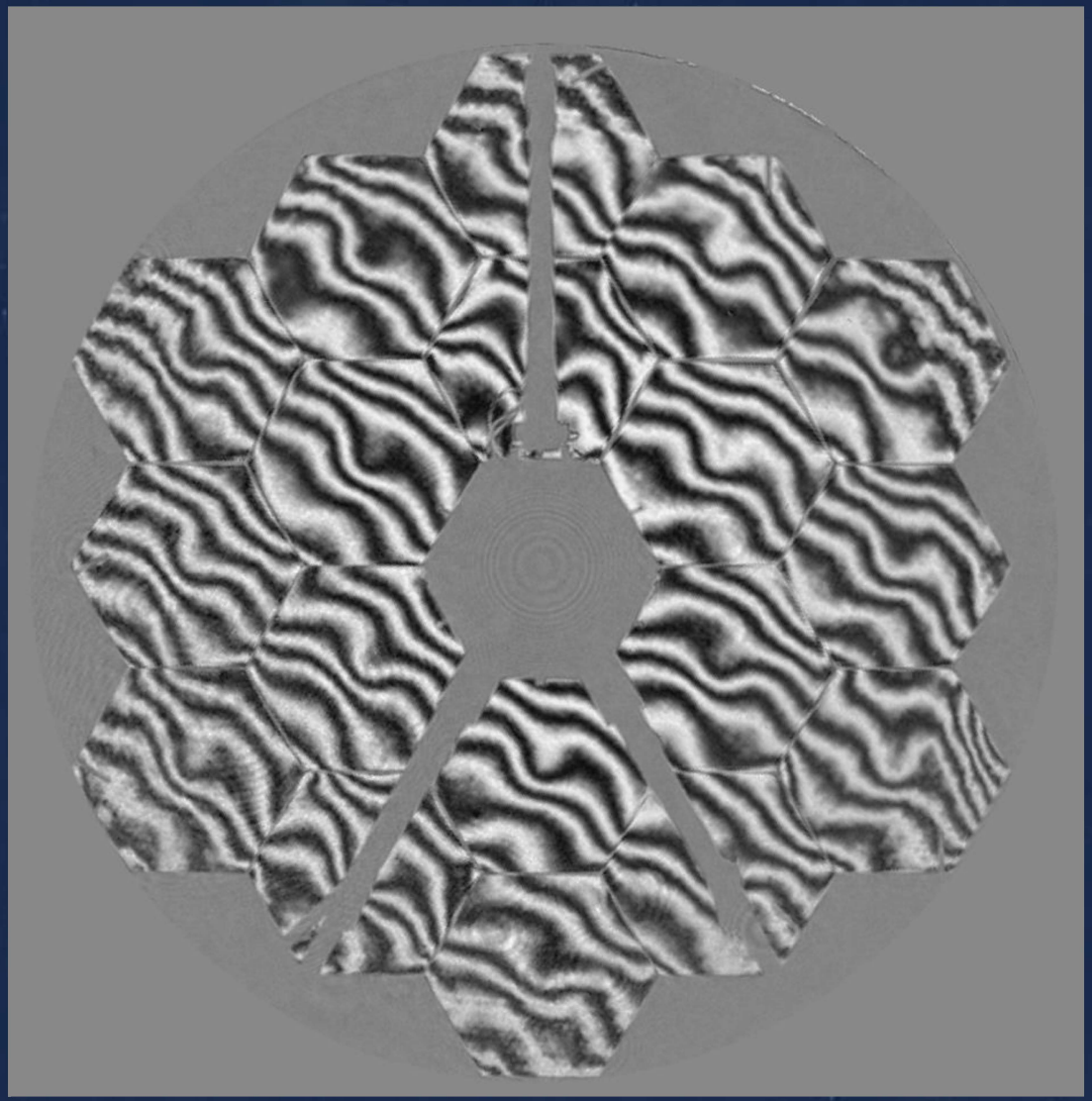
Hurricane Harvey 8/25-31





Phased Primary Mirror Interferogram



Ellington – STTARS loading into C5

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OTE and Spacecraft at NGAS

OTE leadership team stable for 15 years!

OTE + Project Mgt Visit Keck 2004

Picture of Assembled Observatory ((If Available)