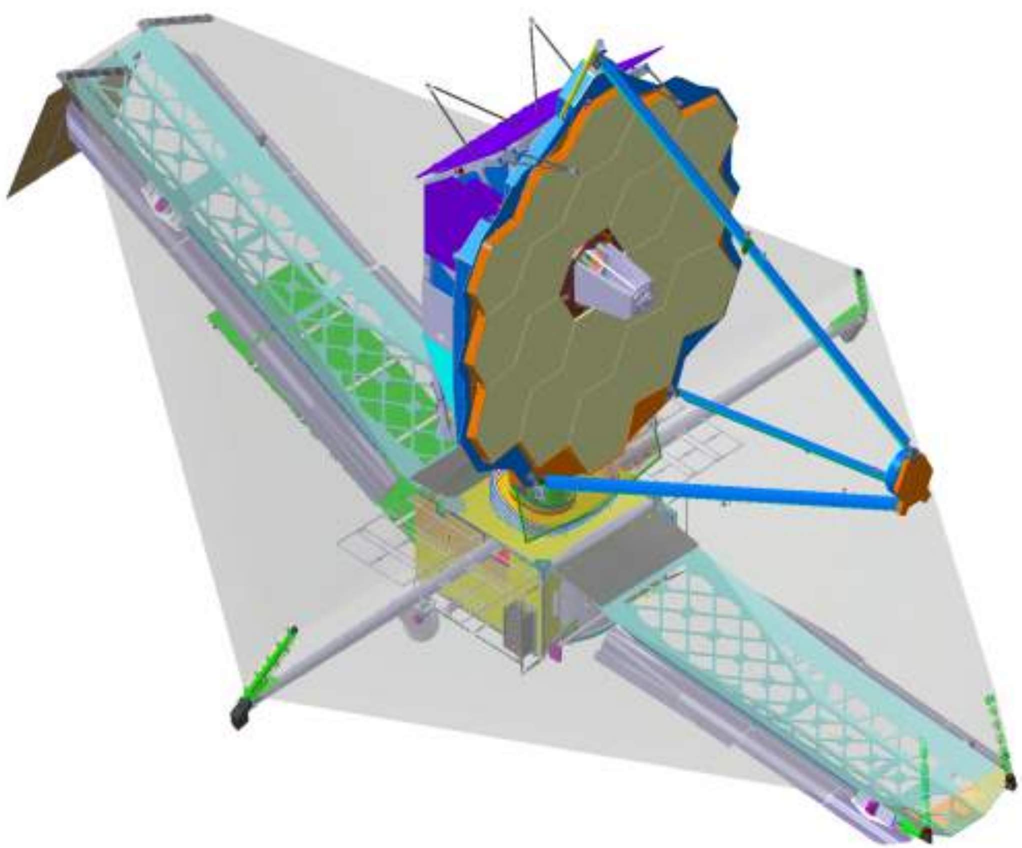
James Webb Space Telescope (JWST)
Technology Discussion For APPEL Forum

August 7, 2008



John Decker

Deputy Program Manager

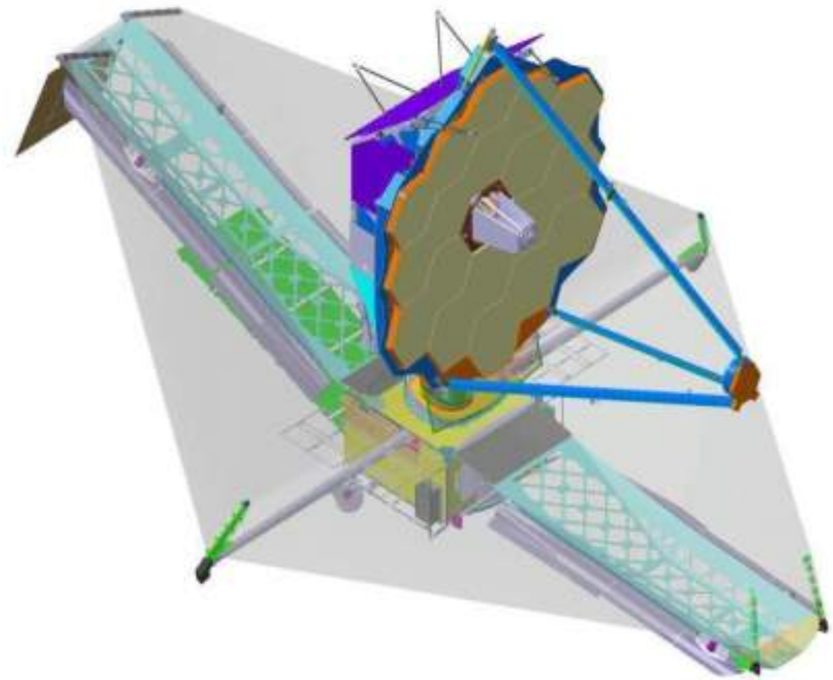
(GSFC)

JWST Full Scale Model at the GSFC

JWST Mission “At a Glance”

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



Description

- Deployable infrared telescope with 6.5 meter diameter segmented adjustable primary mirror
- Cryogenic temperature telescope and instruments for infrared performance
- Launch June 2013 on an ESA-supplied Ariane 5 rocket to Sun-Earth L2
- 5-year science mission (10-year goal)

JWST Science Themes

End of the dark ages: First light and reionization

The assembly of galaxies

Birth of stars and proto-planetary systems

Planetary systems and the origin of life

JWST Technology Development Perspective

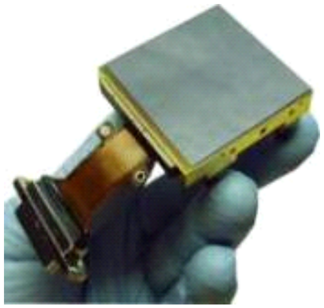
- As a condition of obtaining Agency approval to enter the implementation phase (Phase C), projects are required to "Complete development of mission-critical or enabling technology, as needed, with demonstrated evidence of required technology qualification…" (ref. NPR 7120.5D, para. 4.5.2.b.(6))
  - This completion is normally confirmed by a Non-Advocate Review Team (NRT) as part of the Mission Preliminary Design Review (PDR) and Non-Advocate Review (NAR)
- At the inception of the JWST program, NASA adopted a strategy of making significant, early investments in the enabling technology development efforts, with the goal of ensuring that the JWST enabling technologies would reach a maturity level of TRL-6 before the transition to Phase C
  - This was based on lessons learned from other NASA programs that carried significant technology development risks (and therefore significant cost and schedule risks) into Phase C
- JWST enabling technology development efforts were initiated just as soon as the needs for the enabling technologies were identified
  - In several cases this involved partnering with other programs (and even other agencies) at the earliest stages of development
- The Project underwent a significant replan in 2006 that moved the transition to Phase C from January 2007 to July 2008
  - The Project made a strategic decision to continue to pursue its original commitment to retire its enabling technology development risk by January 2007 and requested a formal review in January 2007 to confirm the maturation of its enabling technologies to Technology Readiness Level 6 (TRL-6)
  - Headquarters agreed to assemble a NRT to conduct only the technology readiness portion of the readiness to enter Phase C in January 2007 (called the Technology NAR (T-NAR))

JWST Technology Development Summary

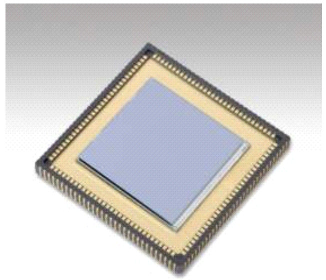
- The JWST program identified ten enabling technologies required to achieve the performance needed to achieve the JWST science mission
  - Near Infrared Detectors
  - SIDECAR ASIC
  - Mid Infrared Detectors
  - MIRI Cryocooler
  - Microshutters
  - Heat Switch
  - Sunshield Membrane
  - Wavefront Sensing and Control
  - Primary Mirror
  - Large Cryogenic Stable Structure
- The NRT assessed the readiness of these technologies in January 2007, more than a year before the Mission PDR and NAR
  - In their assessment report dated April 2007, the NRT confirmed that the TRL-6 success criteria had been met for all of the JWST enabling technologies
- The NRT (now known as the Standing Review Board, or SRB) re-convened for the JWST Mission PDR in March 2008 and the JWST NAR in April 2008, both of which were deemed successful by the SRB
- The JWST program received the Agency's official approval to enter Phase C in July 2008

JWST Enabling Technologies “At a Glance”

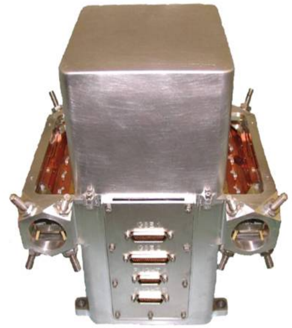
Near IR Detectors



Mid IR Detectors

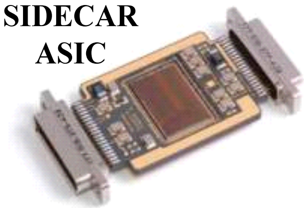


Heat Switch



Sunshield Membrane

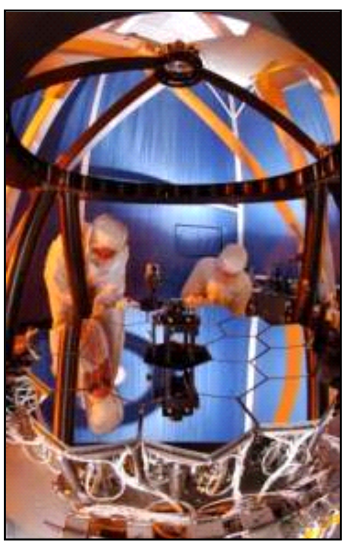
SIDECAR ASIC



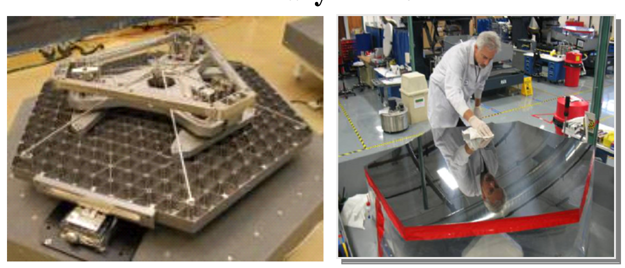
Stable Large Cryogenic Structures
Backplane Stability Test Article (BSTA)

MIRI Cryocooler

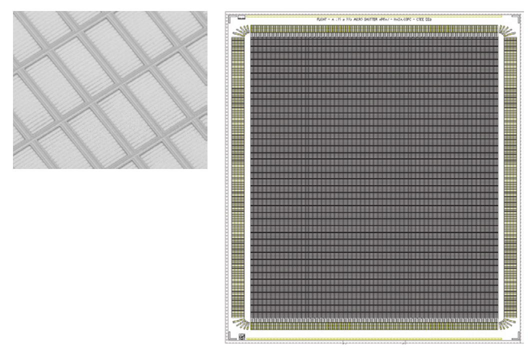
Wavefront Sensing & Control
Test Bed Telescope



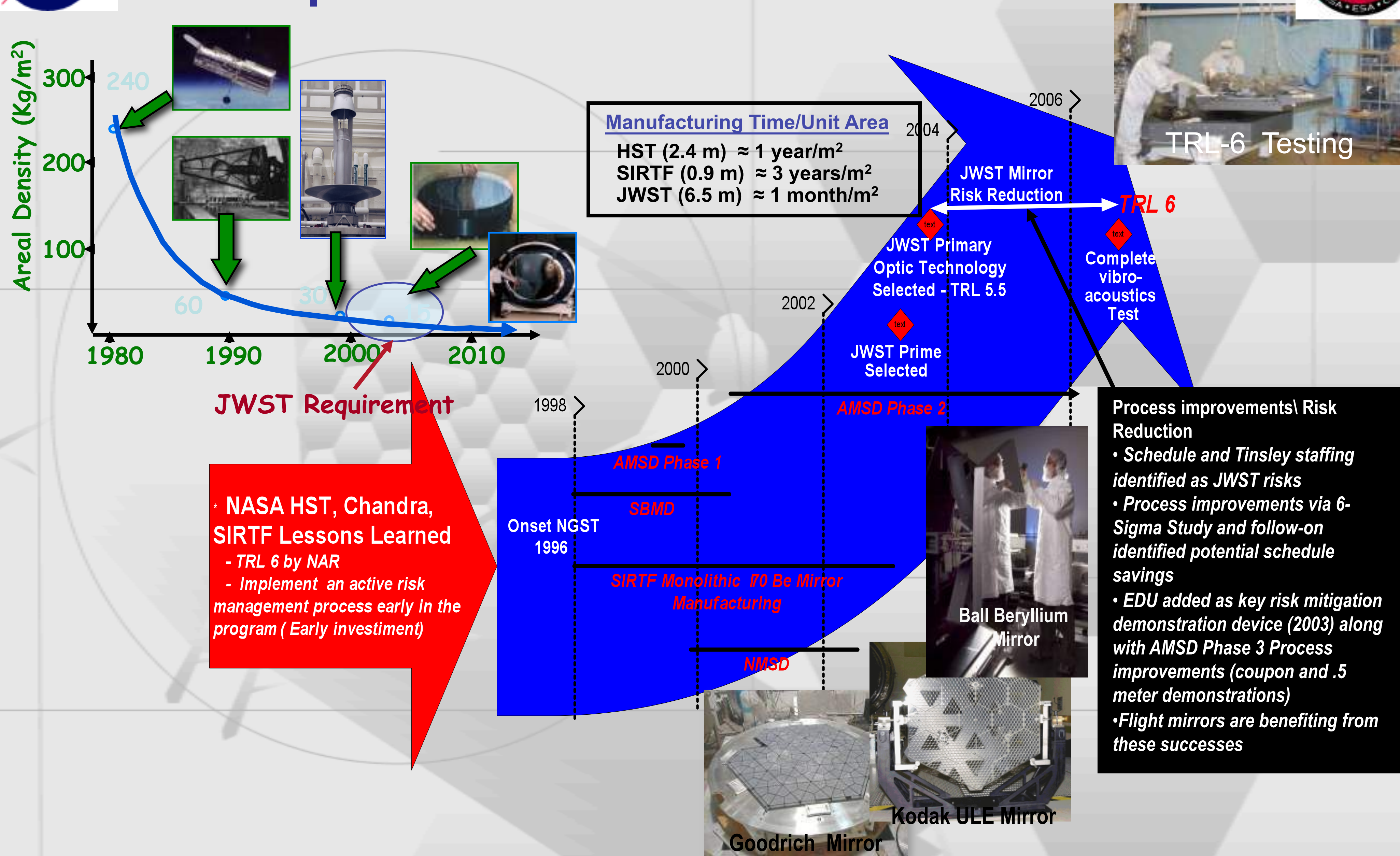
Primary Mirror



Micro Shutter



Example: JWST Mirror Technology Development



Based on lessons learned, JWST invested early in mirror technology and mirror production to address lower areal densities and manufacturing time

Summary

- Top-level technology development lessons from JWST:
  - Identify enabling technologies early
  - Respect the cost and schedule risks that they represent
  - Invest in them early and aggressively
  - If at all possible, try to mature enabling technologies early
    - The sooner you can demonstrate that the enabling technologies have reached the required level of maturity, the sooner you retire the associated cost and schedule risks and avoid carrying those risks into Phase C

Backup Charts

Technology Readiness Levels (for reference)

- **Appendix E.11 of the Space Science Enterprise Management Handbook (SSE MH2002, dated September 4, 2002) documents the TRL definitions, and the summary of those levels is as follows:**

  - TRL-1: Basic principles observed and reported
  - TRL-2: Technology concept and/or application formulated
  - TRL-3: Analytical and experimental critical function and/or characteristic proof-of-concept
  - TRL-4: Component and/or breadboard validation in laboratory environment
  - TRL-5: Component and/or breadboard validation in relevant environment
  - **TRL-6: System/subsystem model or prototype demonstration in a relevant environment (ground or space)**
  - TRL-7: System prototype demonstration in a space environment
  - TRL-8: Actual system completed and "flight qualified" through test and demonstration (ground or space)
  - TRL-9: Actual system "flight proven" through successful mission operations

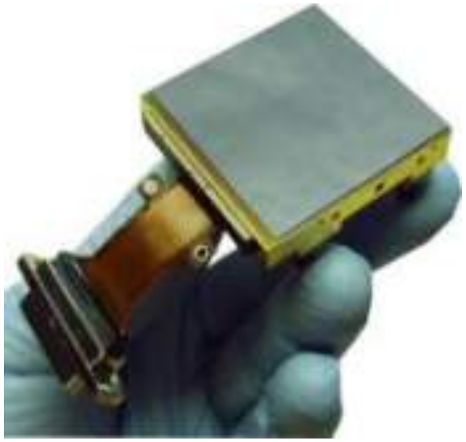
TRL-6 Definition (for reference)

- **Appendix E.11 of the Space Science Enterprise Management Handbook (SSE MH2002, dated September 4, 2002) details the individual TRL definitions, and the TRL-6 definition reads as follows:**

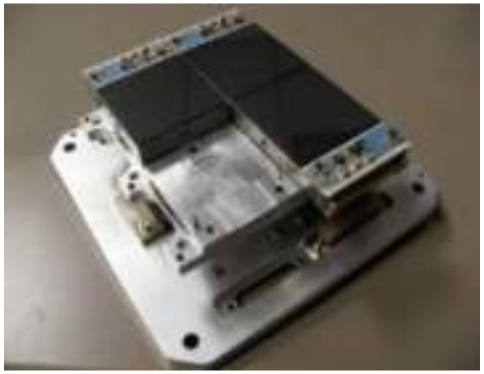
> **"TRL 6** ***System/subsystem model or prototype demonstration in a relevant environment (ground or space)***
>
> A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype system or system - which would go well beyond ad hoc, 'patch-cord' or discrete component level breadboarding - would be tested in a relevant environment. At this level, if the only `relevant environment' is the environment of space, then the model/prototype must be demonstrated in space. Of course, the demonstration should be successful to represent a true TRL 6. Not all technologies will undergo a TRL 6 demonstration: at this point, the maturation step is driven more by assuring management confidence than by R&D requirements. The demonstration might represent an actual system application, or it might only be similar to the planned application, but using the same technologies. At this level, several-to-many new technologies might be integrated into the demonstration. For example, a innovative approach to high temperature/ low mass radiators, involving liquid droplets and composite materials, would be demonstrated to TRL 6 by actually flying a working, subscale (but scale-able) model of the system on a Space Shuttle or International Space Station `pallet'. In this example, the reason space is the `relevant' environment is that micro-gravity plus vacuum plus thermal environment effects will dictate the success/failure of the system - and the only way to validate the technology is in space."

Near-Infrared Detectors – Overview

- **Driving Level 1 Requirements**
  - L1-1: Density of Galaxies […], λ=0.6-27 μm
  - L1-2: Spectra of Galaxies […], λ=0.6-5 μm
  - L1-3: Physical and Chemical Properties of Young Stellar Objects […], Requires spectroscopy & imaging, λ=0.6-27 μm
  - L1-4: Observing Time […], 5 year mission & 1.1×10^8 seconds on targets located anywhere on the celestial sphere
- **Existing NIR detector arrays did not meet JWST sensitivity and format requirements**
- **JWST's NIR detectors required a TRL-6 demonstration because they significantly advanced the state of the art in a number of areas, including: total noise, 2048×2048 pixel format for space, and λ=0.6-5 μm mercury-cadmium-telluride (HgCdTe) sensor chip assemblies (SCAs) at T=37 K**



The Teledyne Imaging Systems (TIS; formerly Rockwell) HAWAII-2RG SCA was developed for JWST



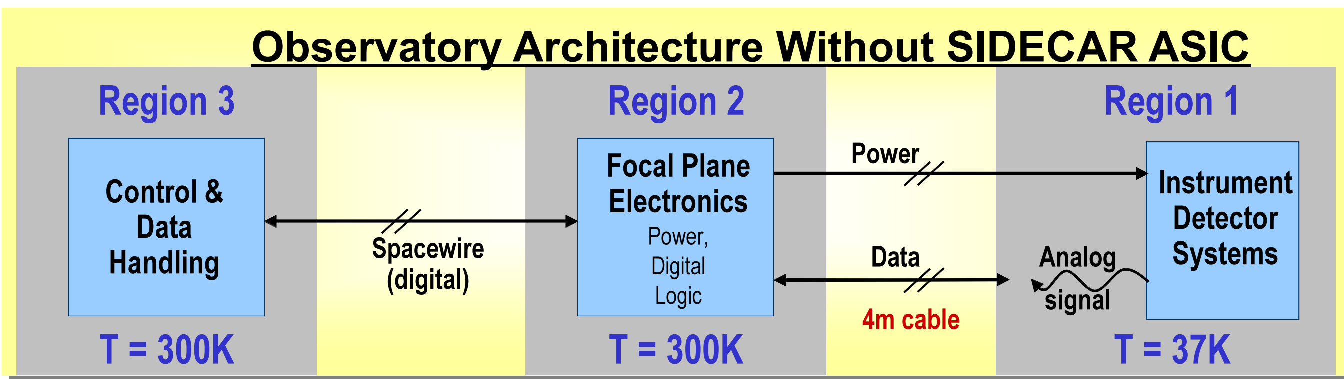
Partially populated model of NIRCam focal plane assembly at U. Arizona

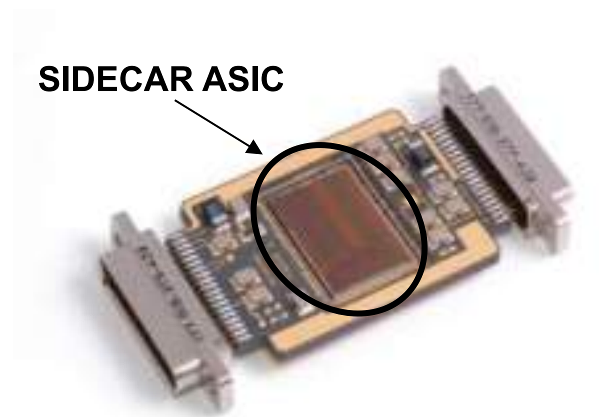
The edge-on spiral galaxy NGC 891, as seen by a 2x2 mosaic of JWST NIR SCAs on the U. Hawaii 2.2-m telescope.

Cryogenic SIDECAR ASIC – Overview

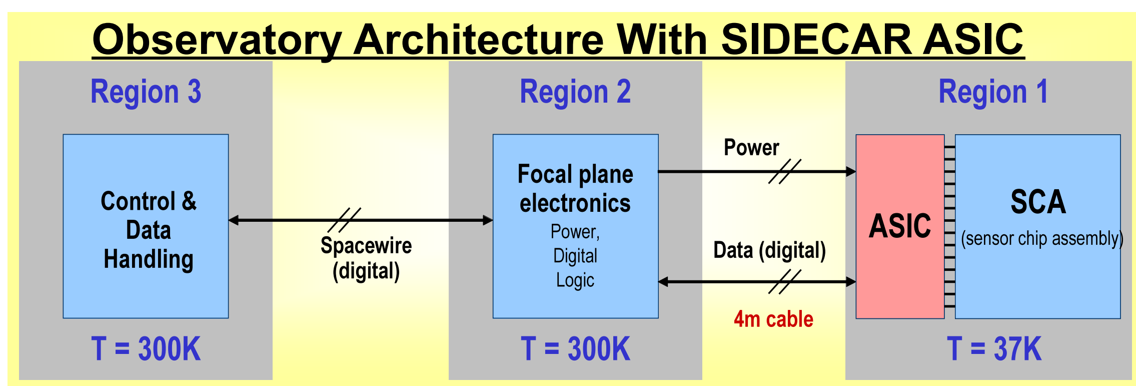
System for Image Digitization, Enhancement, Control and Retrieval

- JWST observatory has 3 Near Infrared (NIR) science instruments: NIRCam, NIRSpec and FGS (Fine Guidance Sensor) including the Tunable Filter Imager (TFI), each using the HAWAII-2RG detectors.
- The observatory architecture is such that the analog signals from the detectors would need to be transmitted from the cold detector side to the warm electronics side over 4 meter harnesses.
- A low noise analog signal transmitted over such distances runs the risk of cross talk among different Science Instrument (SI) harnesses and perhaps other observatory harnessing/electronics





SIDECAR ASIC is used to replace conventional electronics for detector signal digitization and processing



Mid-Infrared Detectors – Overview

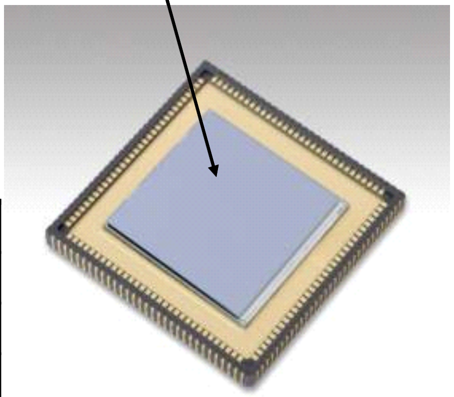
- **Mid-infrared observations enable all four key science themes of JWST**

- **Driving Level 1 Requirements**
  - MR-51: The observatory system shall reach the sensitivity performance levels shown

10 μm	MIRI Broad-Band	7.0×10^{-33} W m^{-2} Hz^{-1} SN=10 in 10,000 s or less and R=5 bandwidth
21 μm	MIRI Broad-Band	8.7×10^{-32} W m^{-2} Hz^{-1} SN=10 in 10,000 s or less and R=4.2 bandwidth
9.2 μm	MIRI Spectrometer	1.0×10^{-20} W m^{-2} SN=10 in 10,000 s or less and R=2400 bandwidth
22.5 μm	MIRI Spectrometer	5.6×10^{-20} W m^{-2} SN=10 in 10,000 s or less and R=1200 bandwidth

  - MR-107: The Observatory spectral coverage shall extend from 0.6 µm to 27 µm.
  - MR-185: The SIs shall perform imaging with spectral bandwidths in the range of 3 < R < 200 over a wavelength range of 0.6 - 27 µm.
  - MR-186: The SIs shall provide spectroscopy with spectral resolution in the range of 50 < R < 5000 over a wavelength range of 0.6 - 27 µm.

Sensor Chip Assembly – this is the TRL6 item



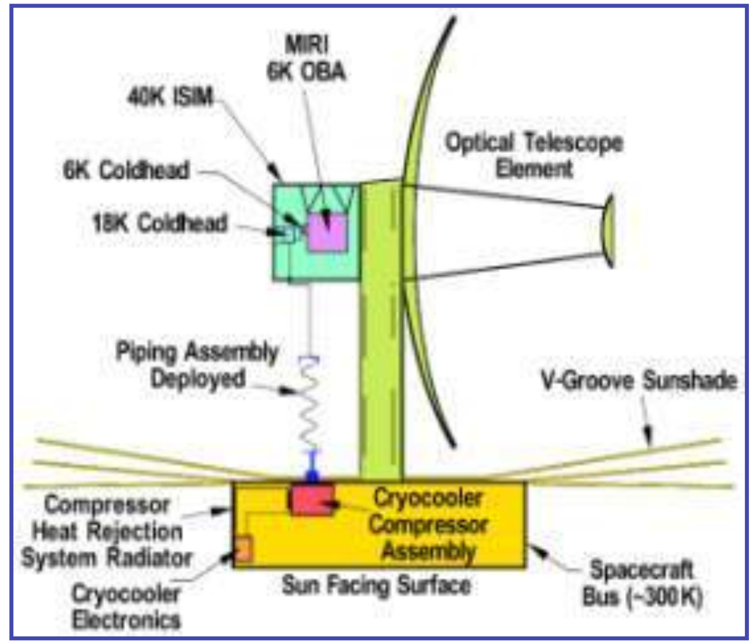
- **The MIRI detectors are closely related to the arsenic-doped silicon (Si:As) Spitzer/IRAC arrays**
  - The MIRI detector layers are developed using exactly the same processes as the Spitzer devices
  - The readouts, while implementing a slightly different design, use the same Integrated Circuit design rules and foundry processes

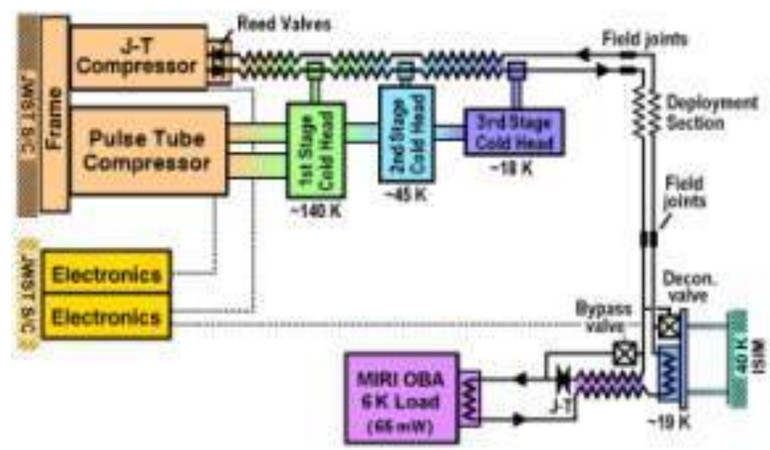
Property	Spitzer/IRAC	JWST/MIRI
Format	256x256	1024x1024
Dark Current	< 10 e-/s (1-4 e-/s)	< 0.03 e-/s
Read Noise	< 20 e- (15 e-)	< 19 e-
QE	> 23% @ 6.3 μm	> 50%

MIRI Cryocooler – Overview

- **The need for the MIRI Cryocooler is driven by the following 2 MIRI functional requirements:**
  - MIRI Optics Temp ≤ 15.5K
  - MIRI Detector Temp ≤ 6.7K

- **JWST requires the first long life, 6K mechanical cooler, with the 6K load several (~10-15) meters from the compressors**
  - Most of the previously flown coolers are for T~50-80K
  - 6K cooling is much harder than 50K
    - **Carnot limit order of magnitude larger**
    - **Best previous 6K coolers require ~100X more power per W of cooling**
  - Pre-cooling must be located meters from final 6K temperature sink
    - **Previous sub-10K coolers (including Planck) pre-cool in the cold (18K) environment, cm from final sub-10K heat sink**
  - Long life “Oxford style” Pulse Tube and Stirling mechanical coolers are TRL 9 for T~50-80K.
    - **Multiple systems currently operational on-orbit**
    - **Technology is the basis for the MIRI Cooler application**



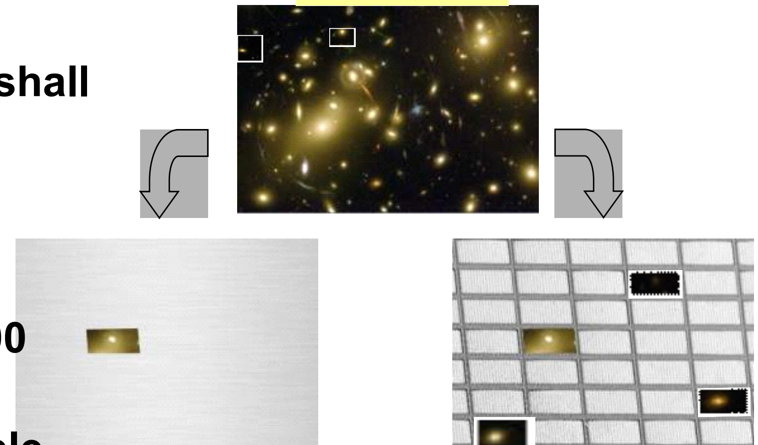


None of the existing flight technologies for ~6K cooling are directly applicable to the JWST application of 65mW at 6K, 10+ meters away from the pre-cooler (imposing a large (77mW) additional load on the 18K pre-cooler), and with >5 year life.

Microshutters – Overview

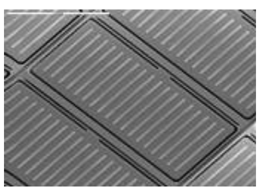
- So as to enable the 5 year mission and the mission operations concept observing time allocation to NIRSpec
  - ISIM Requirements Document -- ISIM-463: The NIRSpec shall enable multi-object spectroscopy of up to 100 objects simultaneously
- Previously flown spectrometers had fixed slits which only permitted the viewing of one object at a time. A fixed slit spectrometer would not meet the level 1 requirement of 2500 galaxies in 5.5 years.
- The Microshutter arrays are a controllable and reconfigurable aperture-mask to allow multi-object optical transmission to a spectrograph
- No flight cryogenic technology existed for this application prior to this development.

Astronomy Scene

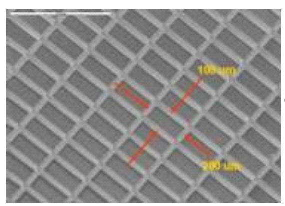


Metal Mask/Fixed Slit

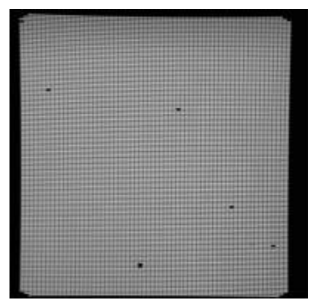
Shutter Mask



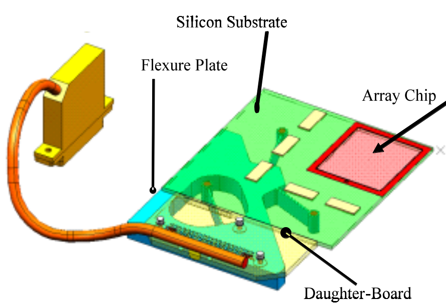
Individual Shutter
100 x 200 microns



Backside of Array

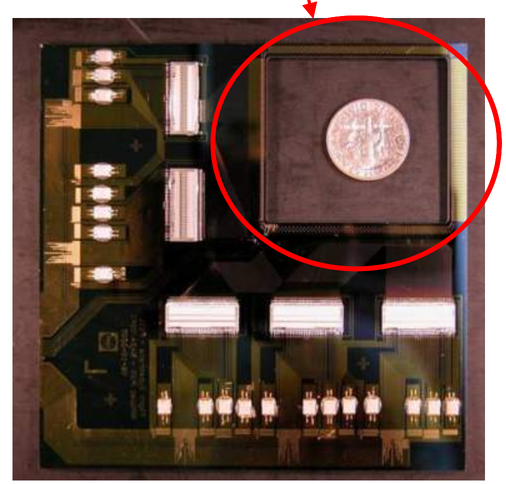


171 X 365 Array
62,415 shutters



Quadrant

TRL-6 Item is the Array



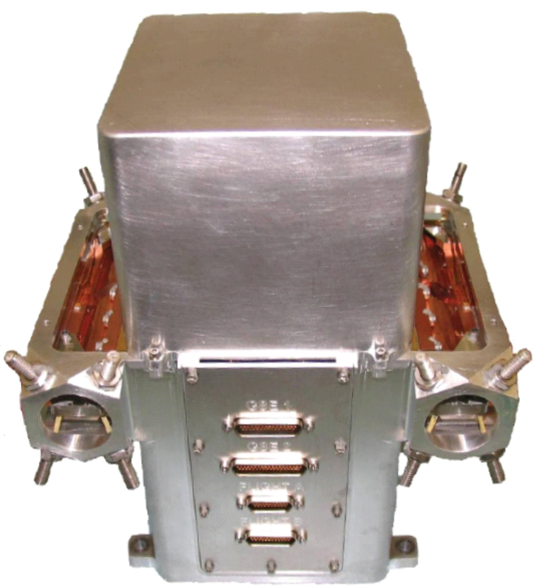
Heat Switch – Overview

Key Requirement (ISIM Requirements Document)

ISIM-726 - The ISIM TCS shall provide a controllable thermal conductance between the SIs' optical benches and the instrument radiator to permit SI-provided heaters on contamination sensitive components to maintain them at or above 160K until the ISIM Structure cools to 140K.

Pre-JWST state of the art switches did not meet requirements because they were designed for different use

- **Reliability: Single string devices not readily adaptable for higher reliability**
- **Prior switches developed for other purposes, did not have high enough conductance at JWST operating temperature**
- **OPEN/CLOSE:**
  - **Many switches are OPEN until cooled to certain temperature**
  - **Existing cryogenic "gas gap" type heat switches require power to stay "CLOSED", not acceptable for JWST mission**



JWST needs beyond state of the art

- **<u>High reliability</u>: Single failure-tolerant configuration**
- **<u>High closed conductance</u>: Thermal conductance of 1.125 W/K, passively CLOSED at instrument operational temperatures (29-40K), 1 of 4 individual switches failed "OPEN"**
- **<u>Capability to open over entire temperature range</u>: Low thermal conductance while OPEN at any temperature between ambient and survival (306K-22K)**

Sunshield Silicon-Coated Membrane Material – Overview

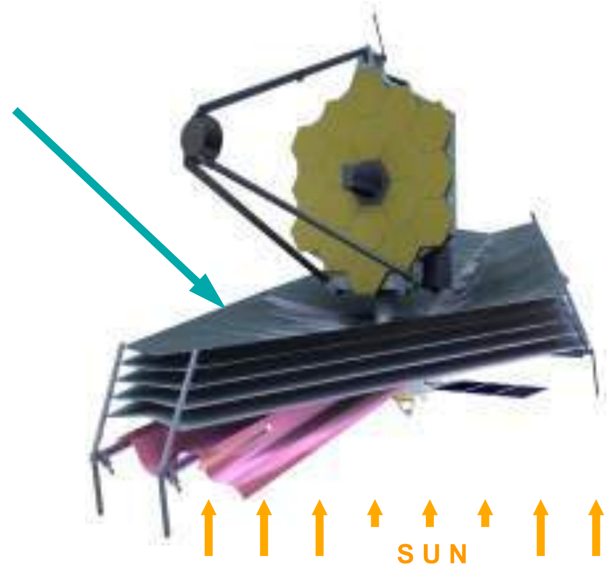
- **A lightweight deployable sunshield enables passive cooling of JWST telescope & instruments to stable, cryogenic temperature levels**

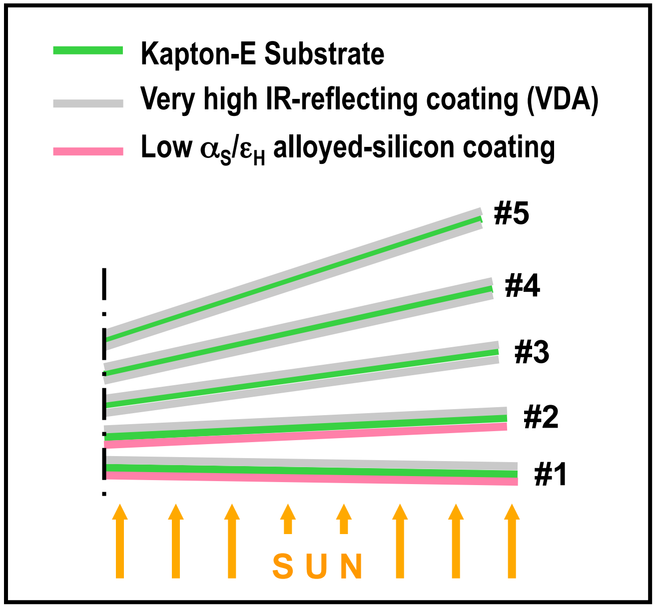
- **Sunshield requires a robust material system that meets thermal, electrical, mechanical and contamination performance requirements over JWST lifetime**
  - Low α_S/ε_H to minimize absorbed solar heat load
  - Semi-conductive (ρ_{ESD}) to provide a groundable surface and prevent discharge events

- **Material must be producible in large areas with consistent properties**

- **Existing technology coatings could not meet JWST requirements:**
  - Conductive paints are too thick and incompatible with folded thin membranes
  - Metallic coatings have $\alpha_S/\varepsilon_H > 1$
  - Brittle ITO coatings cannot maintain surface conductivity
  - ITO-SiO_2-VDA has brittleness/contamination problems
  - Ge coating corrodes in humid environment

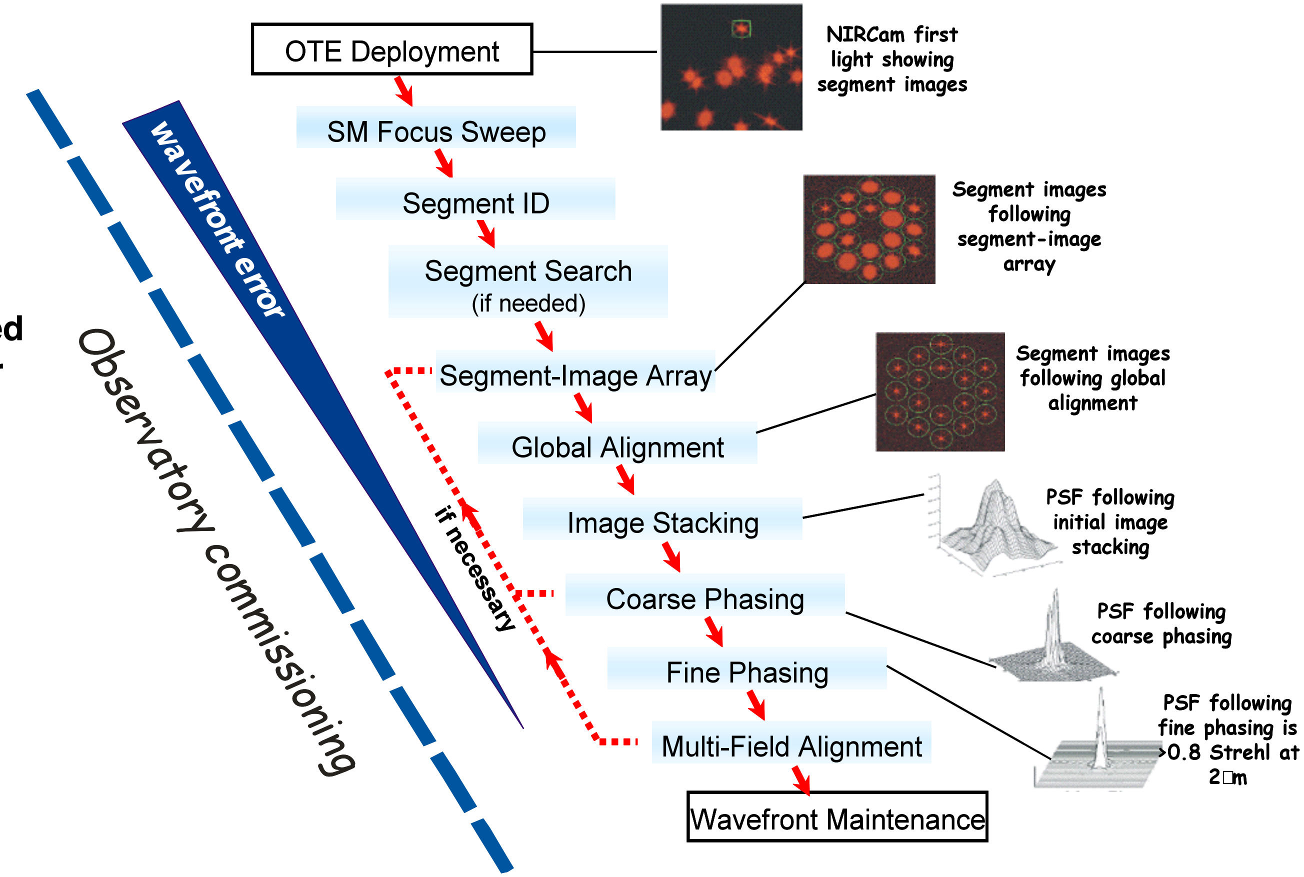
- **Alloyed-silicon based coated Kapton selected for sun-facing surface of layers 1 and 2**
  - Existing NGC proprietary batch-coating process
  - Provides tailorable α_S/ε_H and ρ_{ESD} properties
  - Existing technology VDA rear surface for low α_s/ε_H
  - 50-µm (2-mil) layer 1 & 25-µm (1-mil) layer 2 substrates





Wavefront Sensing and Control – Overview

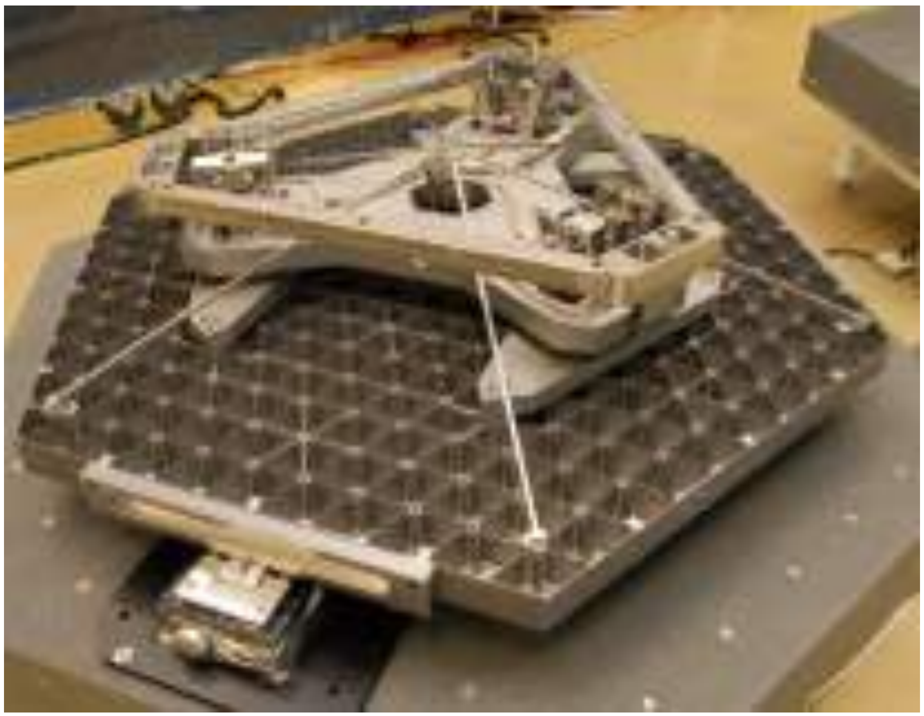
- WFSC algorithms are required to align the JWST telescope using a camera (NIRCam) as a wavefront sensor thus enabling a segmented primary mirror system.
- WFSC Algorithms build on image based software and algorithms developed for HST Prescription Retrieval, ground telescopes, and on a large array of testbeds



- **Key challenge for JWST was to demonstrate image based techniques could be used to fine align a segmented, adjustable telescope**
  - **WFSC Testbed Telescope is a 1/6th scale, fully functional model of the JWST telescope with performance traceable to JWST (TMA, 18 7-dof segments, etc.).**
  - **Testbed provides functionally accurate simulation platform for developing deliverable WFSC algorithms and software.**

Primary Mirror – Overview

- **Since the inception of the James Webb Space Telescope (JWST) program, to achieve its Level 1 Science Objectives, 6-8 meter class segmented primary mirror was required that could operate at < 50K with 2 micrometers diffraction limited performance.**
- **Such a mirror was a fundamental enabling technology that had never before been demonstrated – and did not exist.**



- **AMSD Phase 1 – 1999**
  - 5 Vendors selected for studies
  - Down select to 4 mirror architectures
- **AMSD Phase 2 – 2000**
  - 3 vendors (Goodrich, Kodak, Ball)
- **Prime Contractor Selection 2003**
  - Ball (Beryllium) and ITT/Kodak (ULE) proposed as options
- **Mirror Material/Technology Selection, Sept 2003**
  - Beryllium chosen for technical reasons (cryogenic CTE, thermal conductance, issued with glass)
- **Process improvements\ Risk Reduction 2004**
  - Process improvements via 6-Sigma Study and follow-on identified potential schedule savings
  - EDU added as key risk mitigation demonstration device along with AMSD Phase 3 Process improvements (coupon and .5 meter demonstrations)
- **Most recent activities focused on closing the gap between where AMSD fell short of demonstrating TRL-6 readiness relative to JWST requirements**
  - Specifically, demonstration of mirror survival through exposure to launch-load testing of a full integrated Primary Mirror Segment Assembly (PMSA)

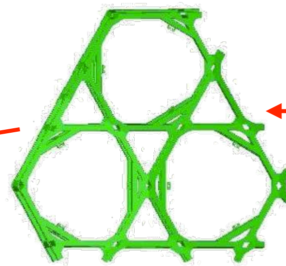
Stable Large Cryogenic Structures – Overview

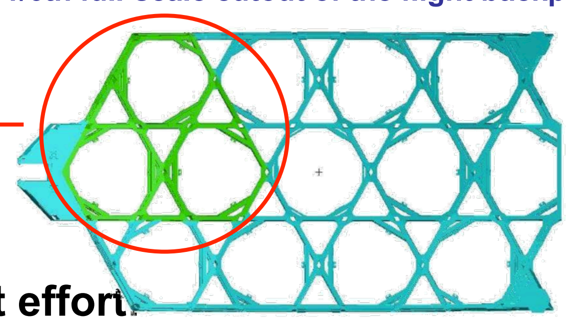
A stable, lightweight, and cost-effective backing structure for JWST's segmented Primary Mirror is necessary to meet both the thermal stability requirements and the overall image quality requirements given a WFS&C update rate of every 14 days.

Technology State-of-the-Art before JWST

- Cryogenic, thermally stable telescope structures much smaller than JWST were produced for SIRTF and other missions.
- Similarly, thermally stable structures operating at room temperature had been produced the size of HST.
- Prior to JWST, there were no thermally stable, cryogenic, large scale, composite structures produced.
- The thermal stability requirements are also more stringent, as JWST is the first mission to utilize a segmented Primary Mirror riding on a Backplane.

Backplane Stability Test Article (BSTA) – a 1/6th full-scale cutout of the flight backplane.





Objectives of the technology development effort:

1) **Demonstrate the ability to limit the magnitude of, and to accurately predict the operational response of, a large cryogenic composite structure under prescribed temperature disturbances.**
2) **Successful test results validate the analysis approach, material characterization approach, and fabrication approach being used for JWST.**