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

OSA Student Leadership Conference
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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 Aerospace, 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)
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
Onset of James Webb Space Telescope

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

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

Subscale Beryllium Mirror Demonstrator (SBMD): 5 meter diameter,
Medium Authority Glass (ULE)

Low Authority Beryllium

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

Machining Facility Complete
Polishing Facility Complete

PM Manufacturing of 18 segments
Primary Mirror Segment Assemblies Complete

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

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

JWST Requirement
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

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<td>PMSA #3 (12 / C3)</td>
<td>PMSA #4 (5 / A2)</td>
<td>PMSA #5 (6 / B2)</td>
<td>PMSA #6 (7 / C2)</td>
<td>PMSA #7 (13 / A4)</td>
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<td>PMSA #13 (8 / A3)</td>
<td>PMSA #14 (22 / B7)</td>
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<td>PMSA #18 (21 / C6)</td>
<td>PMSA #17 (3 / B1) (TRL6 PMSA)</td>
<td>PMSA #18 (21 / C6)</td>
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Tinsley Built A New Large Optics Facility To Support the JWST Program
JWST Dedicated Mirror Coating Chamber at QCI/Denton
Coated Primary Mirror Segment Assembly
6 PMSAs ready for cryo testing

**Measured Primary Mirror Cryogenic Surface Figure Error meets requirements**

- **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.
The fully integrated Aft Optics Systems (AOS)

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<th>Mirror</th>
<th>Measured (RMS SFE)</th>
<th>Uncertainty (RMS SFE)</th>
<th>Total (RMS SFE)</th>
<th>Requirement (RMS SFE)</th>
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<tbody>
<tr>
<td>Tertiary</td>
<td>18.1 nm</td>
<td>9.5 nm</td>
<td>20.5 nm</td>
<td>23.2 nm</td>
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<tr>
<td>Fine Steering Mirror</td>
<td>13.9 nm</td>
<td>4.9 nm</td>
<td>14.7 nm</td>
<td>18.7 nm</td>
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The Tertiary Mirror and Fine Steering Mirror are key components of the AOS system, designed to meet stringent performance requirements.
JWST Wavefront Sensing & Control Process

OTE Deployment

SM Focus Sweep

Segment ID

Segment Search (if needed)

Segment-Image Array

Global Alignment

Image Stacking

Coarse Phasing

Fine Phasing

Multi-Field Alignment

Wavefront Maintenance

NIRCam first light showing segment images

Segment images following segment-image array

Segment images following global alignment

PSF following initial image stacking

PSF following coarse phasing

PSF following fine phasing is >0.8 Strehl at 2 μm

Observatory commissioning

wavefront end

wavefront error
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

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

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

Successful TRL-6 JWST Coarse Phasing Demonstration on Keck Telescope in 6/05

Max piston error=0.66 microns
Rms=0.18 microns

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

Analysis and Error Budget Model Versus Test Measurement

All Error Bars are 2-Sigma

MUF = 1.4

BSTA ready for test in XRCF

53K Hold

ACAP4

ESPI Fringes
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)

OTE lift to AOAS

First PMSA being installed
Mirror installation
OTE/ISIM (OTIS) Instrument Module Integration
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
Hurricane Harvey 8/25-31
Phased Primary Mirror Interferogram
Ellington – STTARS loading into C5
OTE and Spacecraft at NGAS
OTE leadership team stable for 15 years!

Paul Lightsey/Ball Aerospace
Matt Mountain/AURA

Mark Clampin/GSFC (now Mike Mcelwain)
Scott Texter/NGAS
Mark Bergeland/Ball (later Allison Barto)
Charlie Atkinson/NGAS

Lee Feinberg/GSFC
Ritva Keski-Kuha/GSFC

OTE + Project Mgt Visit Keck 2004
Picture of Assembled Observatory
((If Available))