Systems Engineering of the James Webb Space Telescope

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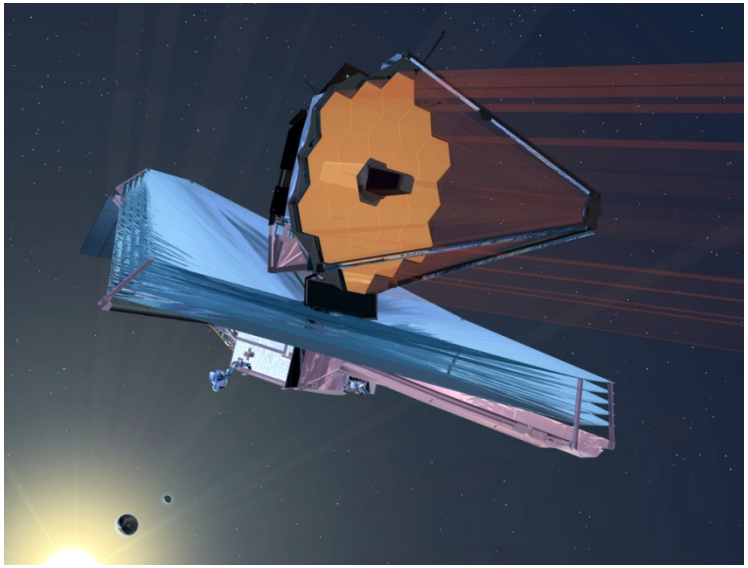
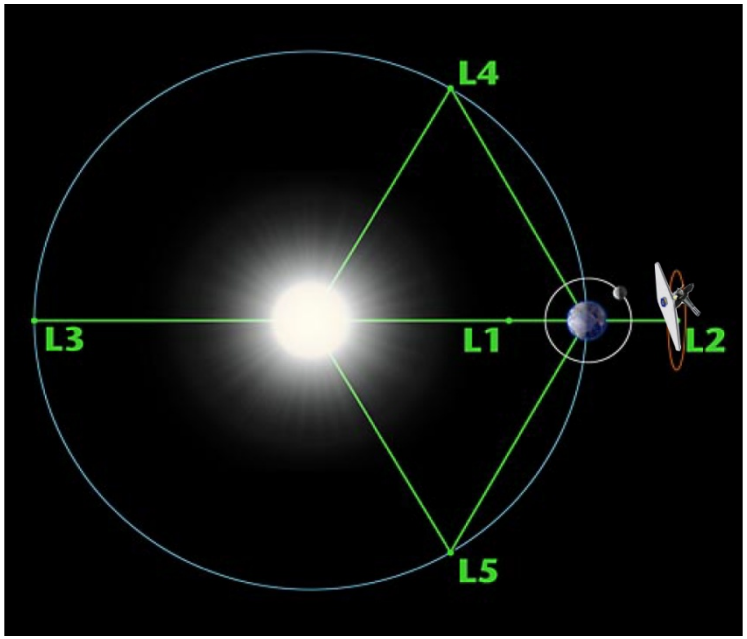
Abstract and Challenges

- **Abstract: This presentation will give an overview of the JWST system and describe some of the more unique systems engineering challenges of this "first of its kind" mission. The presentation will also describe some of the systems engineering techniques used by the team to address these challenges to achieve launch readiness in 2018.**
- **Present an overview of the James Webb Space Telescope via the frame work of the Systems Engineering Process.**
  - Project Overview
  - Science Objectives
  - Requirements
  - Design and Performance
  - Technology Development, Challenges and Risk
  - Verification
  - Status and Summary

JWST Project Overview

- **Mission Objective: Study the origin and evolution of galaxies, stars and planetary systems by providing Infrared imagery and Spectroscopy**
- **JWST Team:**
  - Mission Lead: GSFC
  - International Collaboration with ESA and CSA
  - Prime Contractor: Northrop Grumman Space Technology with Ball Aerospace as Telescope Subcontractor
  - Ground Segment: Space Telescope Science Institute
  - Science Instrument Providers:
    - Near Infrared Camera (NIRCam): University of Arizona
    - Near Infrared Spectrometer (NIRSpec): ESA
    - Mid Infrared Instrument (MIRI): JPL / EC
    - Fine Guidance Sensor / Near Infrared Imager and Slit-less Spectrograph (FGS-NIRISS): CSA
- **Observatory Description:**
  - Deployable telescope w/ 6.5m diameter segmented adjustable primary mirror
  - Cryogenic operating temperature telescope and instruments
  - Deployable Sunshield to allow passive cooling of telescope and instruments
  - Launch in 2018 to Sun-Earth L2
  - 5-year science mission (10-year goal)





What Does Systems Engineering Do?

Science Objective:

- Detect and Investigate the First Light Sources
- Study the Assembly of Galaxies Since First Light
- Study the Birth of Stars
- Study the evolution of Planetary Systems

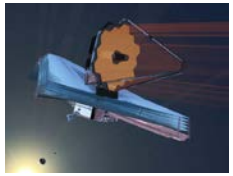
Formulate Mission Requirements

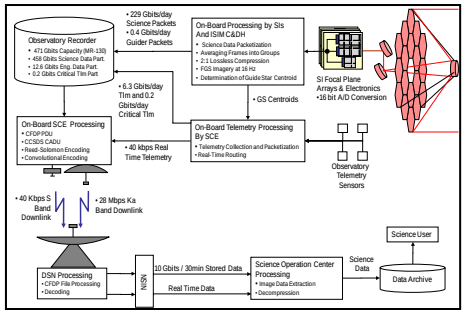
- Sensitivity
- Image Quality and Resolution
- Field Of View
- Data Throughput
- Observing Efficiency

Design the System

James Webb Space Telescope System

- Launch Segment
- Observatory Segment
- Ground Segment



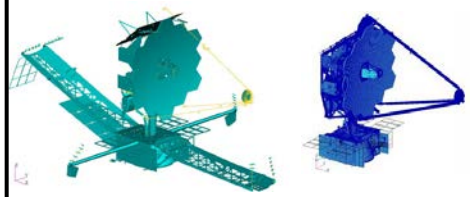


WFE Budget

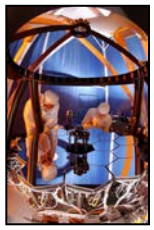
Power Budget

Mass Budget

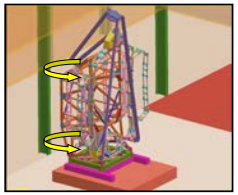
Systems Analyses and Performance Assessments

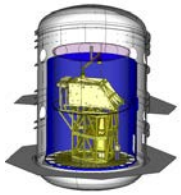


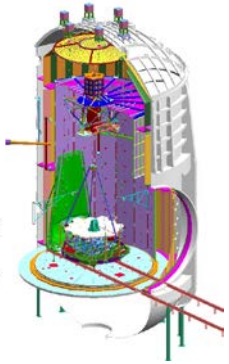
Risk Management and Technology Development



Verification of the "As Built" System







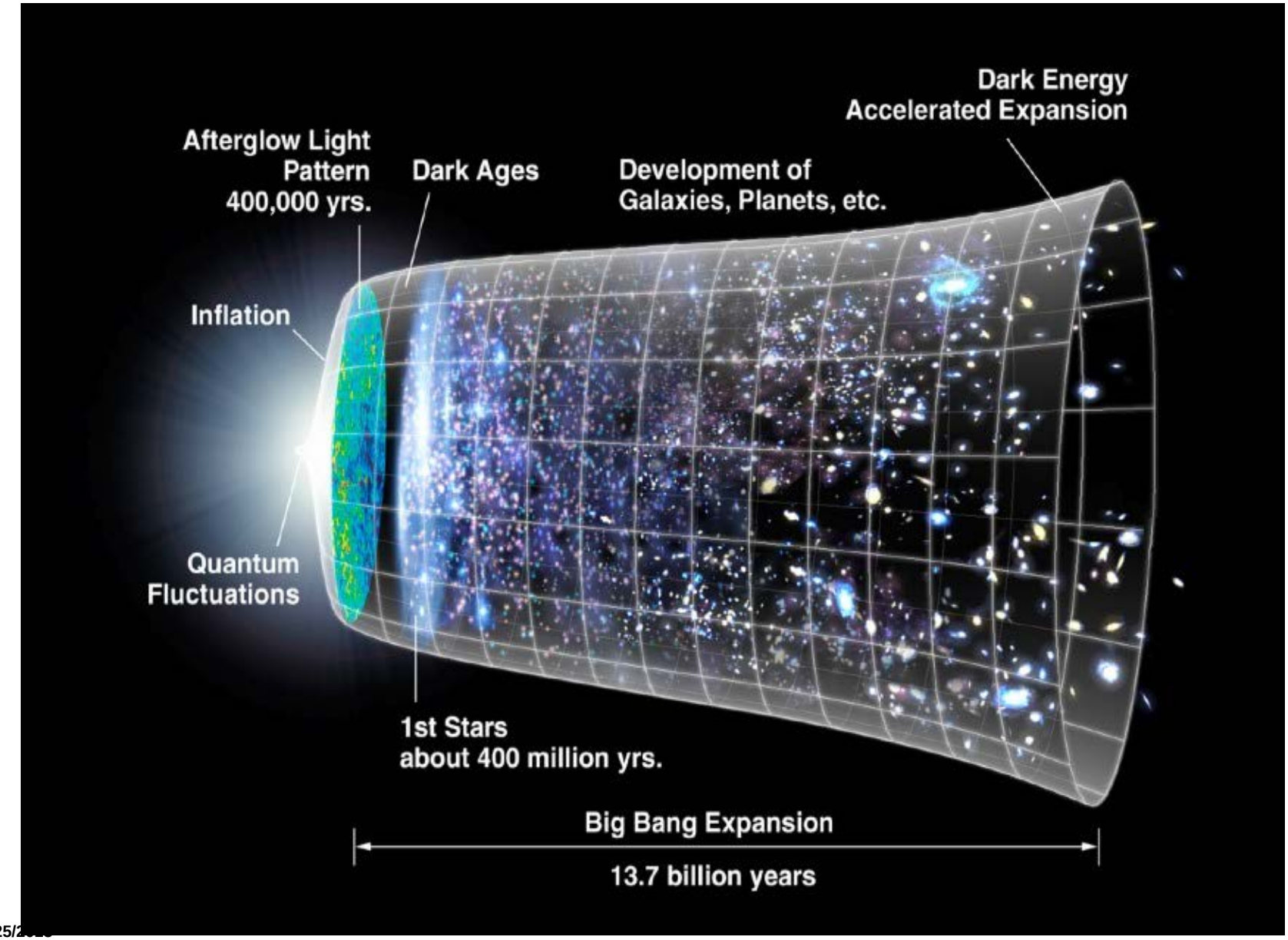
JWST Science Objectives

Science Objective:

- Detect and Investigate the First Light Sources
- Study the Assembly of Galaxies Since First Light
- Study the Birth of Stars
- Study the evolution of Planetary Systems

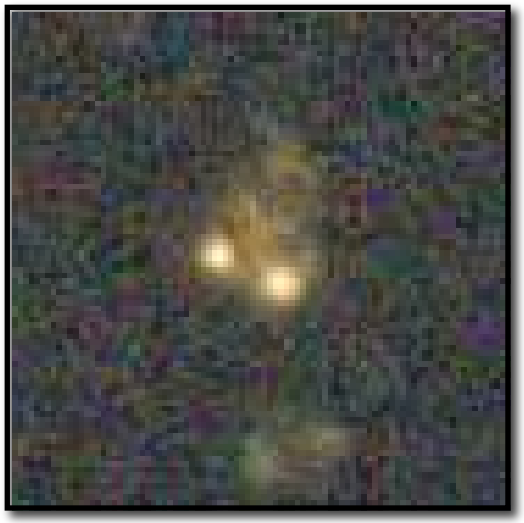
- **Scientists considered what telescope would replace the HST in 1989, and in 1990 the "HST and Beyond Committee" recommended a large Infrared telescope to address 4 science themes:**
  - Detection of First Light and Re-Ionization
  - Evolution of Galaxies over Cosmic History
  - Birth of Stars and Planetary Systems
  - Evolution of Planetary Systems
- **Recently an additional yet related area of investigation has become important; the study of exoplanets.**

First Light and Re-Ionization



How Galaxies Evolve Over Cosmic History

Galaxies in the Distant – Early Universe
Seem to Lack Structure



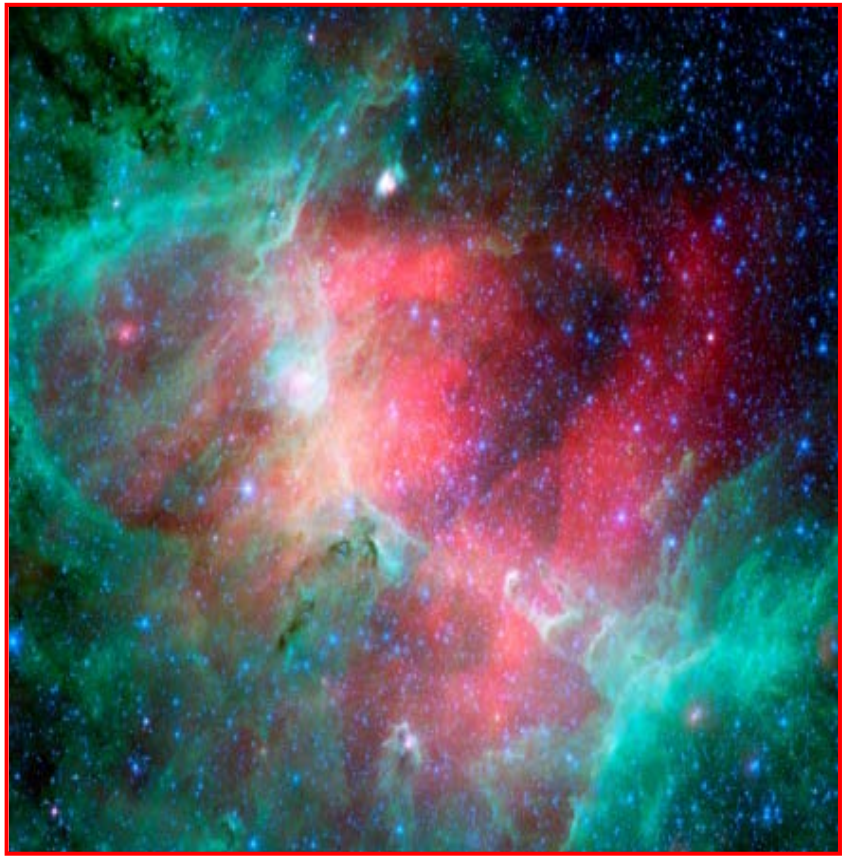
How do Galaxies Like These…

Evolve into Galaxies Like These

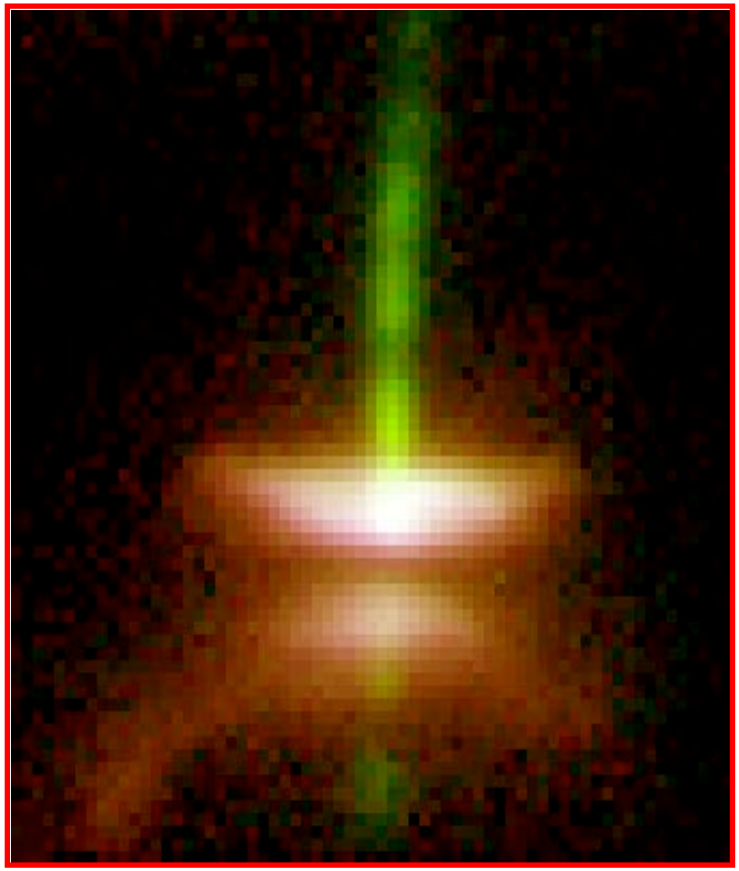
Galaxies in the Nearby – Contemporary Universe
Have Structure, Ellipticals and Spirals

The Birth of Stars and Planetary Systems

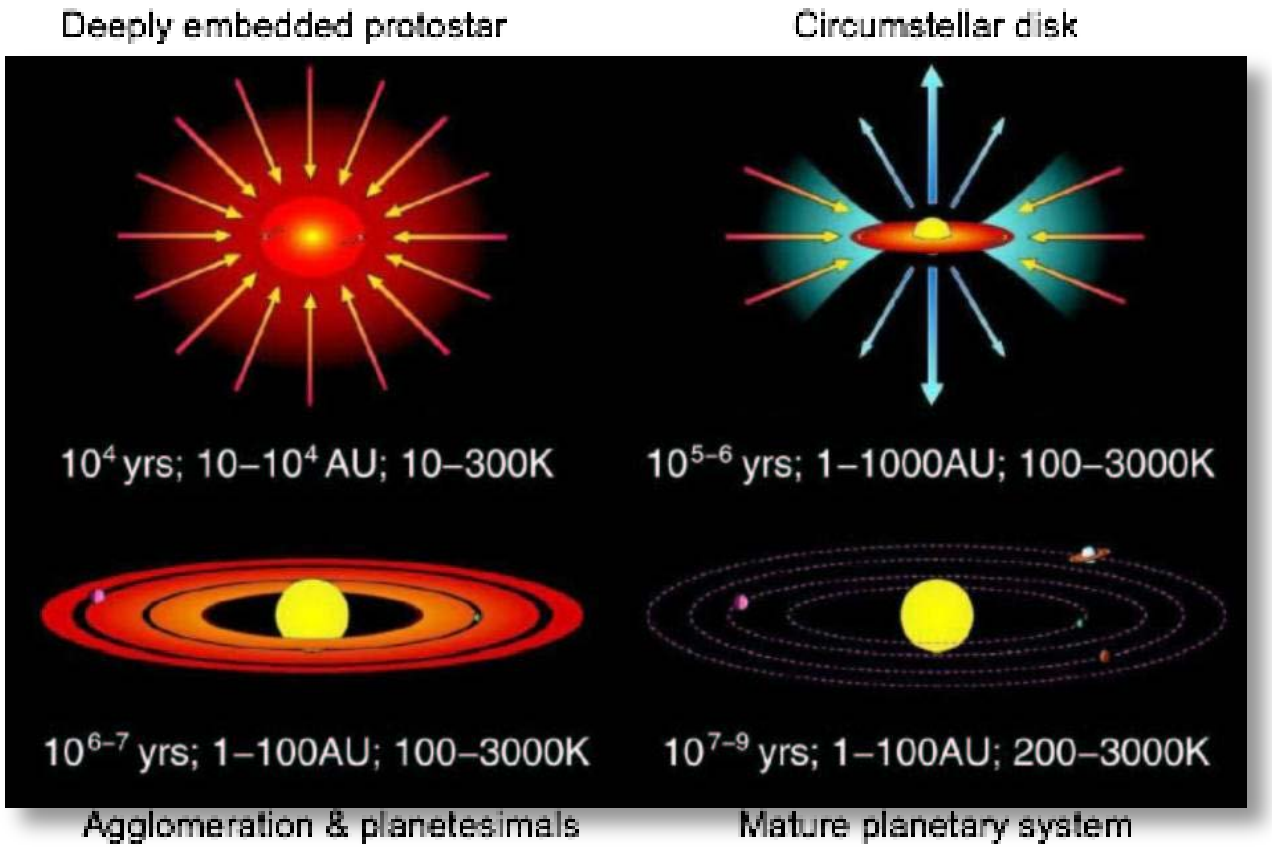
Star Forming Regions in Giant Molecular Complexes

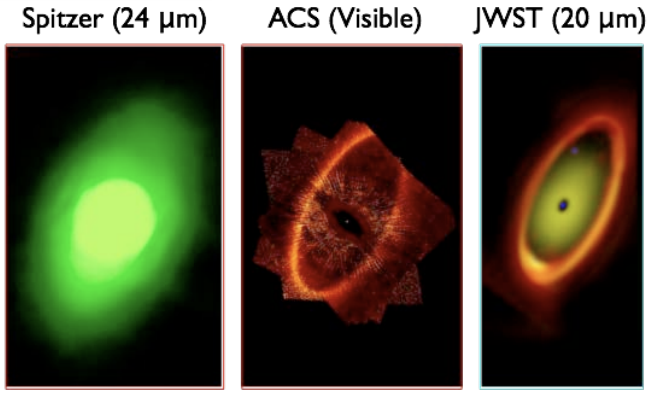


Formation of Disks and Bi-Polar Jets Near Young Stellar Objects



The Origins of Life and the Formation and Evolution of Planetary Systems





Transiting Exo-Planets

Observation	Targets	R	Science
Transit light Curves	Gas giants Intermediate planets Superearths	5 5 5	- Exoplanet properties e.g. Mass, radius -> Physical structure - Confirmation of Terrestrial planet transits - Transit timing: detection of unseen planets
Phase light curves	Gas giants Intermediate planets	5 5	- Day to night emission mapping: dynamical models of Exoplanet atmospheres
Transmission Spectroscopy	Gas giants Gas giants Intermediate planets Superearths planets	3000 100-500 100-500 ≤100	Spectral line diagnostics - atmospheric composition e.g. C, CO_2, CH_4 - follow-up of survey detections: TESS & Kepler
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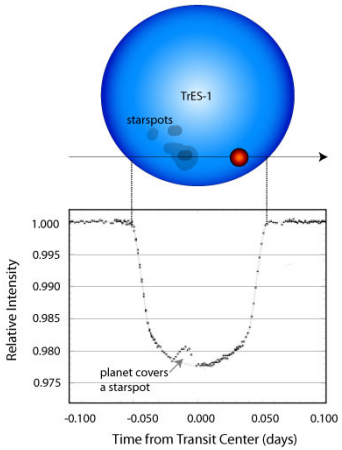

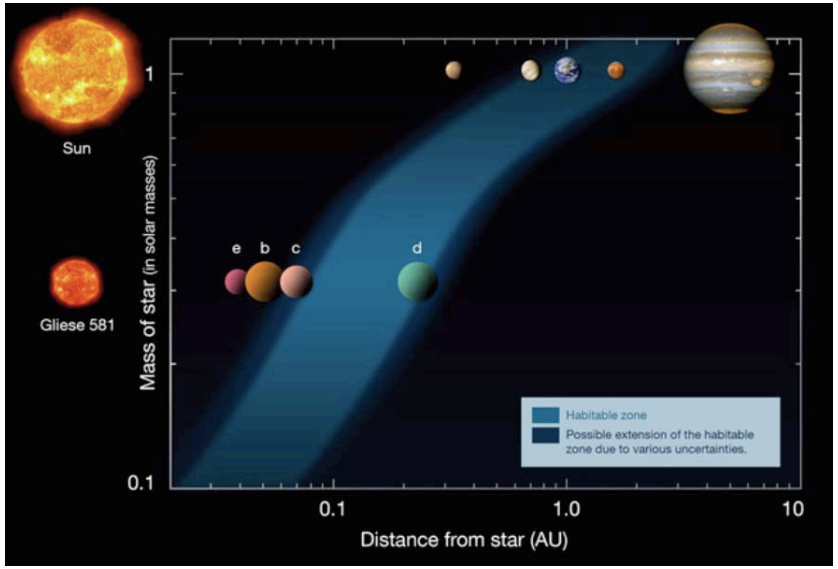

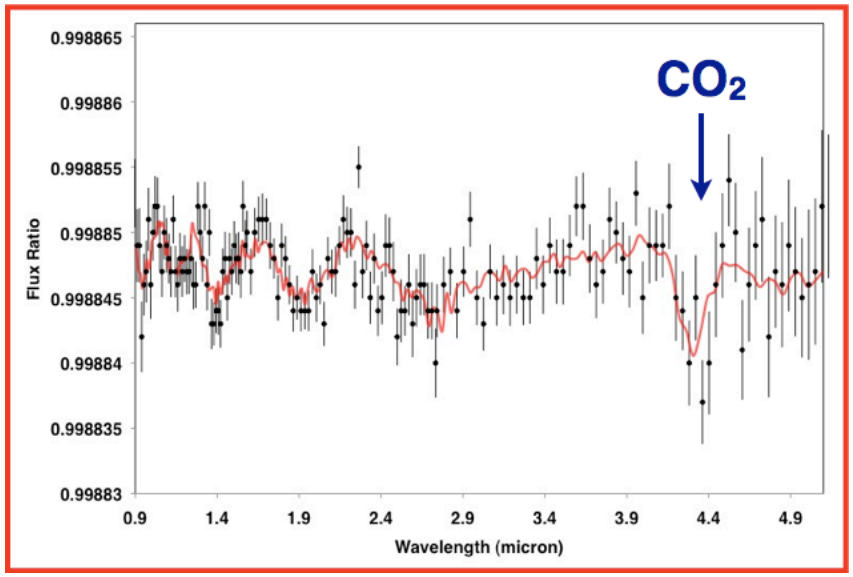

Simulated spectrum of a superearth

JWST Systems Engineering

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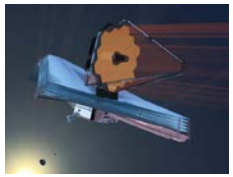

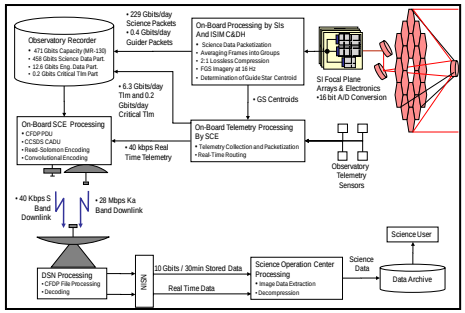

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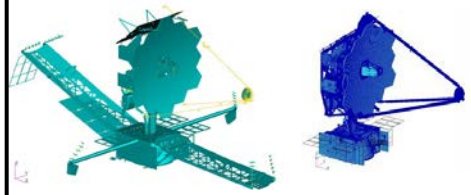

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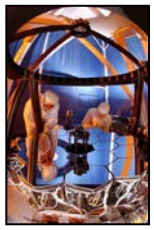

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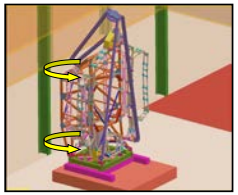
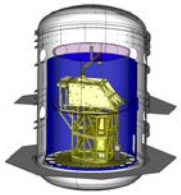
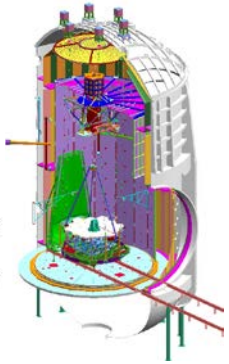






Requirements Formulation

Formulate Mission Requirements

- Sensitivity
- Image Quality and Resolution
- Field Of View
- Data Throughput
- Observing Efficiency

- **Engineering requirements are derived from these science objectives. The following are the primary "drivers' for the system:**
  - Spectral Coverage
  - Radiometric Sensitivity
  - Image Quality and Resolution
  - Field of View and Celestial Coverage
  - Data Throughput
  - Observing Efficiency
- **The derivation of engineering requirements must involve preliminary "sizing" of key system attributes to establish feasibility.**

Science Requires an Infrared Telescope

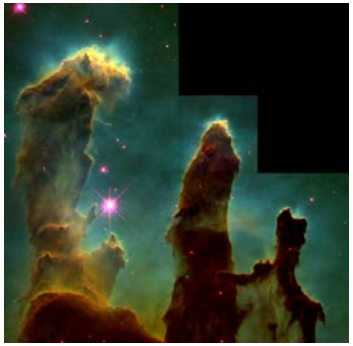
Hubble Deep Field image shows galaxies out to z~5.

Light emitted by young stars is blue

After traveling 13 billion years thru a universe that has been expanding light waves are stretched and become red or infrared

JWST must operate in the Near Infrared (NIR) wavelengths (0.6 to 5 mircons)

JWST will view the universe at red-shift of 10 or greater to search for the first galaxies



M16 viewed in visible light shows dusty pillars and cocoons. Stars are being born in this dust, but this same dust obscures our view of them.

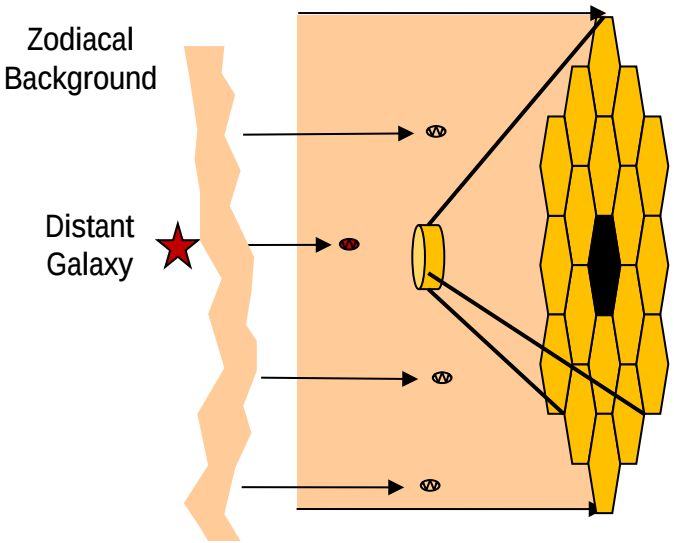
JWST must operate in the Mid Infrared (MIR) wavelengths (5 to 28 microns)

Infrared light can penetrate dust. By observing in the infrared we can see into these dust cocoons. M16 viewed in the IR shows objects hidden by this dust.

Driving Requirements: Radiometric Sensitivity

- Sensitivity: Detect 11 nanoJanksy Point Sources with a Signal to Noise Ratio of 10 for exposure time of 10,000 sec.
  - High Signal Collection
    - 25 m^2 Aperture, 6.5 m Diameter
    - Optical Transmission > 52%
    - Detector Quantum Efficiency > 80%
    - Encircled Energy > 59% to 80 mas
  - Low Noise
    - Low Stray Light Levels (Zodi Limited to λ = 10 μm)
      - Cold Optics T < 55 K
    - Low Electronics Noise
      - NIR Detectors Cooled to T < 40 K for 0.1e-/s Dark Currents
      - Total Electrical Noise < 9e-

Infrared Spectrum between 1.4 μm and 2.6 μm, centered at 2.0 μm (R = 1.68)



- JWST collects 1 photon per second, and registers one electron every 4 seconds.
- JWST collects 3 photons per second from the Zodi Background and registers 3 electrons from this background every 4 seconds.

Signal to Noise and Exposure Time

- **The critical metric used to quantify the ability to detect a faint source is the signal to noise (S/N). Equation 1 defines this for a JWST imager in terms of :**
  - The Source Counts (S)
  - In-Field Background Counts (Z)
  - Added Background Counts due to the Observatory (B) (aka stray light)
  - Dark Current Counts (D)
  - Electrical Read Noise Counts (Rd)
- **Equation 2 shows how exposure time varies with the rates of these parameters to achieve a given S/N. Note that the exposure time varies with square of the inverse of the source brightness (s)**

ξ= Encircled energy in photometric aperture
F_ν = Source flux density in $Wm^{-2}Hz^{-1}$
λ= Central passband wavelength in meters
$\Delta\lambda$ = Wavelength passband width in meters
A_{OTE} = OTE collection aperture in m^2
τ_{OTE} = OTE transmission
τ_{SI} = Science Instrument transmission
η= Detector quantum efficiency
h = Planck's constant
$B_{\nu Zodi}$ = Zodi radiance at OTE entrance in $Wm^{-2}Hz^{-1}sr^{-1}$
Ω= Solid angle of photometric entrance aperture in sr
$B_{\nu SL}$ = Stray Light effective radiance at OTE entrance in $Wm^{-2}Hz^{-1}sr^{-1}$
N_{pixels} = Number of pixels in the photometric aperture
I_{DC} = Dark current per pixel in e/s
r = Read noise per reset per pixel in e

$$\text{Eq 1)}\quad (S/N) = \frac{S}{\sqrt{S+Z+B+D+R_d}}$$

Where:

$$S = \left[\frac{\xi F_\nu \Delta\lambda A_{OTE}\tau_{OTE}\tau_{SI}\eta}{\lambda h}\right]t_{\exp} = s t_{\exp}$$

$$Z = \left[\frac{B_{\nu Zodi}\Delta\lambda\Omega A_{OTE}\tau_{OTE}\tau_{SI}\eta}{\lambda h}\right]t_{\exp} = b_Z t_{\exp}$$

$$B = \left[\frac{B_{\nu SL}\Delta\lambda\Omega A_{OTE}\tau_{OTE}\tau_{SI}\eta}{\lambda h}\right]t_{\exp} = b_{SL} t_{\exp}$$

$$D = \text{Dark Current} = N_{pixels} I_{DC} t_{\exp} = d t_{\exp}$$

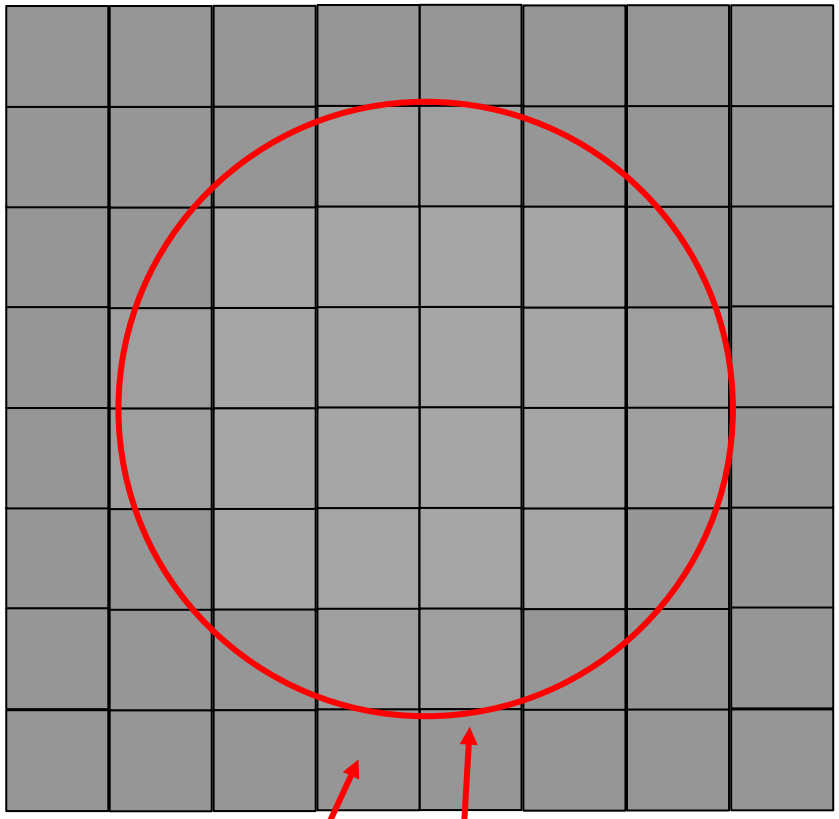
$$R_d = r^2 N_{pixels}\frac{t_{\exp}}{t_r}\left[1 - \frac{C_r t_s}{t_r}\left[\frac{t_r - t_d}{t_r}\right] - \frac{t_d}{t_r}\right]^{-1} = r_d t_{\exp}$$

$$\text{Eq 2)}\quad t_{\exp} = \frac{(S/N)[s + b_z + b_{SL} + d + r_d]}{s^2}$$

How a 10 nanoJanksy Point Source Appears Compared to Anticipated Background

Electron Counts for a 10 nJy Point Source at λ= 2 Micron (R=5) Over 20 pixels For a 10,000 Sec Exposure

	10,000 Sec Exposure	
	Counts	**Variance**
Signal (10 nJy Point Source) (S)	2145	2145
In Field Zodiacal Background (Z)	13396	13396
Observatory Stray Light (B)	14897	14897
Dark Current (D)	1828	1828
	Read Noise	13765
	Total Noise = SQRT(Sum of Variance)	**214.5**



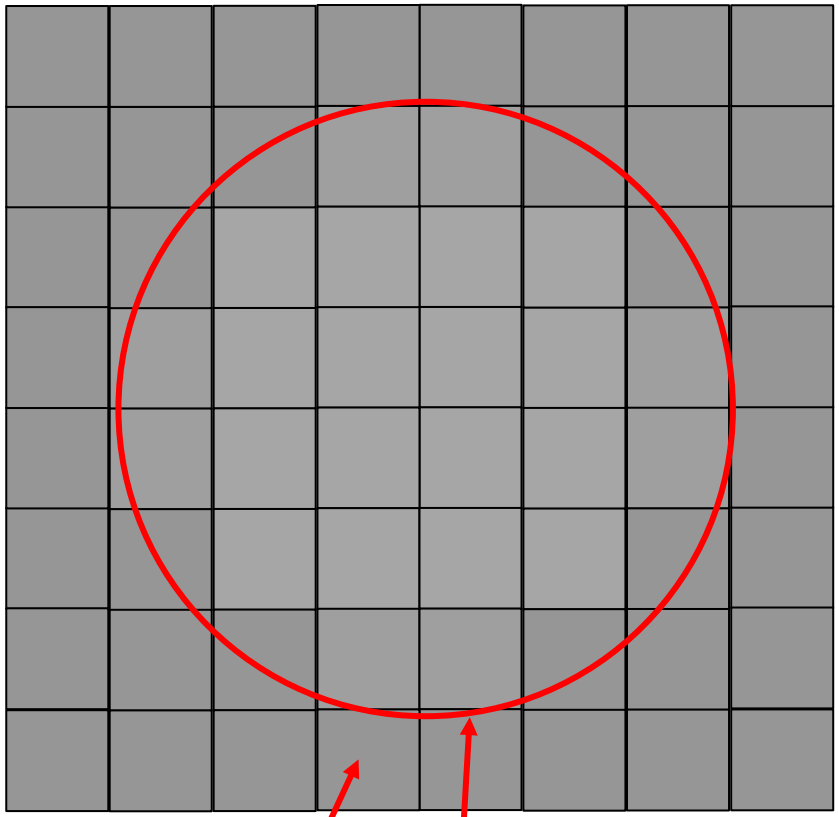
Each Background Pixel Accumulates 1883 Counts

Each Pixel Within the Core of the Point Source Image Accumulates 2017 Counts

How a 1 nanoJanksy Point Source Appears Compared to Anticipated Background

Electron Counts for a 1 nJy Point Source at λ= 2 Micron (R=5) Over 20 pixels For a 1,100,000 Sec Exposure

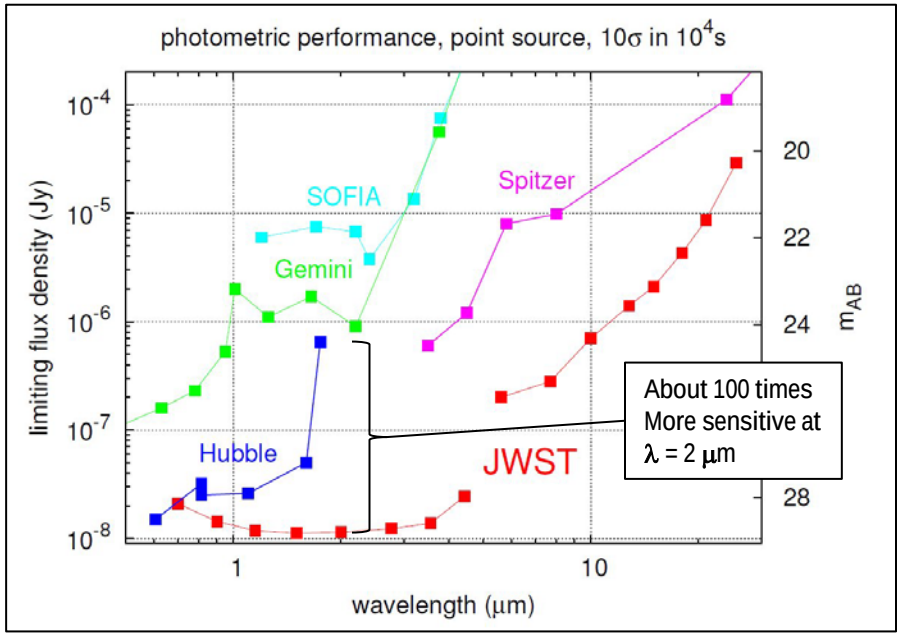
	1,100,000 Sec Exposure	
	Counts	Variance
Signal (10 nJy Point Source) (S)	22021	22021
In Field Zodiacal Background (Z)	1473525	1473525
Observatory Stray Light (B)	1638669	1638669
Dark Current (D)	201050	201050
Read Noise		1514172
Total Noise = SQRT(Sum of Variance)		2202.1

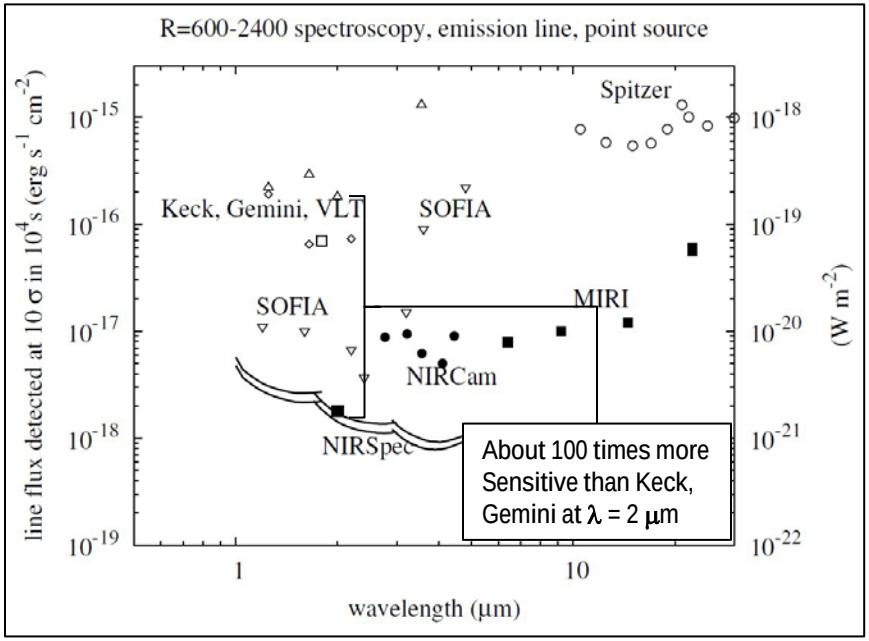


Each Background Pixel Accumulates 207077 Counts

Each Pixel Within the Core of the Point Source Image Accumulates 208454 Counts

Sensitivity Comparisons (Imaging and Spectroscopic)



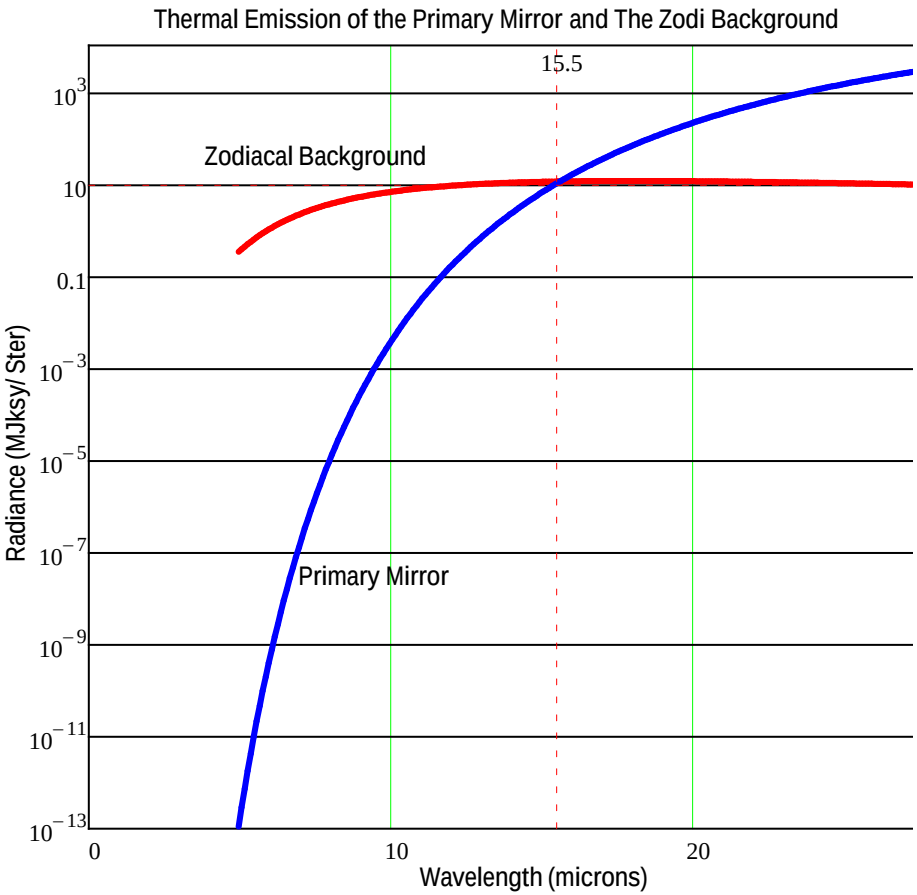


- **Imaging sensitivity is measured by the faintest point source flux that can be detected to a signal to noise of 10, in a 10,000 sec (2.78 hour) exposure.**
  - Limiting flux in Janskys (Jy = 10^{-26} $wm^{-2}Hz^{-1}$) for various observatories are plotted above.
- **Within the bands where there is commonality, JWST is between and 100 times more sensitive than HST. (WFC3)**
- **JWST is roughly 100 times more sensitive than comparable ground base observatories. (Gemini)**

- **Spectroscopic sensitivity is measured by the faintest line source flux that can be detected to a signal to noise of 10, in a 10,000 sec (2.78 hour) exposure.**
  - Limiting flux in wm^{-2} for various observatories are plotted above.
- **JWST is roughly 100 times more sensitive than comparable ground base observatories. (Keck, Gemini and the VLT)**

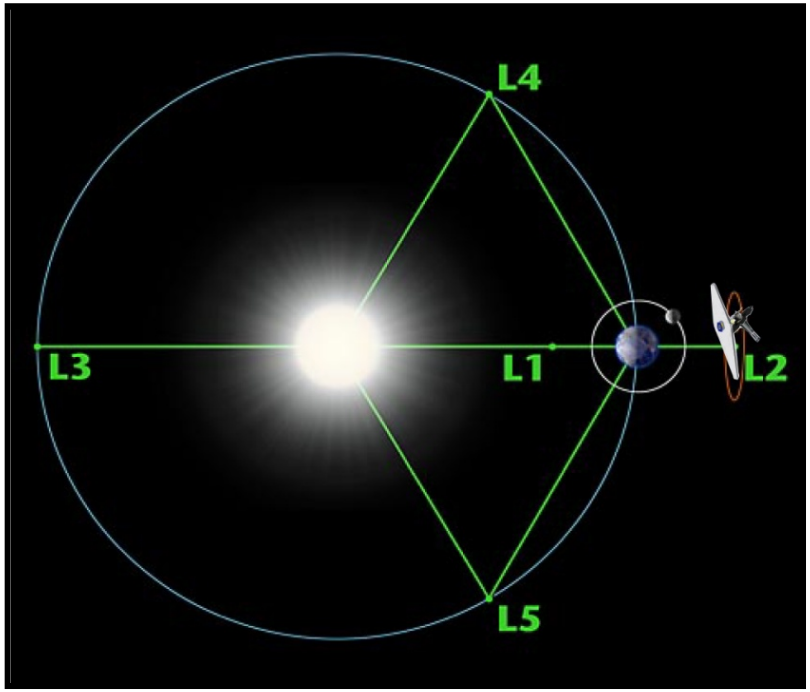
Infrared Observatories Must be Very Cold

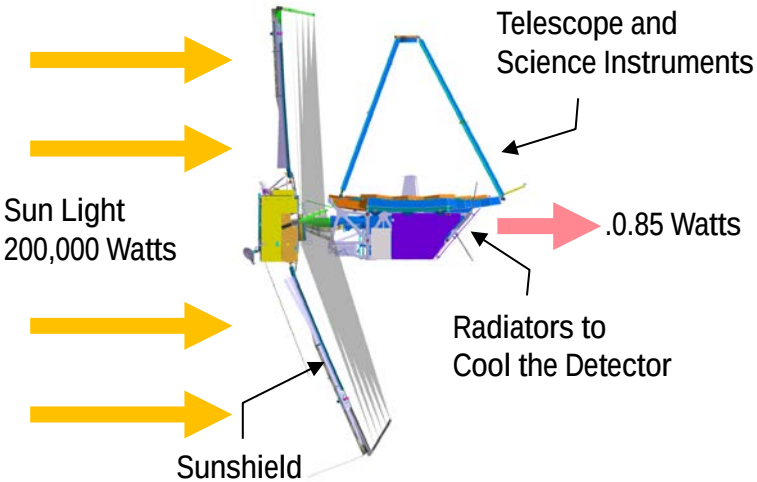
- **Both the telescope and the instruments glow in the infrared. To make sure this glow does not overwhelm the faint signal, both the telescope and instruments must be cold.**
  - Colder than 55 K. (-223° C or -369°F)
  - At ambient temperature (300K) the primary mirror would emit over 350 photons at a wavelength of 2 μm.
- **JWST is designed to emit less radiation than the natural background out to a wavelength of 10 μm. To achieve this, the optics temperature must be less than 55 k.**
  - The graph to the right compares the thermal emission of the Primary Mirror to that of the natural background (Zodiacal Light) vs wavelength.
- **Additionally the science Instruments detectors themselves must be cold, or they would generate electronic noise. (Dark Current Noise).**
  - The Near Infrared detectors are HgCdTel detectors and must operate colder than 40K.
  - The Mid Infrared detector is Si:As and must operate at 6K.



Cooling JWST

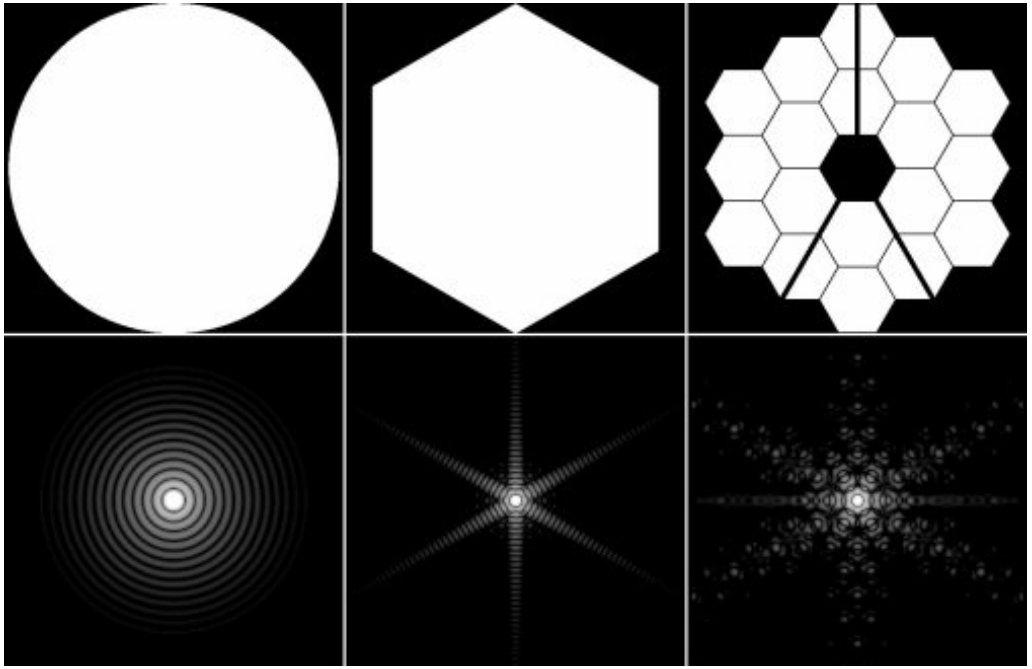
- **A 6-meter telescope and its instruments are too big to refrigerate. Therefore we must allow them to cool down "passively" .**
  - Get it far away from local heat sources, (The Earth, (300K) and the Moon)
  - Keep sunlight off the telescope and instruments
- **Locate the telescope at a point in space called the 2nd Lagrangian Point. This is a stable point 1.5 million km from the Earth opposite the Sun.**
  - The sun, earth and moon are always on the same side of the observatory.
- **A sunshield (umbrella) can shade the telescope from all 3 of these bodies.**
  - This sunshield can also shade the telescope from those electronics that must run hot.
- **The NIR detectors are cooled by dedicated radiators which dump their dissipated power directly to cold space. (Cold Space is 7K)**
- **The MIR detector must be cooled actively by a cryo-cooler to 6K.**

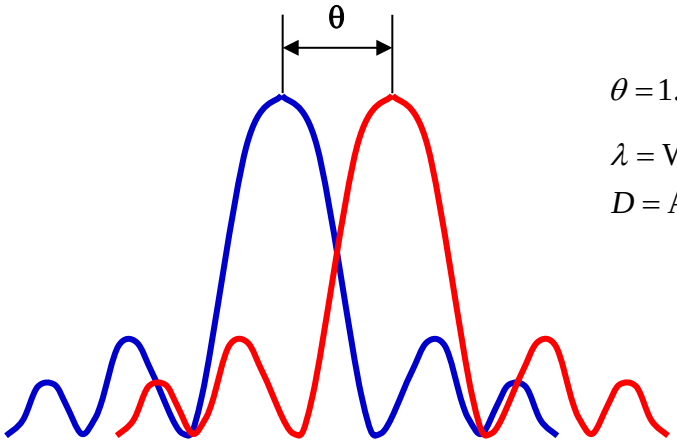




Driving Requirements: Image Quality or Resolution

- **Image quality requirements are driven by the need to resolve detail (resolution).**
- **If a system has the best possible image quality, then the resolution is determined by size and shape of the telescope aperture. Diffraction from the aperture spreads light into a "Point Spread Function" (PSF).**
  - The illustration on the upper right shows point spread functions for various aperture shapes.
- **Resolution is commonly specified by the ability of a telescope to discern two stars at a minimum angle apart, θ. Therefore the ½ width of the point spread functions must be smaller than θ.**
  - This is illustrated on the lower right which shows the cross-section of the point spread functions of two stars in proximity to one another.
- **For JWST, the resolution is required to be 0.084 arcsec.**





$$\theta = 1.22\frac{\lambda}{D}$$

λ = Wavelength,

D = Aperture Diameter

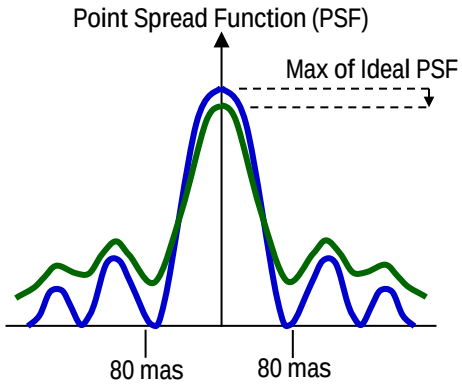
Wavefront Error Budgets

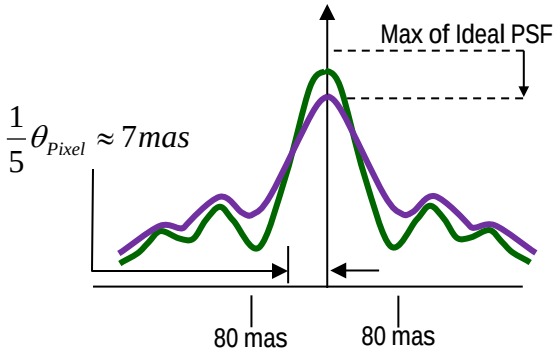
Image Quality: Diffraction limited at a wavelength of 2.0 μm, therefore Strehl Ratio > 80%, Total Wavefront Error (WFE) < 150 nm

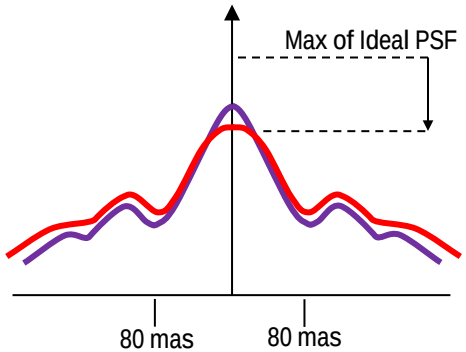
Static Wavefront Error of Optics < 100 nm
- Imperfections in the figure of the optics due to fabrication errors.

Line of Sight Error < 7 milliarcsec (mas), equivalent to ~72 nm of WFE
- Pointing errors of the boresight of the telescope / instruments.

Wavefront Error Stability due to Figure Vibrations and Long Term Drift < 63 nm
- Vibrations of frequency higher than the control system.
- Thermal drifts following observatory slews.







JWST Systems Engineering

Science Objective:

- Detect and Investigate the First Light Sources
- Study the Assembly of Galaxies Since First Light
- Study the Birth of Stars
- Study the evolution of Planetary Systems

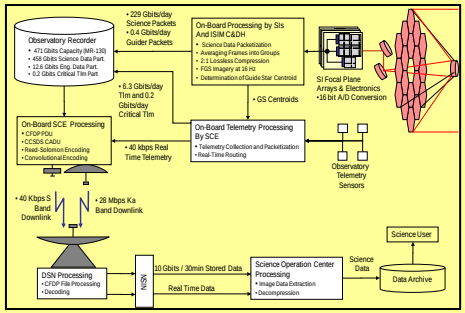
Formulate Mission Requirements

- Sensitivity
- Image Quality and Resolution
- Field Of View
- Data Throughput
- Observing Efficiency

Design the System

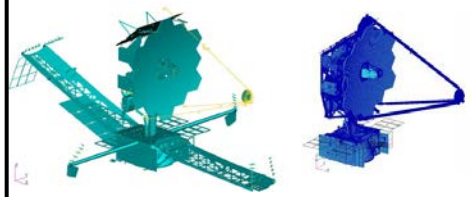
James Webb Space Telescope System

- Launch Segment
- Observatory Segment
- Ground Segment

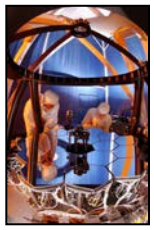


- WFE Budget
- Power Budget
- Mass Budget

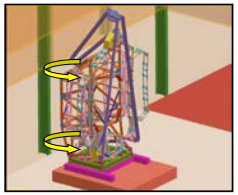
Systems Analyses and Performance Assessments

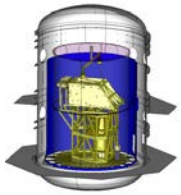


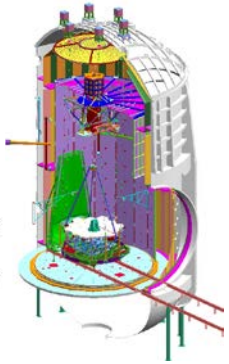
Risk Management and Technology Development



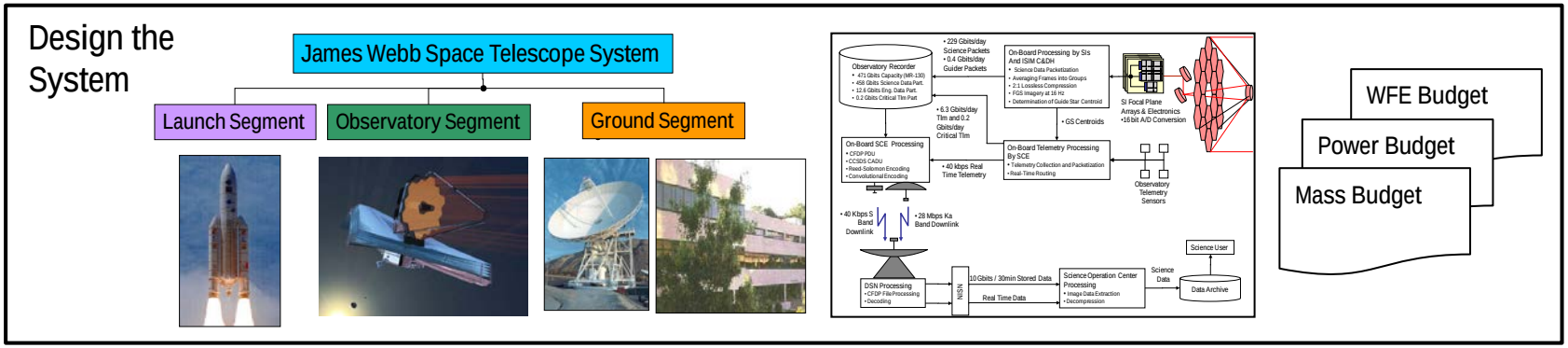
Verification of the "As Built" System







JWST Systems Design

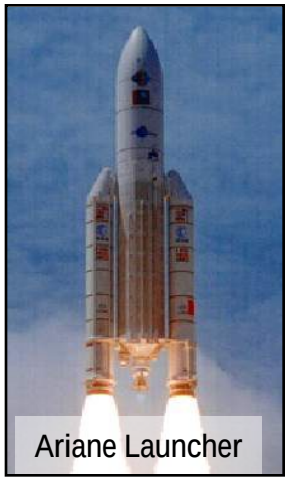


- **Systems design involves establishing system elements, decomposing and allocating requirements to them, defining their functions, interactions and interfaces, and allocating system and resources. The products of system design are:**
  - Hierarchical Diagrams
  - Functional Flow Diagrams and Operations Concepts
  - System Schematics and Data Flow Diagrams
  - Resource and Performance Budgets
  - Element and Subsystem Specifications and Interface Requirements Documents
- **These products are generated by iterations of parametric and trade studies.**

System Hierarchy

James Webb Space Telescope System

Launch Segment

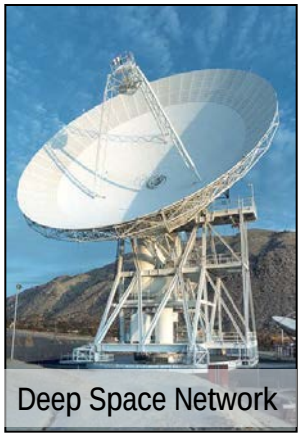


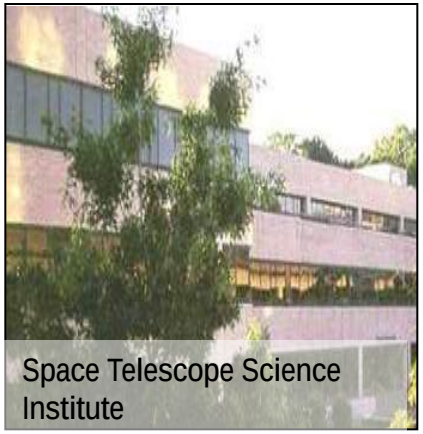
- Launch Vehicle
- Payload Adapter
- Launch Site Services

Observatory Segment

- Optical Telescope Element (OTE)
- Integrated Science Instrument Module (ISIM)
- Spacecraft Element (SE)
  - Spacecraft Bus
  - Sunshield

Ground Segment

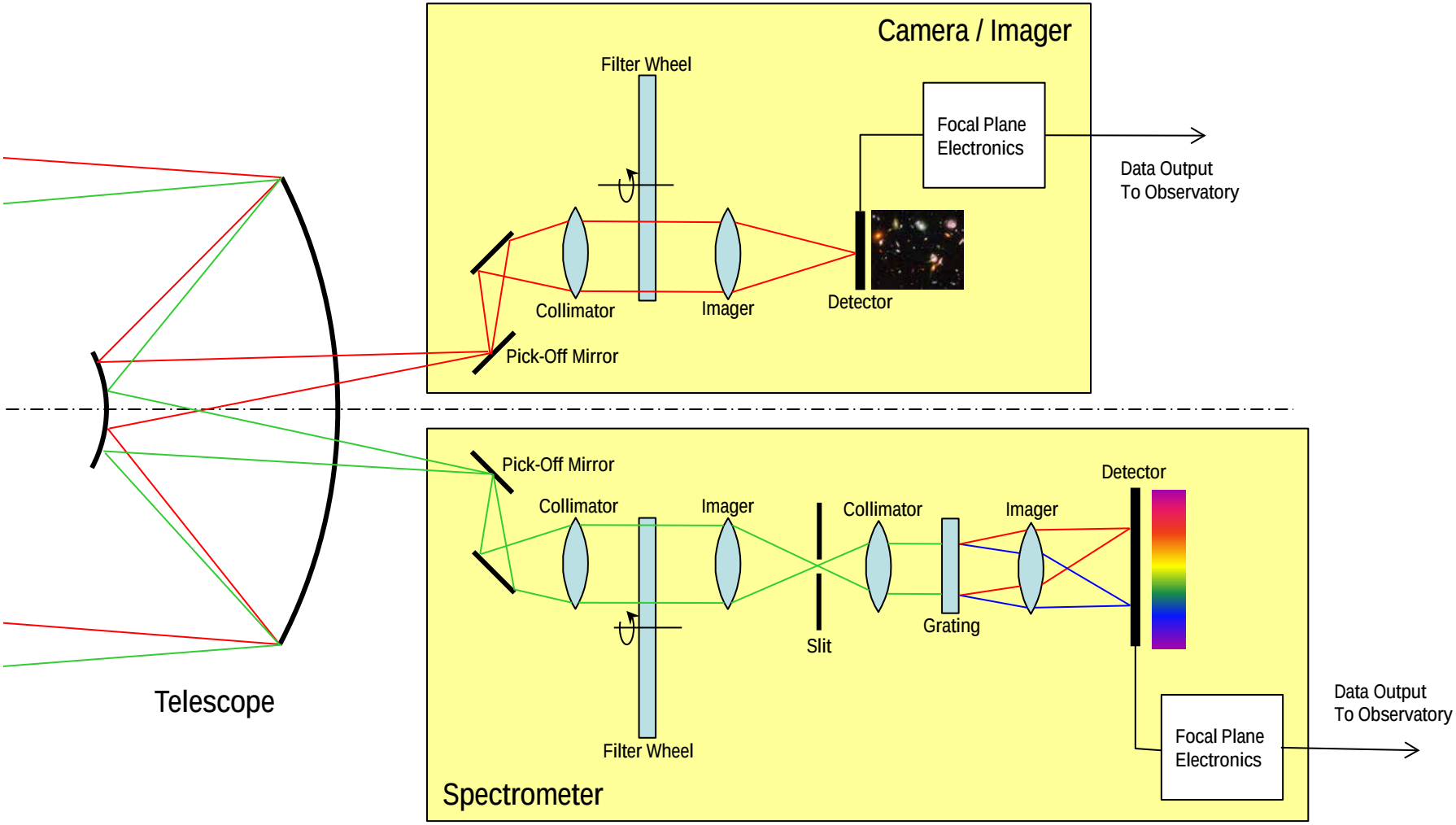




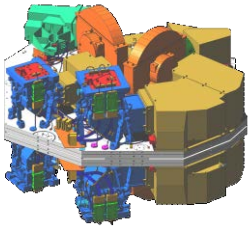
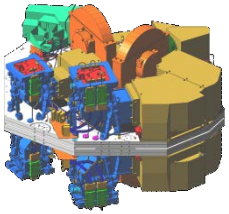
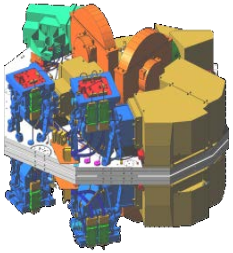
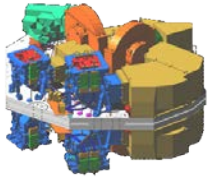
- Science and Operations Center (SOC)
- Institutional Systems
- Common Systems

Provided by NASA
Provided by NGST
Provided by STScI
Provided by ESA
Provided by CSA

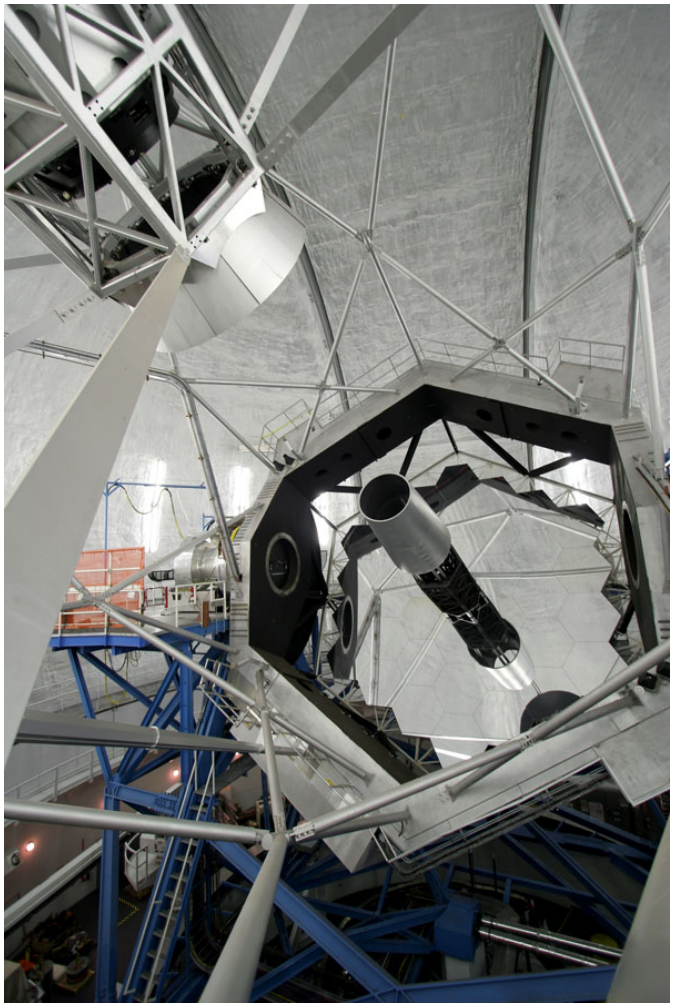
Typical Science Instruments Cameras and Spectrometers



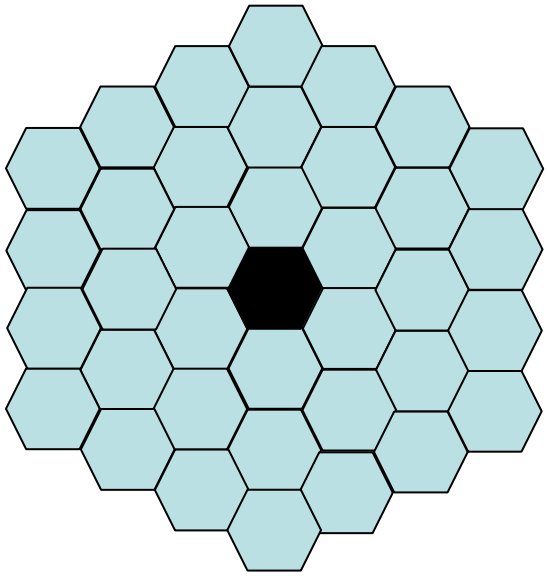
JWST Science Instrument Compliment

Science Instrument	Science Functions	Design Features and Capabilities
• NIRCam • University of Arizona 	• Wide field images with low spectral resolution. • Short Wave (SW) channels 0.6 μm < λ < 2.3 μm • Long Wave (LW) channels 2.4 μm < λ < 5.0 μm • Special filters for Wave Sensing and Control	• Two redundant modules each with one 2' x 2' SW images and one 2' x 2' LW image • Eight HgCd Te 2048 x 2048 pixels SW detectors and two 2048 x 2048 pixel LW HgCdTe detectors. 18 μm pixel pitch • Refractive optics
• NIRSPec • ESA 	• Multi-Object spectroscopy, 100 simultaneous spectra • Waveband 0.6 mm < λ < 5.0 mm • Medium to High resolution spectral resolution (R = 100 to 1000)	• Four microshutter arrays each with 171 x 365 programmable slits. Each slit aperture 0.203" x 463" • Total 9.7 sq arcmin FOV • Two 2048 x 2048 pixel LW HgCdTe detectors 18 μm pixel pitch
• MIRI • ESA / JPL 	• Mid infrared imaging between 5 mm < l < 27 mm • Single slit spectroscopy • High resolution Integral Field Spectroscopy from 4.9 mm < l < 28.8 mm	• 1.4' x 1.9' imager FOV • One 1024 x 1024 pixel Si:As detector for imager • 5" x 0.6" FOV slit spectrometer with one 1024 x 1024 pixel Si:As detector • 7" x 7" FOV Integral Field Spectrometer with 4 channel beam slicer and one 1024 x 1024 pixel Si:As detector
• FGS / NIRISS • CSA 	• Medium spectral resolution (R=100) NIR imaging • Fine guidance sensing the observatory fine pointing control system	• 2.2' x 2.2' FOV for medium spectral resolution imaging with one 2048 x 2048 pixel LW HgCdTe detector. • Two 2.3' x 2.3' FOV for fine guider using two 2048 x 2048 pixel LW HgCdTe detecors.

Segmented Mirror Design

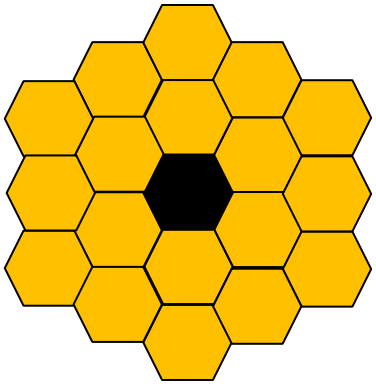


The Keck I Telescope on Maunea Kea Summit in Hawaii



The 10 meter Diameter Keck I Primary Mirror

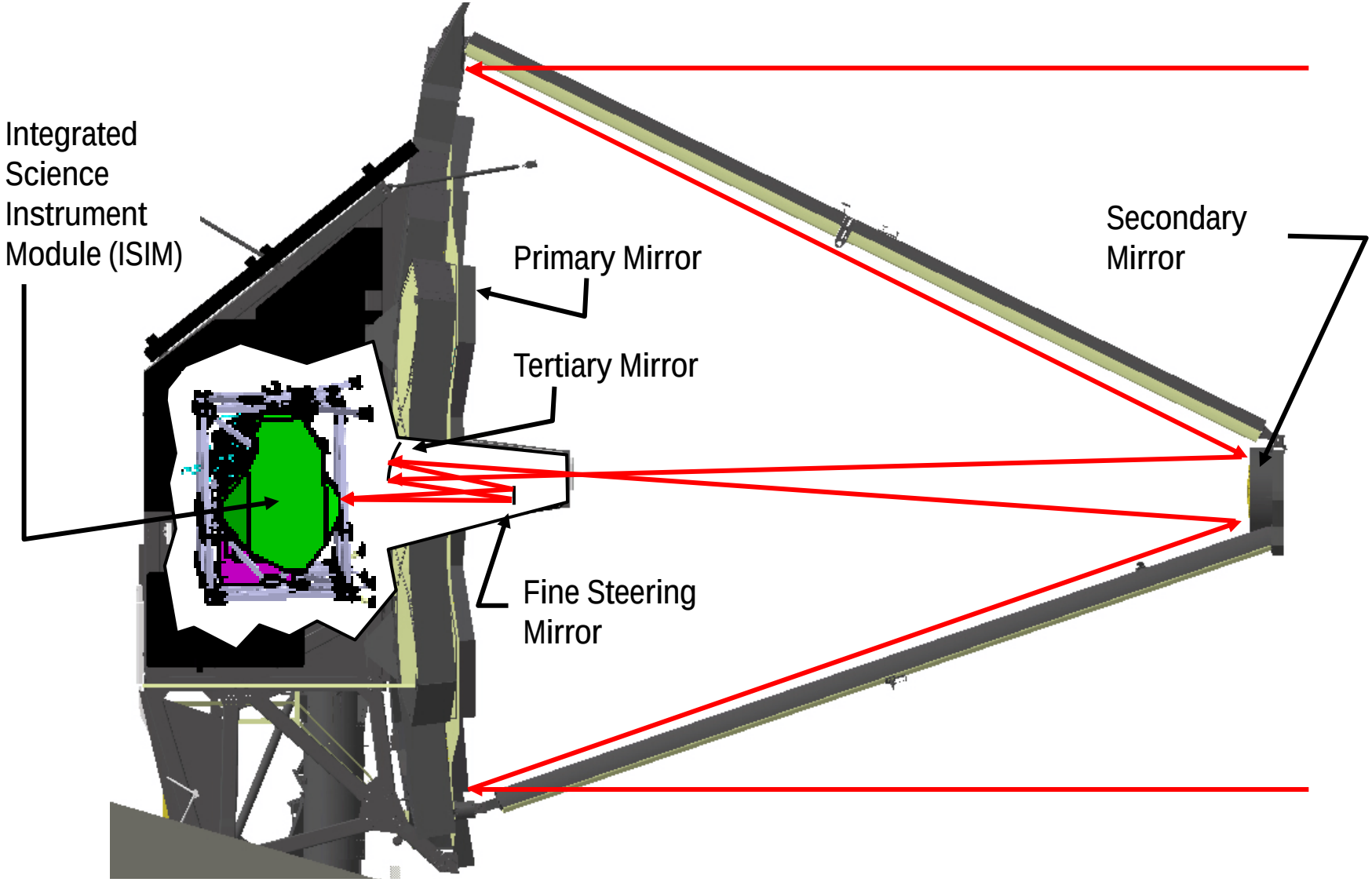
- The Keck 10 m Telescope uses a segmented primary mirror design with 36 individually controlled hexagonal segments.
- The segments are easier to manufacture and to maintain.



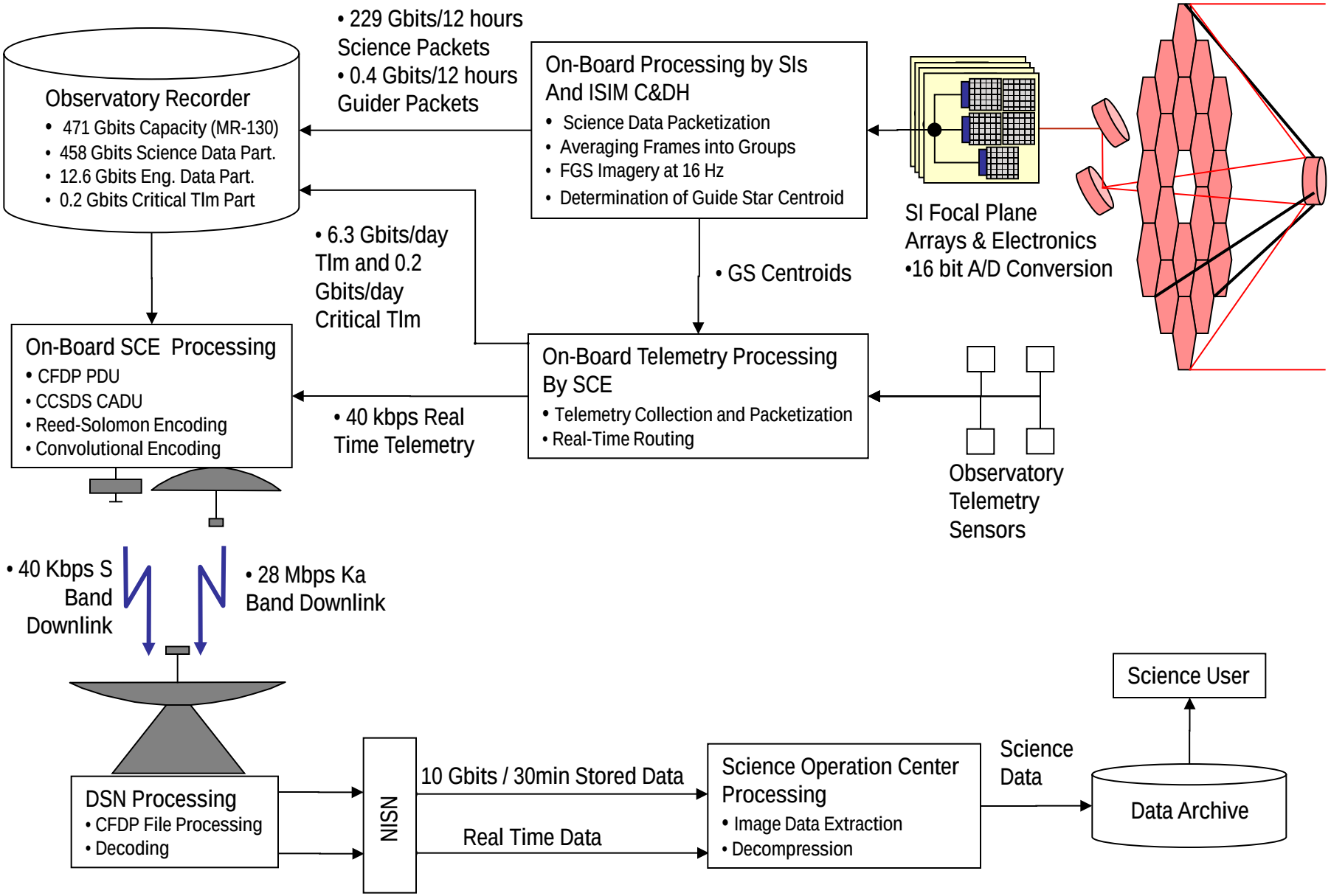
The 6.3 meter Diameter JWST Primary Mirror

- JWST adopted an 18 segment primary mirror design.
- Each segment will be controllable in 7 degrees of freedom.
- In addition to the advantages of manufacturability and maintainability, the segmented design was necessary to stow in the Launch Vehicle.

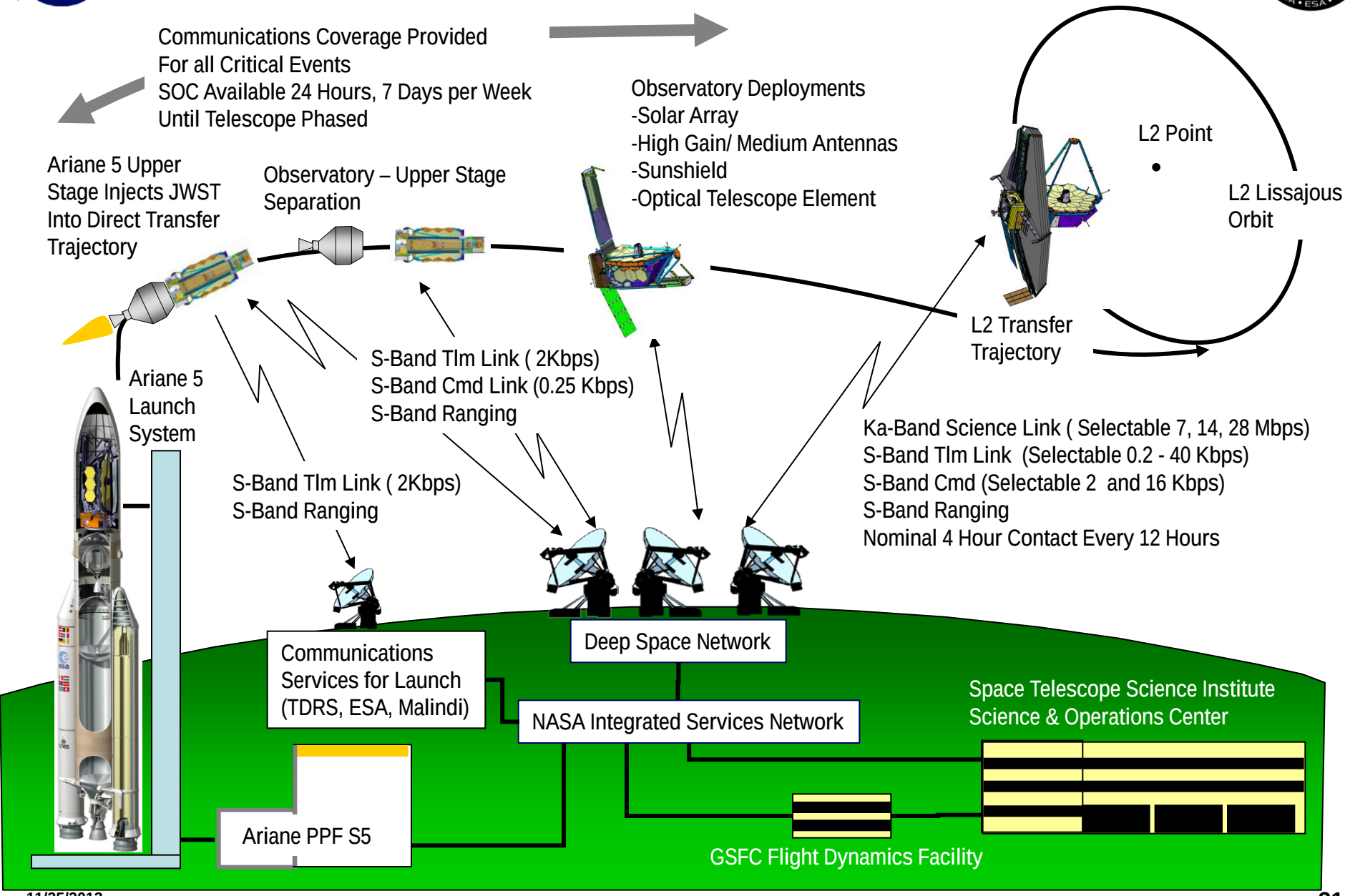
Tri-Mirror Anastigmatic Telescope Design



Data System Design Schematic

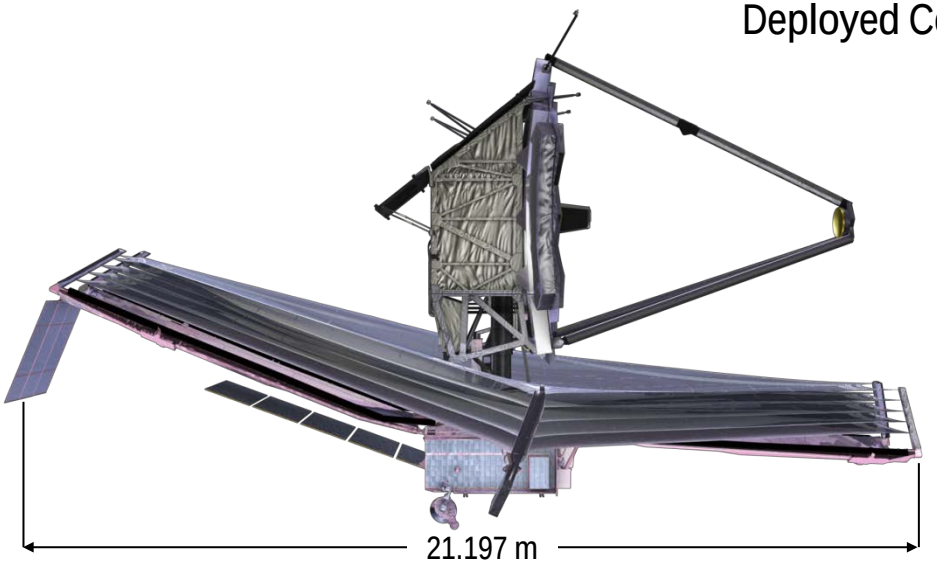


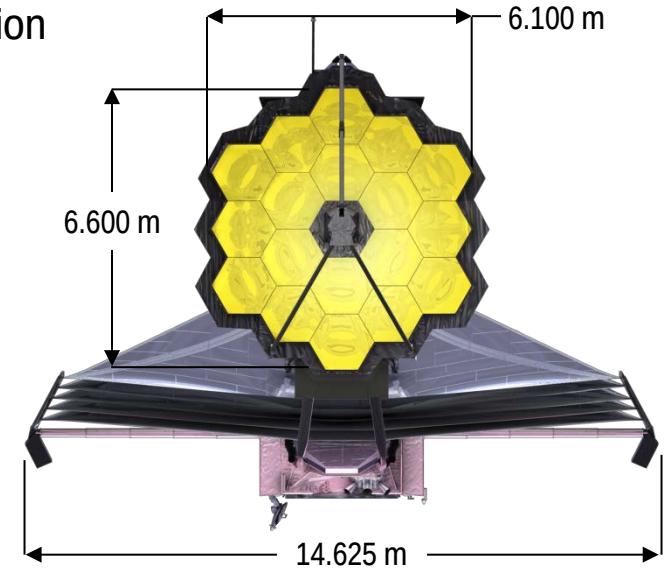
JWST System Architecture



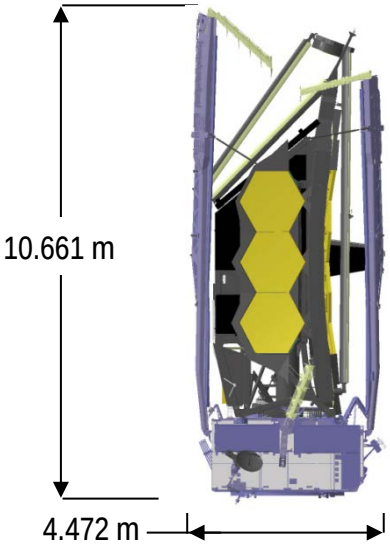
JWST Observatory Summary

Deployed Configuration



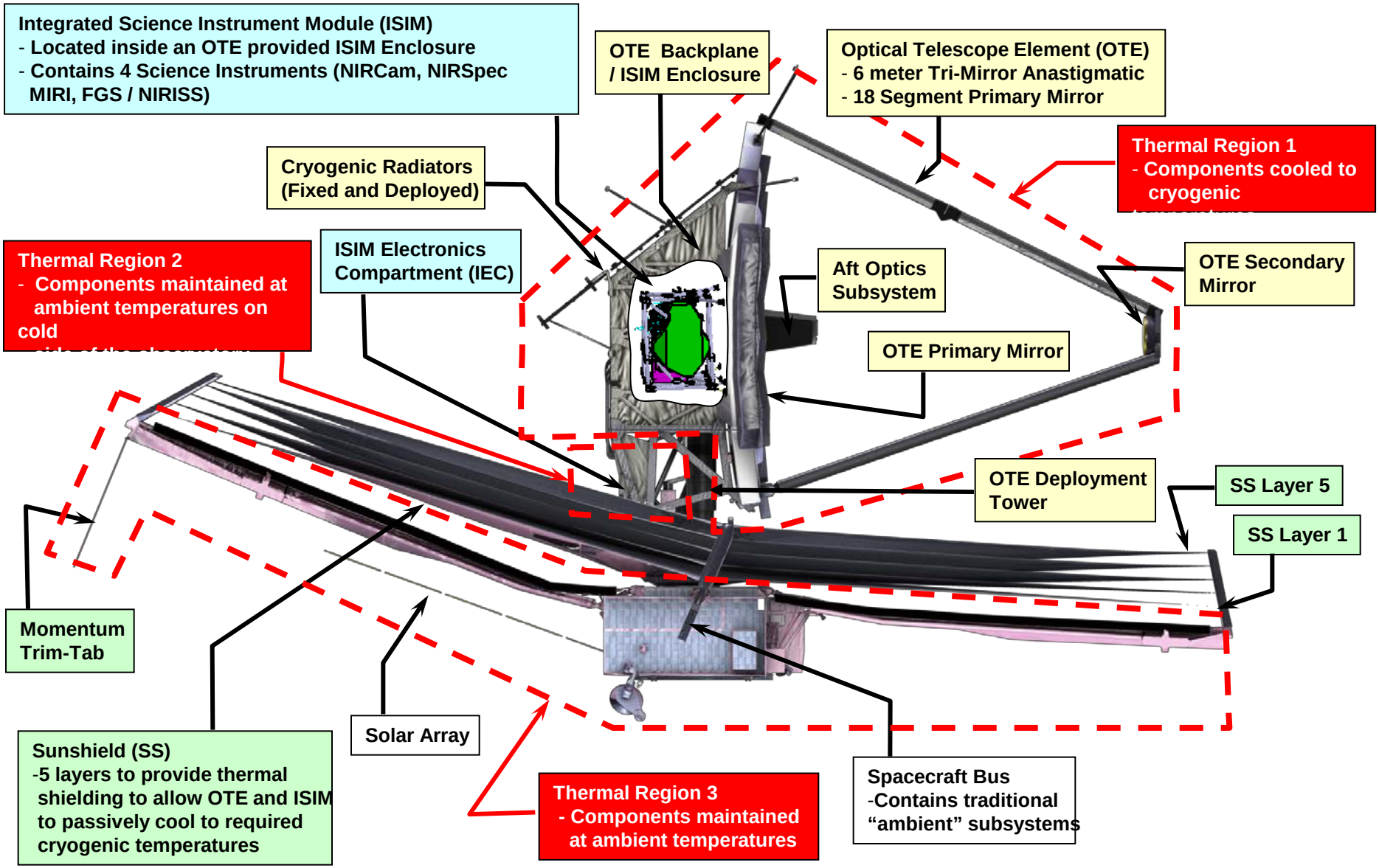


Stowed Configuration

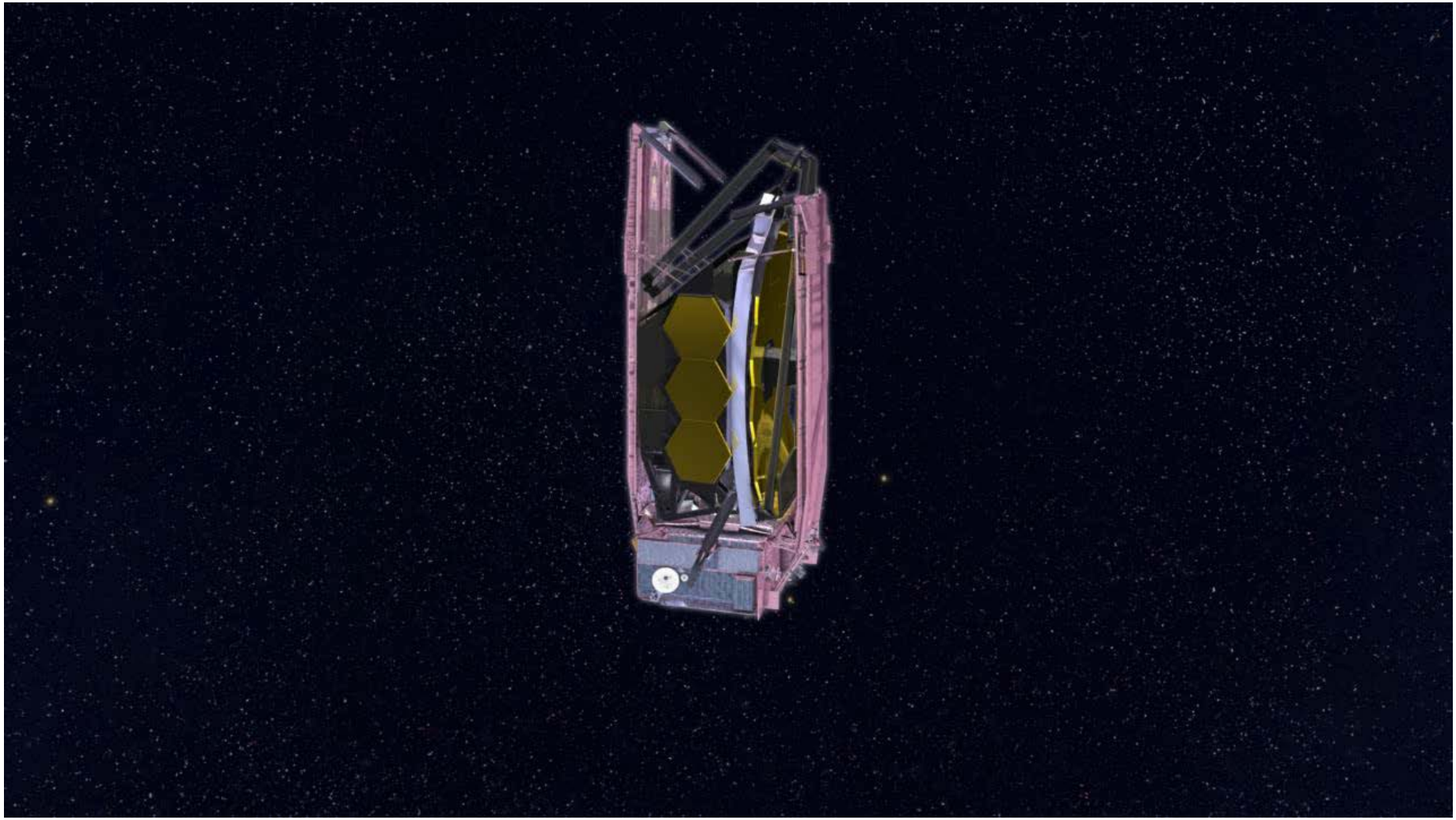


- Optical Telescope Element (OTE) diffraction limited at 2 micron wavelength.
  - 25 m^2 , 6.35 m average diameter aperture.
  - Instantaneous Field of View (FOV) ~ 9' X 18'.
  - Deployable Primary Mirror (PM) and Secondary Mirror (SM).
  - 18 Segment PM with 7 Degree of Freedom (DOF) adjustability on each.
- Integrated Science Instrument Module (ISIM) containing near and mid infrared cryogenic science instruments
  - The NIRCam SI functions as the on-board wavefront sensor for initial OTE alignment and phasing and periodic maintenance.
- Deployable sunshield for passive cooling of OTE and ISIM.
- Mass: < 6530 kg .
- Power Generation: 2000 Watts Solar Array.
- Data Capabilities: 471 Gbits on-board storage, 229 Gbits / 12 hours science data.
- Science Data Downlink: 28 Mbps.
- Life: Designed for 10 years of operation.

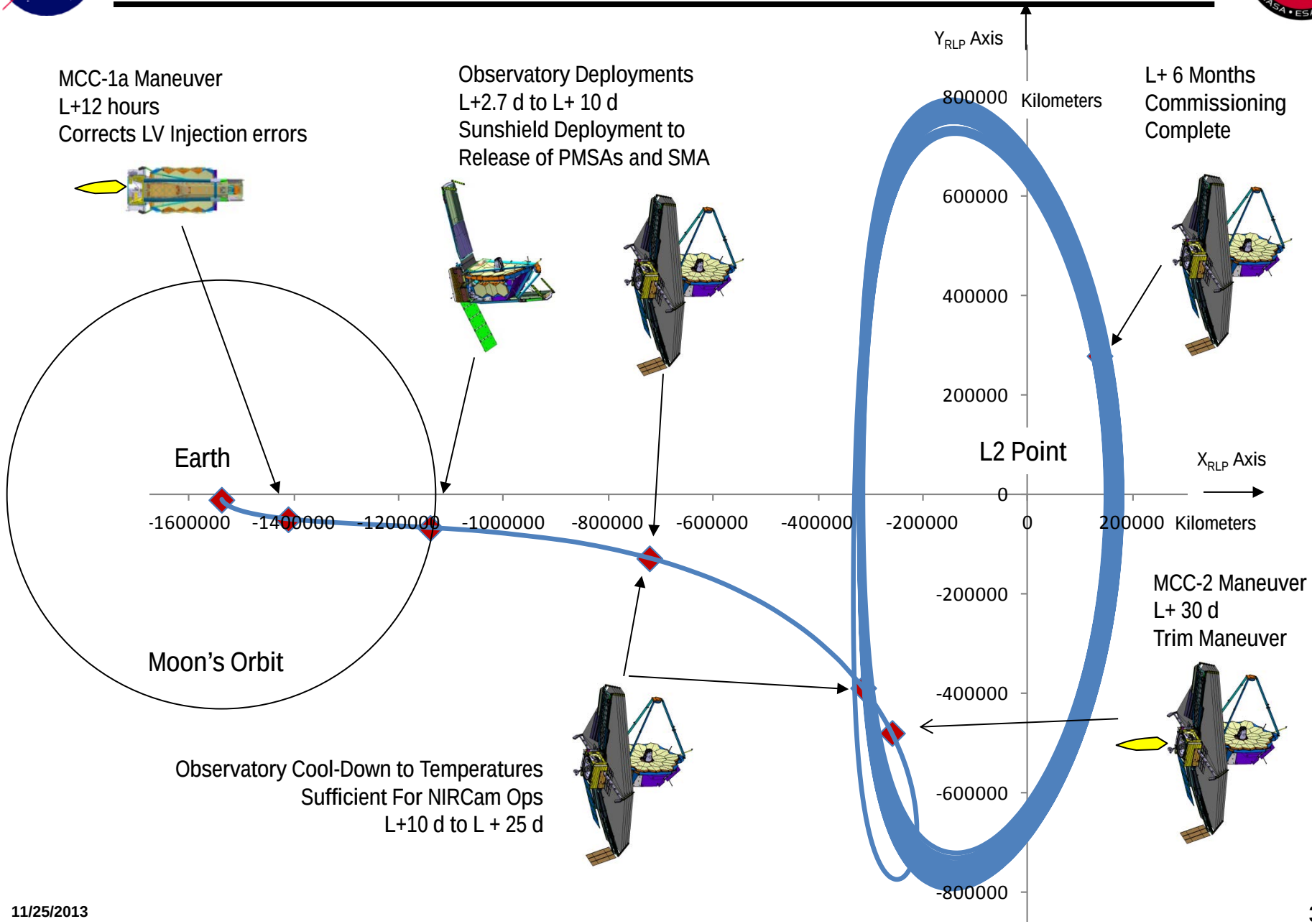
The JWST Observatory Elements and Regions



JWST Observatory Deployment



JWST Mission Orbit and Key Events



JWST Trade Studies

- **There have been dozens of system and subsystem level trade studies which led to the formulation of the JWST design.**
  - Many had to be conducted in parallel
  - Many were very complex and very pervasive
  - Required significant coordination from systems engineering
- **Among the more significant of these trades:**
  - Science Instrument Complement
  - Thermal Architecture / ISIM Electronics
  - Momentum Management
  - Mission Orbit Geometry
  - Telescope Optics Material
  - Data Compression
  - Cosmic Ray Correction
  - Science Instrument Detector
  - MIRI Cooling

Hierarchical List of Major JWST Trade Studies

Mission Trade Studies
- Orbit Trade
- Momentum Management Trade
- Observation Plan Executive Trade
- Launch Vehicle Adapter Trade
- Science Assessment Team (SAT) Mission Rescope Trades
- Encryption / Authentication Trade

Ground Segment Trades
- Design Reference Mission Studies
- Scheduling Flexibility Studies
- Science Operations Studies

Observatory Segment Trade Studies
- ISIIM Electronics Compartment Trades
- Alternate Backplane Support Trade
- MIRI Cryo-Cooler vs Dewar Trades
- Sunshield Configuration Trades
- OTE / ISIM Interface Trades
- Omni Antenna Trade
- OTE Deployment Tower Trades
- IC&DH to CTP I/F Trade
- ISIM Radiator Trades
- Stray Light Control Trades
- Sensitive Surfaces Protection Studies

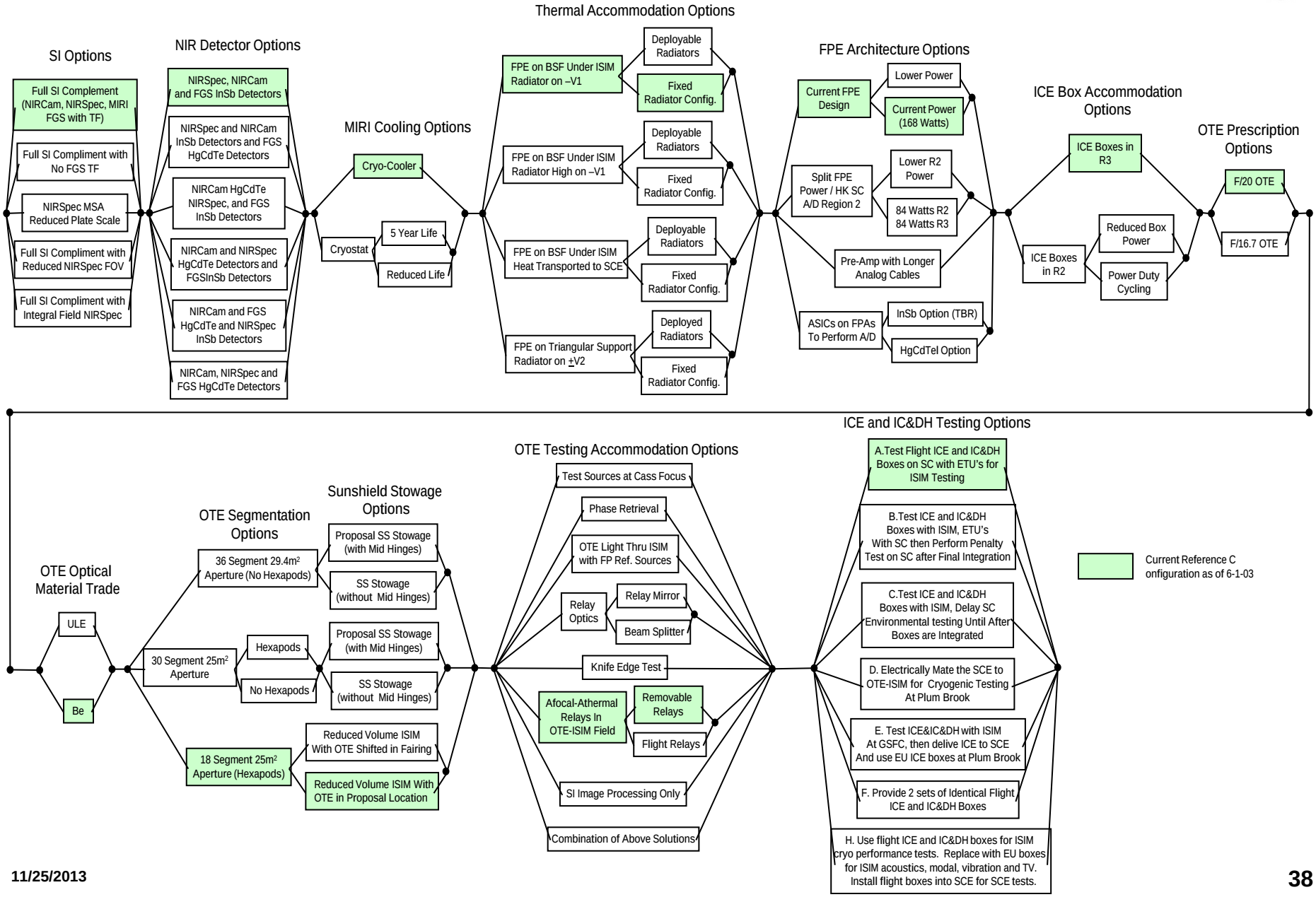
Verification / I&T Trades
- Plum Brook vs JSC Trade
- OTE / ISIM Metrology Trade
- OSIM Trade
- Observatory Transportation Trade
- OTE / ISIM Test Trades
- Electrical End-to-End Testing Trade
- Contamination Control Trades

ISIM Element Trade Studies
- NIR FPE ASIC Trade
- NIRCam 3-DOF POM Trade
- ISIM Contamination Prevention
- Elimination of FGS C&DH Trade
- IRSU Trade

OTE Trade Studies
- WFSC Trades
- PMSA to Backplane Interface Trade
- PMSA Be Delta Frame Trade

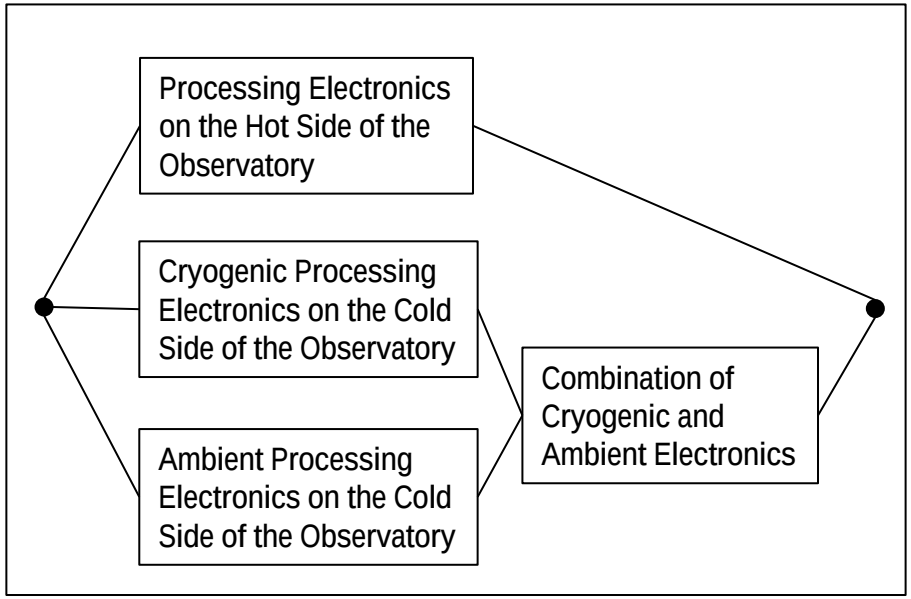
SCE Trade Studies
- Monopropellant vs Bi-Propellant Trade
- Spacecraft Structure Trade
- Solar Array Drive Trade
- Lithium Ion Battery Trade

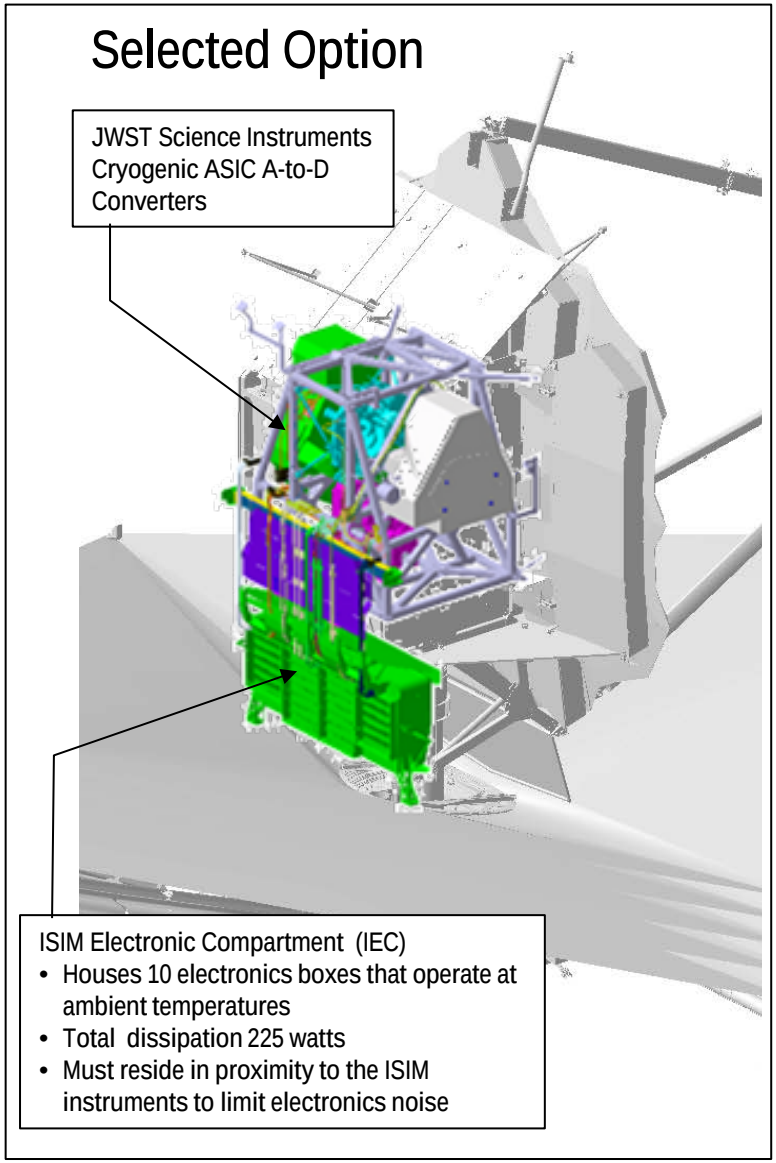
Coordination of the System Trade Space



Thermal Architecture / ISIM Electronics Trade

- **Early architecture trades considered where to locate the science instrument processing electronics.**
  - Options are shown on the figure below.
  - If the boxes were too far from the SI's electronics noise would be too high
- **The trade concluded that ambient boxes needed to be located on the cold side of the observatory.**
  - The solution is shown on the right
  - If these boxes were located in the warm spacecraft we would NOT be able to test the final ISIM with its electronics without breaking the harness connections. THERE ARE OVER 2500 WIRES!





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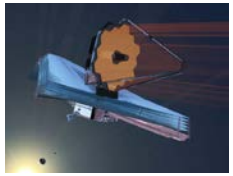
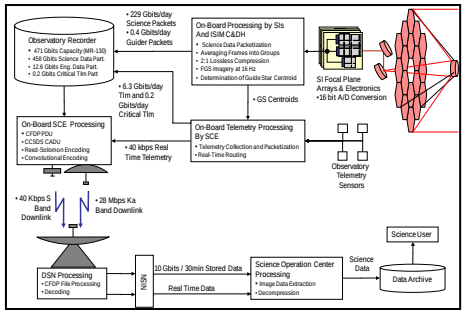
Design the System

James Webb Space Telescope System

Launch Segment | Observatory Segment | Ground Segment



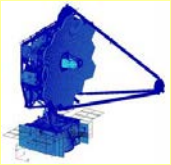


WFE Budget

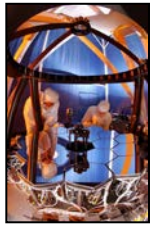
Power Budget

Mass Budget

Systems Analyses and Performance Assessments



Risk Management and Technology Development



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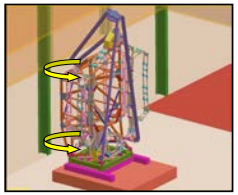
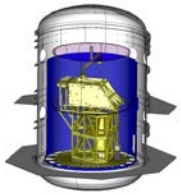
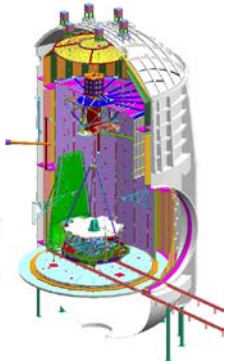
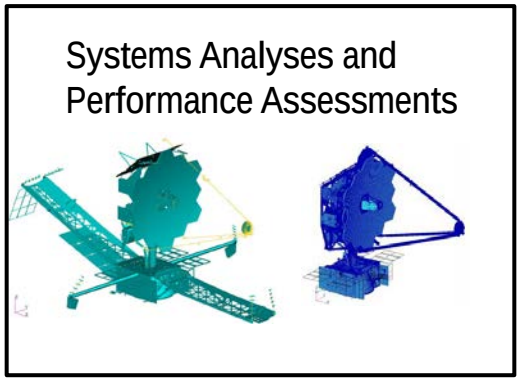






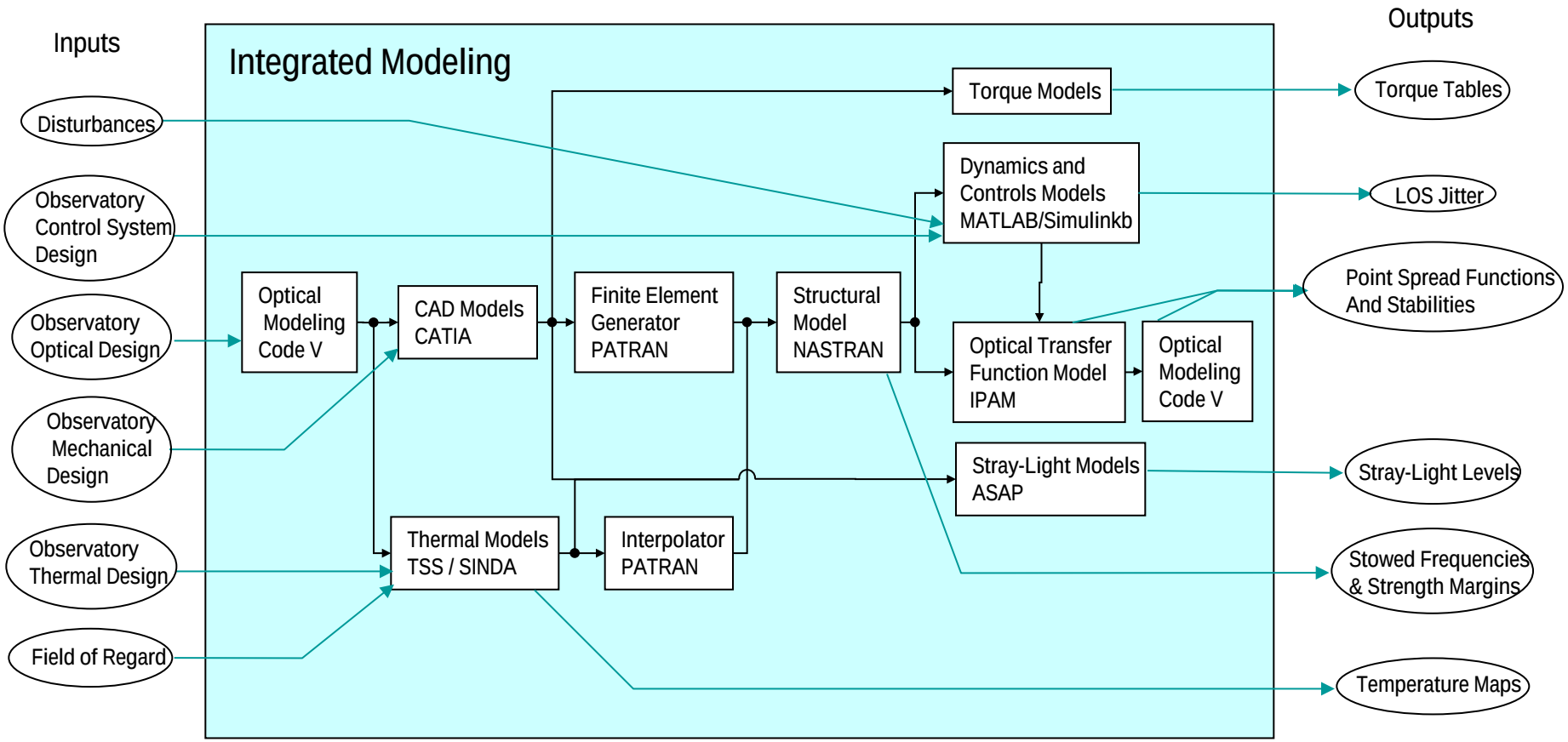
Systems Analysis and Performance Assessment



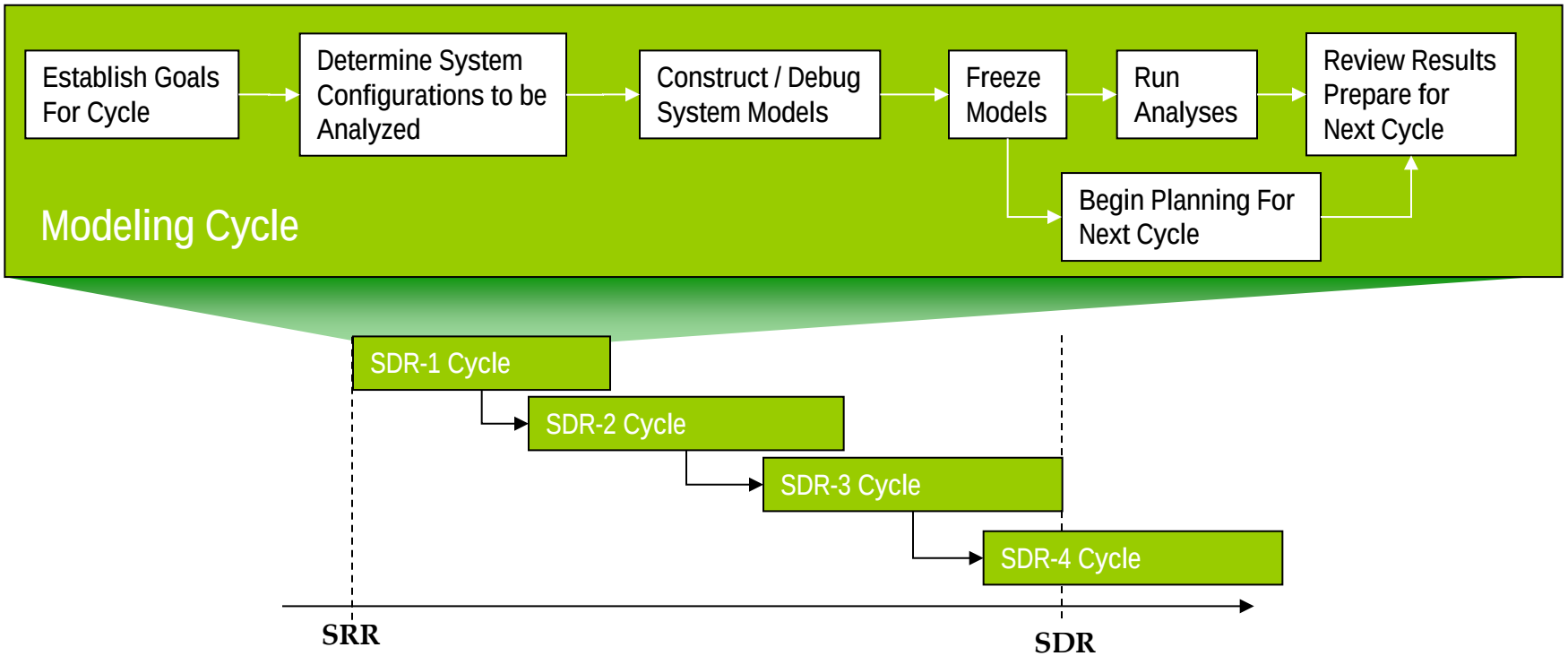
- **Performance assessments of the observatory are accomplished with analytic mechanical, thermal, control and optics models.**
- **Critical performance metrics such as thermal distortion, jitter, Line of Sight Errors and stray light levels requires multiple models for their computation. Integrated Modeling refers the process which coordinates these models. The coordination includes:**
  - Physical configurations
  - Boundary Conditions and Cases
  - Uncertainty Factors and model accuracy
- **The modeling process can be time consuming and so it is performed in cycles similar to the process of "Load Cycles"**.

Integrated Modeling

- **Guidelines for model conventions are in the "Math Models Guidelines Document" (NGST D36124)**



JWST Integrated Modeling Cycles



- **Analytical models are run in cycles (much like the familiar "Load Cycles")**
  - **Typically 2 to 3 cycles between major reviews, each taking between 3 to 6 months**
- **These cycles address system level performance issues**
  - **Used for major system level trade studies**
  - **For Requirements / Architecture Validation**
  - **In the later part of the Program for verification**
- **The pedigree of the models and the specific configuration of the architecture they represent is managed by the Integrated Modeling Working Group**

List of Primary TPMs

Performance / Resource Parameters	Capability / Requirement	Estimate or Predict 11-13	Comments
Sensitivity Parameters			
NIRCam SI Sensitivity @ 2 microns (nJy)	11.4	10..2	Prediction at EOL from 6-19-13 SI TPM Report
MIRI SI Sensitivity @ 10 microns (nJy)	700	679	Prediction at EOL from 6-19-13 SI TPM Report
Straylight (MJy/ster @ NIR 2 microns)	0.091	0.090	Prediction from 8-20-13 Integrated Modeling Review (13-JWST-0207K)
Straylight (MJy/ster @ NIR 3 microns)	0.07	0.068	Prediction from 8-20-13 Integrated Modeling Review (13-JWST-0207K)
Straylight (MJy/ster @ MIR 10 microns)	3.9	0.95	Prediction from 8-20-13 Integrated Modeling Review (13-JWST-0207K)
Straylight (MJy/ster @ MIR 20 microns)	200	271	Prediction from 8-20-13 Integrated Modeling Review (13-JWST-0207K)
OTE Transimission* Ap m^2	22	22.219	2013 03 20 Transmission X Budget - RevE.xlsx predictions at 2 microns min margin wavelength
Image Quality Parameters			
Strehl (NIR 2 microns)	0.80	0.838	Strehl at $\lambda = 2.0\ \mu m$ computed by M. Menzel for WFE of 134 nm
Strehl (MIR 5.6 microns)	0.80	0.859	Strehl at $\lambda = 5.6\ \mu m$ computed by M. Menzel for WFE of 347 nm
NIRCam ChannelWavefront Error (nm)	150	134	WFE Summary 6-3-13 (13-JWST-0191) with Liens and Accepted Opportunities (NIRCam)
NIRSpec Channel Wavefont Error (nm)	238	231	WFE Summary 6-3-13 (13-JWST-0191) with Liens and Accepted Opportunities
NIRISS Channel Wavefront Error (nm)	180	156	WFE Summary 6-3-13 (13-JWST-0191) with Liens and Accepted Opportunities
MIRI Channel Wavefront Error (nm)	421	347	WFE Summary 6-3-13 (13-JWST-0191) with Liens and Accepted Opportunities
EE Stability at 2 microns Over 24 hours	2.30%	1.10%	WFE Summary 6-3-13 (13-JWST-0191) with Liens and Accepted Opportunities (NIRCam)
EE Stability at 2 microns Over 14 days	3.00%	2.30%	WFE Summary 6-3-13 (13-JWST-0191) with Liens and Accepted Opportunities (NIRCam)
Image Motion, rms for 10,000 sec for NIRCam (mas)	6.6	6.4	WFE Summary 6-3-13 (13-JWST-0191) with Liens and Accepted Opportunities (NIRCam)
Image Motion rms for 15 sec Slidinging Window for NIRCam (mas)	6.6	6.3	Initial Predict from P. Maghami 5-13-13 with no Liens, Threats or Opportnities
Operations Parameters			
Observing Efficiency	70%	77.0%	From "Observation Efficiency Allocations Report JWST-RPT-004166, Revision F"
Slew Time for 90 Degree Slew with 5 RWAs (min)	60.0	57.3	Prediction as cited in Pointing Budget D36177 RevH Para 5.1
Momentum Accumulation LV1 (Nms/d)	22	18.11	Updated on 8-1-2013 (13-JWST-207D) from Torque Tables for SC Bus IM Cycle (Nom+rss)*MUF
Momentum Accumulation LV4 (Nms/d)	23	18.45	Updated on 8-1-2013 (13-JWST-207D) from Torque Tables for SC Bus IM Cycle (Nom+rss)*MUF
Thermal Parameters			
Cryo Parastic Margin (NIRCam)	60%	53.3%	Predicts with Liens and Accepted Opportunities per 2013.06.03_Obs_v5.1d_LTO-P2_v57.xlsx
Cryo ParasiticMargin (NIRSpec FPA)	60%	56.8%	Predicts with Liens and Accepted Opportunities per 2013.06.03_Obs_v5.1d_LTO-P2_v57.xlsx
Cryo Parasitic Margin (FGS/NIRISS)	60%	35.3%	Predicts with Liens and Accepted Opportunities per 2013.06.03_Obs_v5.1d_LTO-P2_v57.xlsx
ISIM Cavtity Temperature (K)	41K (TBR)	42.9	Area Average with Liens and Accepted Opportunities per 2013.06.03_Obs_v5.1d_LTO-P2_v57.xlsx
Cryo-Cooler Line Load Margin (Pinch Point / Steady State)	83%	65%/69%	Cryo-Cooler Predicts from K. Banks and S. Thomson 6-17-13
Cryo-Cooler OM Load Margin (Pinch Point / Steady State)	83%	154%/69%	Cryo-Cooler Predicts from K. Banks and S. Thomson 6-17-13
Data and Link Parameters			
S-Band Uplink Margin (dB)	3.00	7.20	Adverse Margin From 2013.02.26 S-Band Links_CDR.pdf (SC Omni at 2000 bps)
S-Band Downlink Margin (dB)	3.00	3.60	Adverse Margin From 2013.02.26 S-Band Links_CDR.pdf (MGA at 40 kbps)
Ka-Band Downlink Margin (dB)	3.00	5.44	Adverse Margin From 2013.02.20 Ka-band Link (CDA Baseline)(1).pdf (28 Mbps)
Observatory Resources			
Observatory Wet Mass (kg)	6530	6082	Estimate with Pendings From 9-12-13 Mass Report
Observatory CG Offset	Area in DCI	15.5	CG uncertainty ellipse to 5 mm margin Ariane Static Unbalance Domain with Pendings (9-12-13)
Observatory Power Load (W)	1808	1534	Estimate + Pendings, 8-15-13 Power Report vs SA at 6 years
Observatory Power Generation (W)		1928	Power Generation at 6 Years, 8-15-13 Power Report
I&T Parameters			
JSC Timeline (Days)	120	88	Partners Workshop Presentation 2-11

JWST Systems Engineering

Science Objective:

- Detect and Investigate the First Light Sources
- Study the Assembly of Galaxies Since First Light
- Study the Birth of Stars
- Study the evolution of Planetary Systems

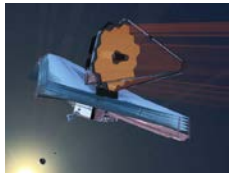
Formulate Mission Requirements

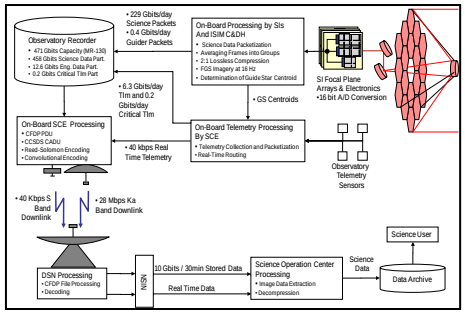
- Sensitivity
- Image Quality and Resolution
- Field Of View
- Data Throughput
- Observing Efficiency

Design the System

James Webb Space Telescope System

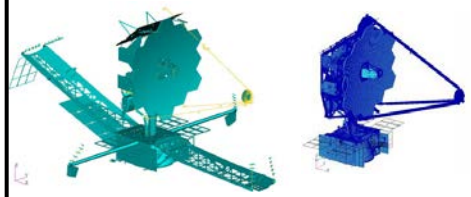
- Launch Segment
- Observatory Segment
- Ground Segment



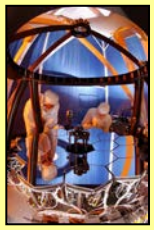


- WFE Budget
- Power Budget
- Mass Budget

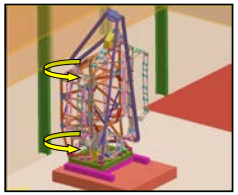
Systems Analyses and Performance Assessments

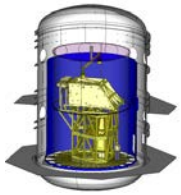


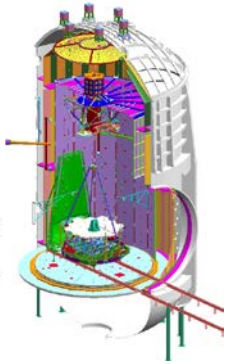
Risk Management and Technology Development



Verification of the "As Built" System

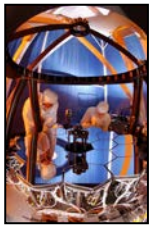






Technology Development and Risk Management

Risk Management and Technology Development



- **Systems Engineering and Product Engineering identify areas in need of Technology Development and formulate plans to mature them, according to the NASA schedule for Technology Readiness Level (TRL)**
  - Plans are documented as Technology Development Plans
- **Systems Engineering participates in a continuous process of Risk and or Issue Identification and Risk Management.**

JWST Technology Readiness Metric

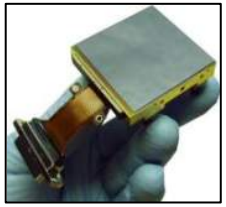
- **TRLs are used to systematically assess the maturity of technologies**
  - NASA uses a nine step TRL scale (from NPR 7120.5C):

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

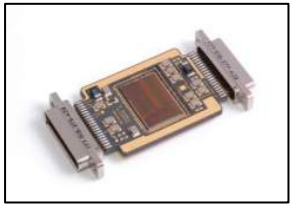
- **NASA Management Handbook requires that mission-enabling technologies reach *TRL 6* before the Project is confirmed**

Critical Technology Development Items

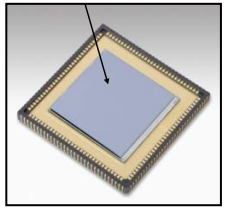
- **JWST adopted a strategy of early development of critical technology items.**
- **Ten critical items (Shown below and on the right) were initially identified and programs to mature their TRL were initiated.**
- **JWST instituted a Technology Non-Advocate Review (T-NAR) in January 2007.**
  - Nine of the ten Items were assessed to be TRL 6 or higher at this T-NAR.
  - All items were assessed to be at TRL 6 by the Program NAR which was held in March of 2007.



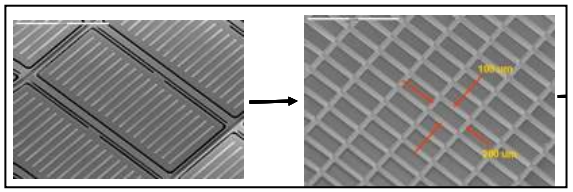
NIR Detector



Cryogenic ASIC

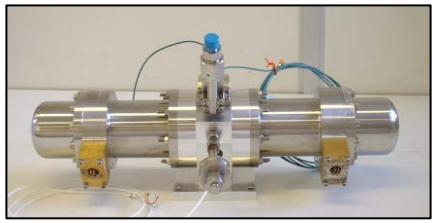


MIR Detector



Microshutter Arrays

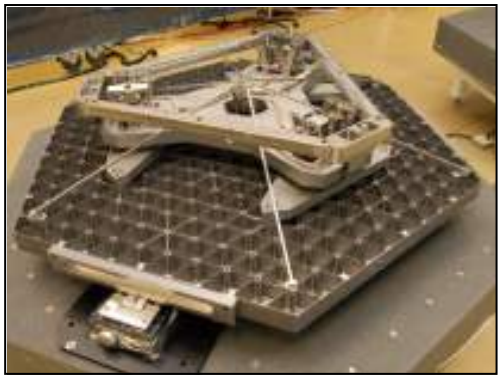
Heat Switches



MIR Cryo-Cooler

Wavefront Sensing & Control

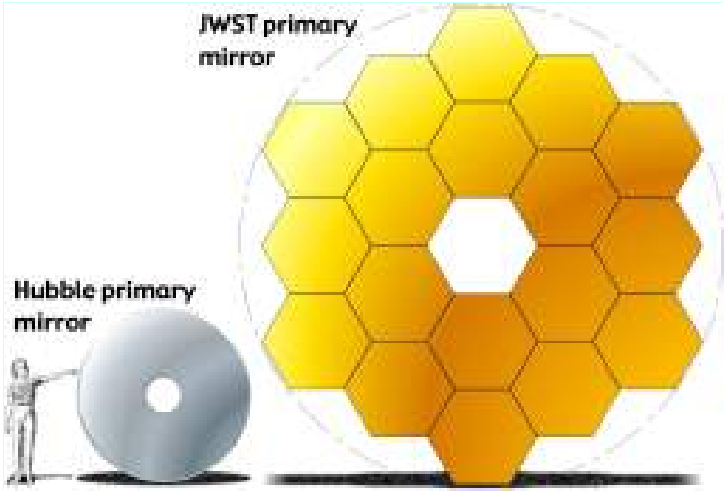
Large Cryogenic Composite Structures



Primary Mirror Segment

Sunshield Membrane Material

Comparison of JWST to HST System Challenges



JWST Challenges

Performance Parameter	HST	JWST
OTE Diameter (meters)	2.4	6.1 by 6.6
Mass (kg)	11600	6530
Power (watts)	2400	2079
Light Collecting Aperture (Sq meters)	3.8	25
Overall Optical Transmission	45 to 25%	62% to 43%
OTE FOV (Arcmin)	14.6 (Radius)	~18 by 9
Wavelength of Diffraction Limit (Microns)	0.5	2
Rayliegh Radius (Arcsec)	0.043	0.069
OTE Strehl	80%	80%
Bulk Observatory Operating Temperatures	283K to 313K	40K to 400K
Pointing Accuracy (Arcsec)	22	7
Pointing Stability (Arcsec)	0.007	0.007
Total Pixels (mpixels)	56.8	66.1
Data Throughput (Gbits/day)	27	458
Observing Efficiency	50%	70%

JWST Deployments Over 6m dia. Into a 5m LV Fairing

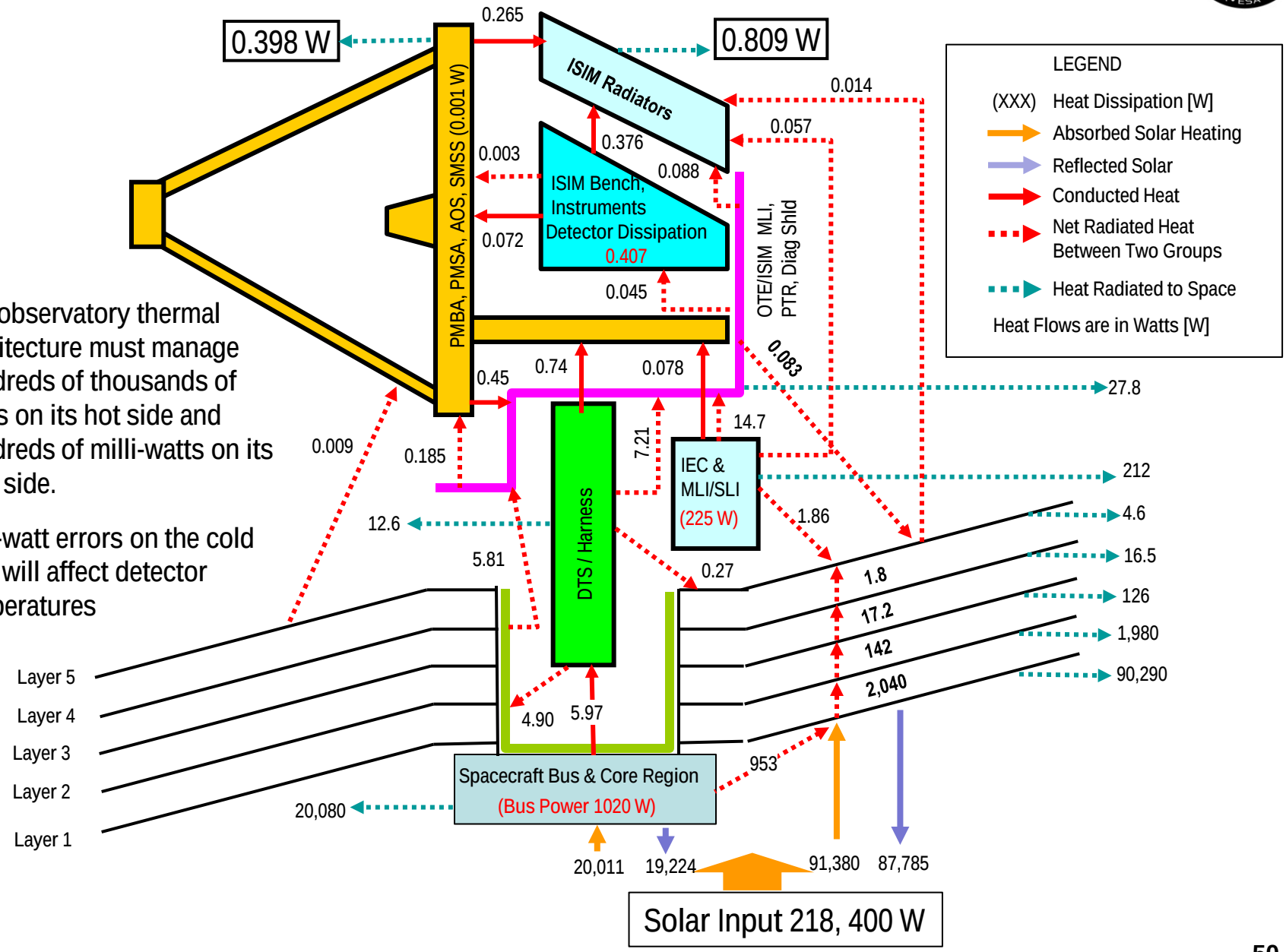
½ the mass of HST

Over 6.5 times the light collecting area of HST

Order of magnitude colder than HST. Roughly 4000 kg needs to be cooled below 50K

Cryogenic Design Challenges

- The observatory thermal architecture must manage hundreds of thousands of watts on its hot side and hundreds of milli-watts on its cold side.
- Milli-watt errors on the cold side will affect detector temperatures

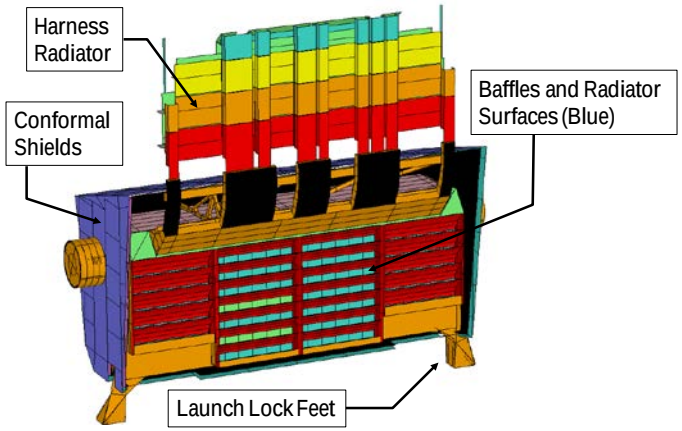


Approach to Cryogenic Challenges

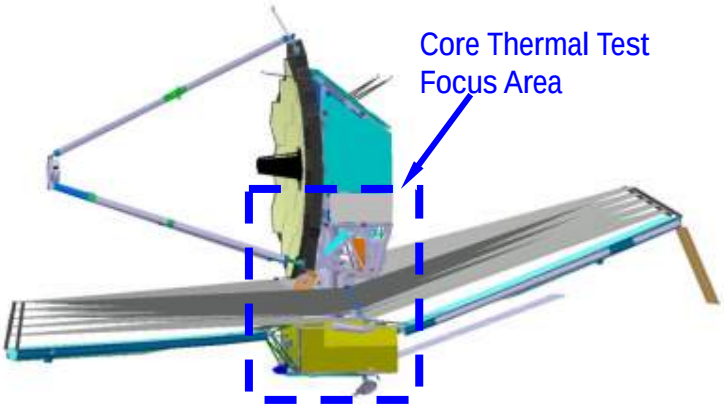
$$\text{Margin} = \frac{\text{Radiator Capability} - \text{Thermal Loads}}{\text{Radiator Capability}}$$

Provide robust thermal margins for uncertainties and verification margin.

Characterize and optimize the design of the sunshield.



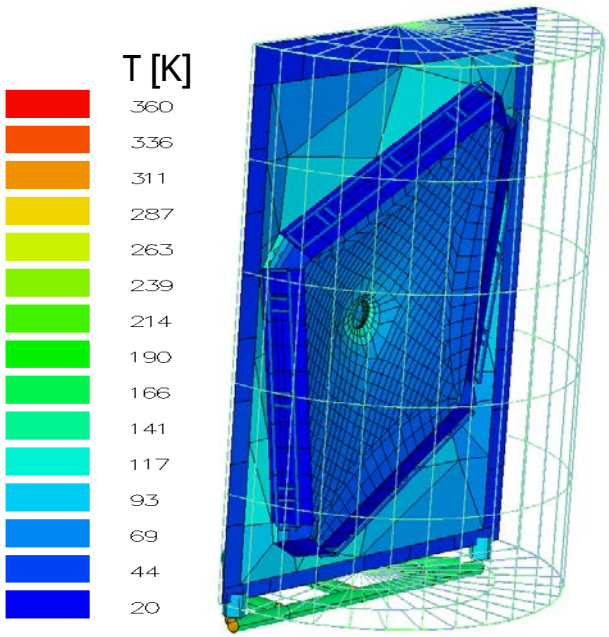
Design a well insulated IEC which directs its heat load in the proper directions.



Characterize and optimize the design of the Core area.

1/3 Scale Sunshield Model Validation

- Thermal balance tests of a 1/3 scale engineering model of the sunshield were performed in December 2009 to correlate the thermal models.
- The test went well, but there was a mechanical failure one of the pulleys that held the layers in place, which corrupted some of the measured data.
- Despite the pulley anomaly, the level of correlation of the test data and model predicts translate to roughly 6.6% in terms of cryogenic radiator margin.

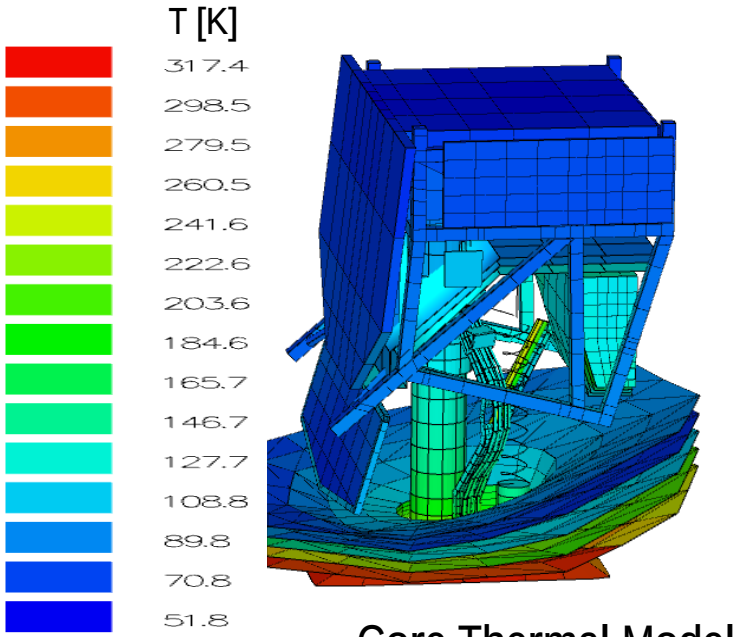


1/3-Scale Sunshield Thermal Model

1/3 Scale Sunshield Test Article Being Loaded in the Thermal Chamber

Core Thermal Balance Test

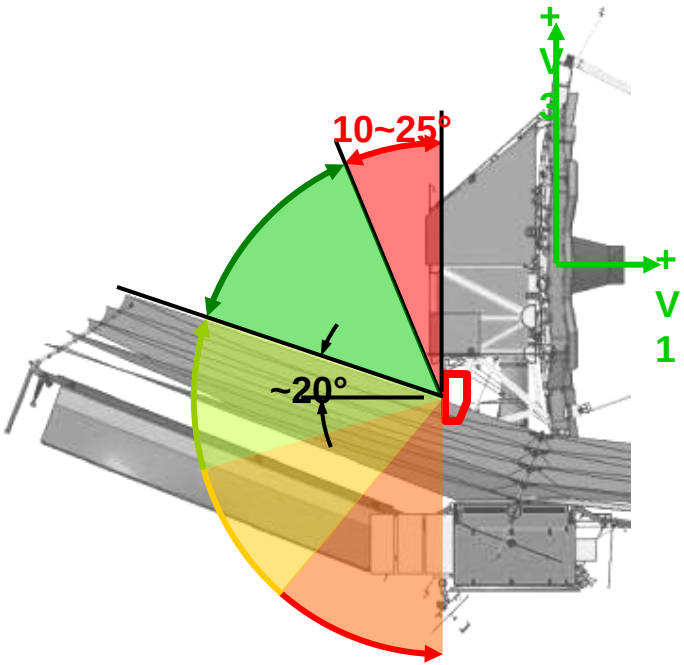
- Thermal balance tests of a full scale engineering model of the core region were performed in May 2009 to correlate the thermal models of this region.
- The design performed as expected and even with ambient IEC with > 200 watts of dissipation, cryogenic temperatures were achieved.
- The level of correlation of the test data and model predicts translate to roughly 6.2% in terms of cryogenic radiator margin.



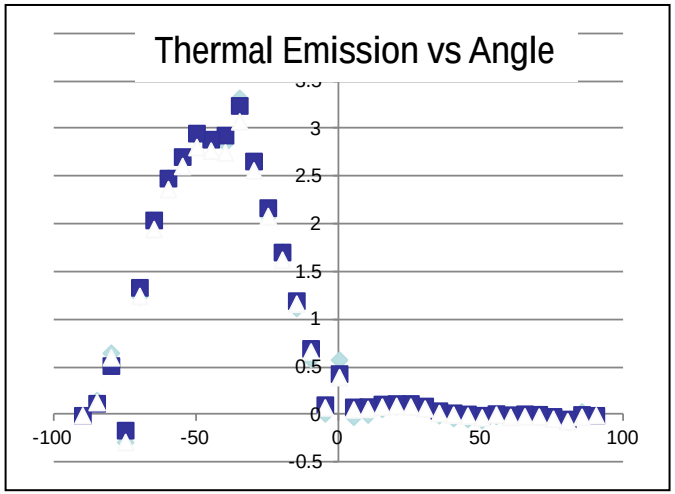
Core Thermal Model

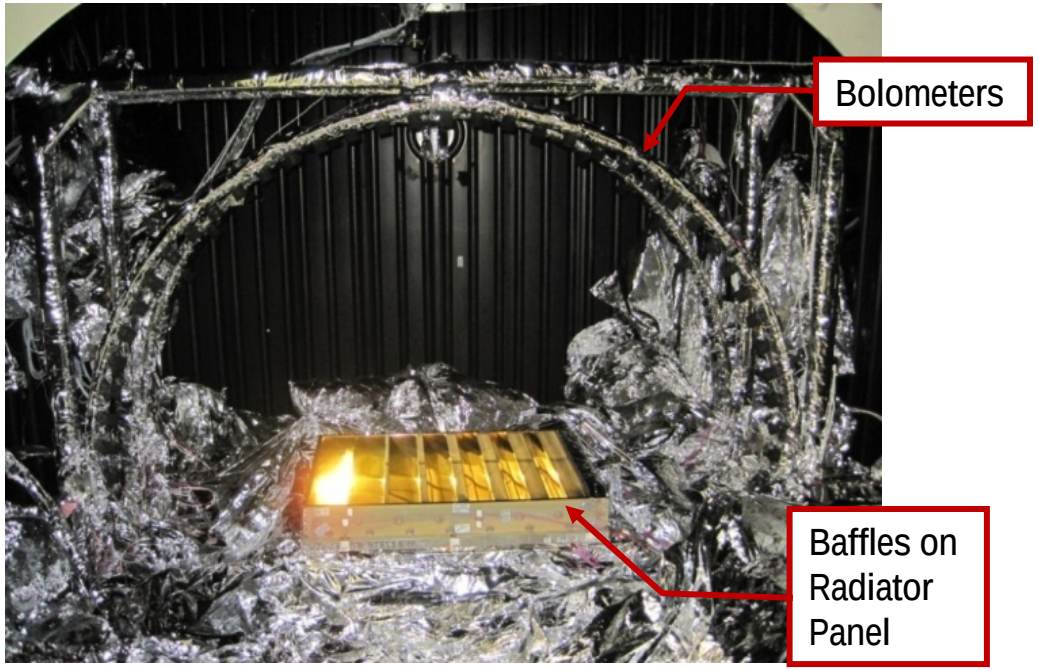
Core Test Article Being Loaded into the Thermal Vac Chamber

IEC Directional Baffle Test



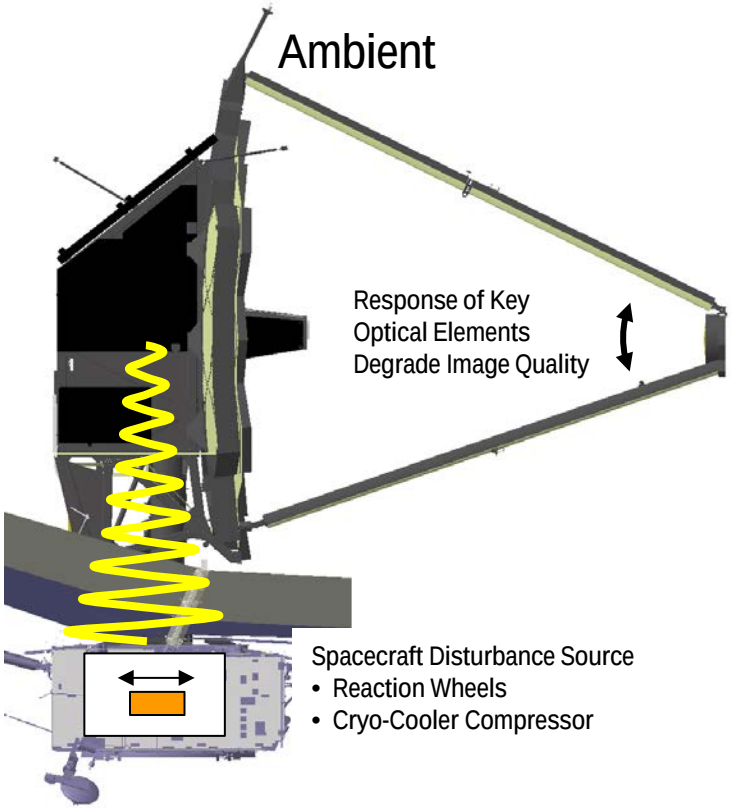
- Tests to confirm the directionality of the IEC radiator baffles were conducted in Spring of 2011.
- The test results demonstrated that the baffles behaved as predicted for emission directionality.

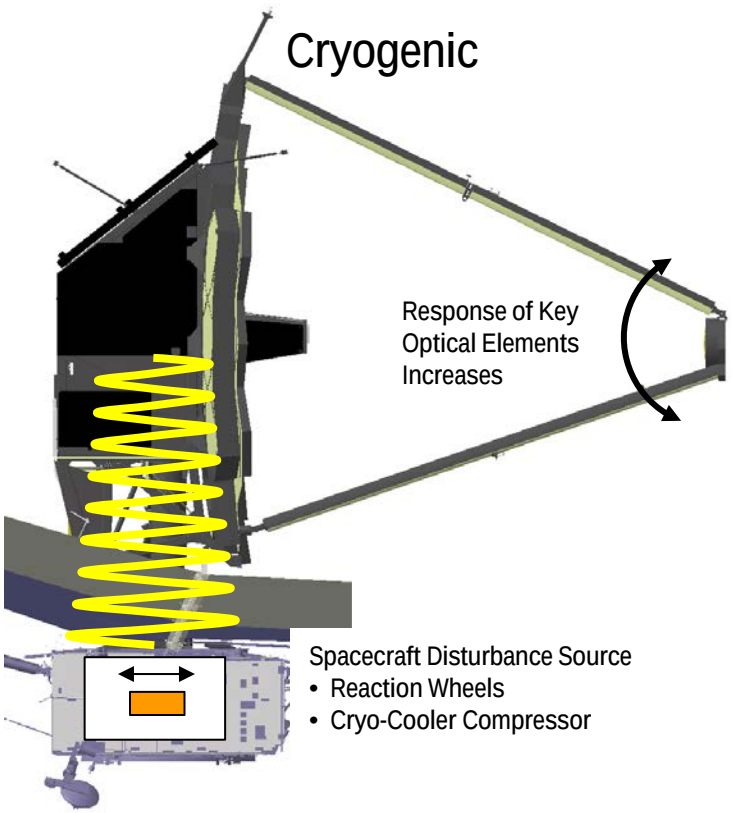




IEC Baffle Test Set-Up

Vibration Damping at Cryogenic Temperatures

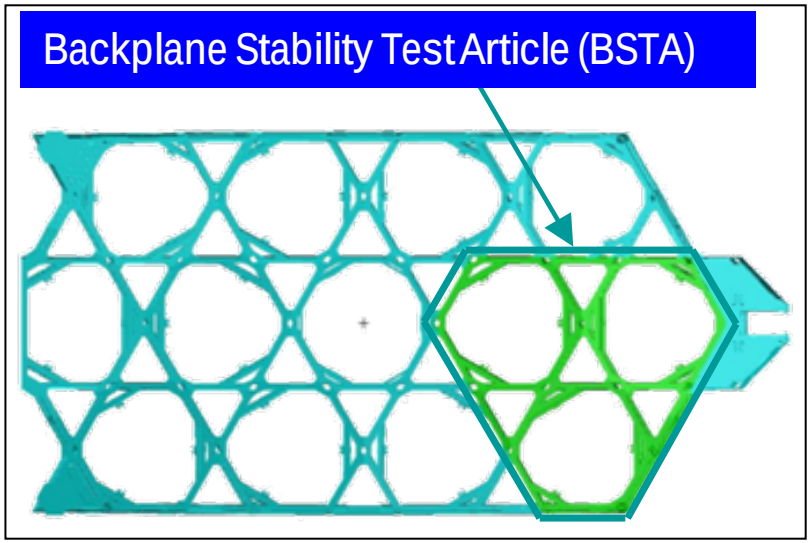


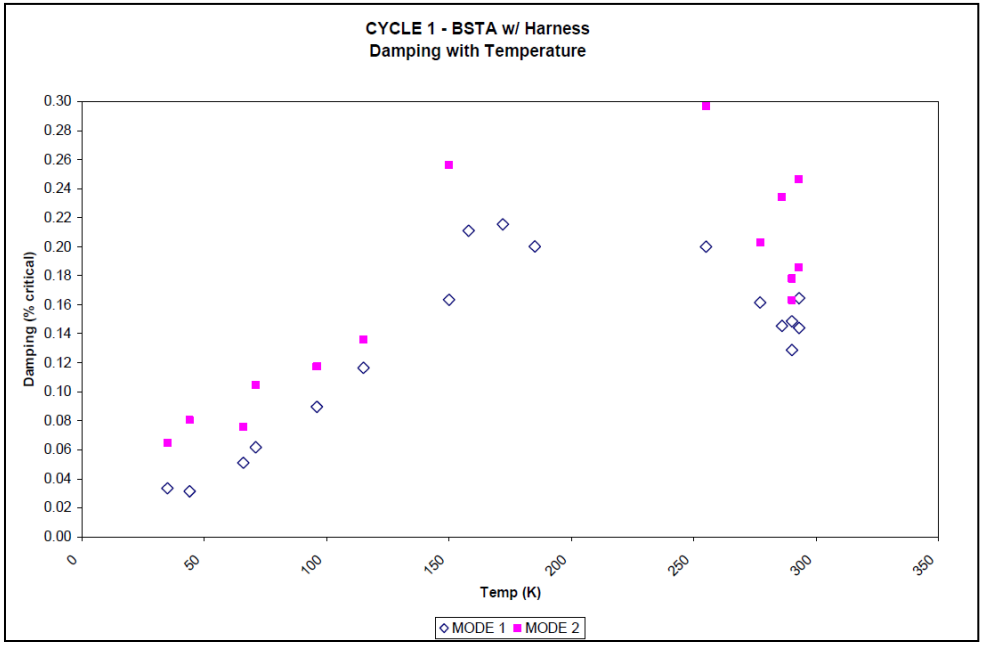


- **Mechanical vibrations from sources such as Reaction Wheels or Cryo-Cooler Compressors propagate thru the structure to excite modes of the optical elements. The response of these elements degrades image quality.**
- **At ambient temperatures, most structures have vibration damping ratios of roughly 0.3 to 0.2% of critical damping**
- **At cryogenic temperatures the damping ratio of structures decreases dramatically, to levels roughly 0.05% of critical damping. This results in increased image quality degradation.**
- **Careful vibration isolation and additional provisions to increased damping are required.**

Backplane Stability Test Article (BSTA)

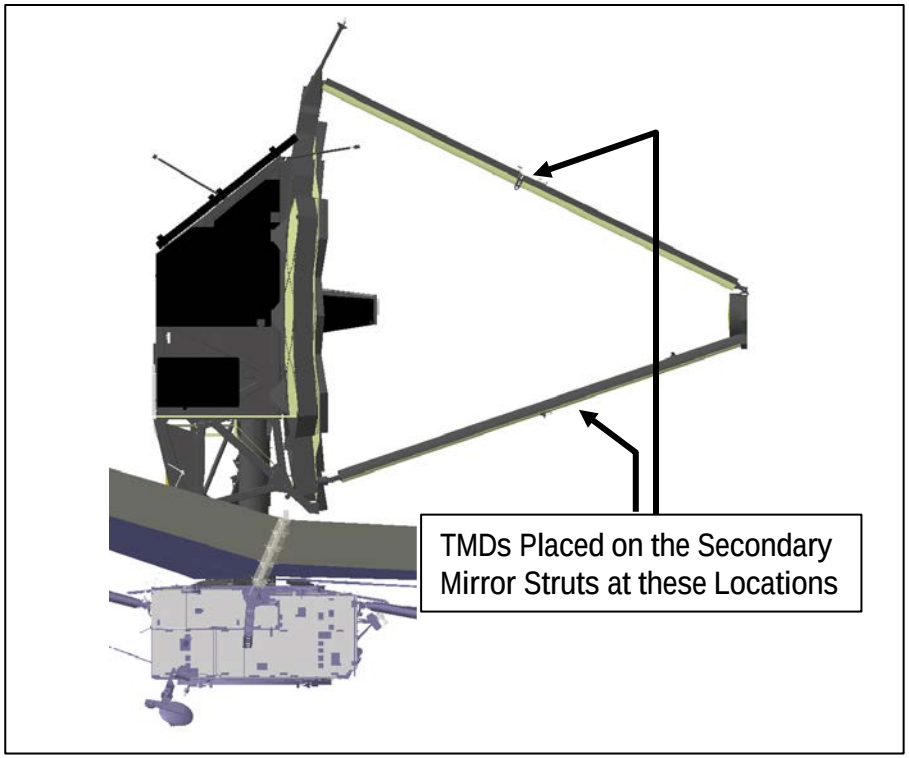
- **The BSTA is a full scale 1/6th substructure cut out of the flight PMBSS design, shown on the right.**
- **The BSTA demonstrated fabrication techniques and was subjected to:**
  - Thermal Stability Tests
  - Cryo Damping Measurements
- **Test results were used to correlate / anchor analytical models used to predict thermal cool down structural stability and vibration propagation.**
- **Damping measurement results are shown below.**



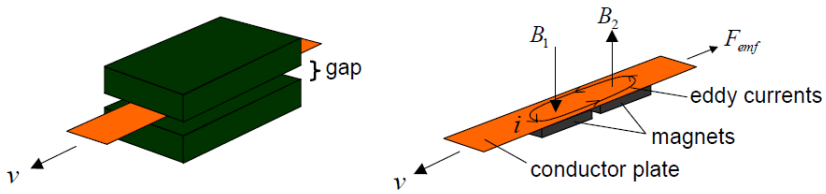


Magnetic Dampers

- **Analytic modeling of the deployed dynamics of JWST identified modes which had the greatest impact to Line of Sight (LOS) or Wavefront Errors (WFEs).**
  - Not surprisingly motions of the secondary mirror relative to the OTE have significant impact to LOS and WFE.
- **Incorporating Tuned Magnetic Dampers (TMDs) to the Secondary Mirror Struts provided the damping to reduce these errors.**
- **TMDs work by allowing a conductor to move in a magnetic field provided by permanent magnets. Eddy currents in the conductor induced by this movement set up an Electromotive Force (EMF) which opposes this motion. (See figure on lower right from Bronowicki, Brennan and Simonian[1]).**
- **Unlike visco-elastic dampers, these TMDs have no issues operating at cryogenic temperatures.**



Basic Operation for Magnetic Dampers



JWST Systems Engineering

Science Objective:

- Detect and Investigate the First Light Sources
- Study the Assembly of Galaxies Since First Light
- Study the Birth of Stars
- Study the evolution of Planetary Systems

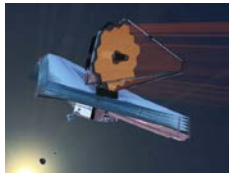
Formulate Mission Requirements

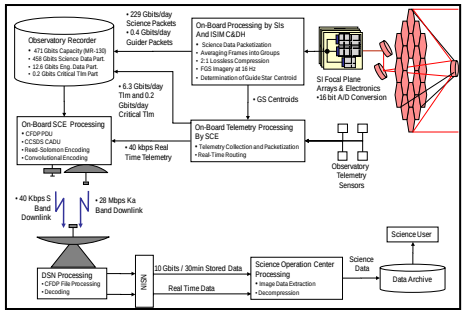
- Sensitivity
- Image Quality and Resolution
- Field Of View
- Data Throughput
- Observing Efficiency

Design the System

James Webb Space Telescope System

Launch Segment | Observatory Segment | Ground Segment



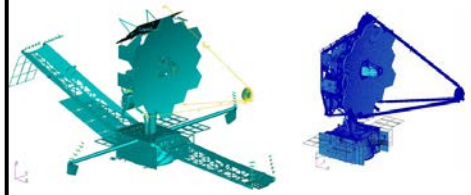


WFE Budget

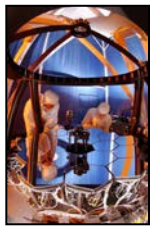
Power Budget

Mass Budget

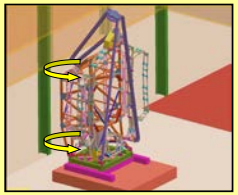
Systems Analyses and Performance Assessments

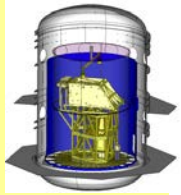


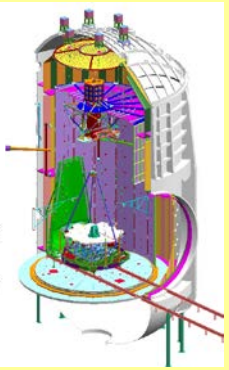
Risk Management and Technology Development



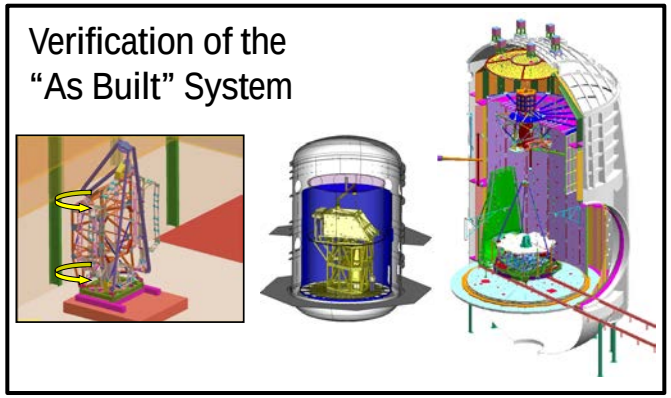
Verification of the "As Built" System







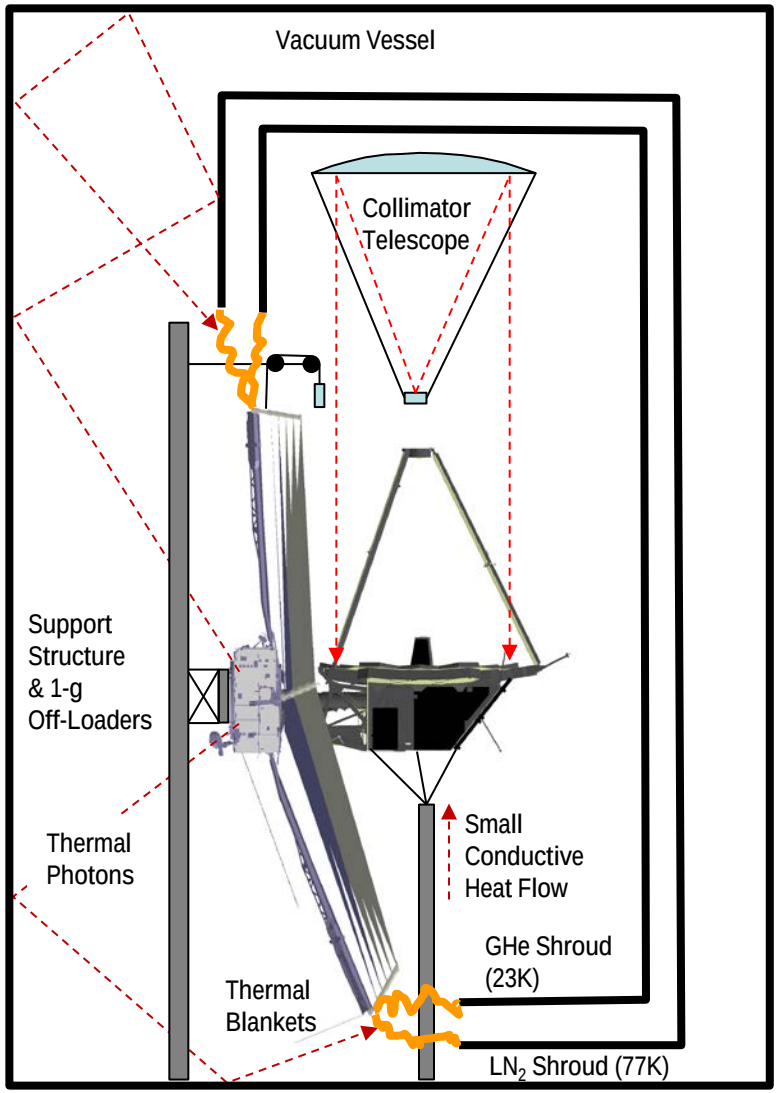
Verification



- **The verification program proves that the "as-built" system meets its requirements in a flight-like environment and is ready for deployment.**
  - Verifies both performance and workmanship.
- **Ultimately the verification process produces a complete set of Requirements Verification Reports (RVRs) for each requirement or requirements set proving the systems compliance.**
  - These reports will consolidate the results of Inspections, Tests and Analyses.
  - A set of detailed Expanded Verification Matrices (EVMs) and "Thread" Roadmaps show the necessary interplay of these Inspections, Tests and Analyses.
- **The overall verification process is documented in a System Verification Plan, which shows the coordination of these activities with the Integration and Test Program.**

Challenges of JWST System Tests

- **To test the 6 m diameter cryogenic telescope we need either another 6 m cryogenic telescope as a test source or a 6 m cryogenic test flat.**
- **To simulate the thermal environment, a "black" shroud colder than 30K needs to enclose the cold side to make sure thermal emission from the observatory doesn't bounce back.**
  - Requires a two stage shroud system, GHe and LN_2
- **Thermal radiation from the Observatory's hot side has to be "strictly" prohibited from leaking to the cold side of the observatory**
  - Careful blanketing and a large chamber to minimize bounces of thermal radiation. (Small Fill Factor)
- **Finally the observatory must be supported with gravity off-loaders to maintain its 0-g shape, particularly the sunshield.**
  - The off-loaders cannot introduce excessive radiative or conductive perturbations that alter the thermal environment.
- **The vacuum chamber must be very large, the Ground Support Equipment complicated and the Optical Test Equipment as demanding as the flight telescope.**

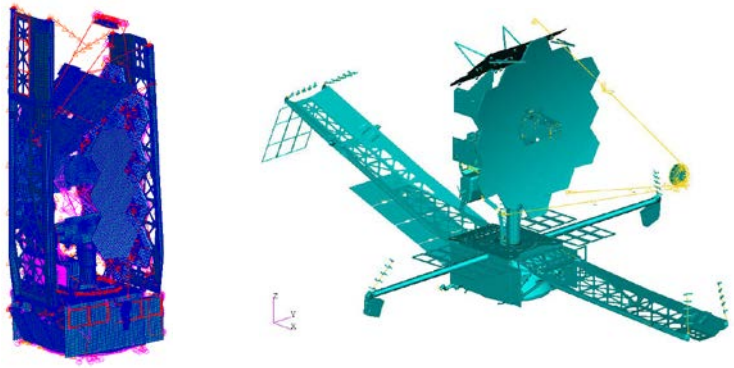


Observatory Level Testing is Not Practical

Verification Using Analytical Models

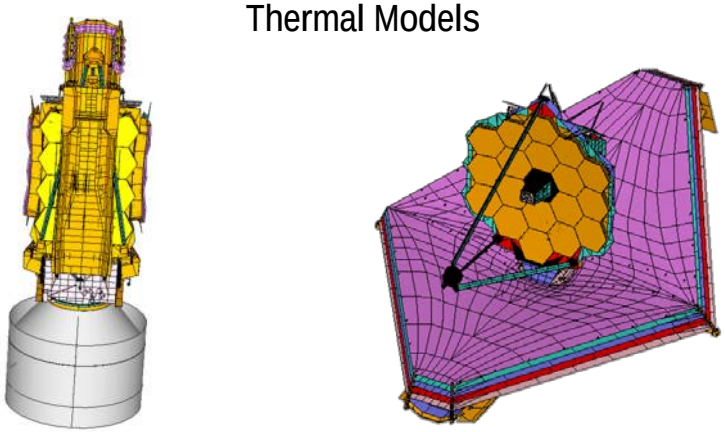
- **The verification of the on-orbit performance of JWST will involve analytical models which are correlated / anchored to "as-built" hardware by tests at lower levels of assembly.**
  - This proves that what is mathematically modeled is what was actually built.
- **Observatory system models are then assembled from these lower level models. The observatory level models are then correlated as practical to the as built observatory by system level tests.**
  - This proves the interfaces are modeled correctly.
- **The correlated models such as those shown on the right will be used to predict and verify the on-orbit performance of:**
  - Thermal Performance
  - Optical Thermal Stability
  - Dynamics
  - Stray Light
- **Tests at high levels of assembly will be conducted to verify "workmanship" and behavior of critical interfaces**

Structural Dynamics Models



Stowed Deployed

Thermal Models



Stowed Deployed

From EVM Entry To EVM Metric

A piece of the Observatory Spec Expanded Verification Matrix
Illustrating verication flow of OBS-145 "Command Verification"

When the Step Is performed

When the 3.7-level RVR is written

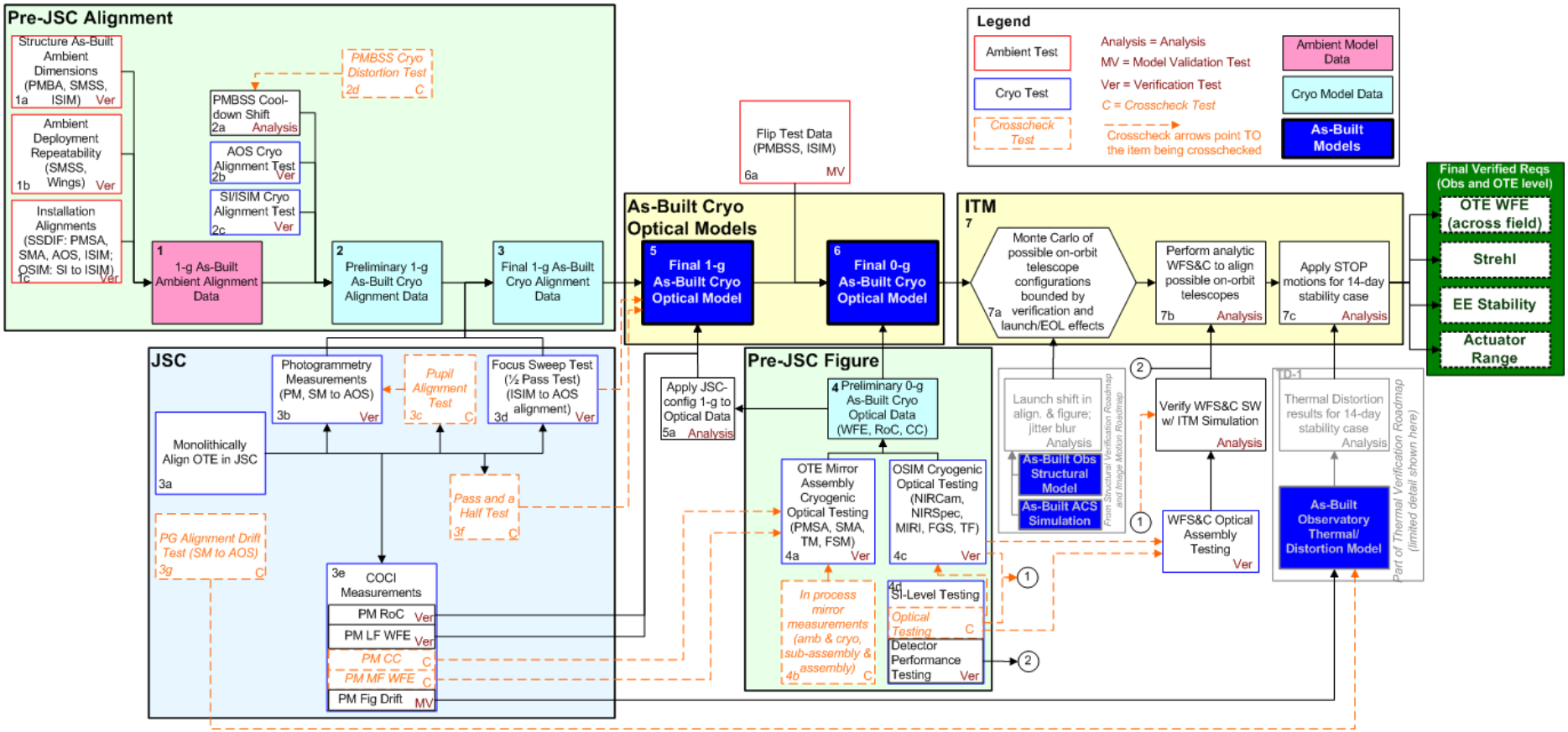
When the 3.2-level RVR is written

Verifies	Requirement Text	Verification Step	Ver Type	Verification Description	Verification Activity	RE POC	RVR	Step Ver Pt	Comp Ver Pt	Final Ver Pt
OBS-145 Cmd Validation	The Observatory shall validate all commands prior to execution.									
OBS-145 Partial Trace Verify @ OTE lvl	OBS-1846 Cmd Verification/Validation OTE-322 Cmd Verification/Validation For all cmds, prior to execution, the OTE shall perform tests associated with the CCSDS cmd protocol, verify checksums if used, and verify that the executable portion of the cmds met applicable rqmts for structure	OTE to verify OTE-322	Partial Verification	See verification for OBS-144	ADU Performance Test	Rich Rifelli	RVR	OTE SO	OTE SO	
OBS-145 Partial Trace Verify @ SC lvl	OBS-396 Cmd Verification/Validation SC-430 Cmd Verification/Validation For all cmds, prior to execution, the SC shall perform tests associated with the CCSDS cmd protocol, verify checksums if used, and verify that the executable portion of the cmds met applicable rqmts for structure	SC to verify SC-430	Partial Verification	See verification for OBS-144	JWST-CDH-101 CCSDS COP-1 Protocol (Cmd Decoding & Validation)	Mallen/Arisumi	RVR	SC I&T	SC I&T	
OBS-145 Partial Trace Verify @ ISIM lvl	OBS-584 Cmd Verification/Validation ISIM-275 ISIM Cmd Verification/Validation For all cmds, prior to execution, the ISIM shall perform tests associated with the CCSDS cmd protocols, verify checksums if used, and verify that the executable portion of the cmds met applicable rqmts for structure	ISIM to verify ISIM-275	Partial Verification	See verification for OBS-144	ISIM-TST-20701 ISIM SFT	Lionel Mitchell	RVR	ISIM I&T	ISIM I&T	
OBS-145 Partial		OBS I&T	Partial Verification	Final verification is OBS I&T	GSEG-1 portion of OBS I&T	Mallen/Arisumi		OBS I&T		
OBS-145 Validate			Validation	Validate ISIM-275 during JSC Testing	JSC	Lionel Mitchell		JSC Val		
OBS-145 Full			Full Verification	SET: document RVRs for OTE-322, SC-430, ISIM-275 complies SET to generate RVR after OBS I&T that compliance was established with OTE, SC, ISIM and Ground Segment.	Review of Records Review of OBS I&T results	Rick Sabatino	RVR	OBS I&T		OBS I&T

Image Quality/WFE Verification Roadmap

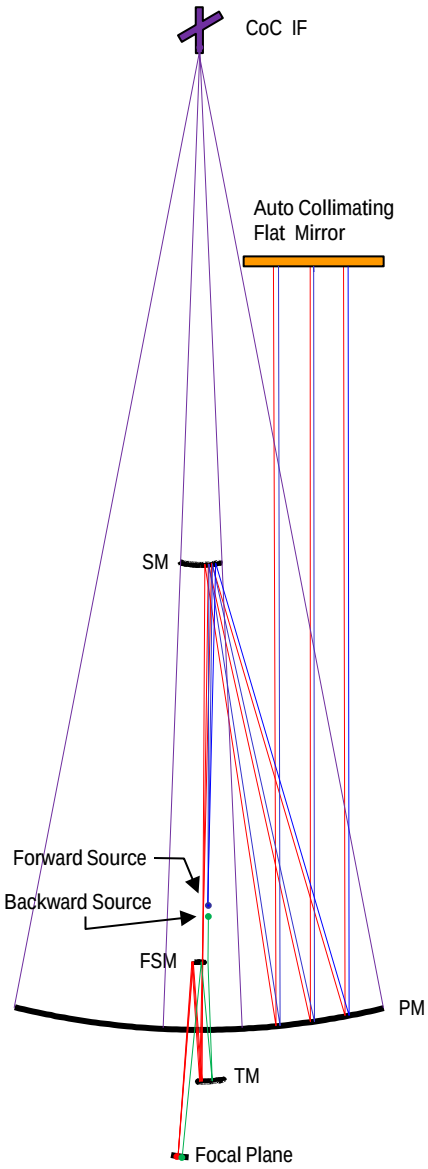
Notes on the Roadmap

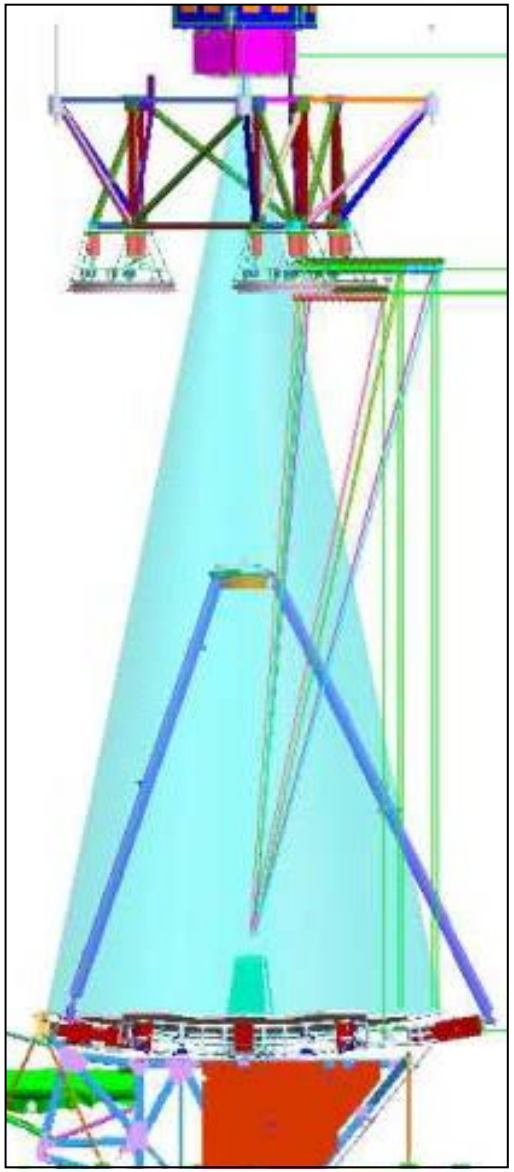
- Shows Data used in final as-built models – NOT a chronological flow
  - For example, shows one 1-g and 0-g model. In reality these models will be developed in parallel and both alignment and figure data will be updated as it becomes available
- Analysis is generally needed to convert test data into the form needed for input into the model. This detail is not shown
- Assume data from each test/analysis includes both measurement data and uncertainty data



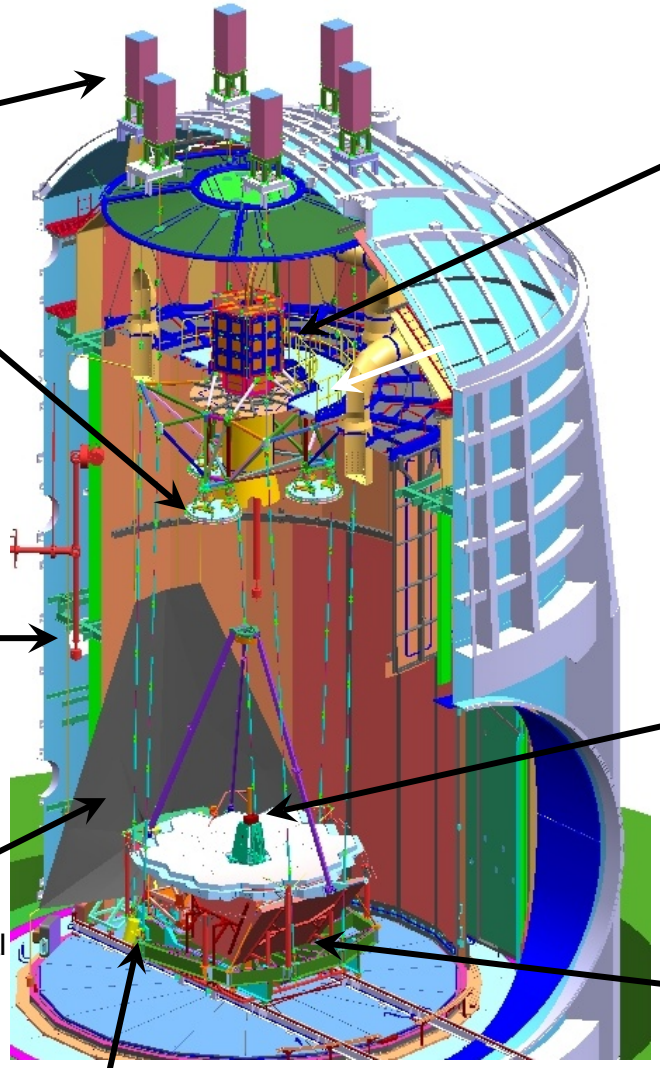
JWST Telescope Testing

- All optical components, Primary Mirror (PM), Secondary Mirror (SM), Tertiary Mirror (TM) and Fine Steering Mirror (FSM) are individually tested.
- The figure of the primary mirror is verified by testing with a Center of Curvature Interferometer (CoC IF)
- The performance of the "conic" match of the PM, SM and TM is verified by using three 1 meter auto collimating flats, and a pass and ½ test from Forward Sources located near the cassegrain focus.
- Separate sources at the cassegrain focus pointing Backward test the optical performance of the Aft Optics Subsystem.
- The physical layout of this test equipment is illustrated on the right of the ray diagram
- This complement of tests verifies that the flight telescope can achieve the required performance with more than 100% of the range of all the actuators.





Optical Testing at the Johnson Space Center



Chamber Isolator Units
- 6 isolators to limit external vibration sources from impacting the optical test results
- Controls vibration to near flight levels

Auto collimating Flat Mirrors (ACFs)
- Three, 1.5m flats that provide the ability for end-to-end optical testing through the telescope optical chain and into the flight instruments
- Provides the ability to complete a wavefront sensing and control exercise.

Cryo Position Metrology (CPM)
- Four photogrammetry systems on rotating booms inside thermal and pressure controlled canisters
- Allows measurements of hardware to 100 microns inside the cryo cavity

Space Vehicle Thermal Simulator (SVTS) and Sunshield Simulator
- Provides interfaces for electrical and thermal hardware that attaches to the flight spacecraft
- Simulates the flight spacecraft thermally to replicate the flight thermal conditions

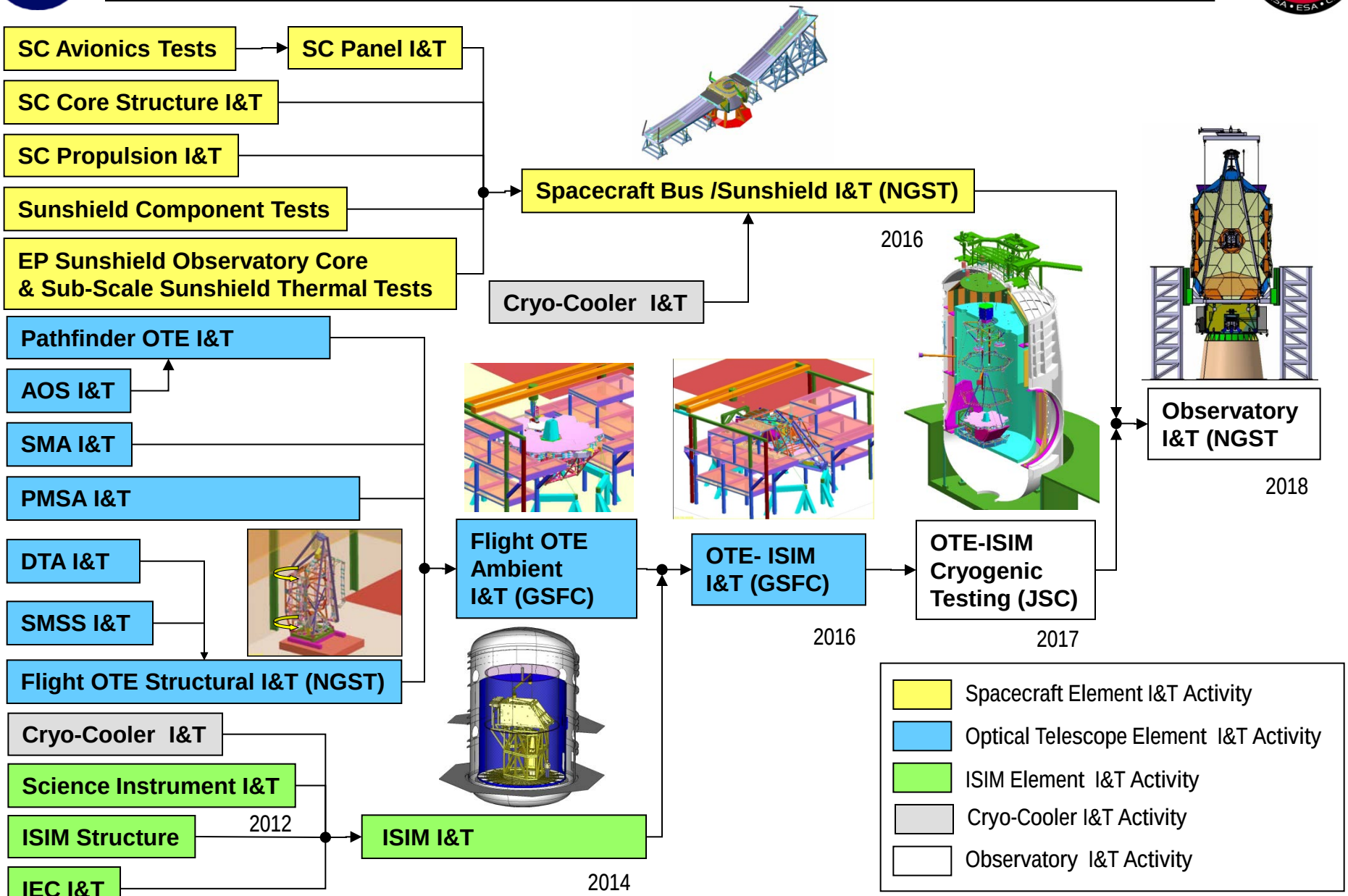
Absolute Distance Measuring (ADM)
- Lieca ADM allows the PM radius of curvature and conic to be measured at cryo.

Center of Curvature Optical Assembly (COCOA)
- Contains multi-wavelength interferometer system that allows the 18 segment primary mirror (PM) to be phased and the figure adjusted with the flight actuators
- Hexapod system allows the alignment system to track the PM during testing
- Contained multiple features to assist in the alignment of the PM
- Contains absolute distance measuring interferometers to track mirror distortion during thermal testing

AOS Source Plate and Cable Support
- Inward light sources to allow the tertiary mirror to be evaluated against the flight ISIM instrument suite
- Outward sources that allow the entire optical train to be evaluated and a wavefront sensing and control system to tested

Deep Space Edge Radiation Sink (DSERS)
- Deep space thermal simulators allow the flight radiators operate in flight configuration

JWST Integration & Test Flow



Program Status

Observatory Status

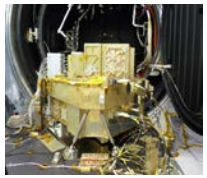
ISIM Structure

OTE Backplane Structure

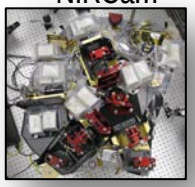
Science Instrument

NIRSpec

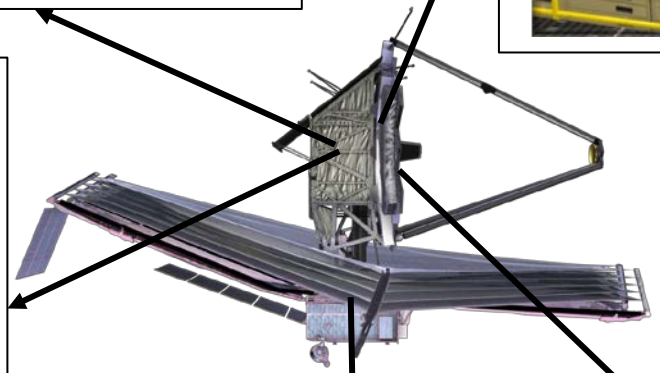
FGS



NIRCam

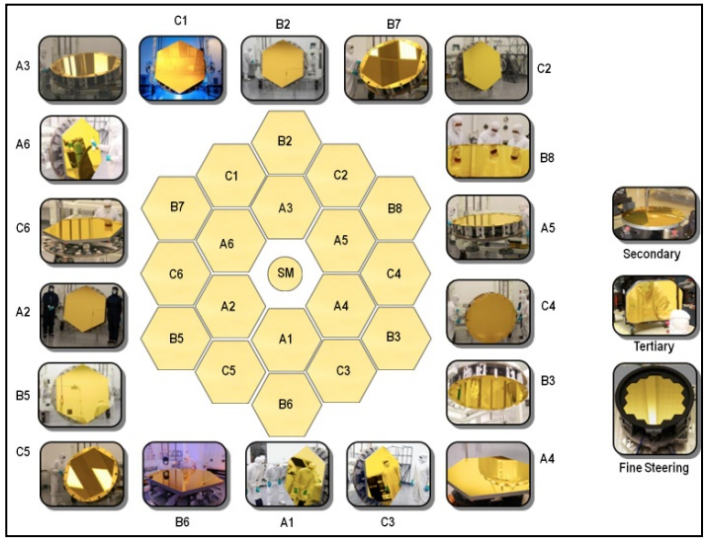


MIRI



Sunshield Membranes

Telescope Optics



Six PMSAs in the Last XRCF Cryo Test, #8

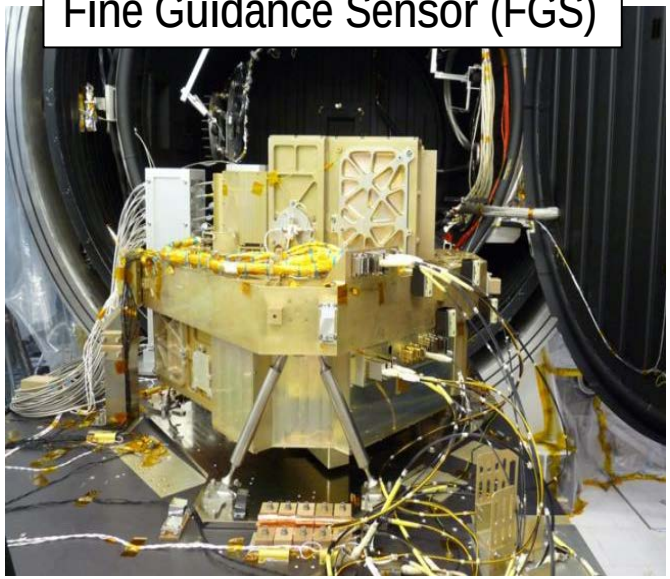
Viewers look on from the Gallery as the test stand is removed from the carriage in preparation for removal of the PMSAs, packing and return to BATC.

Mirror Segments in Their Storage Containers

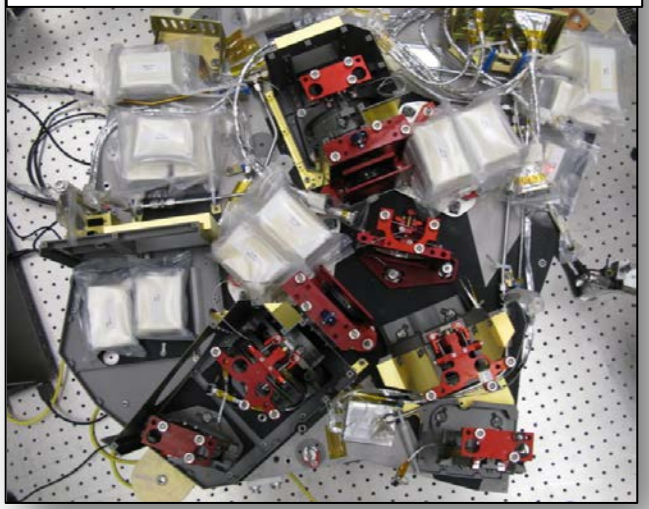
JWST Flight Science Instruments

Mid Infrared Instrument (MIR)

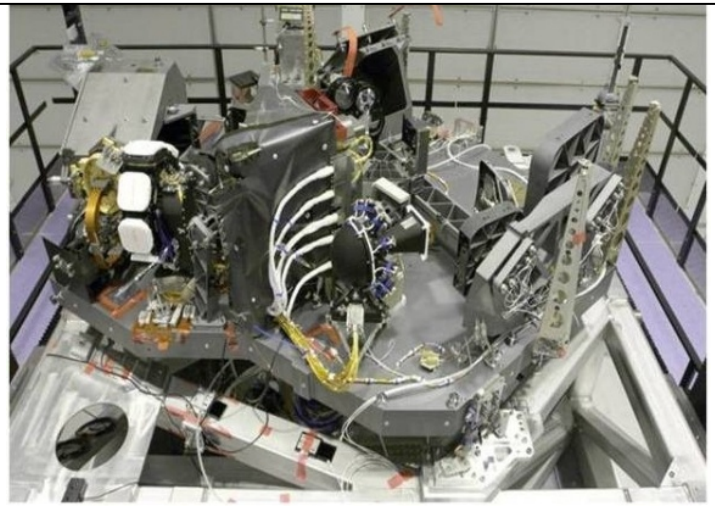
Fine Guidance Sensor (FGS)



Near Infrared Camera (NIRCam)



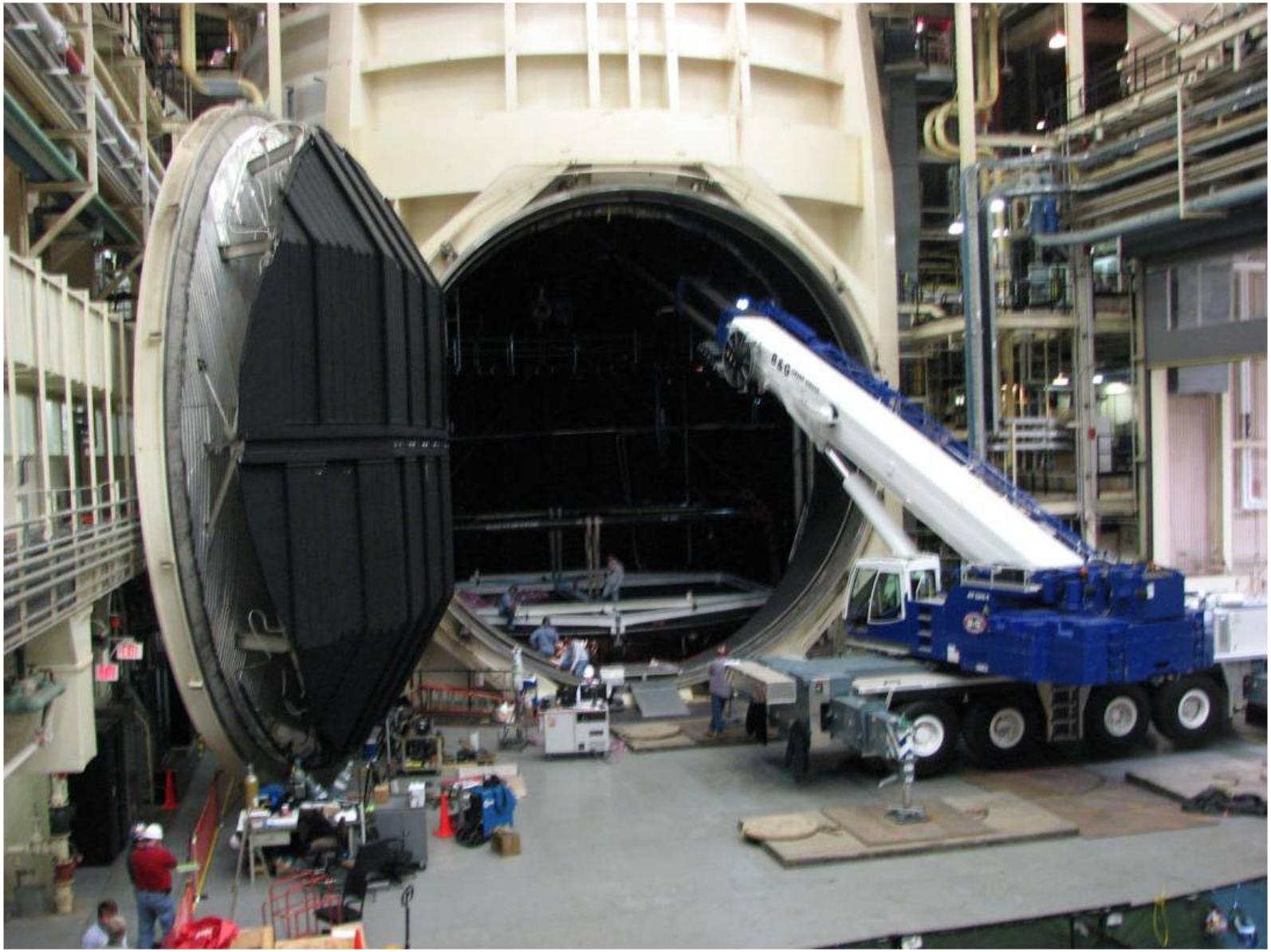
Near Infrared Spectrometer (NIRSpec)



Sunshield Membranes (1 of 2)

- **Template Layer 5 in test stand at full tension (3 x flight load) for shape measurements**

Modifications to the JSC Vacuum Chamber



Closing Thoughts on JWST Systems Engineering

Personal Lessons Learned from JWST (1 of 3)

- **Tactics for Leading Large Teams:**
  - Need to delegate to trustworthy leads.
    - I believe in having a redundant deputy
  - Need to find correct balance between a flat org and a hierarchical
  - Do not underestimate the needs of the bureaucracy, as well as management, public and independent review visibility.
  - Need efficient communication channels. (More is not always better!) Make sure the mechanisms are in place to have the CORRECT info communicated.
  - Get the team into a temporal cadence. (regular meetings, status reports, etc)
  - Find ways to minimize stove-piping.

Personal Lessons Learned from JWST (2 of 3)

- **System Engineering Challenges / Practices:**
  - Cost efficiency, and operating in cost constrained conditions.
  - Getting accurate cost data to support “good” engineering decisions
    - Avoiding biased estimates so that parties get the answers they want
  - Verification will rely less and less on tests and more on modeling. Need to establish guidance. (required MUFs, burn downs, best practices, etc.)
  - Have sanity checks to check analytical models. Try to do these yourselves.
  - Carefully consider cross-check tests as part of your test program.
  - The test facilities and ground support equipment for jobs as big as this are system onto themselves. They require considerable systems engineering.
  - Have sanity checks to check analytical models. Try to do these yourselves.

Personal Lessons Learned from JWST (3 of 3)

- **Program Management:**
  - Relationship with the Program Manager, must balance program direction and cooperation, with technical independence.
    - We are lucky here at GSFC in as much as most of the Program Managers have excellent engineering backgrounds.
  - Contractor management is an art, and very dependent on the contractors involved. Do not underestimate its difficulty.
  - International collaboration is the way of the future. Must be cognizant of ITAR, foreign norms and engineering practices, etc.

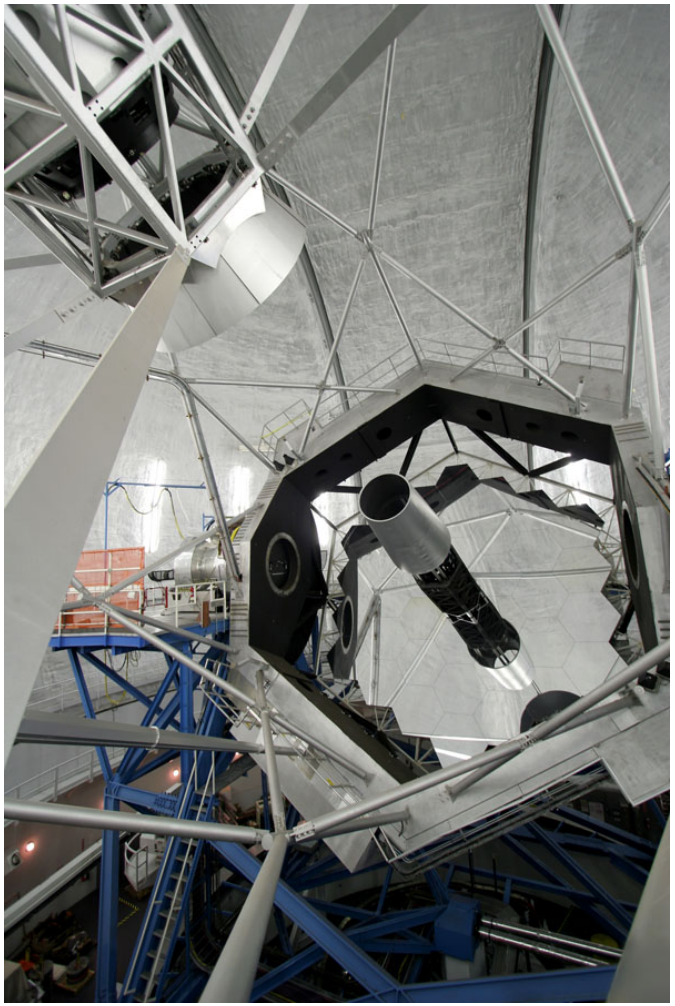
- **Pure Technical (The "if I could do it again wish list"):**
  - Would have required articulating Pick-Off Mirrors on all the science instruments.
  - Would request that NASA establish environmental standards for the L2 environment, in particular the plasma environment.

Telescopes Then and Now

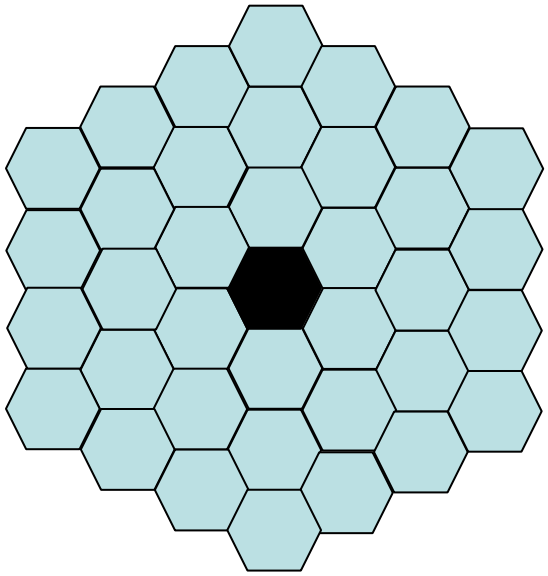
- In 1970 when most of the senior scientists and engineers on JWST were growing up, the Mount Palomar Telescope was the largest telescope in the world.
- Located in hills of San Diego County, California.
- Its massive primary mirror was 5.1 meters in diameter, and the telescope was approximately 17 meters long.
- The telescope and its mount weighed in at 545 tons or 495,000 kg.

- Forty one years later, we find ourselves making JWST which will be bigger than Palomar and launched into outer space!
- Located beyond the moon, 1.5 million kilometers from the Earth.
- Its primary mirror will be 6.1 meters in diameter, and the telescope length will be 8 meters
- JWST will weigh 6530 kg, (~1 /100 of the Palomar Telescope)

Comparison To the 10 m Keck I Telescope

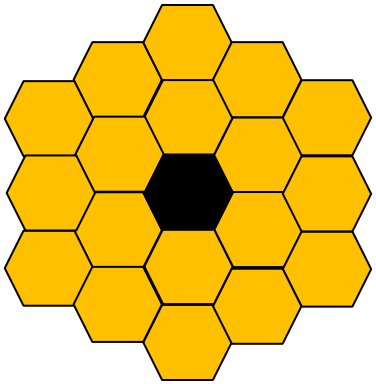


The Keck I Telescope on Maunea Kea Summit in Hawaii

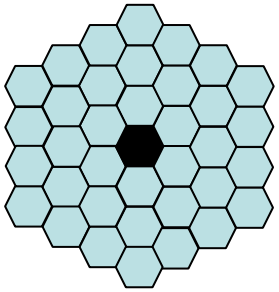


The 10 meter Diameter Keck I Primary Mirror

When one factors in the light lost from the atmosphere, the Keck I Telescope's light collecting power is ~50% less at a wavelength of 2 microns. Therefore its equivalent aperture in space is:



The 6.3 meter Diameter JWST Primary Mirror



The 5 meter Diameter Equivalent Keck

Summary

- **The James Webb Space Telescope will be one of the premier astronomical tools of the next couple of decades, with the potential to address some of the most fundamental questions before us.**

- **It is truly a first of its kind space observatory and has offered the Systems Engineering Team some very unique and difficult challenges.**
  - Cryogenic Design of Large Observatories
  - Constrained Technical Resource (aka Mass)
  - Verification by Analysis

- **In a very real sense JWST will re-write the books on astronomy AND engineering of future space observatories.**

- **I consider myself very lucky to be a part of this Team and this Program!**

Possibles

Typical Trade Study Plan

Document Study Results to Date In EM.
-Status of models for each option
-Resource Allocations for each

Select Most Likely Option for Cycle 1 Development and Define Initial Trade Space for Cycle 2

Jan 15, 2004

Cycle 1 Analysis

CAD Layout

-Mass Props
-Volume / Layout
-Launch Locks
-etc

Thermal Analysis

Structural Analysis

Optical Analysis

Controls Analysis

IPT Assessments

Initial Trade Space

ISIM Electronics Accommodation Trade Matrix

Options	Thermal Margin: CTE temperature, OTE temperature stability, heat dissipation	Electrical Integration: Signal quality, EMI, timing, wire count across deployment	Observatory Mass	I&T: Access after assembly, ISIM and S/C testing with flight units, schedule impacts	Cost: including risk cost
1 Saddlebag IEC FPE + ICE in R2					
2 Saddlebag IEC FPE in R2;ICE in R3					
3 -V3 IEC FPE + ICE in R2					
4 -V3 IEC FPE in R2; ICE in R3					
5 No IEC FPE + ICE in R3					
6 No IEC, No Tower Deploy FPE + ICE in R3					
7 FPE on ISIM Enclosure ICE in R2 (IEC)					
8 FPE on ISIM Enclosure ICE in R3 (SIC)					

Preliminary Development Of Cycle 2 Trade Space

Refine Cycle 2 Trade Space
-Eliminate options
From initial trade space

Feb 28, 2004

April 15, 2004

Review of Cycle 1 Results, Select Cycle 2 Trade Options

Updates from Other Concurrent System Trades
-BSF Trade
-Sunshield Trade
-ISIM Enclosure Trade

Cycle 2 Analysis

Cycle 1 Option Upgrade

Cycle 2 Alternate 1

Cycle 2 Alternate 2

July 15, 2004

Cycle 2 Review Final Selection

Cycle Review Products

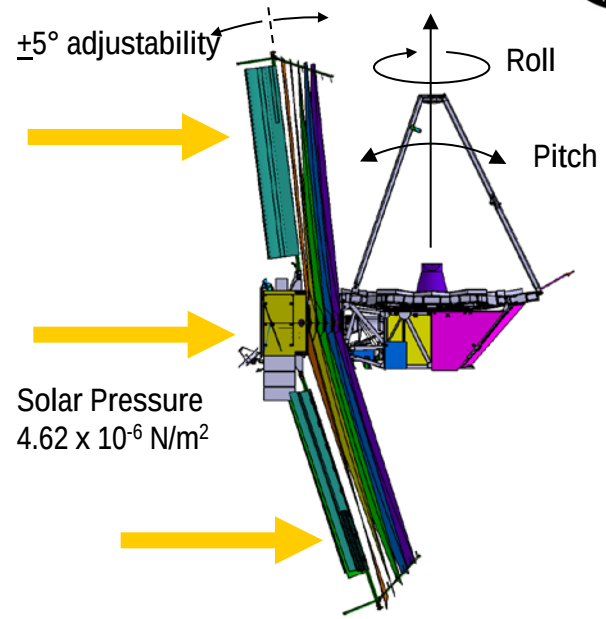
Design Analyzed
-CAD Models
-Thermal Design / Models
-Structural Design / Model
-Resource Allocations
-Schematics

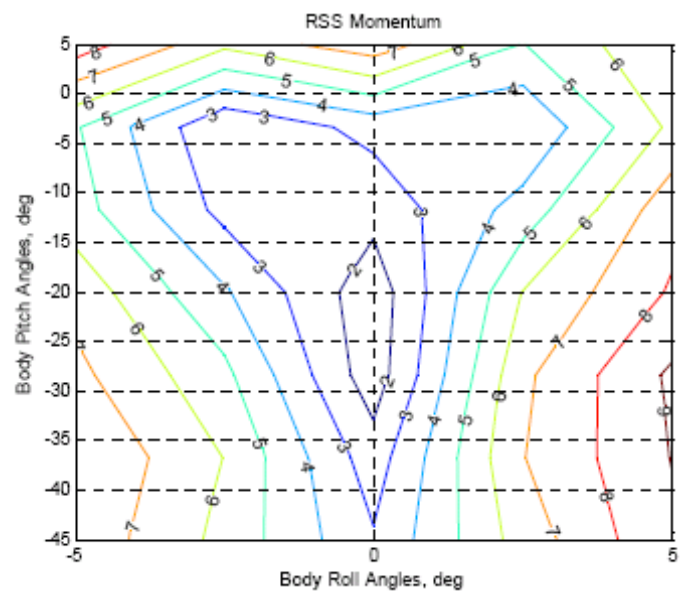
Results of Analysis
-Thermal Margins
-Structural Margins
-WFE and WFE Stability
-LOS Performance

IPT Assessment
-Costs
-Schedule
-I&T Impacts / Testability
-Risks

Factors Driving JWST Momentum Management

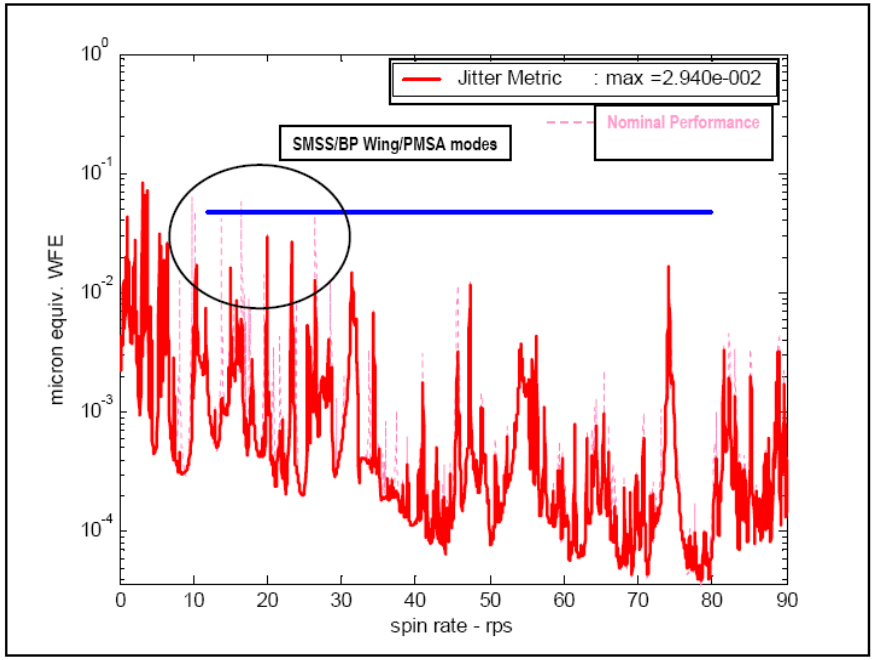
- The large sunshield, observatory attitude changes, and shadowing effects conspire to produce unbalanced torques which allow significant momentum accumulation.
  - Sunshield geometry is designed to minimize momentum accumulation
  - Sunshield has a ±5° on-orbit adjustability for further minimization
  - Momentum accumulation (Nms/day) is plotted as a function of Roll and Pitch attitude as shown lower right. (Torque Tables)
  - For a given RWA size this drives unload frequency.
- In order to avoid plume impingements on the cold side, thrusts are only made away from the sun
  - Therefore momentum unloads are not done by means of a pure couple, and therefore impart a residual ΔV disturbance
- In order to perform orbit determination, the observatory must have limited disturbances in a 21 day period. This limits momentum dumping:
  - 1 dump in this period between days 4 and 17
  - Remaining momentum dumped at day 22 just before station keeping
- Since orbital perturbations resulting from the interim dump are naturally amplified over time and cannot be corrected when they occur, this dumping impacts the stationkeeping ΔV budget





Momentum Management Studies (1 of 2)

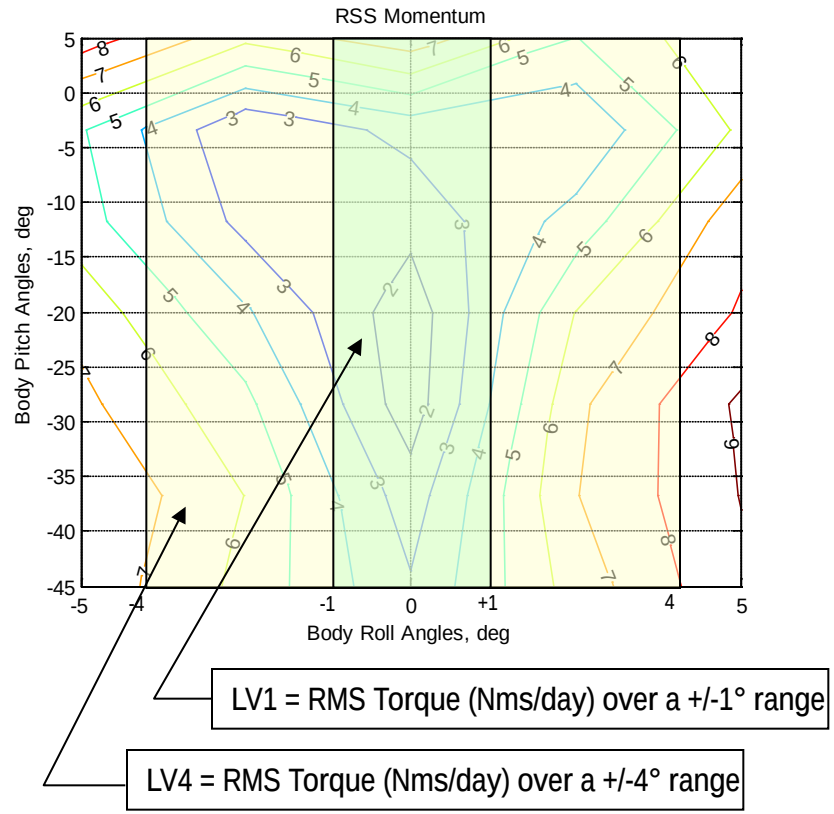
- Momentum Management Working Group performed a trade study to consider methods to address momentum management.
  - Study concluded in October and results documented in Report 05-JWST-0402
- Study used best available observatory configuration at that time, realizing that analyses would need to be repeated as observatory design evolved
- Teams Recommendations:
  - Increase observatory momentum storage capacity by allowing RWAs to run thru zero
    - This increases capacity from 40 Nms to 123 Nms
    - Analysis indicated jitter and dynamic WFEs were within spec even at low wheel speeds except for isolated "poke-thrus", as shown on right
  - Formulate specific requirements for momentum management in order to allow scheduling to be workable
  - Modify ΔV and propellant budgets to allow one 40 Nms momentum dump in the 21 day orbit determination period
- Teams Recommendations (Cont):
  - Hold option to unload momentum components with yaw thrusters in a true "couple" configuration if needed.
  - Hold option to incorporate magnetic dampers on the cold side of the observatory to mitigate jitter risks if needed.



Momentum Management Studies (2 of 2)

- Studies were conducted by the STScI as part of the MMWG to determine requirements for observatory torque which would allow minimization of momentum unloads via observation scheduling
  - A scheduling metric was defined, the P factor as shown to the right
  - In random walk simulations, visits could be manageably scheduled to reduce momentum build up when P<0.5
  - From these studies 2 limits on the RMS torques were defined
    - LV1 and LV4 as shown in figure on right
- Further studies by STScI indicated sensitivity of scheduling effectiveness to the roll offset
  - Offset = Roll value of min RMS torque
    - A non-zero roll offset is caused by observatory asymmetries relative to the V1-V3 plane
  - Studies indicated offsets larger than 1.5° significantly degraded scheduling effectiveness
- Proposed requirements for observatory torque:
  - LV1 $\leq$ 8.6 Nms/day
  - LV4 $\leq$ 11.8 Nms/day
  - Roll Offset $\leq$ 1.5°

$$P \equiv \frac{\text{Mean Momentum Accumulation Between Unloads}}{\text{Total Momentum Storage Capacity}}$$



First Cut at Observatory Design to LV1 and LV4 Requirements

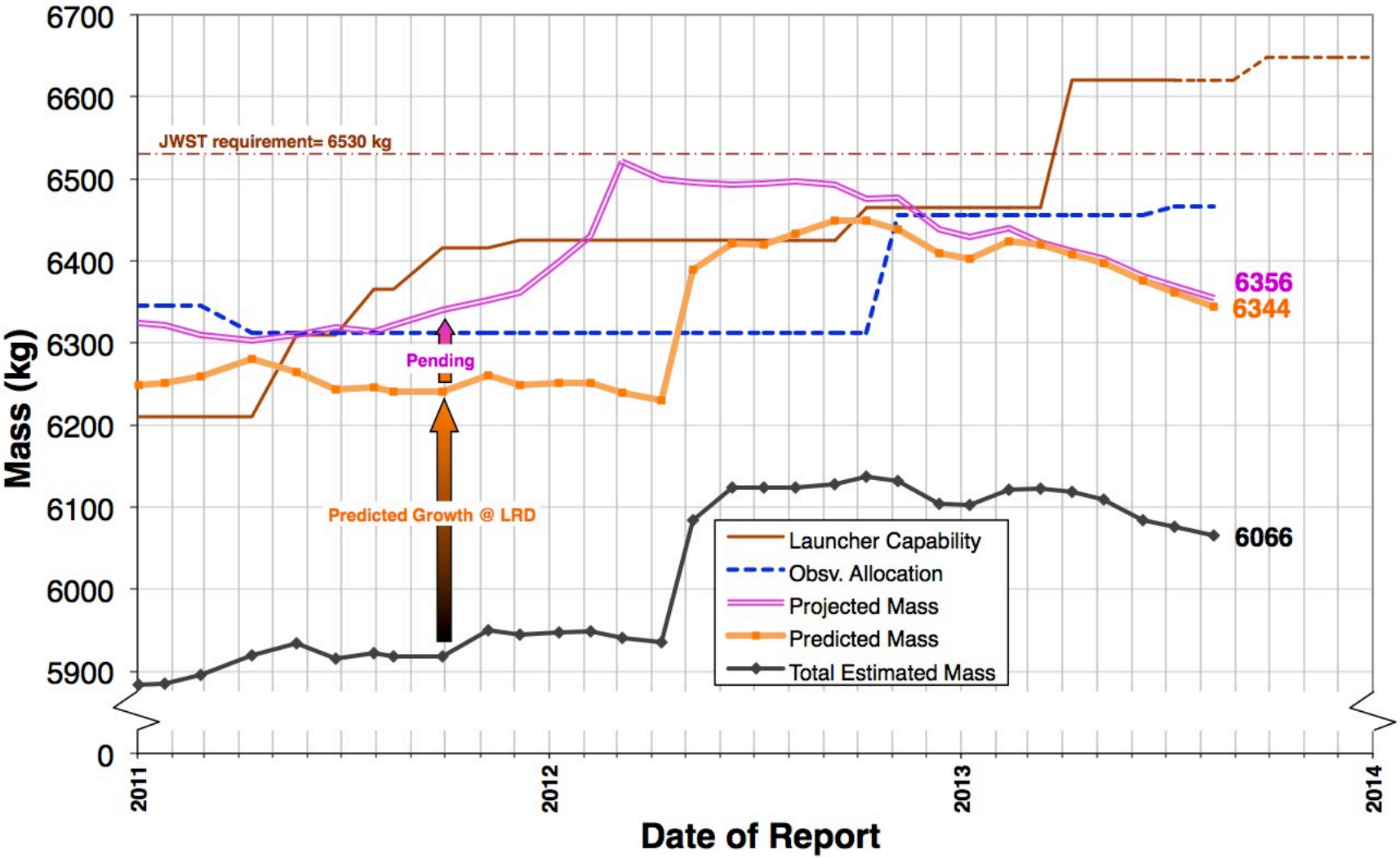
- Following the Momentum Management Trade Study, design changes were incorporated into the observatory as part of the SDR-3 analysis cycle.
  - Elimination of the MIRI Dewar
  - Sunshield shape changed to have straight edges to solve stray light concerns
  - Observatory CG box enlarged based on a preliminary tolerance assessment
  - Sunshield shape constraints modified, including boom length and containment shell angles
- Preliminary results of torque assessment was presented at the Sunshield Concept design Review on 12/8/05
  - LV1 = 13.65 Nms/day and LV4 = 14.53 Nms/day
  - Since then adjustments of sunshield parameters have been identified which lower these values to 10.22 Nms/day and 11.49 Nms/day respectively.
  - Further degrees of freedom are still to be exercised, among them redefinition of the allowable volume for the observatory CG
    - The Momentum Management Trade sensitivity studies are being used to determine the optimum set of “knobs” to turn to keep torque at controllable levels

The Mass Challenge

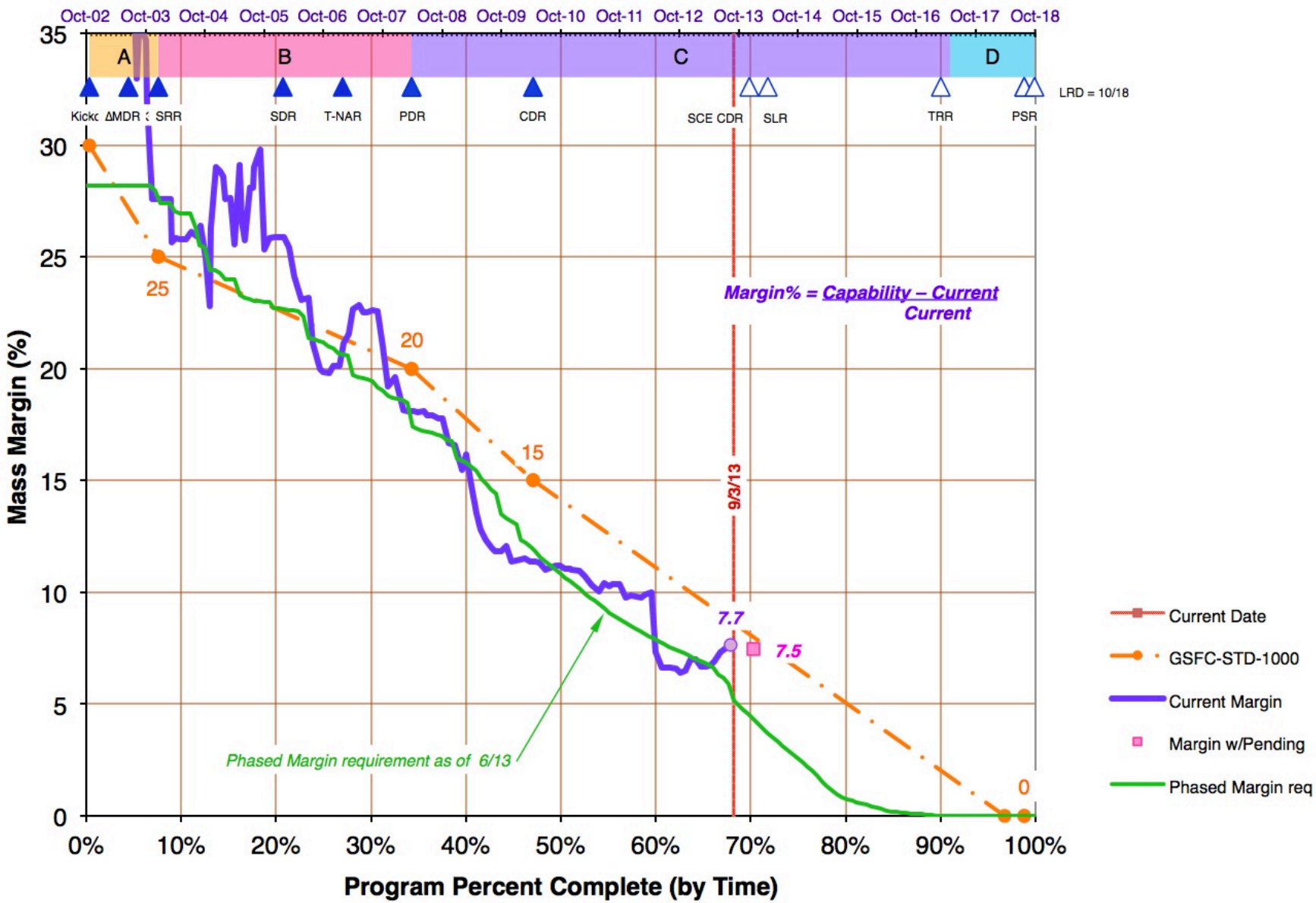
The Observatory Mass Issue

- **The JWST Project has faced a mass challenge since its inceptions, however in late 2011, mass increases due to unexpected high probability threats (Pendings) and lower probability threats (Potentials) started to be indentified:**
  - Spacecraft Bus increases from harness
  - Mass impacts due to CLA5++
- **Although the Project was carrying 217 kg of mass reserve, these increases had the potential to decrease this to unacceptable levels if uncorrected.**
- **A series of mass reduction activities was initiated to address these threats and to lower overall observatory mass.**
  - Mass savings greater than 200 kg was required at the start of this effort.
- **The effort concluded in April of this year. Necessary mass savings and threat mitigation was achieved and as of today the JWST observatory is 101 kg under its mass allocation of 6456. In addition to this the Project Office is holding 164 kg of mass reserves.**
- **This mass savings was achieved WITHOUT ANY LOSS OF PERFORMANCE or INCREASE to RISK.**

Recent Mass Trends



Long Term Trends for JWST Mass Margin



Mass Control Methods that Helped

- **A realistic Mass Control Plan.**
- **A Mass Control Board to make sure that the realistic estimates of the mass and High and Low Probability mass threats are always known and reviewed.**
- **When systems trades are performed make sure they do not close too early.**
  - Try to coordinate trades so that systems engineering has a menu of options to maximize mass savings and minimize systems performance impacts.
- **Have a notional / "strawman" plan for the release of System Mass Reserves.**
  - The first one to mass trough may not always be the highest risk.
  - Look at the history of mass growth of other programs.
- **Sensitize the team to keep an eye out for opportunities. The largest mass saving came from an area where mass growth was expected, the RTG effort.**

Engineering Challenges Ahead

- **The Critical Design Review (CDR) of the Spacecraft Bus is scheduled for December of this year. The final spacecraft subsystem CDRs are finishing up now, as are the system level analyses to support the Bus CDR.**
  - Challenges to spacecraft pointing performance are being identified and addressed. These issues were not unexpected.

- **The Project is entering the Verification and Testing Phase.**
  - There will undoubtedly be issues problems uncovered.
  - The engineering team is preparing the analytical models necessary for these tests. These models are being developed not only for the purposes of verification, but also to trouble shoot potential problems.

- **The engineering teams will developing "What If Scenarios" for both Flight and Test to explore work around solutions.**

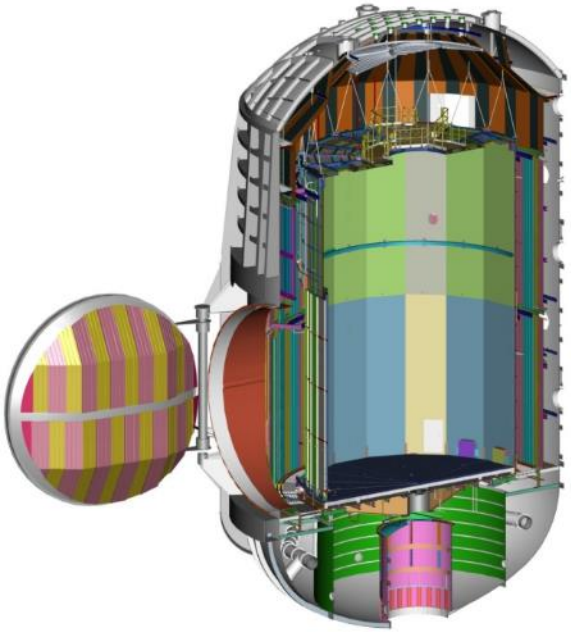
Summary

- **The James Webb Space Telescope is truly a first of its kind space observatory and has offered the engineering team some very unique and difficult challenges.**
  - Cryogenic Design of Large Observatories
  - Constrained Technical Resource (aka Mass)
  - Verification by Analysis

- **The JWST Team has met these challenges, and has kept the Project moving. The team looks forward to the transition from design to verification and test.**

- **In a very real sense JWST is writing the book for the engineering of future space observatories.**

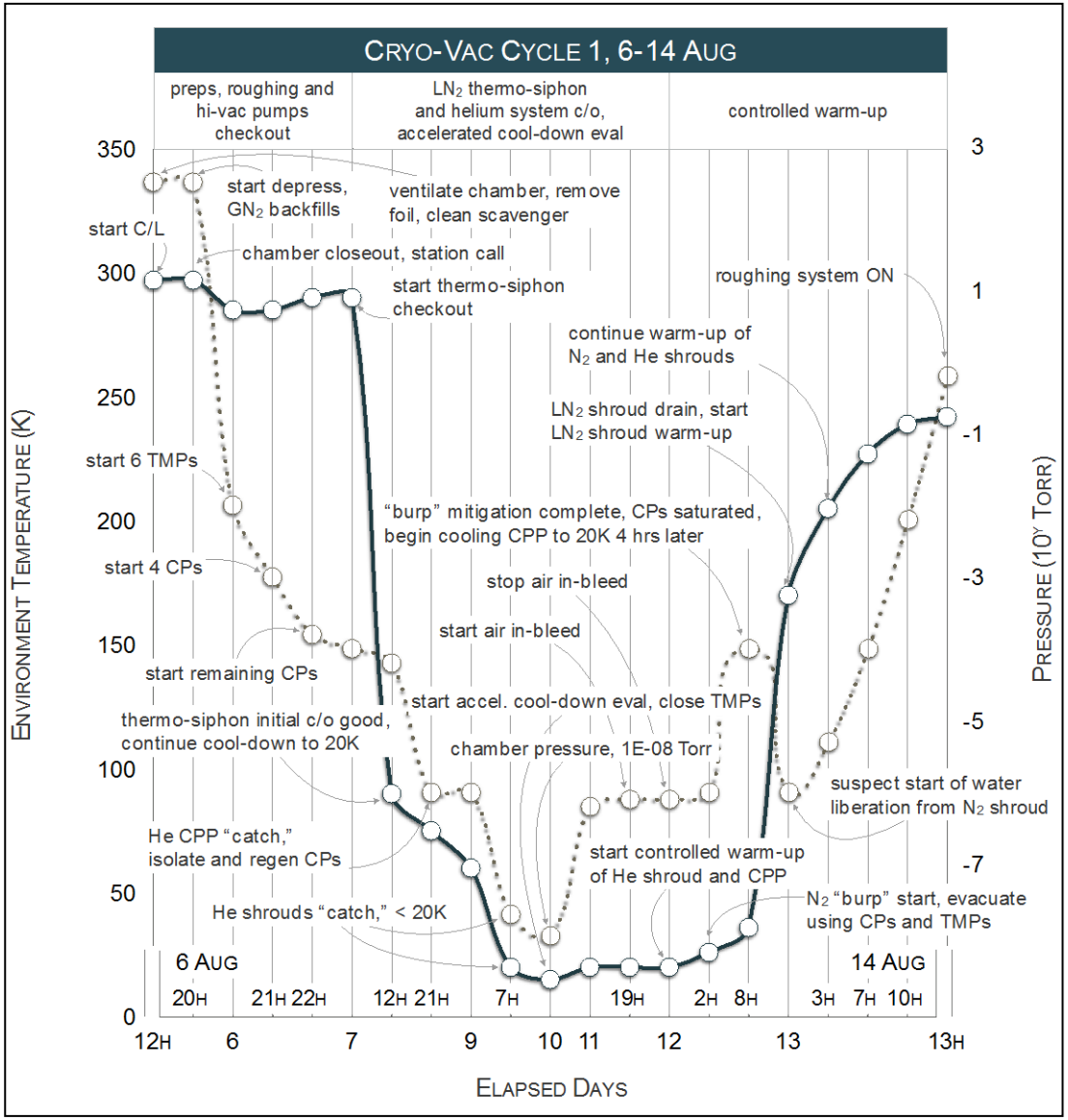
Chamber A Capability Enhancements



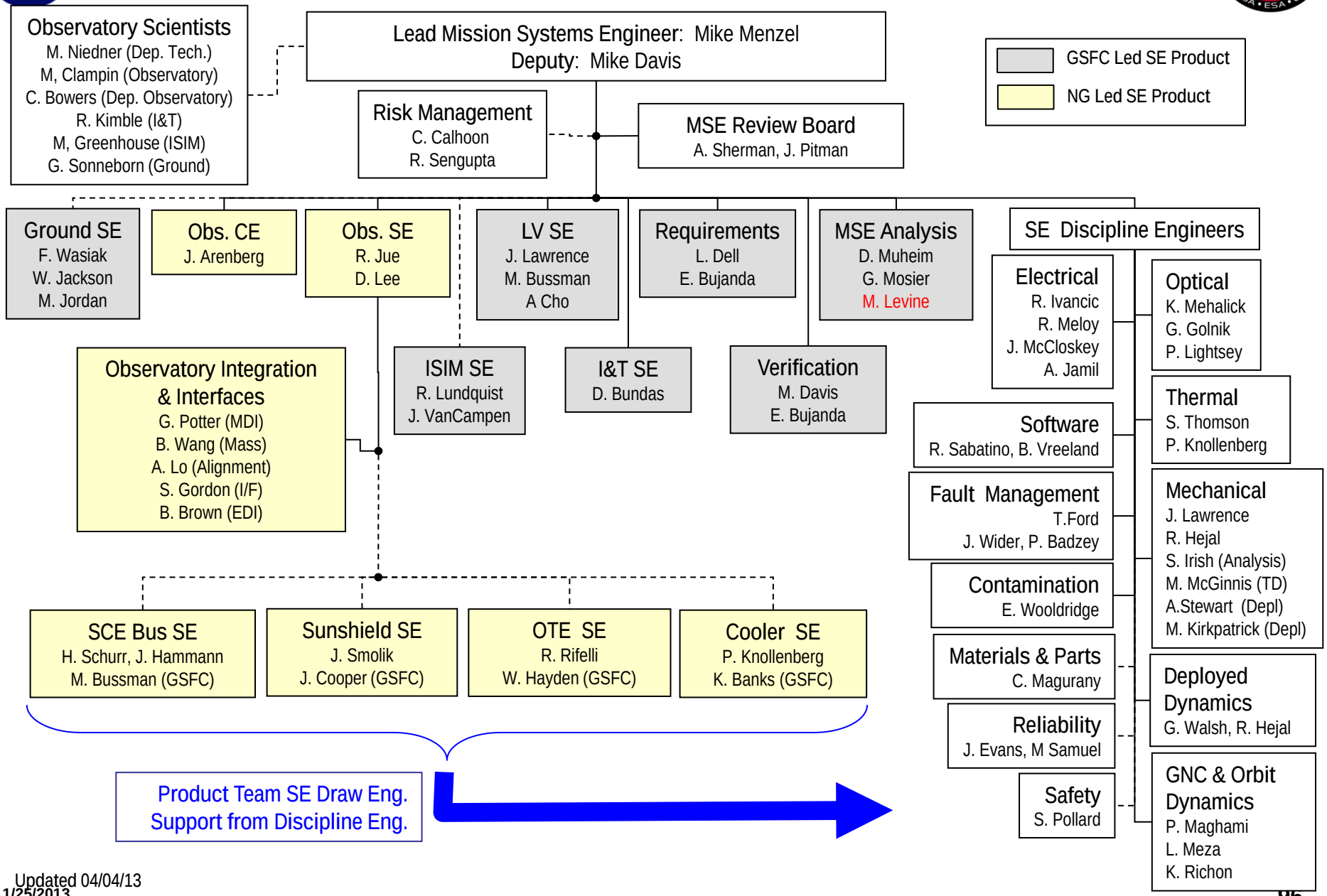
	Apollo	JWST
Chamber Vacuum	< $1x10^{-5}$ Torr	< $5x10^{-6}$ Torr (lower is desired)
Environment Temperature	< 100K	< 20 K, stable to ± 0.25 K per day for 5 consecutive days at steady state
Test Duration	2 weeks	4 months
Vibration Sensitive	No	Yes
Cleanliness	Generally Clean	ISO Class 7
Test Emergency Systems	Human Safety	Thermal, Optical, Contamination considerations

JSC Chamber A Functional Tests

- **Functional testing of the JSC Chamber A was completed in August 2012.**
- **Tests included:**
  - Bakeout
  - Cryo-Cycles
  - Accelerated Cool-down Evaluation
  - Controlled Warm-Up Evaluation
- **Achieved 12 K Temperature on the Gaseous He Shroud and a vacuum level of 10^{-8} Torr.**
- **In addition, ran the He Compressor for 90 continuous days.**



Systems Engineering Team Key Contacts



Updated 04/04/13

3.5 Communication Paths to External Organizations

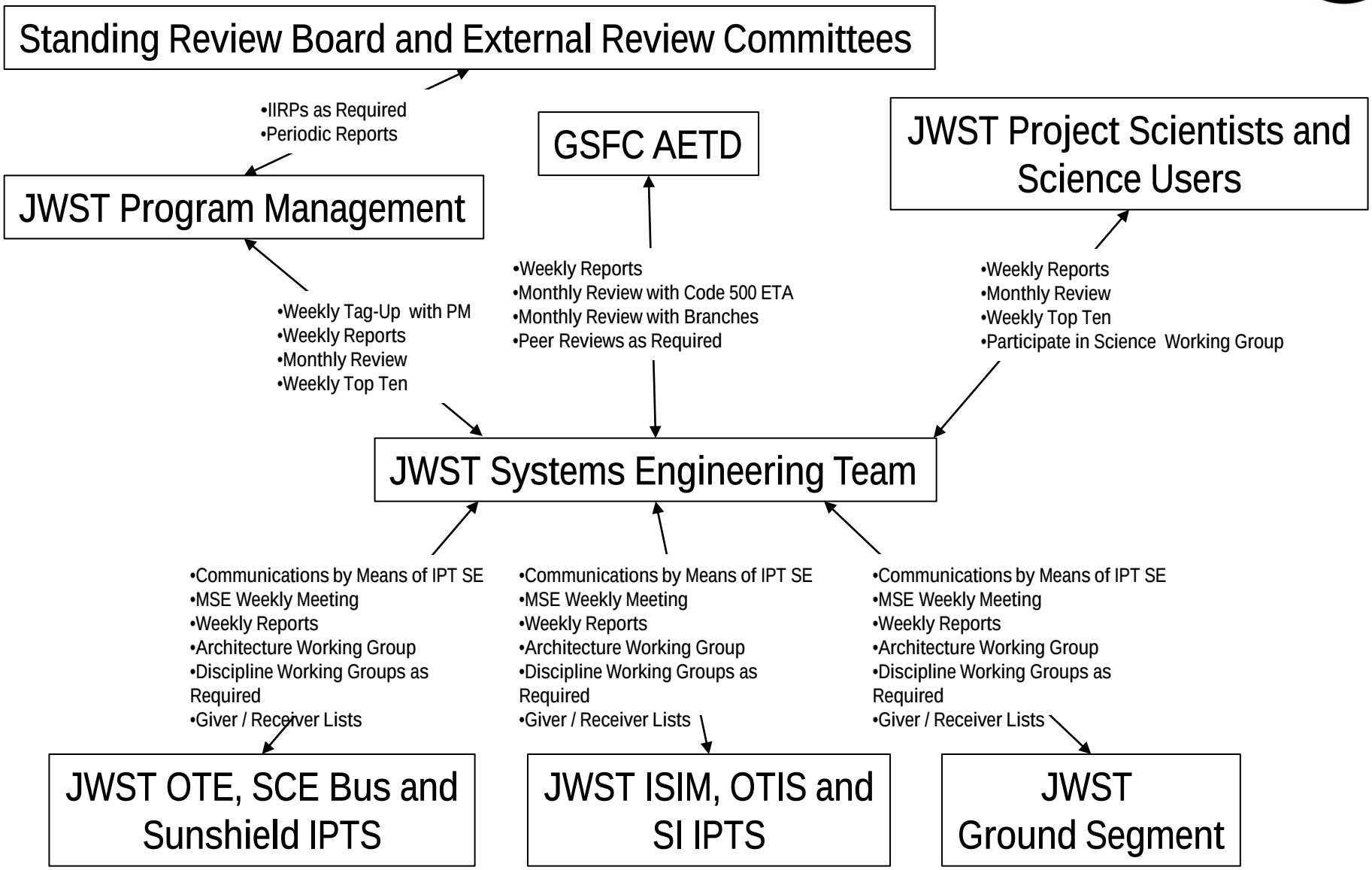
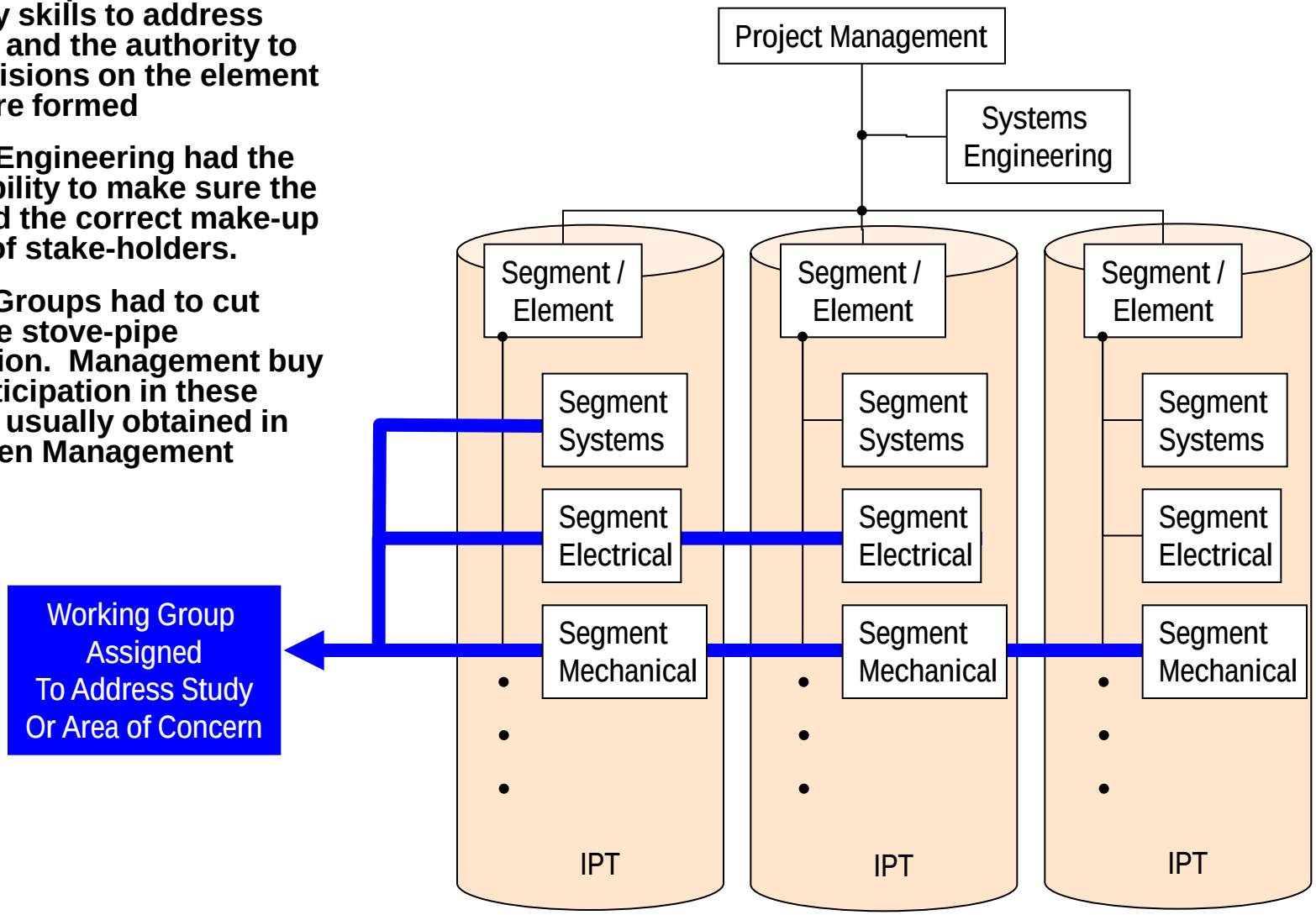
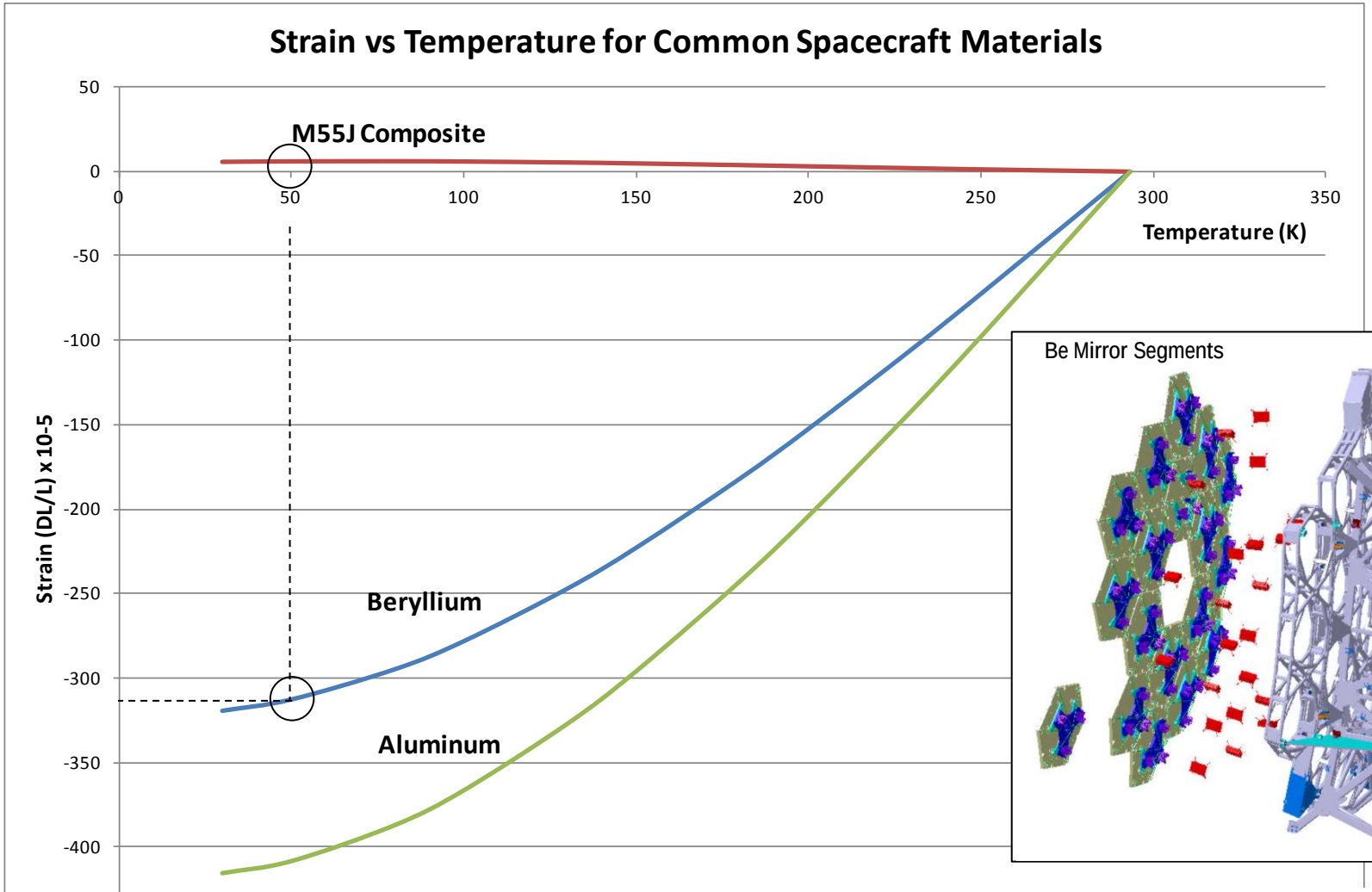


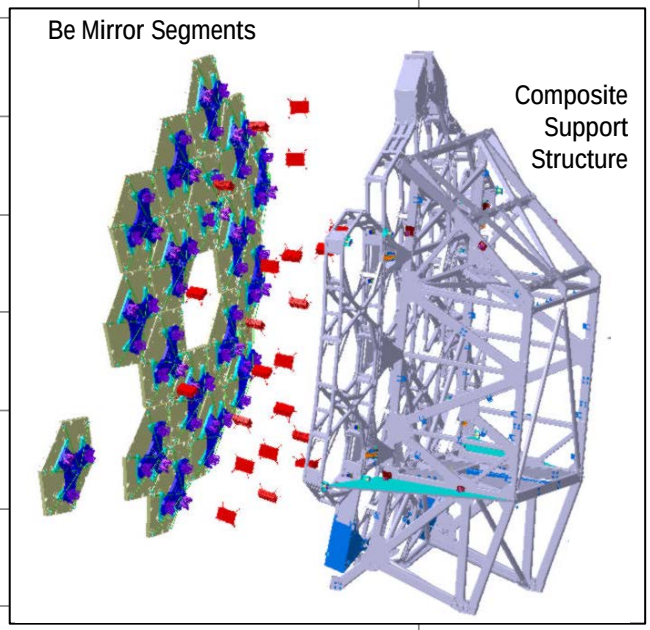
Figure 3-2 Forming Working Groups with the Correct Skill / Responsibilities

- Working Groups with the necessary skills to address problems and the authority to make decisions on the element levels were formed
- Systems Engineering had the responsibility to make sure the teams had the correct make-up in terms of stake-holders.
- Working Groups had to cut across the stove-pipe organization. Management buy in for participation in these groups is usually obtained in the Top Ten Management Meeting



Behavior of Space Vehicle Materials at Cryogenic Temperatures





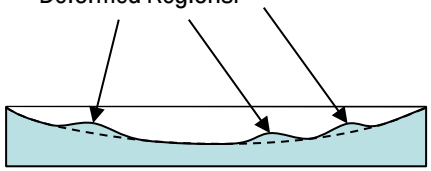
- At 50K, the strain for Be is roughly -310 x 10^{-5} so the 6 meter primary mirror will contract by 1.9 cm. (3/4”).
- The mirror support structure is composite and does not contract as much.
- The mirror interface flexures must be carefully accommodate this mismatch without distorting the mirrors.
- At 50K the difference in the slopes of the curves becomes important as small changes in operational temperature can produce distortions which degrade optical performance

Cryo Null Figuring the Optics

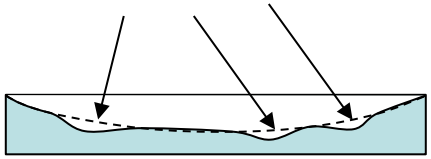
- **Optical surfaces deform at cryogenic temperatures due to non-uniformities and anisotropies of material properties.**
- **The process of Cryo-Null Figuring is used to compensate for these deformations.**
- **The process uses iterations of measurements at ambient and cryogenic temperatures with figure correction at ambient. The Process is illustrated on the right.**
- **The final Wavefront Error Maps of a mirror segment resulting from this process is shown below.**

Perfect Mirror Figure at Ambient

The Mirror Deforms at Cryogenic Temperatures. Wavefront Error Measurements at Cryo Identifies Deformed Regions.

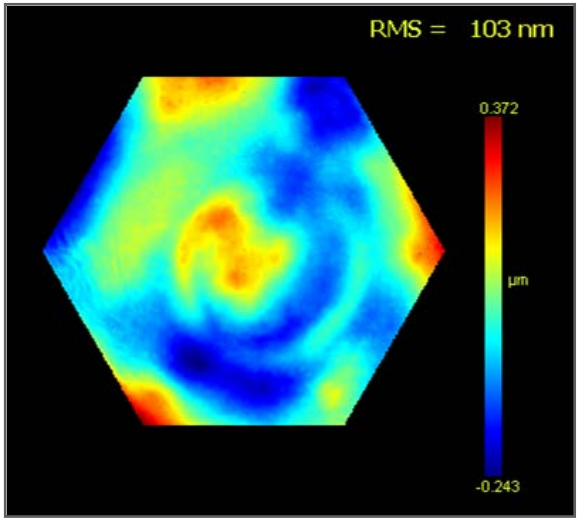


At Ambient Temperatures, the Mirror is Re-Figured to Compensate the Wavefront Errors of these Regions

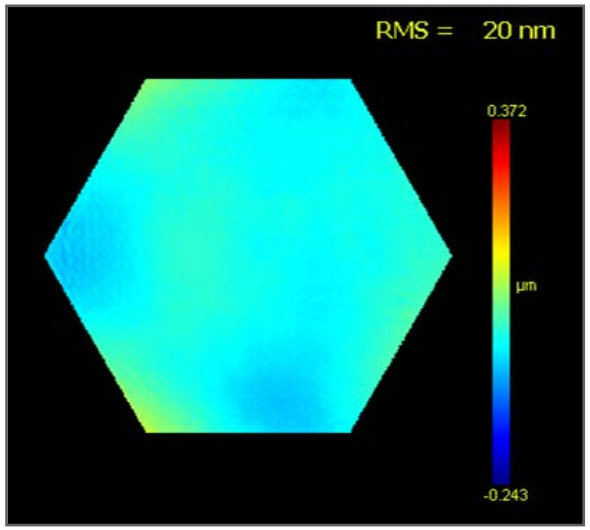


After Cool Down to Cryogenic Temperatures the Mirror Deforms to the Desired Figure

Ambient Wavefront Error Map



Cryogenic Wavefront Error Map

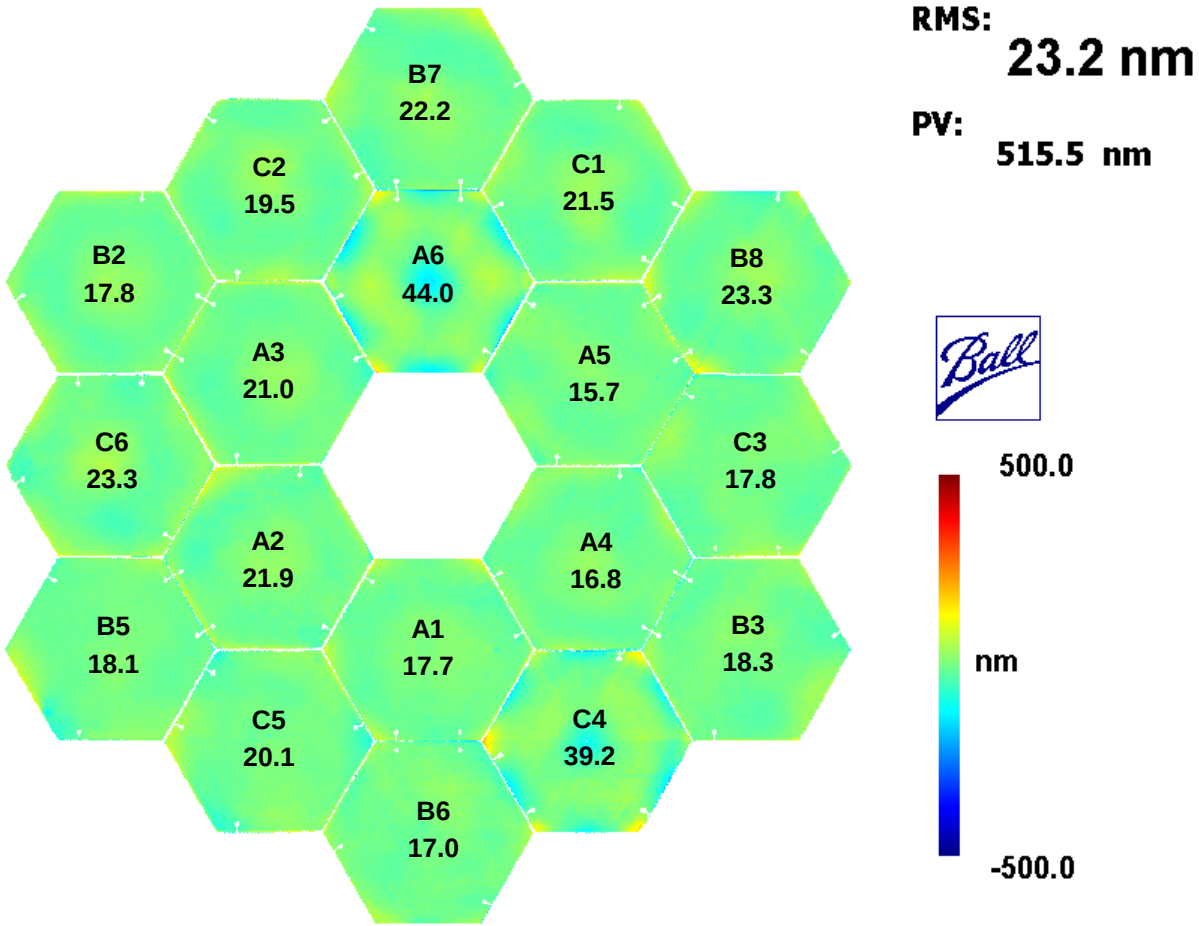


Composite Cryogenic "Total Surface Figure"

	Total Figure XRCF Measurement	Very High Freq Sub Aperture Tinsley Measurement	Metrology Uncertainty
A1	17.7	2.9	8.0
A2	21.9	3.4	8.0
A3	21.0	5.8	8.0
A4	16.8	3.2	8.0
A5	15.7	5.0	8.0
A6	44.0	4.5	8.0
B2	17.8	5.7	8.2
B3	18.2	4.2	8.2
B5	18.0	3.9	8.2
B6	17.0	4.0	8.2
B7	22.2	4.3	8.2
B8	23.3	4.6	8.2
C1	21.5	5.1	8.2
C2	19.5	6.0	8.2
C3	17.8	3.2	8.2
C4	39.2	5.0	8.2
C5	20.1	4.2	8.2
C6	23.3	5.4	8.2
Weighted RMS	23.2*	4.6	8.1

Total = rss(23.2, 4.6, 8.1) = 25.0 nm rms

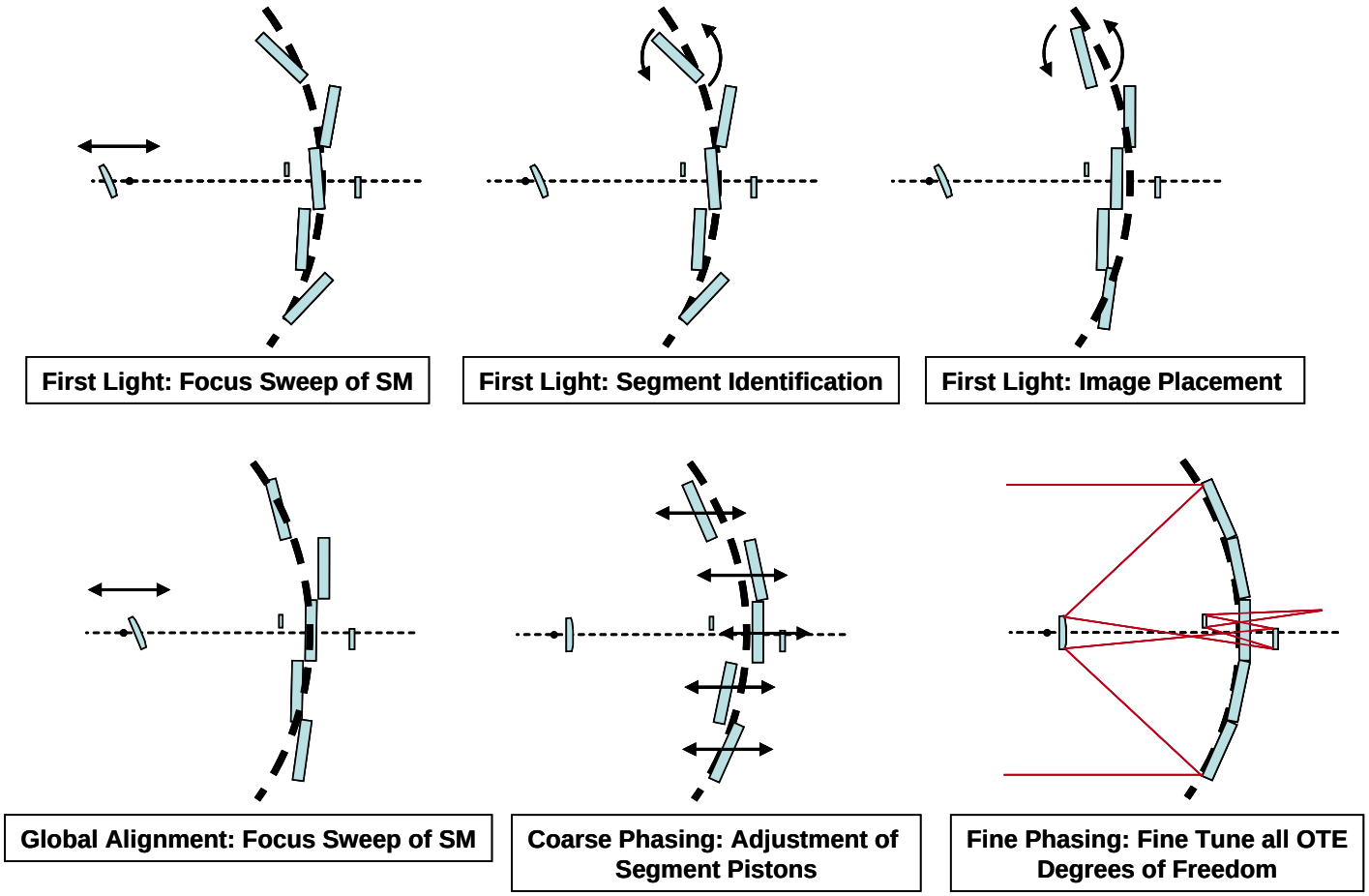
Requirement = 25.8 nm rms
Total Measurement + Uncertainty = 25.0 nm rms



* Composite Figure

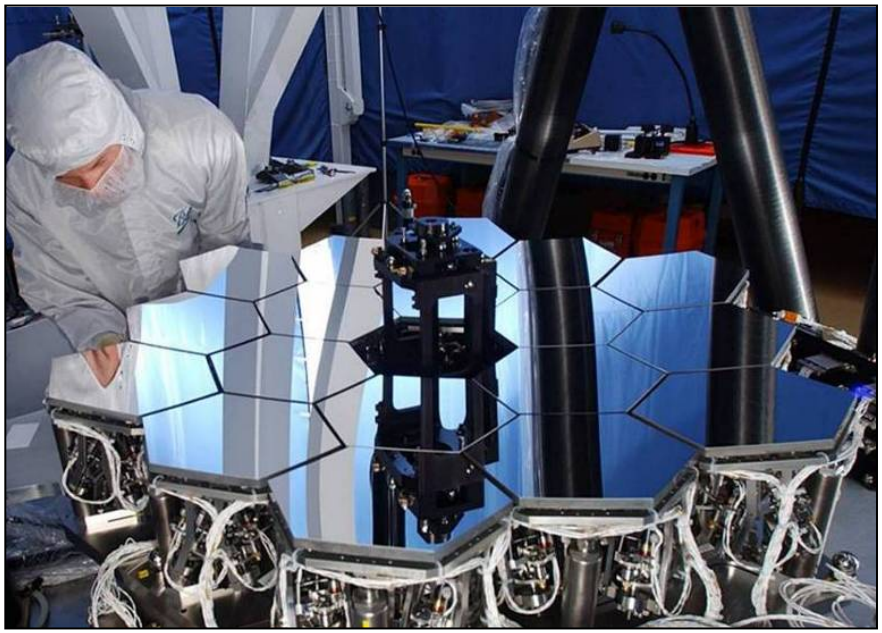
The Tinsley HF number for C2 is only an estimate.

Wavefront Sensing and Control (WFSC)



- The deployment sequence requires that the telescope and all its individual segments must be aligned on orbit.
- A process called Wavefront Sensing and Control will be used to systematically do this alignment.
- This process was developed as part of the effort to correct the original Hubble Space Telescope optical error.

Testbed Telescope (TBT)
Used to Validate WSFC Algorithms



- Primary use is in validation of Flight Algorithms and software
- Will also use to test JSC I&T process
- 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.).
- Used to perform TRL-6 end to end testing.
- Multi-Instrument Multi-Field and Vignetting measurements added late to the plan.