Looking Back in Time: Building the James Webb Space Telescope (JWST) Optical Telescope Element

Lee Feinberg
JWST Telescope Manager
JWST is designed to observe formation of the first galaxies

- **Very first light:** atoms with electrons microwave became transparent.

- **First Light (After the Big Bang):**
  - First luminous objects, proto-galaxies, supernovae, black holes.

Big Bang/
Inflation was incredibly fast.

- **3 minutes**
- **300,000 years**
- **300 million years**
- **1 billion years**
- **13.75 billion years**

**First light:**
- Atoms come together
- Supernova from first collapsed stars, etc??
Looking back, seeing the Edge of Time (cosmic light horizon)

Need to look at farthest region of sky to see 13.4 billion years back (first light) – other first light has already passed us… Fabric of space stretches thus making light red shifted to infrared (1.5um-2um ?) Really far so dim (need > 25 sq meters)

These photons could not have communicated with each other unless inflation took place during the very early Universe

From: http://www.ctc.cam.ac.uk/outreach/origins/inflation_zero.php
Mission Objective

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

Organization

- Mission Lead: Goddard Space Flight Center
- International collaboration with ESA & CSA
- Prime Contractor: Northrop Grumman Space Technology
- 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)
OTE Architecture Overview

Secondary Mirror Support Structure (SMSS)

Primary Mirror Segment Assemblies (PMSA)

Aft Optics Subsystem (AOS)

OTE Electronics
- Cold Junction Box
- Cold Multiplexer Units

Thermal Management Subsystem (TMS)
- Honeycomb Panel Roof Radiators
- Honeycomb Panel +/- V2 Radiators
- ISIM Enclosure (MLI)
- Parasitic Tray Radiator

Primary Mirror Backplane Assembly (PMBA)
- PM Backplane Support Structure (PMBSS)
- PM Backplane Mechanism

Thermal Management Subsystem (TMS)
- Deployable “Batwings”
- Fixed Diagonal Shield
- Deployable Stray-Light “Bib”

Deployment Tower Assembly (DTA)
Three Mirror Anastigmat Optical Design
Provides a Wide Field-of-View

1.32 meters flat to flat
6.6 meters flat to flat

f/#: 20.0
Effective Focal Length: 131.4 m
PM diameter = 6.6 m (circumscribed circle)
NIRCam serves as the main Wavefront Sensor for the OTE

Developed by the University of Arizona with Lockheed Martin ATC
Operating wavelength: 0.6 – 5.0 microns
Field of view: 2.2 x 4.4 arc minutes
2 redundant channels each with Short (.6-2.5um) and Long Wave (up to 5um)
Short wave channels host OTE wavefront sensing elements:
  Weak lenses and filters for fine phasing
  Grisms for coarse phasing
  Pupil imaging lens used by I+T and for pupil illumination and alignment
Why 18 segments?

- Original Northrop Grumman proposal was for a 7 meter, 36 segment telescope with 3-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.
  - Having hexapods drove us more to a few actuator thus fewer segment option
  - 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 NAR/PDR
1-year in advance at Technology NAR
OTE PDR in November 2007, Mission PDR in 2008

- Mirror Phasing Algorithms
- Beryllium Primary Mirror Segment
- Sunshield Membrane

Backplane

- Near-Infrared Detector
- Mid-Infrared Detector
- Cryogenic ASICs
- Cryocooler
- pShutters
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
MIRRORS
Based on lessons learned, JWST invested early in mirror technology and mirror production to address lower areal densities and manufacturing time.

- NASA HST, Chandra, SIRTF Lessons Learned
  - TRL 6 by NAR
  - Implement an active risk management process early in the program (Early investment)
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 History


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

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

Low Authority Beryllium

Medium Authority Glass (ULE)

Subscale Beryllium Mirror Demonstrator (SMBD): 5 meter diameter,

Machining Facility Complete

Engineering Design Unit.

PM Manufacturing of 18 segments

Oute Optics Review (COR): Beryllium Selected

Cryo Testing

Polishing Facility Complete

Primary Mirror Segment Assemblies 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

OTE Optics Review (OOR): Beryllium Selected

Technology Readiness
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Low Authority Beryllium

Medium Authority Glass (ULE)
Mirror Technology Choices

~30 K minus Ambient

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

Full 15mm
=155572

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

Full 15mm
=152064

ULE

Gravity

15.0 mm

Vertex

Y

X

1.339

µm

-1.548

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

Be

Gravity

15.0 mm

Vertex

Y

X

1.339

µm

-1.548

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

Beryllium Mirror Selected Because of Superior Cryogenic Properties
Primary Mirror Segment Actuations

Actuators for 6 degrees of freedom rigid body motion, independent of ROC control

Lightweighted Beryllium Mirror Substrate

Actuator for radius of curvature adjustment

Actuator development unit

Observatory optical quality (mid and high spatial frequency) is manufactured into segments
Primary Mirror Vibration Testing
Secondary Mirror
Secondary Mirror Cryo-Optical Testing
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>
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<td>PMSA #8 (17 / B5)</td>
<td>PMSA #9 (4 / C1)</td>
<td>PMSA #10 (16 / A5)</td>
<td>PMSA #11 (20 / B6)</td>
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<td>PMSA #15 (18 / C5)</td>
<td>PMSA #16 (19 / A6)</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
## Mirror Grinding/Polishing Status at L-3 SSG-Tinsley

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PMSA Assembly Technology Demonstrator
External metrology has been demonstrated as part of JWST Mirror Test Configuration.

AMSD

Test Configuration
X-Ray Calibration Facility
Building 4718

National Aeronautics and Space Administration
George C. Marshall Space Flight Center

NASA • ESA • CSA
First test with Coated EDU
Instantaneous Acquisition Phase Shifting Interferometry for JWST

- Instantaneous phase shifting interferometry is key to successfully test the large, deployable, JWST telescope at cryo.
- Interferometer requirements:
  - High sensitivity
  - Fast exposure time <100μs
  - Insensitivity to vibration
- 4D Technology is developing two new interferometers:
  - Multiple wavelength interferometer provides independent test of phasing of the Primary Mirror and the Telescope
  - Electronic Speckle Pattern Interferometer allows testing of deformations in large, diffuse structures to nanometer level at cryo
- Pixelated phase mask that allows simultaneous capture of four phase shifted interferograms is the key feature in both interferometers.
Testing at XRCF
JWST Dedicated Mirror Coating Chamber at QCI/Denton
Coated Primary Mirror Segment Assembly
Aft Optics Subsystem Bench
Tertiary Mirror
Fine Steering Mirror
6 PMSAs ready for cryo testing

Composite Primary Mirror Cryogenic Surface Figure Error meets requirements

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

RMS: 23.2 nm
PV: 515.5 nm

248.9 nm
-266.6 nm
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

14.7nm RMS

PV: 134.1 nm

83.8 nm

50.3 nm
The fully integrated AOS

<table>
<thead>
<tr>
<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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</thead>
<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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</table>
System transmission meets requirements
PMSA process durations improved with each production batch

Final batch CCOS iterations < ½ EDU iterations
So, the final batch completed months ahead of schedule.

Flight Segment Figure Convergence at Tinsley

Excellent convergence rate on flight mirrors
Completed Mirrors in Storage
Wavefront Sensing and Control
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 2µm
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 last July on the inner 18 segments of the Keck Telescope demonstrated the specific coarse phasing portion to be used on JWST (coarse phasing now at TRL-6)
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
Coarse phasing performed on the TBT using the DHS to detect segment-to-segment piston.

Before Coarse Phasing

- Piston: RMS=1608 nm
  P-V = 5935 nm

After Coarse Phasing

- Coarse Actuators Engaged
- RMS=191 nm
  P-V=765 nm
- RMS=49 nm
  P-V=149 nm
- RMS=35 nm
  P-V=138 nm

Separate segment-to-segment piston values measured with DHS are consistent with the overall, reconstructed piston map to ≈18 nm (RMS)

After Fine-Phasing: No 2π ambiguities occurred: confirmed by defocused PSFs at two wavelengths (1550 & 1900 nm)
End-to-End Commissioning

8. Fine Phasing Convergence

Repeatability Criteria Met:

Summary of Repeatability Results (55nm requirement):

<table>
<thead>
<tr>
<th></th>
<th>GSFC/Dean Analysis</th>
<th>Ball/Acton Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median of Differences</td>
<td>49 nm</td>
<td>50 nm</td>
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</table>

Repeatability defined to be the median of the direct subtraction of controllable mode wavefronts of 6 December datasets.

Table of Differences using the 6 phase maps:

<table>
<thead>
<tr>
<th>RMS Diff (nm)</th>
<th>rnis (phase 1 - phase 2)</th>
<th>rnis (phase 1 - phase 3)</th>
<th>rnis (phase 1 - phase 4)</th>
<th>rnis (phase 1 - phase 5)</th>
<th>rnis (phase 1 - phase 6)</th>
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<th>rnis (phase 2 - phase 4)</th>
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<td>43.9319</td>
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<td>rnis (phase 5 - phase 6)</td>
<td>45.8155</td>
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Equivalent RMS piston exiting coarse phasing from previous slide

Best Aligned Telescope (107nm) RSS'd With Typical Drift=118nm

Exit Coarse Phasing here

RMS values include non-controllable modes:

WFSC repeatability is well within the TRL-6 criterion
18 Segment Fine Phasing Demonstrated on JWST Testbed Telescope

- Double Pass Phase Retrieval estimate
  - \(~0.94\) Strehl ratio (single pass at 1550 nm on TBT)
  - Flight requirement is \(>0.8\) Strehl @ 2 \(\mu\)m

- Stacked Point Spread Function (left) contains random small tip/tilt and piston errors [Before]
- Phased PSF clearly indicates coherent addition and success of closed loop fine phasing [After]
Lightweight Composite Structure (Backplane)
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
Metrology Tool Invented: Electronic Speckle Pattern Interometer

- Instantaneous phase shifting interferometry is key to successfully test the large, deployable, JWST telescope at cryo.
- Interferometer requirements:
  - High sensitivity
  - Fast exposure time <100μs
  - Insensitivity to vibration
- 4D Technology developed two new interferometers:
  - Multiple wavelength interferometer provides independent test of phasing of the Primary Mirror and the Telescope (more on this later)
  - Electronic Speckle Pattern Interferometer allows testing of deformations in large, diffuse structures to nanometer level at cryo (BSTA)
- Pixelated phase mask that allows simultaneous capture of four phase shifted interferograms is the key feature in both interferometers.
BSTA Results

Analysis and Error Budget Model Versus Test Measurement

MUF = 1.4
All Error Bars are 2-Sigma

BSTA PMSA Fitting Label

- ATK As-Built Predict
- MC 95% Confidence Bandwidth
- Total Error Bar (w/ MUF)
- Test Measurement
- Reference Datum Points

Temperature, K

53K Hold

ACAP4

ESPI Fringes
Microdynamic testing of all deployment latches completed

- Two types of SMSS hinge/latches and DTS tested
  - Wing latch was tested in 2000
- In all cases, no “nano lurches” were observed (with a noise floor of about 10nm) when loads were applied that were at least 10x greater than will be seen operationally
Integration and Testing
Avoiding a Hubble Error: Independent Testing

- The primary mirror segments have numerous cross checks built into the testing program
  - Ambient Primary Mirror Segment Level Testing using a CGH null at Tinsley and Ball
  - Ambient and Cryo measurements at the XRCF, made by Ball
    » Ball and Tinsley nulls designed and procured independently
  - Double Pass System level testing at JSC using the Autocollimating Flats, interferometry and PSF analysis
  - Center of Curvature Test at JSC using a null lens (made on all 18 mirror segments)
  - System optical alignment verification and secondary mirror testing are also important optical verification risks being managed via the risk management system.
- Cross checks also being employed on other optics and alignment
- In addition, an independent group of optical and telescope experts are reviewing test plans and key results (chaired by Duncan Moore, includes Jim Fienup)
JSC Optical Test Architecture

- Integrated Test Assembly supported from top of chamber with vibration isolation
- Center of Curvature Interferometer for PM WFE
  - Absolute Distance Meter (ADM) for axial distance
  - Alignment cameras for initial capture and setup
  - Displacement Measuring Interferometers (DMI) to monitor axial change during thermal distortion test
- Photogrammetry for position measurements
- Inward and Outward Facing Sources at PM-SM intermediate image for imaging to SI’s
  - Direct to SI’s “Half Pass”
  - End-to-End “Pass and a Half”
    » Autocollimating Flat Mirrors
- Fiducial lights around PM for PM pupil alignment tests
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
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.
Pathfinder Overview

- Includes one coated PMSA (A4) and one uncoated PMSA (C4), flight spares
  - Secondary Mirror is uncoated, flight spare
  - AOS (flight) and ASPA are added only for OGSE2
Telescope and Pathfinder in Pictures
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
OTE Structure into Shipping Container
August 2015
Welcome to GSFC (August 2015)
August 2015

- In SSDIF at GSFC
Mirror Installation (Nov ‘15 – Jan -16)

OTE lift to AOAS

First PMSA being installed
Pathfinder
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
Pathfinder being lifted from the transportation cart.
Pathfinder mounted to the HOSS as seen from inside the chamber
Pathfinder on the HOSS with the chamber in the background

Cleared the chamber door by 8”
Pathfinder in the chamber.

Note the 12’ step ladder for scale
AOS in the OTIS Cleanroom at JSC, Metrology Preps
AOS Installation into the Pathfinder
Pathfinder in Chamber for OGSE2 (Sept ‘15)
Space Vehicle Thermal Simulator (SVTS) and Sunshield Simulator
Third and final Pathfinder test planned this summer
ADM
Testing complete at JHU
Delivered to JSC

HOSS – Hardpoint Offloader Support Structure
In integration in Clean Room

Center of Curvature Optical Assembly (COCOA)
- Multiwavelength interferometer (MWIF), null, calibration equipment, coarse/fine PM phasing tools, Displacement Measuring Interferometer – Installed in Chamber

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)
Testing complete at Ball
Delivered to JSC

Mag Damper Cryo Test Article
Delivered

Deep Space Edge Radiation Sink (DSERS)
Frame integrated
Where Are We In OTE-ISIM (OTIS Flow)

GSE & Test Preparations
- Facility Functional
- Clean Room
- MSSE Install
- Re-loc
- Commissioning Phase I
- MSSE Inspection, OGSE Install
- Commissioning Phase II

Completed Aug 12
Fall 14

JWST OTIS Integration and Test
- Acronyms
  - AOS: Aft-Optics Subsystem
  - GSE: Ground Support Equipment
  - MGSE: Mechanical Ground Support Equipment
  - NGAS: Northrop Grumman Aerospace Systems
  - OGSE: Optical Ground Support Equipment
  - PF: Pathfinder

- Legend
  - Prep & Transport
  - Functional / Test
  - Assembly / Integration
  - Delivery

Risk Reduction Activities
- Fall 14
- Fall 17

Flight OTIS I&T
- Install Flight ISIM to OTE
- Pre Environmental Test
- Acoustic & Vibe Tests
- Post Environmental Test
- Ship OTIS to JSC
- Receive OTIS at JSC
- OTIS Cryo Preps
- OTIS Cryo Test
- OTIS Cryo Post-Test
- Ship OTIS to NGAS
Pathfinder Early Results

Multi-Wavelength Phasing Using Synthetic Wavelengths

Half pass Prediction vs. Data

Measured RMS WFE = 211 nm

Modeled RMS WFE = 213 nm

Pass and a Half Prediction Vs Data ("Stacked")
The team
Looking Back: THANK YOU to the Incredibly Skilled and Dedicated Teams
OTE management team stable for 14 years!

Charlie Atkinson/NGAS

Ritva Keski-Kuha

Scott Texter

Bill Hayden

OTE + Project Mgt Visit Keck 2014