James Webb Space Telescope (JWST)

Peter Stockman
(thanks to John Nella)
JWST All-Hands
15 November 2002

This briefing package is approved for release to the public.
Observatory Prime Contractor Team

TRW  JWST Prime Contractor

- Observatory performance, schedule, and cost
- Systems engineering and interfaces
- Spacecraft, Sunshield and all deployables

Ball  Optical System Development

- OTE optical design and optics
- WFS&C design and algorithms
- Mirror segment cryogenic testing

Kodak  Telescope Integration and Test

- OTE ground AI&T
- Plum Brook test configuration and interfaces
- Fabricate ULE mirrors (if option selected)
**JWST Observatory Architecture**

**Optical Telescope Element (OTE)**
- Stable over total field-of-regard
- Beryllium (Be) or ULE optics
- Performance verified on the ground
- Simple and low risk
  - Four deployments

**Secondary Mirror (SM)**
- Deployable tripod for stiffness
- 6 DOF to assure telescope alignment

**Primary Mirror (PM) – 7 meter**
- 36 (1 m) hex segments simplify mfg and design
- Simple semi-rigid WFS&C for phasing
  - Tip, tilt, piston, and radius corrections
- Segment performance demonstrated
- Deployable chord fold for thermal uniformity
- Stable GFRP/Boron structure over temperature

**Sunshield**
- Passive cooling of OTE to <40K
- Provides large FOR
- Limits momentum buildup
- Reliable PAMS-type deployment

**Spacecraft Bus**
- Isolates reaction wheel noise
- Heritage components
- Compatible with ESA

**ISIM**
- 3 SIs and FGS
- Large volume
- Simple three-point interface

**Tower**
- Isolates telescope from spacecraft dynamic noise
- OTE rotation not required
Overview of the JWST Observatory

- **Secondary Mirror Subsystem**
  - Secondary Mirror Support Structure
  - Secondary Mirror Assembly
- **PM Subsystem**
  - Aft Optics Subsystem
- **ISIM Element**
  - Primary Mirror Backplane
  - ISIM Enclosure Subsystem (OTE)
  - Integrated Science Instrument Module (ISIM)
    - NIRCam, NIRSpec, MIRI, and FGS
- **Telescoping Tower Subsystem**
  - 1 Hz Isolators (4)
  - Deployment Tower Subsystem
- **Spacecraft Bus**
  - Sunshield Subsystem
  - Spacecraft Element

This material is approved for public use.
Observatory Launch Configuration allows use of ATLAS V EELV with 5m Fairing

Observatory stows in Atlas V with a minimum clearance \( \geq 25\text{mm} \)
Extensive Opportunities for Pre-Commissioning Activities Before Achieving L2 Orbit

Main Engine
Start 1
264 sec

Main Engine
Cut-Off 1
785 sec

Main Engine
Start 2
1694 sec

Main Engine
Cut-Off 2
2084 sec

Trajectory correction maneuver 1
L + 15 hrs

Sunshield deployment
L + 2 days

JWST separation
39 min

Telescope deployment
L + 4 days

Observatory available for ISIM activities
L + 70 days

Observatory first light (ISIM at safe operating temp)
L + 59 days

L2 orbit achieved
L + 109 days

Initiate ISIM testing and certification
L + 113 days

L2

~1,500,000 km

~374,000 km

This material is approved for public use.
Power and Communications are the Initial Deployments

Observatory Separation from LV

Solar Array Deployment

High Gain Antenna Deployment

Solar Array Deployment

Radiator Shade

Solar Array

High Gain Antenna Deployment

This material is approved for public use.
Sunshield Deployment

Flight-proven cable driven boom system provides a predictable and reliable deployment for the Sunshield.
OTE Deployments

Secondary Mirror Deployment

Primary Mirror Deployment

Tower Deployment

Secondary

PM Deployment

Cool Down

1.5 m deployment

Tower Launch Locks

Spacecraft Bus

Primary Mirror Wing

103°
Primary Mirror Chord-Fold Architecture

- Enables passive PSF stability throughout mission
  - Allows thermal strapping between backplane chords and the mirror segment
  - Thermal uniformity and conductivity minimize primary mirror gradients without active control
- Simple and low risk deployment concept – full-scale hinge-line structure (DOTA) tested at temperature
  - Minimum number of actuators
Deployments Use Flight-Proven Technologies

• Based on proven TRW technologies and hardware used on numerous flight programs – over 672 deployable systems (1824 individual articulations) with 100% mission success
  – DOTA tested full-size chord-fold structure at temperature for stability
  – Hinges and latches tested for SMSS and PM deployments and repeatability
  – Sunshield deployment membrane management analyzed using 1/2 scale model

• Simplicity of design relative to past successes
  – TDRS flights A through F have 52 articulations each, were 100% reliable
  – JWST has 39 articulations

• Heaters used to allow latches and hinges to operate at any time
Segmented Primary Mirror Architecture

• Six unique segment Prescriptions
  – A, B, C, D, E and F
  – Six spare PM segments
• Each segment is tested pre & post cryogenic figure
  – Cryogenic tested after coating
• Reference optic (C6) used to link the tests together
• Tests are conducted in groups of seven
  – Reduces the amount of cryo test time and support personnel labor

7 meters flat to flat
Optical Design Provides Wide Field-of-View With Well Defined ISIM Interface

- Three mirror anastigmat (TMA) has few surfaces to provide required wide FOV which supports efficient deep survey science operations

- Simple on-axis conic prescriptions
  - Avoids costly fabrication
  - Generous alignment tolerances between OTE and ISIM

- Fine steering mirror provides low cost, straightforward image motion control
  - Eliminates low frequency jitter
  - Provides FOV offsets (dither)
  - Offloads large angles to spacecraft ACS
Semi-Rigid Hexagonal Segments

Simplifies Wave Front Sensing & Control (144 actuators)
- Tip, tilt, piston, and ROC control
- Rigid body corrections do not induce surface distortions or stress

- Observatory optical quality (mid and high spatial frequency) is manufactured into segments
- Segments fully tested before OTE assembly
- Fabrication and performance demonstrated for baseline Be material
- Mirror architecture can use Be or ULE - both these AMSD developers are on the team
- Efficiency in production - same physical structure
- Simplifies system optic performance end-to-end test at temperature prior to launch

Final selection of mirror material will be made using AMSD results.
Thermally Stable Backplane Structure

- Single layer insulation (SLI) decouples backplane structure from sunshield thermal environment.
- Patent Pending Boron/M55J GFRP Hybrid backplane provides low CTE over OTE operating range.
- Secondary mirror uses six actuators in a hexapod configuration, provides positioning margin for WFS&C.
- Primary mirror segments attached to backplane using actuators in a simple three-point kinematic mount.
Telescope Commissioning Process

1. Coarse Alignment
   - Secondary mirror aligned
   - Primary RoC adjusted

2. Coarse Phasing
   - Fine Guiding

3. Fine Phasing

4. Image-Based Wavefront Monitoring

**First light NIRCam**

<table>
<thead>
<tr>
<th>Initial Capture</th>
<th>Final Condition</th>
</tr>
</thead>
</table>
| 36 individual 1-meter diameter sub-telescope images | • Primary (PM) segments: < 200 μm, < 1 arcmin tilt  
• Secondary Mirror: < 1 mm, < 2 arcmin tilt |
| • PM: < 1 mm, < 2 arcmin  
• Secondary mirror – 3 mm translation – 5 arcmin tilt | • WFE < 200 μm (rms) |
| • WFE: < 250 μm rms | • WFE < 1 μm (rms) |
| • WFE: < 5 μm (rms) | • WFE < 100 nm (rms) |
| • WFE: < 150 nm (rms) | • WFE < 100 nm (rms) |

This material is approved for public use.
Thermo-physical properties of full-scale section of sunshield were measured and our models validated

- 23 mwatts to OTE side from 301 kW solar radiation input

Precision Adjustable Mesh System with numerous flight deployments

Sunshield Material and Configuration tested at Cryogenic Temperature

Deployment Membrane Management Issues Addressed in 1/2 Scale Model
Sunshield Design Details Provide Margin for Daily Operations and Planning

Roll Field of Regard

5° additional margin in pitch and role for operational safety

2.5° to 5.0° dihedral angle separation between plies

Epaulets to control stray light

Pitch Field of Regard

5° additional margin in pitch and role for operational safety

On-orbit adjustability

Daily Momentum Buildup of 3-Plane Configuration

Dihedral Angles and Coating

Vapor Deposited Al (VDA) Coating
Kapton Substrate
Si or Ge Coating

Line of Symmetry

Micrometeoroid punctures

This material is approved for public use.
# Observatory Power Budget

<table>
<thead>
<tr>
<th>Element</th>
<th>Estimated Power (W)</th>
<th>Growth Allocation (%)</th>
<th>Predicted Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Telescope Element</td>
<td>30</td>
<td>35</td>
<td>40.5</td>
</tr>
<tr>
<td>OTE Nominal Power</td>
<td>30</td>
<td>35</td>
<td>40.5</td>
</tr>
<tr>
<td>ISIM Element</td>
<td>130 (allocated)</td>
<td>0</td>
<td>130</td>
</tr>
<tr>
<td>ISIM C&amp;DH</td>
<td>65</td>
<td>0</td>
<td>65</td>
</tr>
<tr>
<td>FPE Boxes</td>
<td>65</td>
<td>0</td>
<td>65</td>
</tr>
<tr>
<td>Spacecraft Element</td>
<td>665.9</td>
<td>20</td>
<td>796.5</td>
</tr>
<tr>
<td>Attitude Control</td>
<td>83.6</td>
<td>11</td>
<td>146.6</td>
</tr>
<tr>
<td>Communications</td>
<td>76.0</td>
<td>20</td>
<td>211.2</td>
</tr>
<tr>
<td>Command and Data Handling</td>
<td>148.8</td>
<td>25</td>
<td>186.1</td>
</tr>
<tr>
<td>Thermal Control</td>
<td>30.0</td>
<td>25</td>
<td>37.5</td>
</tr>
<tr>
<td>Propulsion</td>
<td>83.6</td>
<td>22</td>
<td>101.8</td>
</tr>
<tr>
<td>Electrical Power</td>
<td>95.9</td>
<td>18</td>
<td>113.4</td>
</tr>
<tr>
<td>Observatory Total</td>
<td>825.9</td>
<td>17</td>
<td>967</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Solar Array</th>
<th>Capability (W)</th>
<th>Predicted Margin (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 year Capability @ 35° Sun Angle</td>
<td>1392.8</td>
<td>425.8</td>
</tr>
<tr>
<td>10 year Capability @ 35° Sun Angle</td>
<td>1381.0</td>
<td>414.0</td>
</tr>
<tr>
<td>15 year Capability @ 35° Sun Angle</td>
<td>1365.5</td>
<td>398.5</td>
</tr>
</tbody>
</table>

- Growth allocation and Margin exist for > 10 year operation.
Spacecraft (Bus) Packaging

**VIEW DURING AI&T (Removable Panels Are Shown Before Installation)**

- **L2 Orbit with Contamination Control**
  - Stationkeeping thruster on fixed boom provides \( \Delta V \) in any direction
  -...

- **AI&T Access**
  - Battery access panel

- **Attitude Determination and Control**
  - 3 Star tracker assemblies with clear fields of view
  - Inertial reference unit collocated with Star Tracker to minimize control system errors

- **Limit Heat leakage into OTE**
  - Ample volume for all avionics mounted on removable radiator panels
  - Heat pipes used for heat rejection

- **Dual Frequency High Gain Antenna**
  - Supports X-band and S-band communications
  - 130° of operational pitch angles

**DEPLOYED VIEW**

- **Attitude Determination and Control**
  - Coarse sun sensors (4, located on each outboard solar array tip)
  - Fine sun sensor provides sun position monitoring through all operational attitudes

- **Radiator Shading**
  - Shades improve radiator effectiveness in presence of warm sunfacing sunshield layer

- **Jitter Isolation and LOS pointing**
  - Reaction wheels and isolators located near bus C.G. for best jitter attenuation

- **Power for Observatory**
  - Solar arrays fixed at center of operational pitch range for operational simplicity and reliability
  - Solar cells face outward in stowed configuration to eliminate solar array deployment time constraint

This material is approved for public use.
Focal Plane Layout (sample)

- WFE Budget assumes 13nm for Design Residual
- Example shown is one of many possibilities – requires SI assessment to determine science needs
Seeing First Light: NIR Camera

- Marcia Rieke (UofA) PI
  - LMATC (Palo Alto)
  - EMS & CoM Dev
- Features
  - 2 X 2.3’ x 2.3’ FOV
  - Transmissive cameras
    » Dichroic split between 0.6-2.3 µm & 2.4-5.0 µm detector assemblies
    » R ~ 4 filters plus selected medium bands
    » Wavefront sensing optics
- 2 narrow band cameras, R ~ 100

1 of 2 NIRCam Imaging Chains

This material is approved for public use.
The First Metals & the Epoch of reionization: Near IR Spectrograph (NIRSpec)

- Major ESA Contribution to NGST
- PI: Peter Jackobsen
- Prime Science Goals
  - Confirm high redshift of proto-galaxies
  - Measure properties of galaxies as a function of redshift
- Features
  - 9 arc-min² FOV
  - 1 – 5 μm wavelength coverage
  - R=1000(gratings) & R=100(prism)
  - >100 Simultaneous targets
  - 2kx4k NIR focal plane
A new wavelength frontier (5µm - 27 µm)
Mid-Infrared Instrument (MIRI)

Optics Module concept
developed by European Consortium

FPAs

MIRI Crysotat concept

US/European Instrument
G. Rieke/Gillian Wright Science Leads

This material is approved for public use.
Phase A Investments Have Reduced Risk

This material is approved for public use.
High Fidelity End-to-End Optical Performance Test During End-to-End I&T

- Semi-rigid architecture permits a cost-effective, sampled full aperture, end-to-end test to reduce risk in on-orbit performance
  - Verify total optical system (OTE and ISIM)
  - Verify WFS&C performance (every actuator, every optical element) at vibration levels equivalent to flight
  - No segment 1 “G” offloading
    » Backplane is offloaded with simple devices
- Plum Brook is the best facility for testing JWST
  - Lowest cost to implement
  - Vertical orientation induces minimal impacts on the flight design
  - Lowest vibration levels of any facility in the country
  - Test conditions will better simulate on-orbit conditions
  - Higher confidence in on-orbit predictions

This material is approved for public use.
Sampled Aperture Test Verifies End-to-End Optical Performance Prior to Launch

- Three independent measurements confirm performance
  1) Primary mirror Center of Curvature (CoC)
  2) OTE optical performance using sampled full aperture
     All optical segments and every actuator sensed
  3) Simultaneous verification using NIRCam
     » Includes ISIM and FPA/FPE
     » Recover sampled aperture phase map
     » Verify WFS&C loop and algorithms
- Multiple wavelength interferometers provide absolute phase knowledge
- Full aperture CoC test and sampled full aperture test occur simultaneously
  – Complete, instantaneous insight into Observatory performance
  – >95% of OTE optical surfaces sensed

End-to-end optical performance is thoroughly verified prior to launch.
## Observatory Performance

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
<th>Estimated Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aperture</strong></td>
<td>&gt;25 m² collecting area</td>
<td>29.4 m²</td>
</tr>
<tr>
<td><strong>Encircled Energy</strong></td>
<td>&gt;75% for 150 mas radius at 1 µm</td>
<td>82% (details in later chart)</td>
</tr>
<tr>
<td><strong>PSF Stability</strong></td>
<td>&lt;2% RMS variation about mean over 24 hours at 150 mas radius at 1 µm</td>
<td>≤0.31% worst case over FOR</td>
</tr>
<tr>
<td><strong>Sensitivity</strong></td>
<td>Minimum target sensitivities at 4 wavelengths</td>
<td>Comply (details in later chart)</td>
</tr>
<tr>
<td><strong>Field of Regard (FOR)</strong></td>
<td>100% of celestial sphere over one year &lt;35% at any time &gt;50% of sky for &gt;60 days Continuous within 5° of Ecliptic pole</td>
<td>100% (details in later chart) 48.9% &gt;55% of sky for &gt;194 days Comply</td>
</tr>
<tr>
<td><strong>Observatory Efficiency</strong></td>
<td>&gt;70% (85% OTE and Spacecraft/85% ISIM)</td>
<td>77.2% (details in later chart) (92% OTE&amp;SC/85% ISIM)</td>
</tr>
<tr>
<td><strong>Instrument FOVs</strong></td>
<td>Spatially separated FOVs, SI + FGS FOV &gt; 68 square arc-minutes</td>
<td>105 square arc-minutes can be larger</td>
</tr>
<tr>
<td><strong>Launch</strong></td>
<td>Mass &lt;5400 kg (includes 1400 kg GFE ISIM)</td>
<td>Comply; ~509 kg reserve over and above contingency</td>
</tr>
</tbody>
</table>

This material is approved for public use.
Optical Performance Is Excellent!

**Encircled Energy**
- Mid spatial frequencies Wave Front Errors (WFE) are polished in and verified with semi-rigid mirror architecture.

**Stability of Image Quality**
- Insensitive to average operating temperature.
- Tolerant to slow changes in thermal environment.
- Requirement is stability of EE at 150 mas $< 2\%$ rms about mean at $\lambda=1 \mu m$ over 24-hour period.

### Sun Angle (Hot-to-Cold Case)

<table>
<thead>
<tr>
<th>PSF Stability at 150 mas</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15° to -63°</td>
</tr>
<tr>
<td>≈0.31%</td>
</tr>
</tbody>
</table>

Observatory has margin in meeting image quality requirements without active control.
Observatory Sensitivity surpasses Spec by ~ Factor of 3

- SNR = 10; 100,000 second integration; point target at North ecliptic pole
- End-of-life conditions, worst-case scattering
- ISIM performance from Appendix A of Level 2 Specification
Observatory Background > 3 times lower than Spec.

Scattered and Self-Emission

Level 2 Requirements

Minimum Zodiacal Background (NMS)

Observatory Background (ASAP)

Wavelength (μm)

Watts/m²•sr•µm

3.9 MJy/sr

200 MJy/sr

This material is approved for public use.
Momentum Balanced Sunshield Provides a Large Field of Regard (for simpler Ops)

Observatory Field-of-Regard (FOR)

- Exclusion < 27° from Anti-Sun
- Exclusion Zone < 85° from Sun
- Anti-Sun LOS
- Allowable Observatory Field-of-Regard

Benefits of momentum balanced sunshield include:
- Large FOR, Simple mission operations, and Stable OTE temperature

Requirements:
- 100% of sky visible at least 69 continuous days
- 55% of sky visible at least 194 continuous days
- Requirement: > 50% of sky visible continuously > 60 days
- 0.4% of sky visible continuously throughout year

Annual Minimum Continuous Days Available vs. Percent Sky Coverage

Zone which violates meeting requirements

Benefits of momentum balanced sunshield include: Large FOR, Simple mission operations, and Stable OTE temperature
Excellent Spacecraft Observing Efficiency

<table>
<thead>
<tr>
<th>Overhead Activity</th>
<th>Activity Duration (days) to EOL (EOL = 5 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slew, guide star acquisition, and settling</td>
<td>76</td>
</tr>
<tr>
<td>Small angle slews</td>
<td>14</td>
</tr>
<tr>
<td>Wavefront sensing and control</td>
<td>30</td>
</tr>
<tr>
<td>Momentum control</td>
<td>2</td>
</tr>
<tr>
<td>Stationkeeping</td>
<td>2</td>
</tr>
<tr>
<td>Thermal settling</td>
<td>0</td>
</tr>
<tr>
<td>Safe Mode</td>
<td>18</td>
</tr>
<tr>
<td>High Gain Antenna steering</td>
<td>0</td>
</tr>
<tr>
<td>Image quality monitoring</td>
<td>0</td>
</tr>
<tr>
<td>Sunshield reconfiguration</td>
<td>0</td>
</tr>
<tr>
<td>Predicted OTE/Spacecraft Overhead</td>
<td>142 days (7.8%)</td>
</tr>
<tr>
<td>ISIM Overhead Allocation</td>
<td>274 days (15%)</td>
</tr>
<tr>
<td>Observatory Efficiency</td>
<td>77.2%</td>
</tr>
</tbody>
</table>

Passive stability of Observatory enables science observation immediately after slewing.

This material is approved for public use.
# Observatory Plan

## Program Milestones

<table>
<thead>
<tr>
<th>Calendar Year</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Milestones</strong></td>
<td>ATP</td>
<td>SRR</td>
<td>SDR</td>
<td>PDR</td>
<td>CDR</td>
<td></td>
<td>MOR</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mirror Fabrication</strong></td>
<td>Optics Review</td>
<td>Start Polishing</td>
<td>1st PM Segment</td>
<td>36th PM Segment</td>
<td>Manufacture</td>
<td>Cryo Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>OTE</strong></td>
<td>Flight</td>
<td>Design</td>
<td>Manufacture</td>
<td>AI&amp;T</td>
<td></td>
<td></td>
<td>ISIM Delivery</td>
<td>Pathfinder</td>
<td>Build</td>
</tr>
<tr>
<td><strong>Sunshield</strong></td>
<td>Flight</td>
<td>Design</td>
<td>AI&amp;T</td>
<td></td>
<td>Pathfinder</td>
<td>Design / Build /Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Flight Software</strong></td>
<td>Common C&amp;DH</td>
<td>SDL Delivered</td>
<td>Spacecraft and OTE Flight Software (FSW)</td>
<td>JWST FSW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Spacecraft</strong></td>
<td>Flight</td>
<td>Design</td>
<td>Build, AI&amp;T</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Observatory I&amp;T</strong></td>
<td>Facilitization</td>
<td></td>
<td>Assembly, Test &amp; Verification</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This material is approved for public use.
JWST Science & Operations Center Roles

Hornig NAS Report

HST Exp.

New

• Lead Scientific Community Outreach
• Conduct the science mission from solicitation to grants
• Support NASA and development partners
• Develop Planning and Scheduling System
• Develop Pipeline data reduction & data archive support
• Lead Education and Public Outreach
• Develop Flight Operations System
STScI/AURA Contributions to JWST

- STScI & AURA were the primary leads in developing the scientific case and concept for JWST (1989-1999) with membership on all subsequent Science Working Groups
- STScI staff (and ex-staff) were key “inventors” of the JWST we see today.
  - The passive cooling of a large telescope via an open architecture
    » one-sided sunshade, no baffle tube (Bely)
  - The Ball Be Hex mirror & deployment (Crocker)
  - The initial instrument baseline (NIRCam, NIRSpec, MIRI) in 1996
  - The multi-aperture spectrometer (Mackenty micro mirrors)
- STScI staff continue to play a major role in the definition of science and technical requirements for JWST
  - The Mission Operations Concept
  - The initial Level 1 (now Level 2) requirements -- supports
    » Optical
    » Telemetry
    » Sensitivity
    » Efficiency
    » Fine Guidance
    » Etc.
- STScI continues to play a major role in “re-optimizing” the Observatory prior to Phase B

This material is approved for public use.