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 w/electrons microwave became transparent

3 minutes

300,000 years

300 million years

1 billion years

13.75 billion years

Big Bang/Inflation was incredibly fast

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

First light – Atoms come together Supernova from first collapsed stars, etc??

Century 300 million years

First luminous objects, proto-galaxies, supernovae, black holes
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
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
- 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)

Secondary Mirror Assembly (SMA)

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

Deployment Tower Assembly (DTA)

Thermal Management Subsystem (TMS)
- Deployable “Batwings”
- Fixed Diagonal Shield
- Deployable Stray-Light “Bib”
Three Mirror Anastigmat Optical Design Provides a Wide Field-of-View

- Three Mirror Anastigmat Optical Design

- Provides a Wide Field-of-View

- Tertiary Mirror

- ISIM

- OTE

- Focal Surface

- Primary Mirror

- Fine Steering Mirror

- Cassegrain focus

- V1 (spacecraft)

- V2

- V3 (anti-spacecraft)

- (V1, V3) origin

- f/#: 20.0

- Effective Focal Length: 131.4 m

- PM diameter = 6.6 m (circumscribed circle)

- 6.6 meters flat to flat

- 1.32 meters flat to flat

- "Three Mirror Anastigmat Optical Design Provides a Wide Field-of-View"
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
- μShutters
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.
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
Onset of James Webb Space Telescope

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

Machining Facility Complete
Cryo Testing
Polishing Facility Complete

Low Authority Beryllium

Medium Authority Glass (ULE)

Technology Readiness

Level-6 Demonstrated: All key requirements and environments demonstrated

Engineering Design Unit.
PM Manufacturing of 18 segments
Primary Mirror Segment Assemblies Complete

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

~30 K minus Ambient

RMS: 0.3979 μm
PV: 2.8872 μm
Data Pts: 154,545
Full 15mm = 155,572

RMS: 0.1705 μm
PV: 1.3630 μm
Data Pts: 151,087
Full 15mm = 152,064

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
<table>
<thead>
<tr>
<th>Pathfinder</th>
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<td><img src="image9.png" alt="Image" /></td>
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</tr>
<tr>
<td>PMSA #1 (EDU-A / A1)</td>
<td>PMSA #2 (11 / B3)</td>
<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>
<td>PMSA #8 (17 / B5)</td>
<td>PMSA #9 (4 / C1)</td>
<td>PMSA #10 (16 / A5)</td>
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<tr>
<td><strong>Done at Axsys!!</strong></td>
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</tr>
<tr>
<td>PMSA #13 (8 / A3)</td>
<td>PMSA #14 (22 / B7)</td>
<td>PMSA #15 (18 / C5)</td>
<td>PMSA #16 (19 / A6)</td>
<td>PMSA #17 (3 / B1)</td>
<td>PMSA #18 (21 / C6)</td>
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**Beryllium Flight Mirror Machining Complete at Axsys Technologies**
Tinsley Built A New Large Optics Facility To Support the JWST Program
Mirror Grinding/Polishing Status at L-3 SSG-Tinsley

<table>
<thead>
<tr>
<th>Batch #1 (Pathfinder)</th>
<th>Batch #1 (Pathfinder)</th>
<th>Batch #1 (Pathfinder)</th>
<th>Batch #2</th>
<th>Batch #2</th>
<th>Batch #2</th>
</tr>
</thead>
<tbody>
<tr>
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<td>PMSA #2 (11 / B3)</td>
<td>PMSA #3 (12 / C3)</td>
<td>PMSA #4 (5 / A2)</td>
<td>PMSA #5 (6 / B2)</td>
<td>PMSA #6 (7 / C2)</td>
</tr>
<tr>
<td>Batch #3</td>
<td>Batch #3</td>
<td>Batch #3</td>
<td>Batch #4</td>
<td>Batch #4</td>
<td>Batch #4</td>
</tr>
<tr>
<td>PMSA #7 (13 / A4)</td>
<td>PMSA #8 (17 / B5)</td>
<td>PMSA #9 (4 / C1)</td>
<td>PMSA #10 (16 / A5)</td>
<td>PMSA #11 (20 / B6)</td>
<td>PMSA #12 (15 / C4)</td>
</tr>
<tr>
<td>Batch #5</td>
<td>Batch #5</td>
<td>Batch #5</td>
<td>Batch #6</td>
<td>Batch #6</td>
<td>Batch #6</td>
</tr>
<tr>
<td>PMSA #13 (8 / A3)</td>
<td>PMSA #14 (22 / B7)</td>
<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>
</tr>
</tbody>
</table>
PMSA Assembly Technology Demonstrator
External metrology has been demonstrated as part of JWST Mirror Test Configuration.
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
Measured Primary Mirror Cryogenic Surface Figure Error meets requirements

6 PMSAs ready for cryo testing

Composite Primary Mirror meets requirements
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.
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>
</tr>
</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>
</tr>
<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>
</tr>
</tbody>
</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

NIRCam first light showing segment images

Segment ID

Segment images following segment-image array

Segment Search (if needed)

Segment images following global alignment

Segment-Image Array

PSF following initial image stacking

Global Alignment

PSF following coarse phasing

Image Stacking

PSF following fine phasing is >0.8 Strehl at 2µm

Coarse Phasing

Multi-Field Alignment

Fine Phasing

Wavefront Maintenance

Observatory commissioning
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
End-to-End Commissioning

7. Coarse Phasing on the TBT

• Coarse phasing performed on the TBT using the DHS to detect segment-to-segment piston.

Before Coarse Phasing

\[ \text{Piston: RMS} = 1608 \text{ nm} \]
\[ \text{P-V} = 5935 \text{ nm} \]

After Coarse Phasing

\[ \text{Piston: RMS} = 35 \text{ nm} \]
\[ \text{P-V} = 138 \text{ nm} \]

• Separate segment-to-segment piston values measured with DHS are consistent with the overall, reconstructed piston map to \( \approx 18 \text{ nm (RMS)} \)

• After Fine-Phasing: No \( 2\pi \) 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>Median of Differences</th>
<th>GSFC/Dean Analysis</th>
<th>Ball/Acton Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<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>rms (phase 1 - phase 2)</th>
<th>rms (phase 1 - phase 3)</th>
<th>rms (phase 1 - phase 4)</th>
<th>rms (phase 1 - phase 5)</th>
<th>rms (phase 1 - phase 6)</th>
<th>rms (phase 2 - phase 3)</th>
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<th>rms (phase 5 - phase 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>54.9731</td>
<td>62.4657</td>
<td>41.6916</td>
<td>49.0651</td>
<td>39.6656</td>
<td>52.9011</td>
<td>47.9591</td>
<td>49.9841</td>
<td>53.6143</td>
<td>60.318</td>
<td>62.2399</td>
<td>62.3999</td>
<td>48.622</td>
<td>43.9319</td>
<td>43.8155</td>
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<tr>
<td>median</td>
<td>49.39 nm</td>
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**Equivalent RMS piston exiting coarse phasing from previous slide**

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

**WFSC repeatability is well within the TRL-6 criterion**

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**RMS Wavefront Error (nm)**

- **Exit Coarse Phasing here**

**Coarse Phasing** ➔ **Fine Phasing**

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**Trial 1, Nov 07**

**Trial 2, Dec 12**

**Trial 3, Dec 12**

**Trial 4, Dec 12**

**Trial 5, Dec 12**

**Trial 6, Dec 13**

**Trial 7, Dec 14**
18 Segment Fine Phasing Demonstrated on JWST Testbed Telescope

- Double Pass Phase Retrieval estimate
  - \( \sim 0.94 \) 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

![Test Article Configuration at XRCF](image)
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

BSTA ready for test in XRCF

53K Hold

ESPI Fringes

53K Hold

ACAP4

MUF = 1.4
All Error Bars are 2-Sigma
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 CoC Null Lens test
  – 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)

Tinsley Ambient Configuration
(Ball Config. Is Similar)

JSC System Test

MSFC XRCF Cryogenic Configuration
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

- GSE BSF Handling Fixture Removed for Cryo Test

- Mid Hinge
- Out Board Hinge
- SMM
- PMSA C4
- -V2 Dual Hinge
- +V2 Dual Hinge
- PMSA A4
- AOS (ASPA - OGSE2 only)
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
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
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
AOS on Pathfinder
Pathfinder in Chamber for OGSE2 (Sept ‘15)
Space Vehicle Thermal Simulator (SVTS) and Sunshield Simulator

Third and final Pathfinder test planned this summer

Chamber Isolator Units
Dynamically isolates OTIS
Optical Test – Integration of 6 units complete

Cryo Position Metrology (CPM)
Photogrammetry System
Integration Complete

ADM
Testing complete at JHU
Delivered to JSC

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

HOSS – Hardpoint Offloader Support Structure
In integration in Clean Room

Deep Space Edge Radiation Sink (DSERS)
Frame integrated

Mag Damper Cryo Test Article
Delivered
Where Are We In OTE-ISIM (OTIS Flow)

GSE & Test Preparations
- Facility Functional: Completed Aug 12
- Clean room
- MGSE Install
- Reuse
- Commissioning Phase I
- MGSE Inspection, OGSE Install
- Commissioning Phase II
  - 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
  - OGE & IS Prep
  - Receive IS at JSC
  - OGE1 Prep
  - Receive IS at JSC
  - OGE1 Test
  - OGS2 Prep
  - OGSE Test
  - Ship IS to GSE
  - PF Thermal Prep
  - PF Thermal Test
  - Prep for OTIS Test
  - JSC Chamber Ready

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
- Fall 17
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
Telescope Team

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

[Map of North America showing the locations of various suppliers and associates, including ATK, BRUSH WELLMAN, HAMPTON, SAO, AOA, Now Harris Corporation, ITT, DENTON VACUUM, NORTHRUP GRUMMAN, Ball, AXSYS Technologies, GSFC, NGST ECO, JPL, MSFC, and SAO Adaptive Optics Associates, Inc.]
Looking Back: THANK YOU to the Incredibly Skilled and Dedicated Teams
OTE management team stable for 14 years!

Charlie Atkinson/NGAS

Scott Texter

Bill Hayden

Ritva Keski-Kuha

OTE + Project Mgt Visit Keck 2014