James Webb Space Telescope Systems Engineering

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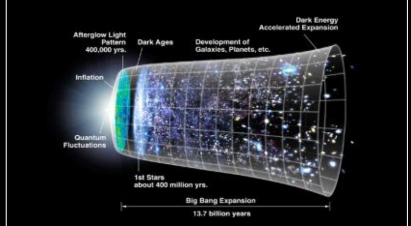
Summary and Topics

- **An overview of System Engineering (SE) performed on the James Webb Space Telescope (JWST) Project. Does not imply this is the only way to perform SE. It is intended to give examples that could be used as "food for thought" to tailor specific SE projects.**
- **JWST is an example of a "first and only of kind" NASA flagship mission. SE was tailored with this in mind. JWST was not the prototype for a future product line. Errors were not going to be fixed by modification of future versions.**
- **Topics**
  - JWST Mission Overview
  - JWST Systems Engineering
    - Requirements Analysis
    - Systems Design
    - Systems Analysis (Integrated Modeling)
    - Technology Development, Risk Management Issue Resolution
    - Verification
    - Commissioning and Operation
  - Systems Engineering Organization and Planning
  - Summary

JWST Mission Overview

JWST: NASA’s Successor to the Hubble Space Telescope

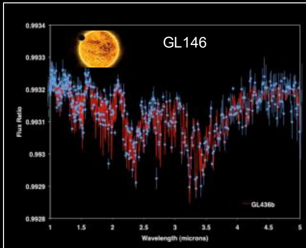
- **Mission Objective: Study the origin and evolution of galaxies, stars and planetary systems by providing infrared imagery and spectroscopy.**
- **Observatory Description:**
  - Deployable telescope w/ 6.5m diameter segmented adjustable primary mirror.
  - Cryogenic operating temperature telescope and instruments.
  - Deployable Sunshield to allow passive cooling of telescope and instruments.
  - Launched on December 25, 2021 to Sun-Earth L2.
  - 5-year required science mission life. (10-year goal)



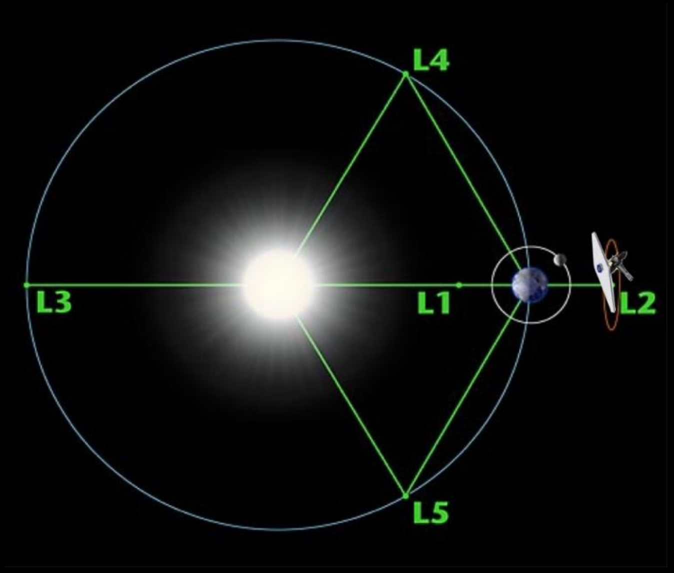
First Light and Re-Ionization

Assembly of Galaxies

Birth of stars and proto-planetary systems



Planetary systems and the origin of life



JWST System Hierarchy

James Webb Space Telescope System

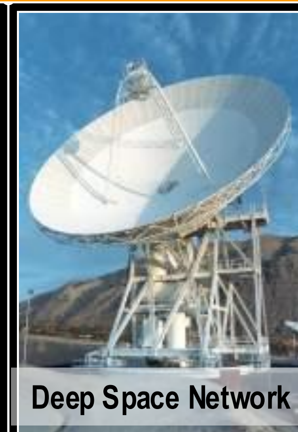
Launch Segment

- 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

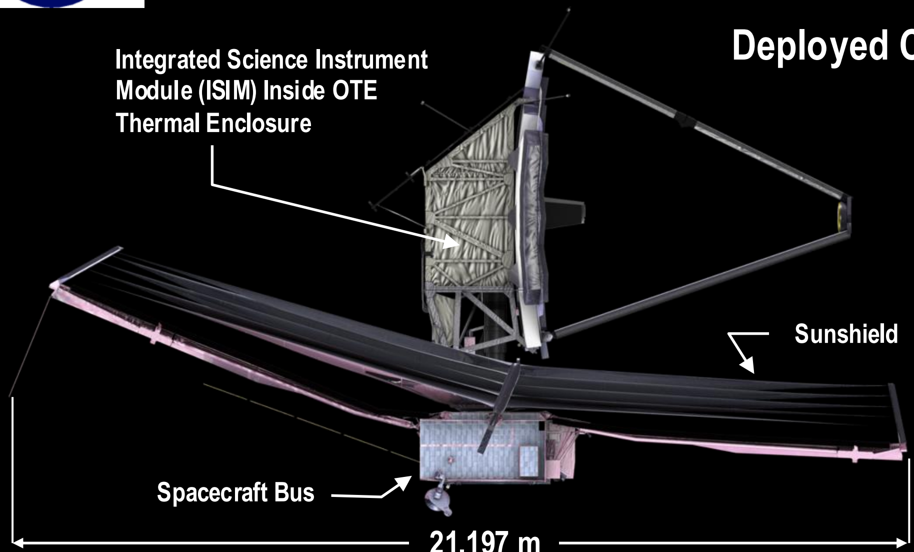
Provided by STScI

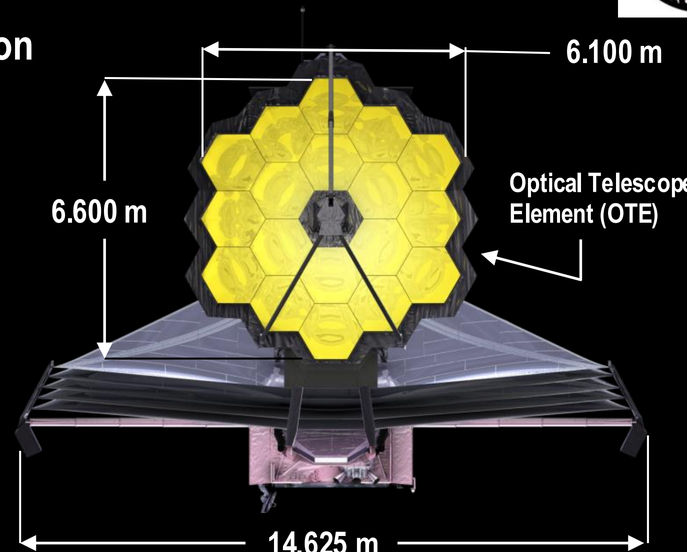
Provided by ESA

Provided by CSA

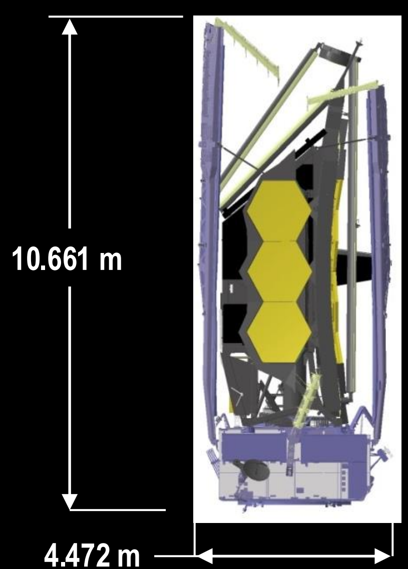
Observatory Design Summary

Deployed Configuration





Stowed Configuration



Optical Telescope Element (OTE) diffraction limited at 2 micron wavelength.

- 25 m^2 , 6.35 m average diameter aperture. (Actual aperture 25.8 m^2)
- 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 4 cryogenic science instruments (SIs) to observe in the near and mid infrared.

- The FGS provides fine guidance error signals to maintain pointing
- The NIRCam 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: < 6310 kg. (Actual Mass at launch 6161 kg)

Power Generation: 2138 Watts Solar Array, and a 105.6 AHr Lithium Ion battery

Data Capabilities: 471 Gbits on-board storage, 229 Gbits / 12 hours science data.

Science Data Downlink: 28 Mbps.

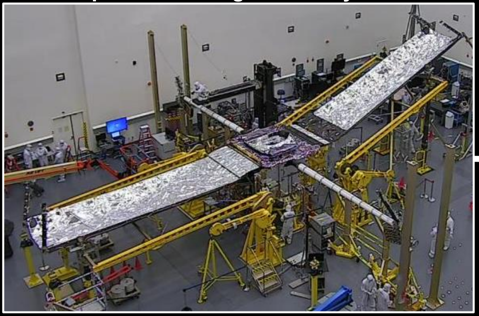
Life: Designed for 10.5 years of operation.

Integration and Test: 2010 to 2021

OTE Integration March 2016

OTIS Cryo Test July 2017

Spacecraft Integration July 2017



Sunshield Deployment Test November 2017

OTIS to SCE Integration and Sunshield Deployment October 2019

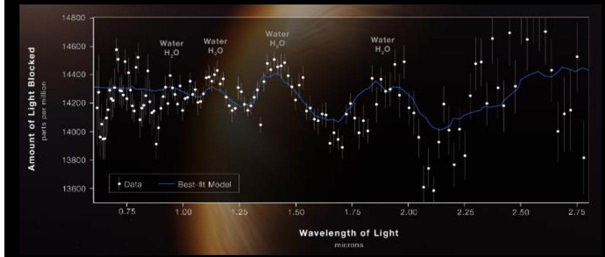
JWST Arrives at Launch Site October 2021

First Images July 12, 2022

First Light and Re-Ionization

Assembly of Galaxies

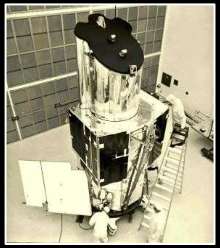
Birth of Stars and Planetary Systems



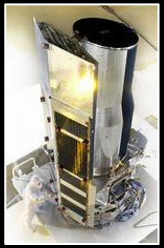
Planetary Systems and Exoplanets

JWST: A First and Only of its Kind Space Telescope

Pervious NASA Space Telescope



Copernicus



Spitzer

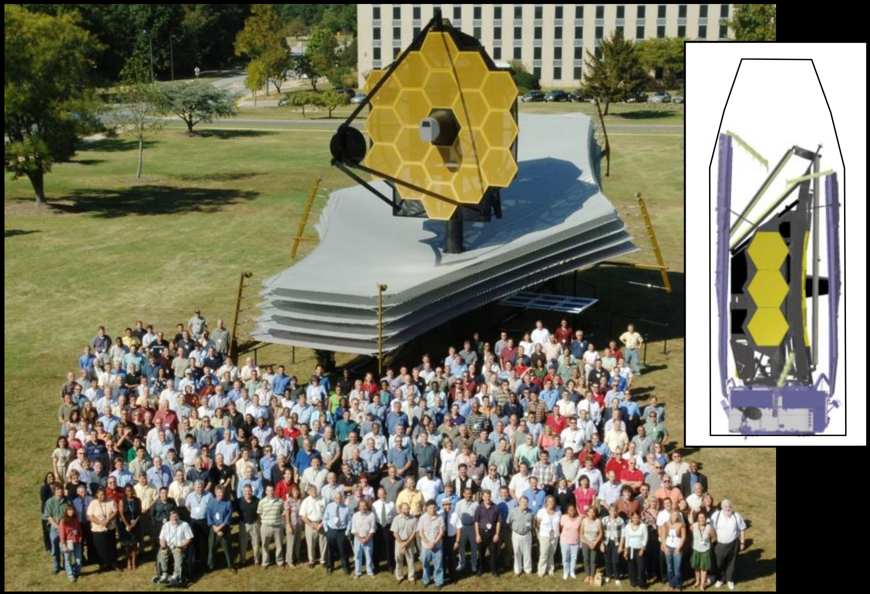
Hubble Space Telescope

The James Webb Space Telescope

- Previous NASA telescopes were in protective barrels are were designed to NOT CHANGE thru launch
- JWST is an open Infrared telescope that must operate cold (55K)
- JWST is bigger than the fairing of the launcher. It must be deployed in space; literally rebuilt and re-aligned.

JWST Engineering Challenges

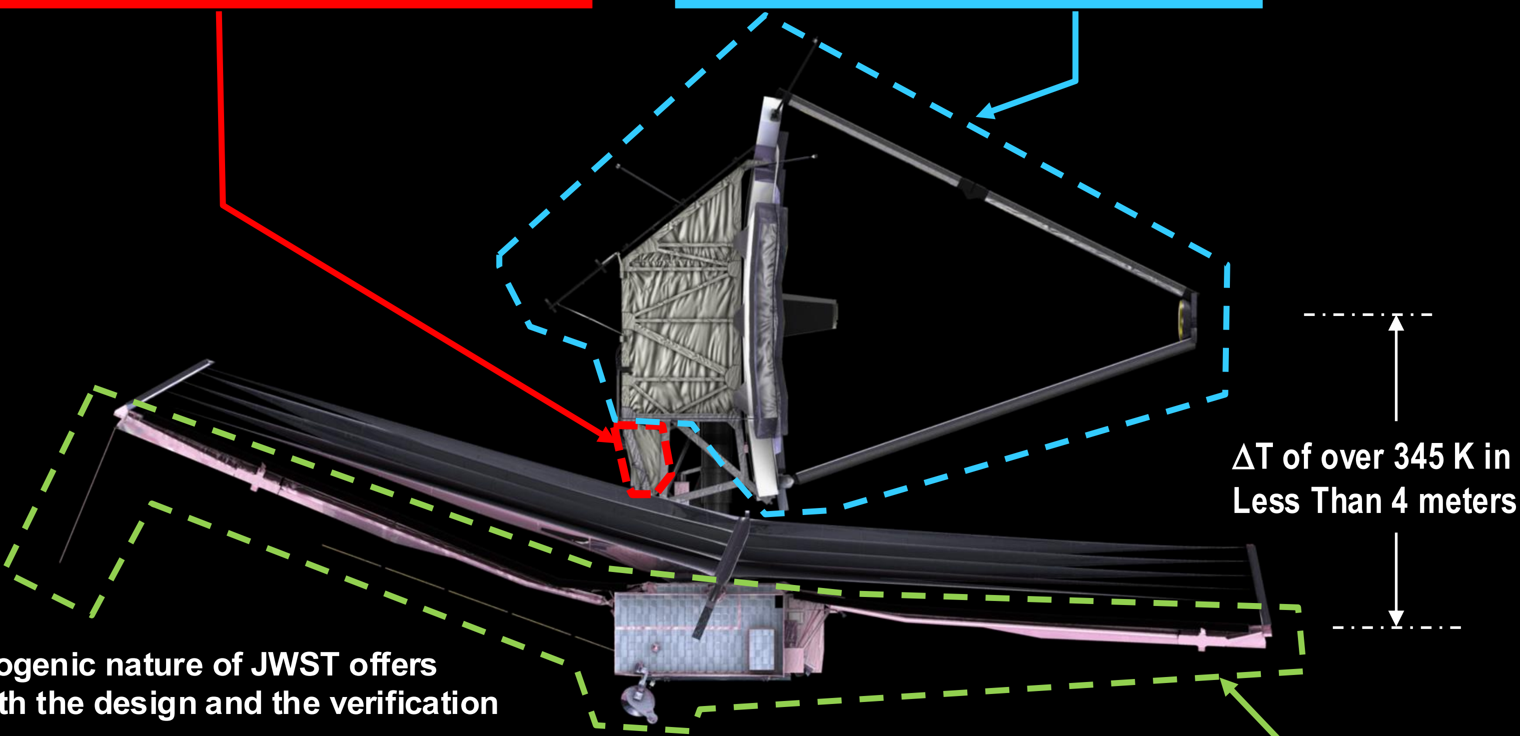
- **Size and Deployment:**
  - Science required the largest telescope ever launched (6 meter class). (See Figures on the right)
  - Larger than existing launcher fairings therefore a complex series of on-orbit deployments was required.
  - Deployments introduced non-linear structural behavior as well as a multitude of Single Point Failure Items.
- **Cryogenic Payload:**
  - Science required an infrared payload, that required payload temperatures below 55K.
  - Fractions of watts of heat become important!
- **Mass Constrained:**
  - Mass margins against launcher capability were very tight. (23% or less in early parts of the development)
  - Tight mass margins drove an integrated design. Interfaces were NOT clean. A small change in one item can result in large system impacts.
- **Passive Optical Stability**
  - Cost and schedule excluded active optical control.
  - Optical stability (50 nm or less) achieved passively.
- **The Observatory was Untestable for Performance :**
  - Observatory level performance tests were not practical.
  - Verification was performed by a combination of Test, Analysis and Inspections.



The JWST Cryogenic Challenge

Thermal Region 2
- **ISIM electrical boxes maintained at ambient temperatures on cold side of the observatory to minimize electrical noise.**
- **Total dissipation of 225 w.**

Thermal Region 1
- **Components cooled to cryogenic temperatures 55K or less.**
- **Over 3,500 kg of the observatory resides in this region.**



- **The size and cryogenic nature of JWST offers challenges to both the design and the verification program.**
  - Observatory temperatures range from 400K to 6K.
  - Cryogenic parasitic heat loads are notoriously hard to predict.
  - The observatory size and temperature range preclude an observatory level thermal test.

Thermal Region 3
- **Components maintained at temperatures from ambient to 400K**
- **Heat flows are typical for ambient spacecraft.**

JWST Systems Engineering

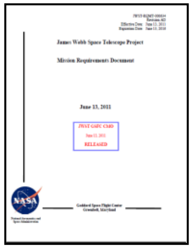
What Does a Systems Engineer Do?

Science Objective:

- Detect and Investigate the First Light Sources
- "Study the Assembly of Galaxies Since First Light "

Formulate Mission Requirements

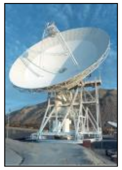
- Sensitivity
- Image Quality and Resolution
- Field Of View
- Data Throughput
- Observing Efficiency

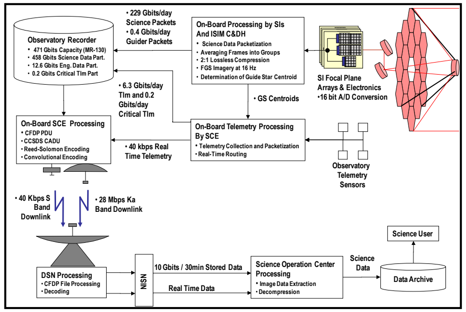


Design the System

James Webb Space Telescope System

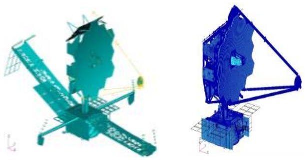
- Launch Segment
- Observatory Segment
- Ground Segment





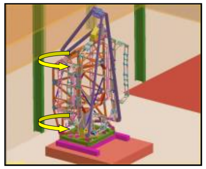
- WFE Budget
- Power Budget
- Mass Budget

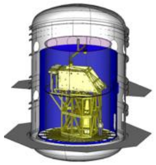
Systems Analyses & Performance Assessments

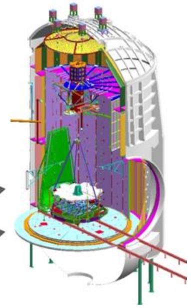


Risk / Issue Management & Tech Development

Verification of the "As Built" System







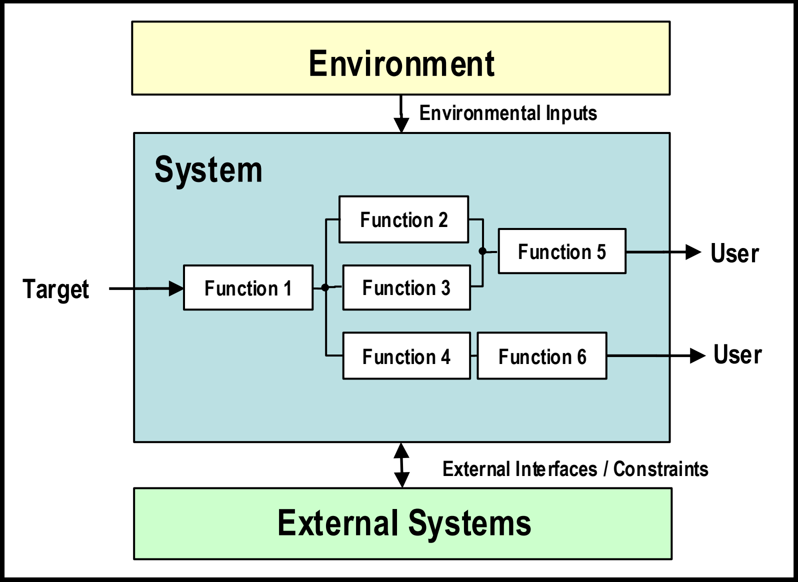
System Commissioning & Operations

Systems Engineering Functions:

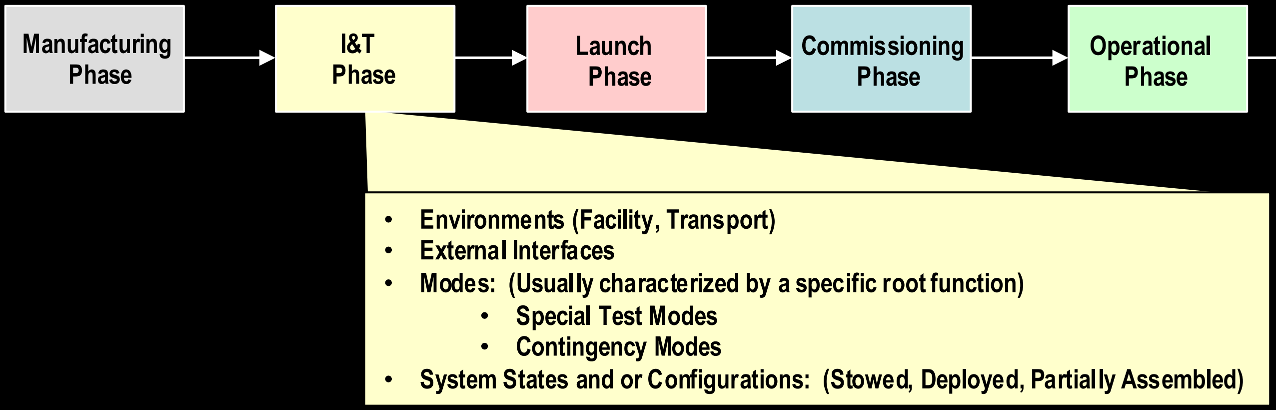
- Requirements Analysis

Requirements Analysis Summary

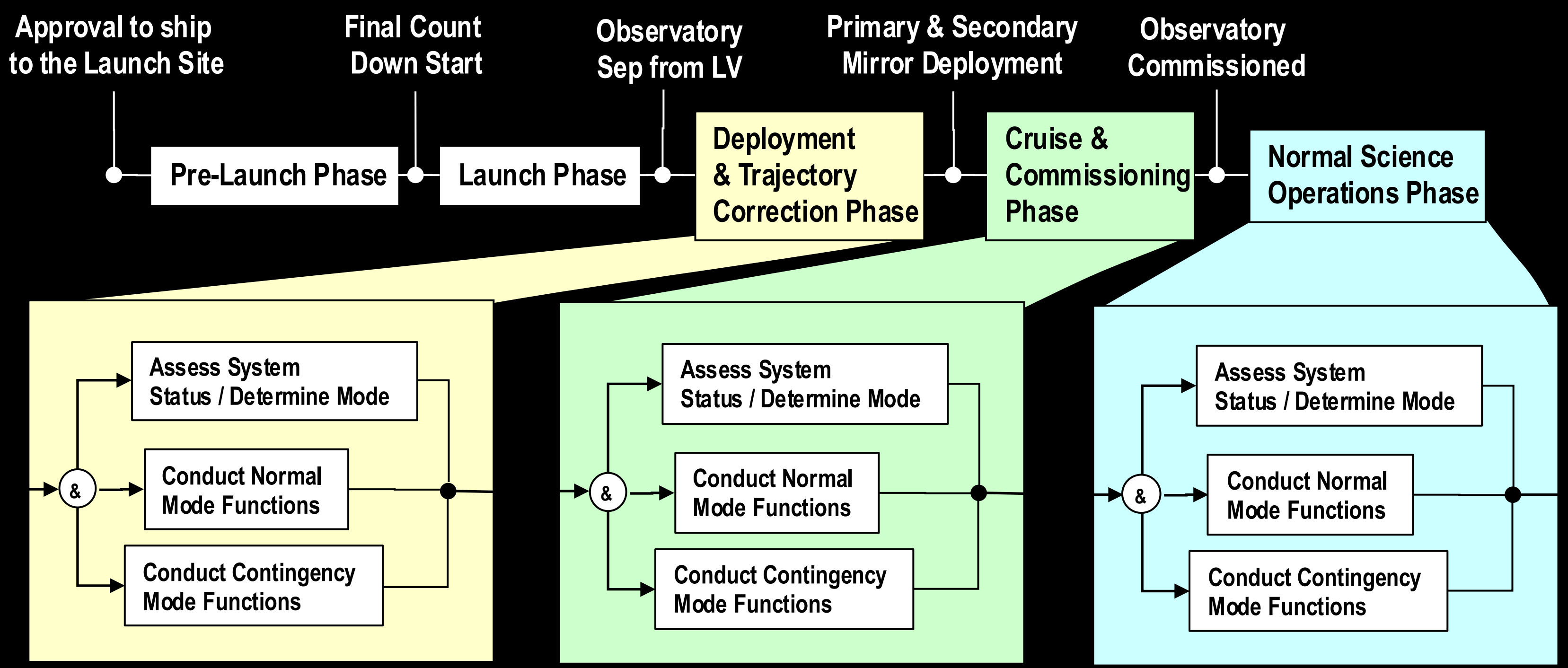
- **Requirements Types:**
  - Functional (What does the system need to do; Functional Analysis)
  - Performance (How well does it need to do it; budgets)
  - Interface Requirements (Inputs / Outputs, Constraints)
  - Environmental Requirements (What does the system have to survive or operate in)
- **Many requirements are time specific.**
  - Mission Phases have to be considered / defined.
- **There are rules and "etiquette" for generating / documenting good requirements.**
  - Requirements will eventually form the basis of contracts.
  - MIL-STD-490 describes how to write and document requirements
- **System level requirements will be decomposed into "child requirements" and allocated to the various parts of the system.**
  - This flow-down is the trail of breadcrumbs for the verification of the system elements, and eventually the verification of the system.



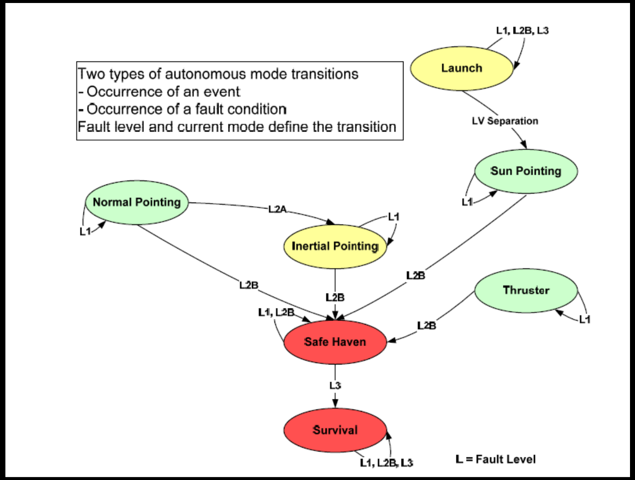
Mission Phases (Specific Time Periods)



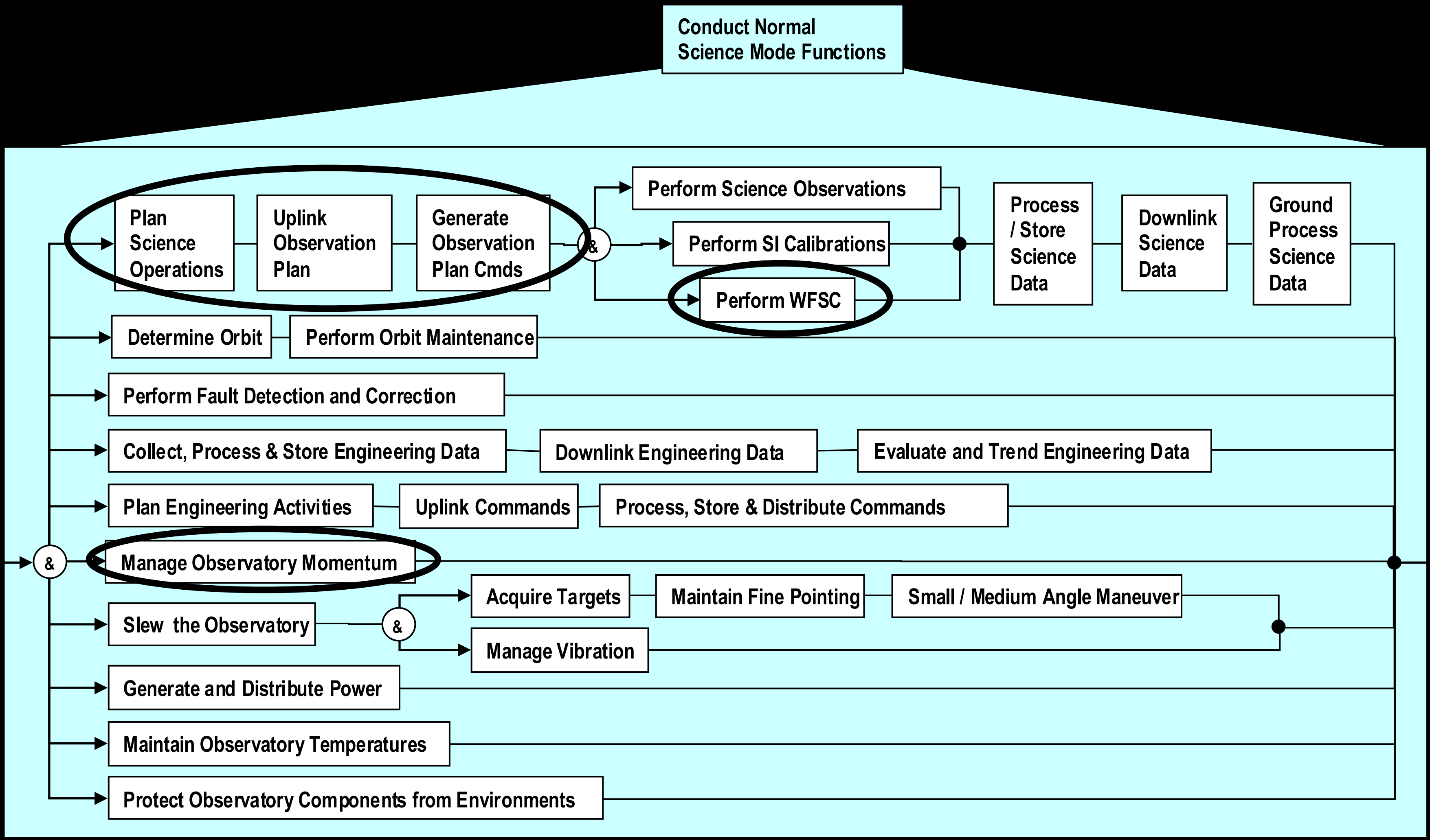
System Functional Flow Block Diagram



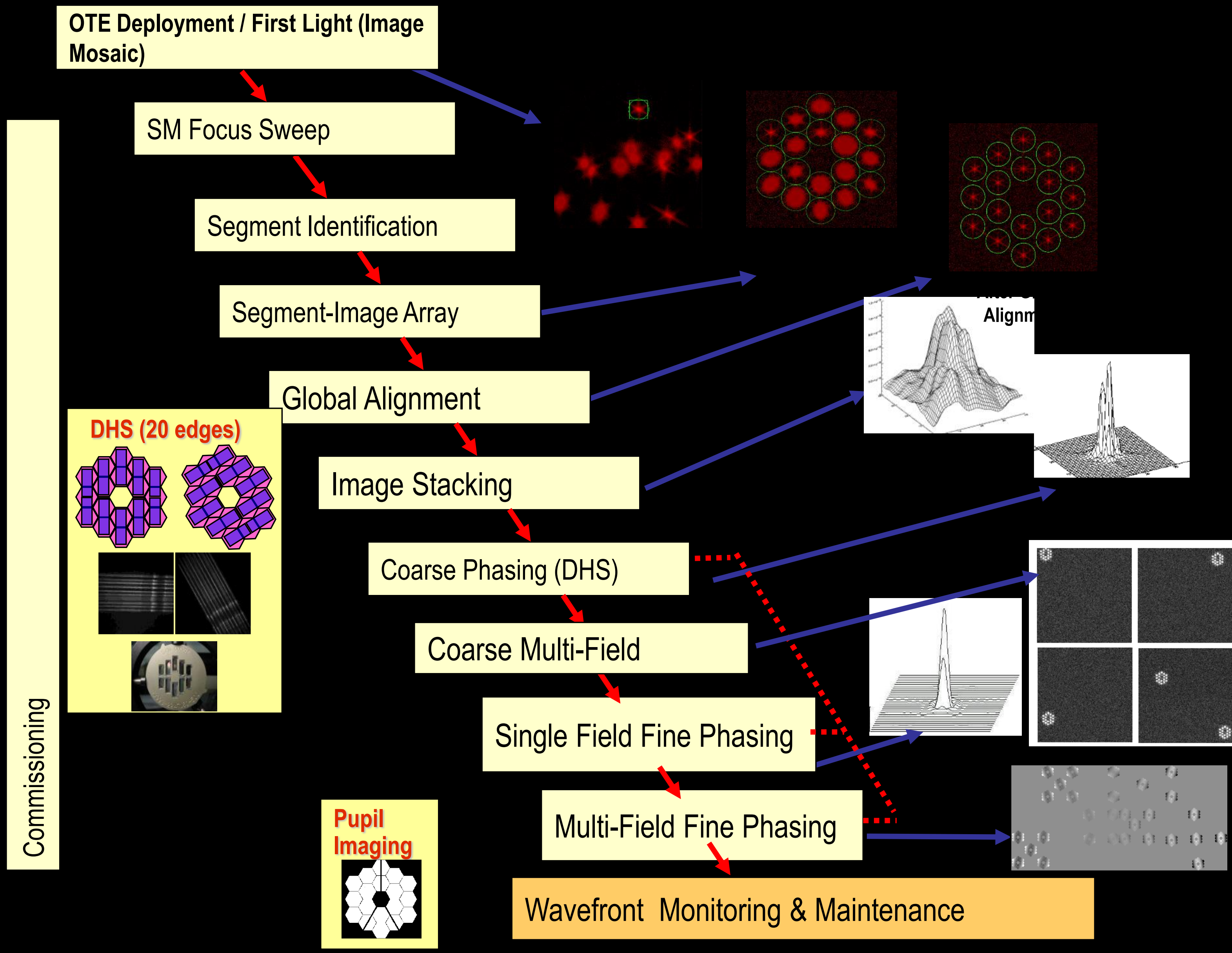
- These functional decompositions form the basis for the Mode-State Transition Diagrams.
- Note that the Contingency Modes and or the criteria for their entry will probably be different for each mission phase.



Functional Flow Block Diagram for Normal Science Ops



Wavefront Sensing and Control Process



Science Requires an Infrared (IR) Telescope

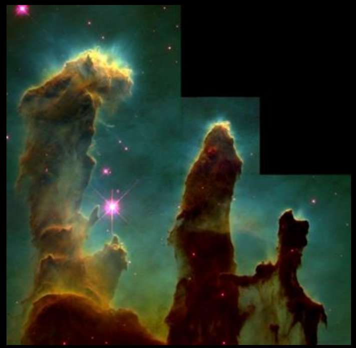
Hubble Deep Field image shows galaxies out to z~5.

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.

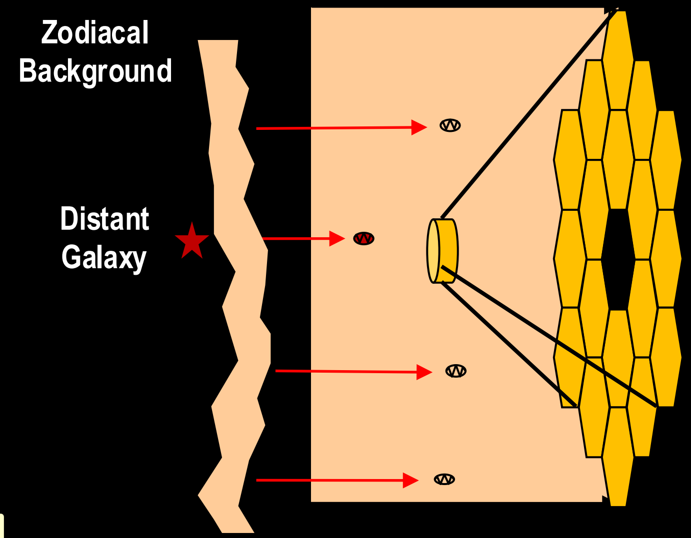
JWST must operate in the Mid Infrared (MIR) wavelengths (5 to 28 microns)

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

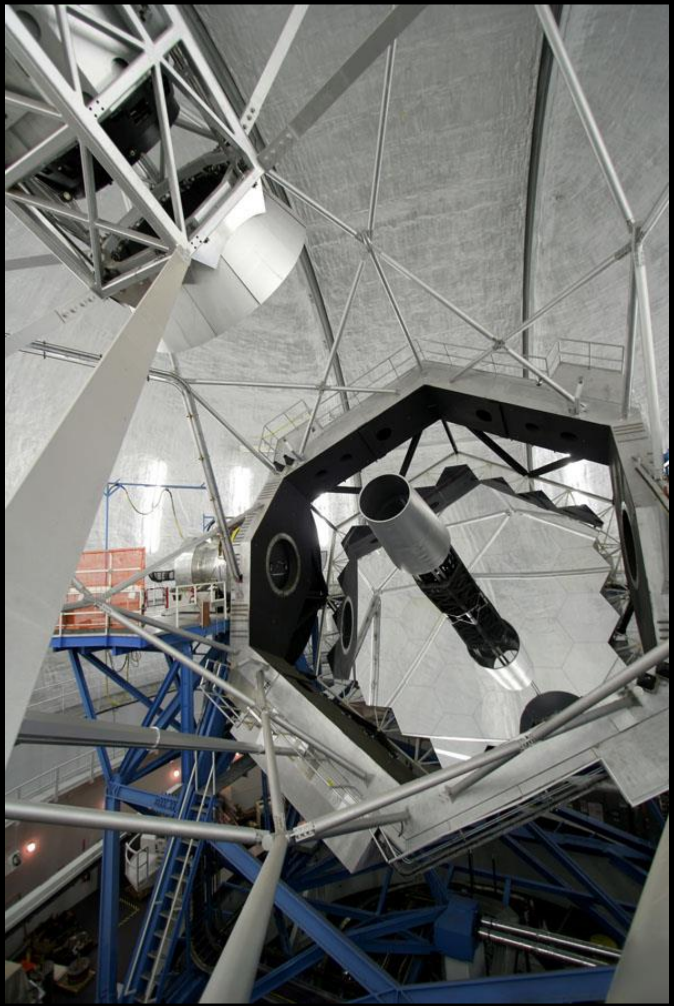
- Sensitivity: Detect 11 nanoJansky Point Sources with a Signal to Noise Ratio of 10 for exposure time of 10,000 sec.
  - High Signal Collection
    - 25 m^2 Aperture, 6.5 m Diameter
    - Optical Transmission > 52%
    - Detector Quantum Efficiency > 80%
    - Encircled Energy > 59% to 80 mas
  - Low 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)

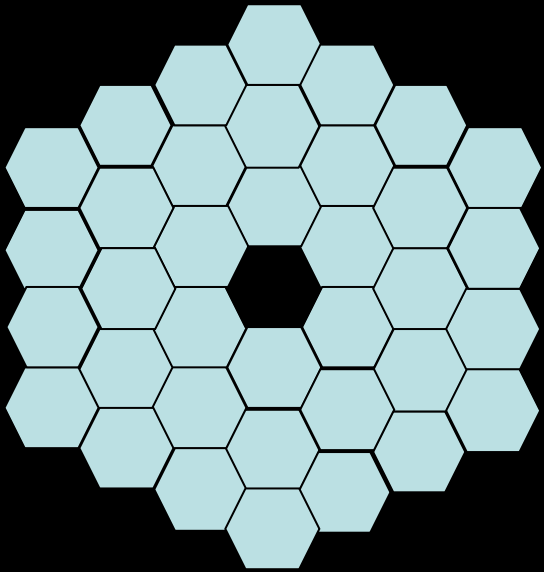


- JWST collects 1 photon per second, and registers one electron every 4 seconds.
- JWST collects 3 photons per second from the natural background and registers 3 electrons from this background every 4 seconds.

Segment Primary Mirror Leverages Keck Technology

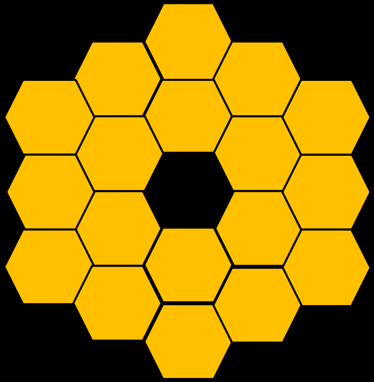


The Keck I Telescope on Maunea Kea Summit in Hawaii

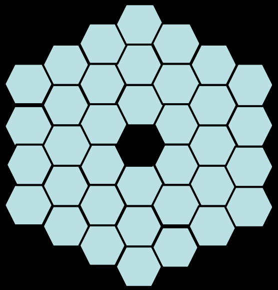


The 10 meter Diameter Keck I Primary Mirror

Factoring 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

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

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

Signal

Temperature Dependent Noise

Where :

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

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

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

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

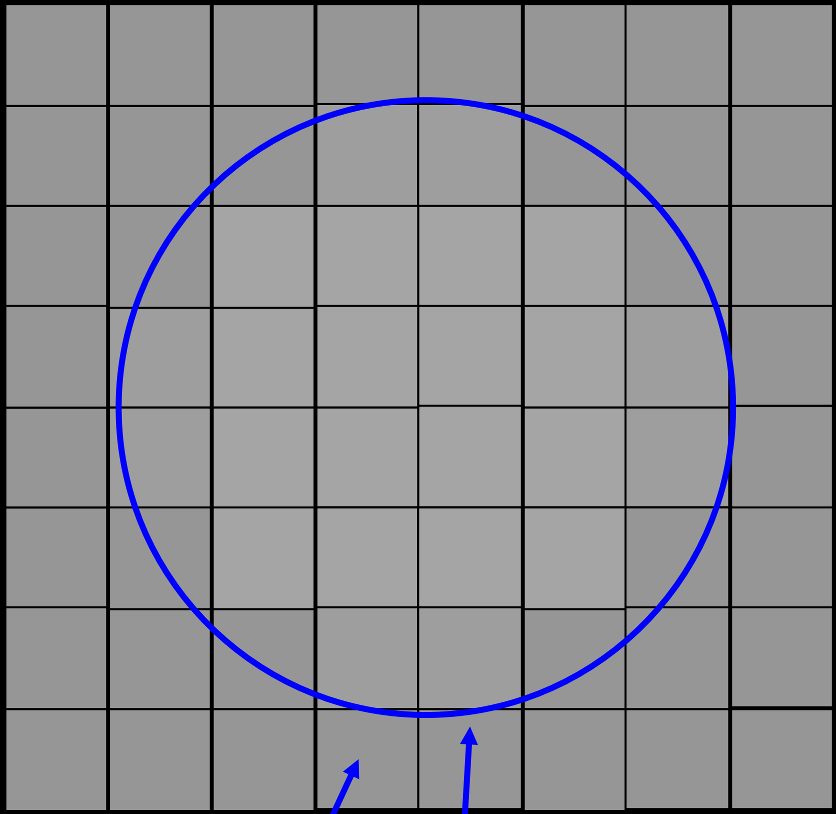
$$R_d = r^2 N_{pixels}\frac{t_{\exp}}{t_r}\left[1 - \frac{C_r t_s}{t_r}\left[\frac{t_r - t_d}{t_r}\right] - \frac{t_d}{t_r}\right]^{-1} = r_d t_{\exp}$$

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

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**

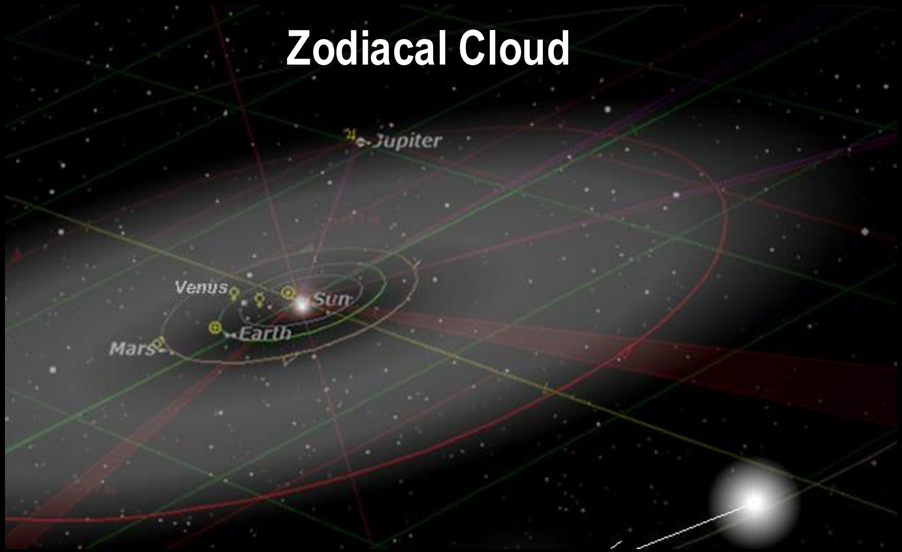


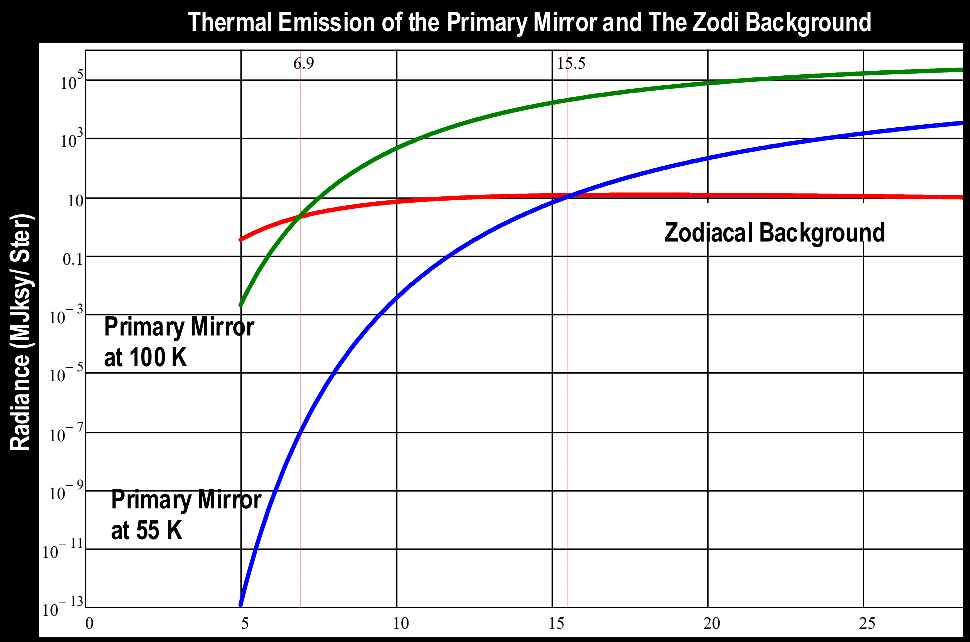
Each Background Pixel Accumulates 1883 Counts

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

Infrared Observatories Must be Very Cold

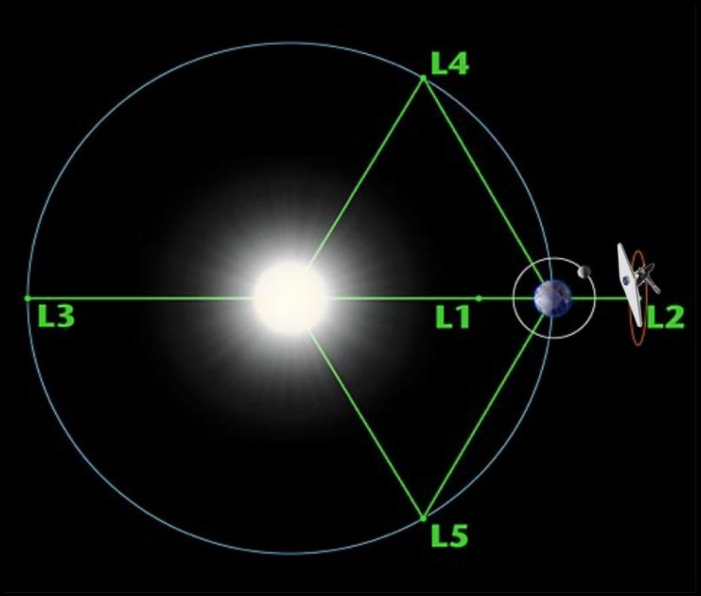
- **The telescope and the instruments glow in the IR. To make sure this glow does not overwhelm the faint signal, both must be cold.**
  - At ambient temperature the primary mirror emits over 350 photons at a wavelength of 2 μm.
- **JWST is designed to emit less IR radiation than the natural Zodiacal background (shown on upper right) out to a wavelengths < 10 μm. This requires optics temperature < 55K (-223° C or -369°F)**
  - The graph on lower right compares the thermal emission of the Primary Mirror to that of the Zodi background vs wavelength.
- **The Science Instrument detectors must be colder to limit their 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.

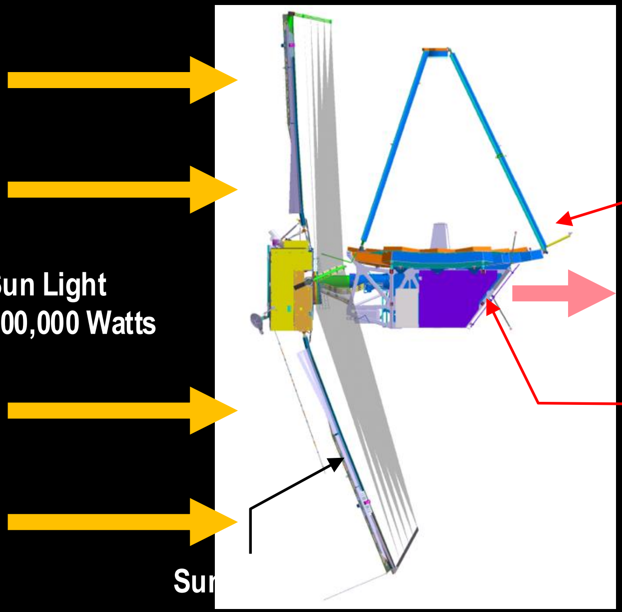




Cooling JWST

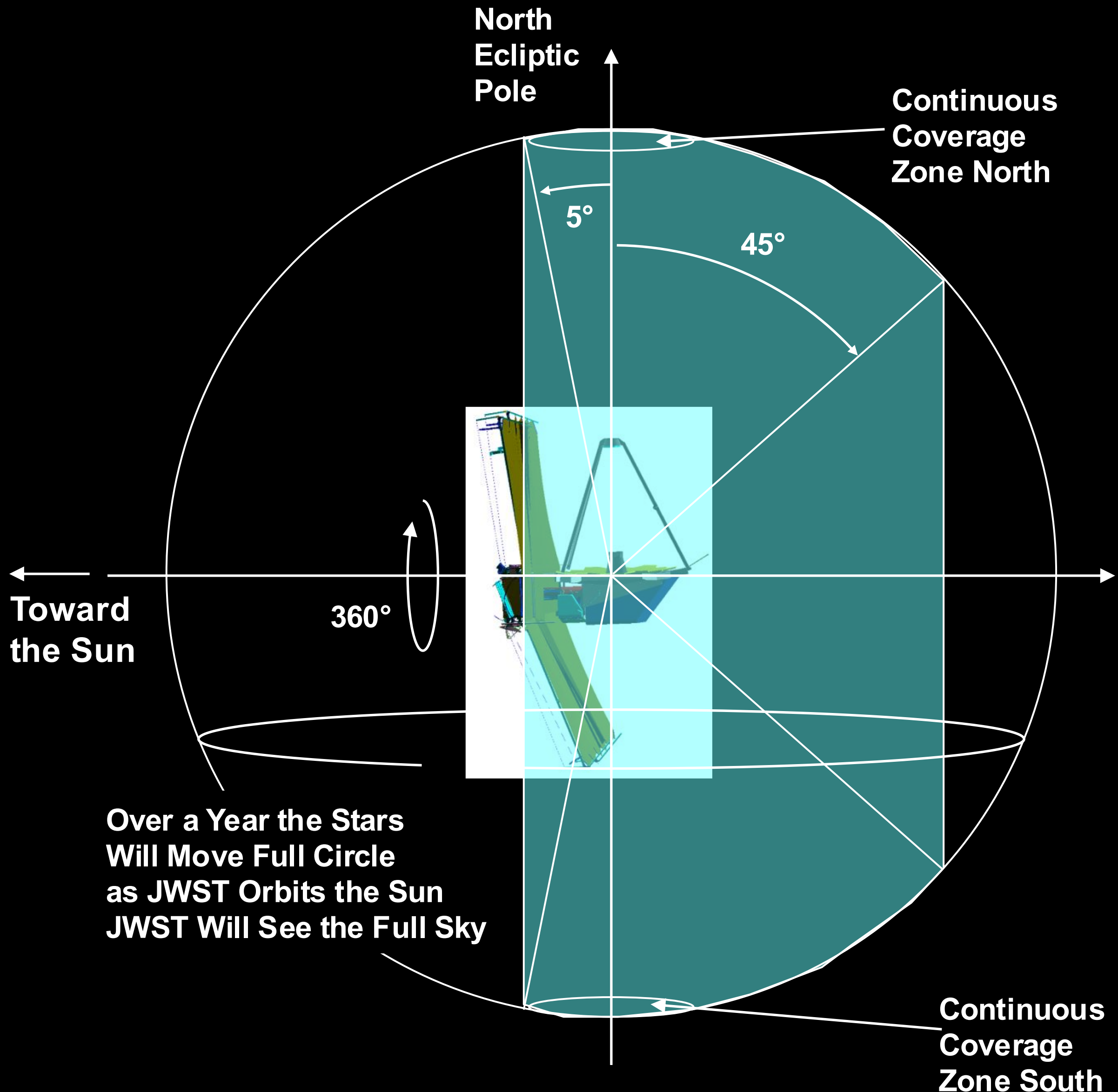
- **A 6-meter telescope and its instruments are too big to refrigerate. Therefore we must allow them to cool down "passively" .**
  - Get it far away from local heat sources, (The Earth, (300K) and the Moon)
  - Keep sunlight off the telescope and instruments
- **Locate the telescope at a point in space 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.**





Observatory Celestial Coverage

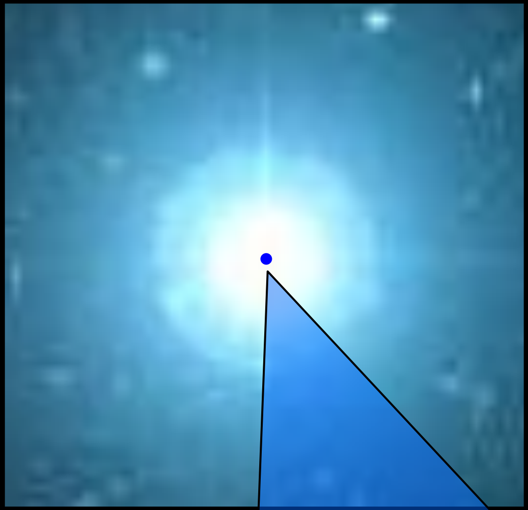
- The required celestial coverage for the observatory is 35% of the celestial sphere at any given time.
- The sunshield is currently sized to give at least 39%.
- Field of Regard is an annulus with rotational symmetry about the L2-Sun axis, 50° wide
- The observatory will have full sky coverage over a sidereal year
- There are continuous viewing zones 5° about the North and South Ecliptic Poles
- The observatory will have a roll capability about the telescope boresight of ±5°



JWST Resolution

- **Resolution refers to a telescope's ability to discern fine detail. (The smallest angle that the telescope can resolve.)**
- **JWST is required to sense objects as small as 0.084". (The angle a penny subtends viewed at 30 miles)**
- **The wave nature of light sets a fundamental limit on the resolution of a telescope. Diffraction prevents a telescope from focusing a point source.**
- **Rather, the telescope images a "Blur Spot" whose angular size under ideal conditions depends on the ratio of (Wavelength (λ) / Diameter (D)).**
- **Most stars are unresolved even in the world's largest telescopes**

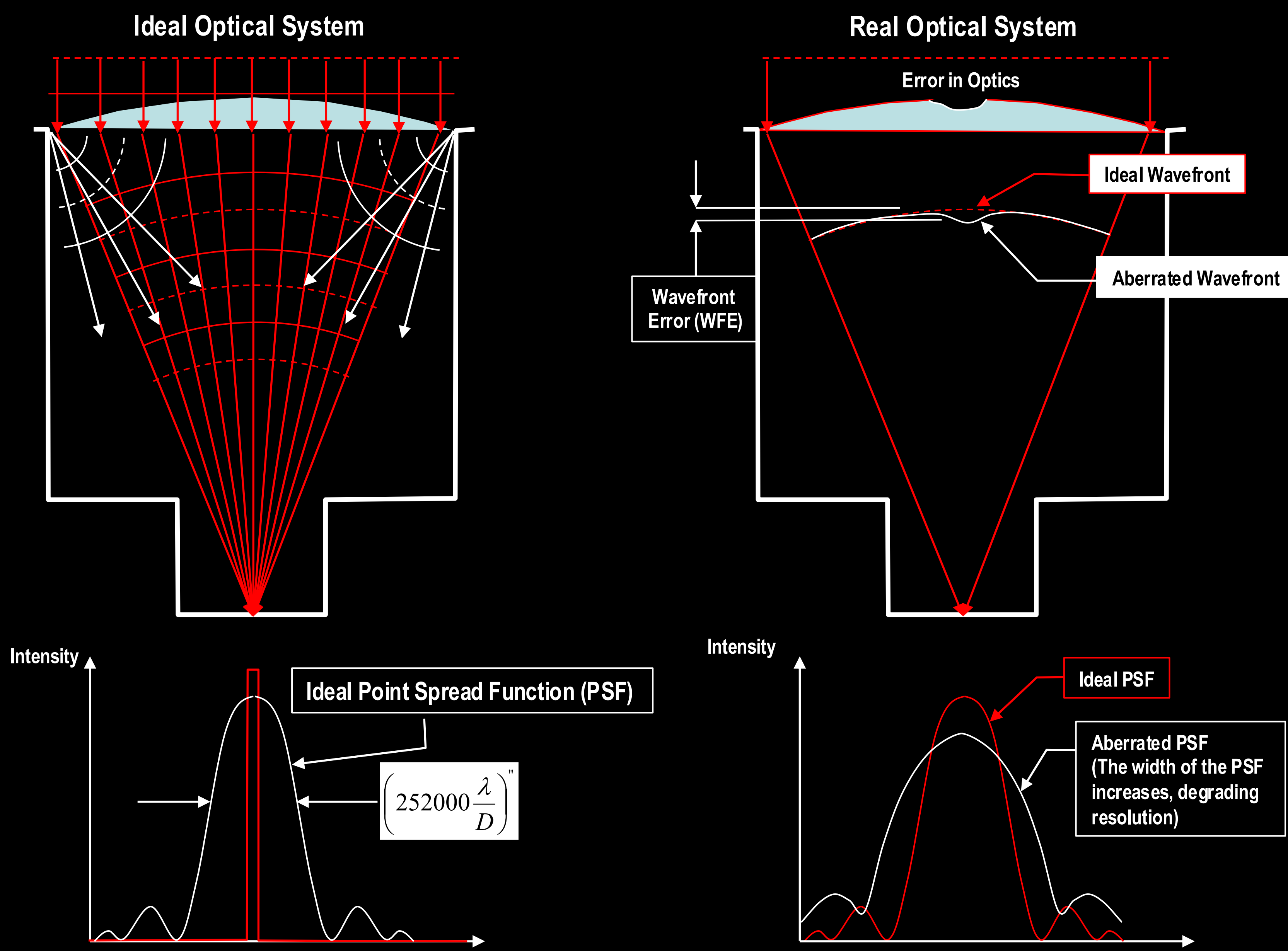
This is NOT the image of the star, but rather the best image the telescope can produce "The Blur Spot" or Point Spread Function



The actual image of the star is usually much smaller than the blur spot of the telescope.

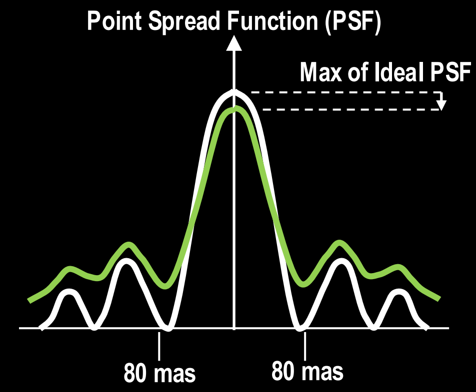
"The star is unresolved"

JWST Resolution and Diffraction (1 of 2)

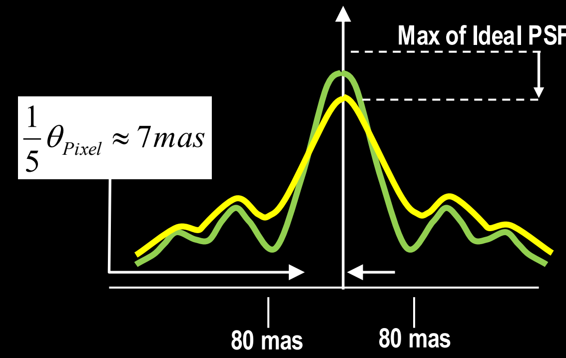


Driving Requirements: Image Quality

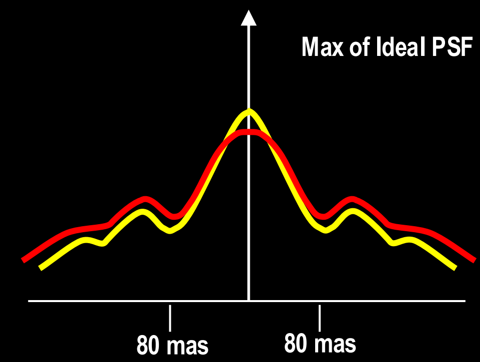
Image Quality: Diffraction limited at a wavelength of 2.0 μm, therefore Strehl Ratio > 80%, Total Wavefront Error (WFE) < 150 nm



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 Jitter / Pointing Stability

224 miles
(361 km)

- JWST is being designed to have pointing stability of 0.007 arcsec.
- This means that if JWST was at the Capitol, it could keep a laser beam pointed on a penny on the Empire State Building in NYC

Driving Level 1 Requirements and Their Flowdown to Level 2

JWST Program Plan (JWST-PLAN-000633)

Science Mission Objectives

L1-1: Measure space density of galaxies to 2 μm flux density of 10^{-34} Wm^{-2} Hz^{-1}

L1-2: Measure spectra of at least 2500 galaxies with R between 100 and 1000 to a 2 μm line flux density of 5.2×10^{-22} Wm^{-2}

L1-3: Measure physical and chemical properties of young stellar objects, circumstellar disks, extra-solar planets and solar system objects

Data Volume

L1-12: JWST shall deliver and process 229 Gbits per contact compressed from 458 Gbits

Data Availability

L1-10: JWST shall deliver 95% of all RT and Stored Data

Observing Time

L1-8: 5×10^{7} sec for 5 years

Mission Life

L1-9: 5 years

Orbit

L1-12: L2 Orbit

JWST Mission Requirements Document (JWST-RQMT-000634)

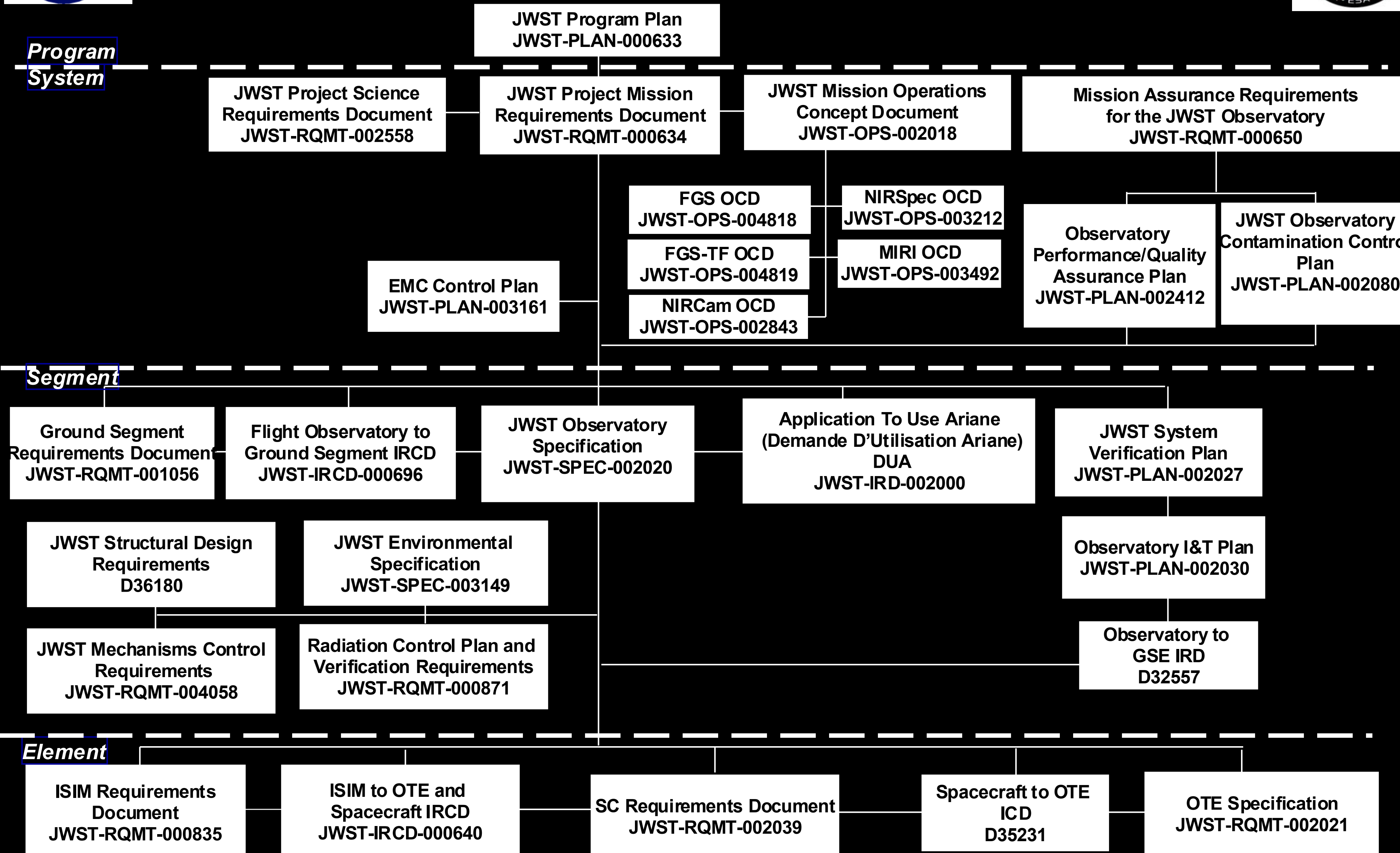
- MR-107: Wavelength Coverage
- MR-51: Sensitivity
- Stray Light
  - MR-121: NIR Stray Light
  - MR-122: MIR Stray Light
- MR-198: OTE Aperture
- Image Quality Requirements
  - MR-110: Strehl (NIR)
  - MR-116: Strehl (MIR)
  - MR-111: Encircled Energy
  - MR-113&114&115: EE Stability
- MR-185 & 186: Spectral Bandwidth / Resolution
- Celestial Coverage
  - MR-103: Annual Coverage
  - MR-104: Field of regard
  - MR-105: Consecutive Coverage
  - MR-106: Continuous Visibility Zone
- MR-177: 10 Day FOV
- MR-369: Science Instrument FOV
- Pointing Control
  - MR-173: Fine Accuracy
  - MR-393: Absolute Knowledge
  - MR-182: 0-0.5" Offset
  - MR-181: 0.5-2" Offset
  - MR-374: 2-20" Offset
  - MR-364: 20-30" Offset

- MR-102: System Efficiency
- Data Efficiency
  - MR-49: Real Time Data
  - MR-50: Stored Data
- MR-130: Data Storage
- MR-257: Data Rate
- MR-77: Contacts

- MR-44: Science Mission Life
- Reliability
  - MR-368: OTE & SCE
  - MR-383: ISIM
- MR-48: Propellant

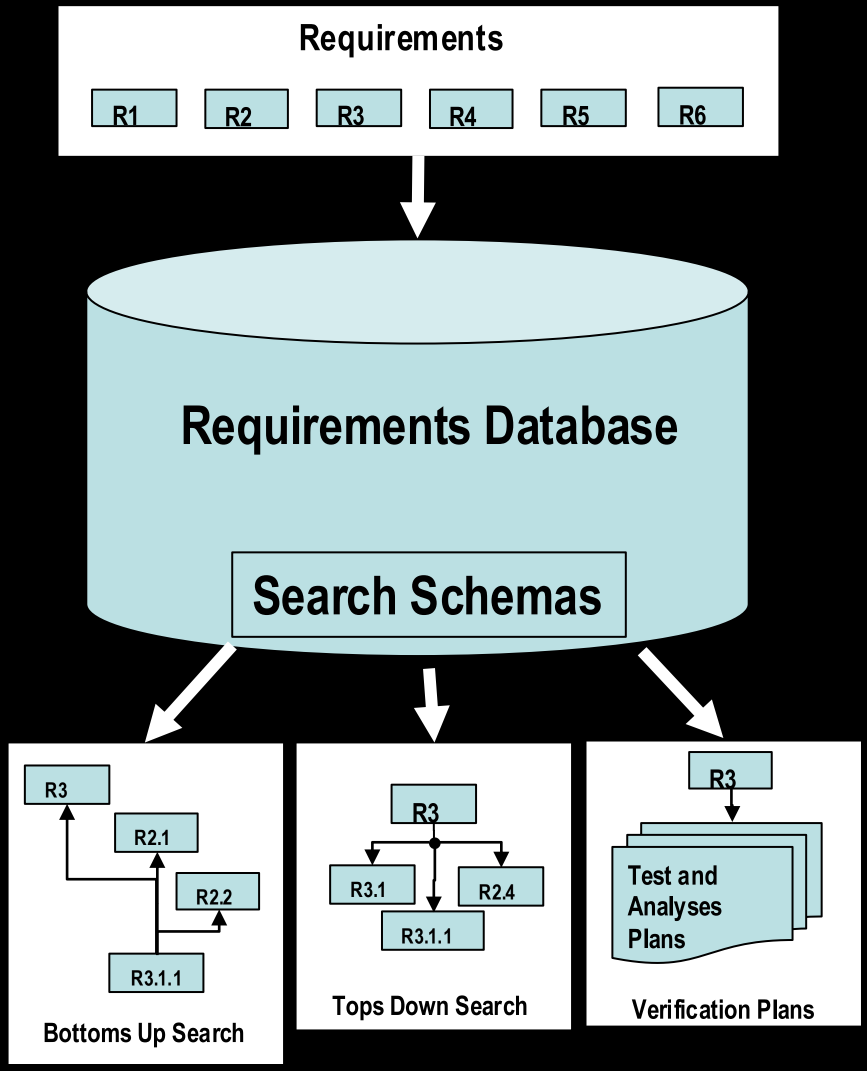
- MR-283: Ariane LV
- Orbit Geometry
  - MR-385: Z Excursion
  - MR-386: Y Excursion
  - MR-387: No Eclipse
- MR- 99: Observatory Mass
- MR- 42: L2 Transfer Orbit

System Requirements Flow



Requirements Databases

- **Requirements are usually recorded into a database such as DOORs.**
- **The database is usually a "relational database" capable of various programmable searches.**
- **Consider carefully the actual searches that need to be performed against:**
  - The complexity of the database,
  - The up-keeping needs of the database,
  - The maturity / stability of the database,
  - The ability of the database to interface with other tools,
  - Licensing provisions and whether other team members will be able to use it or interface with it.

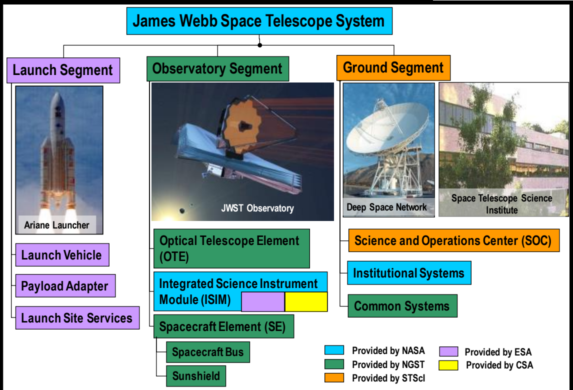


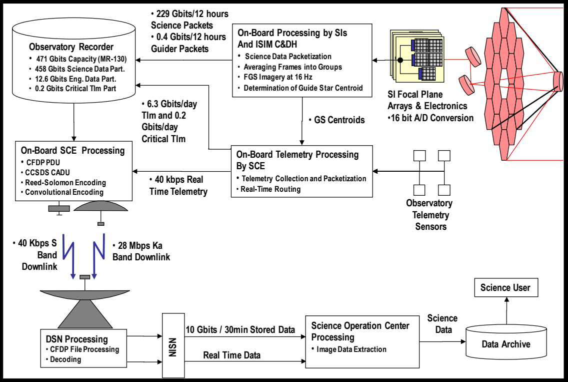
Systems Engineering Functions:

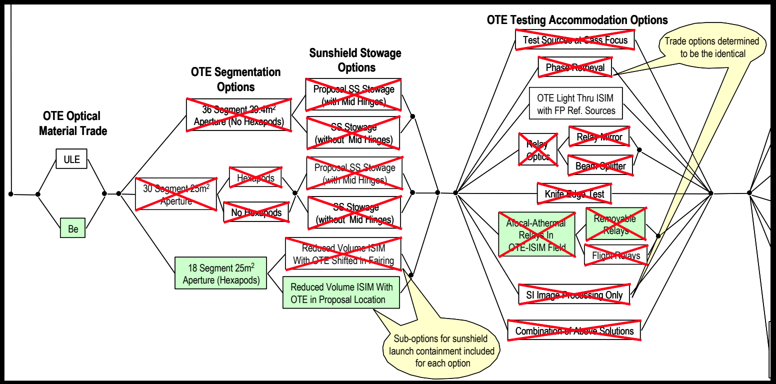
- Systems Design

Systems Design

- **System Design is NOT detailed design but rather a definition of the child requirements, internal interfaces and constraints needed for detailed product designers to design their items.**
- **Typical system design:**
  - Identify and specify Launcher / Ground Segment / Observatory / Trajectory
  - Payload Sizing / Definition: Telescope Aperture / Science Compliment
  - Data Flow and Processing
- **Most systems are NOT linear, and the sum of optimized parts does not usually mean the system is optimized.**
  - Trades are usually not nearly as “decoupled” as folks want.
  - Trades need to be closed with options that optimize the system.
- **System Design is usually iterative. First couple of iterations are usually intended to prove that a system solution is possible / affordable.**
  - An Existence Proof.
  - A reasonably good point of departure for more detailed trades.
- **Baseline control of a system is important during these trades.**
  - The baseline may not be optimal or compliant with requirements, but it should be self consistent. (Budgets / performance predictions / schematics / interfaces / data flows all consistent.)





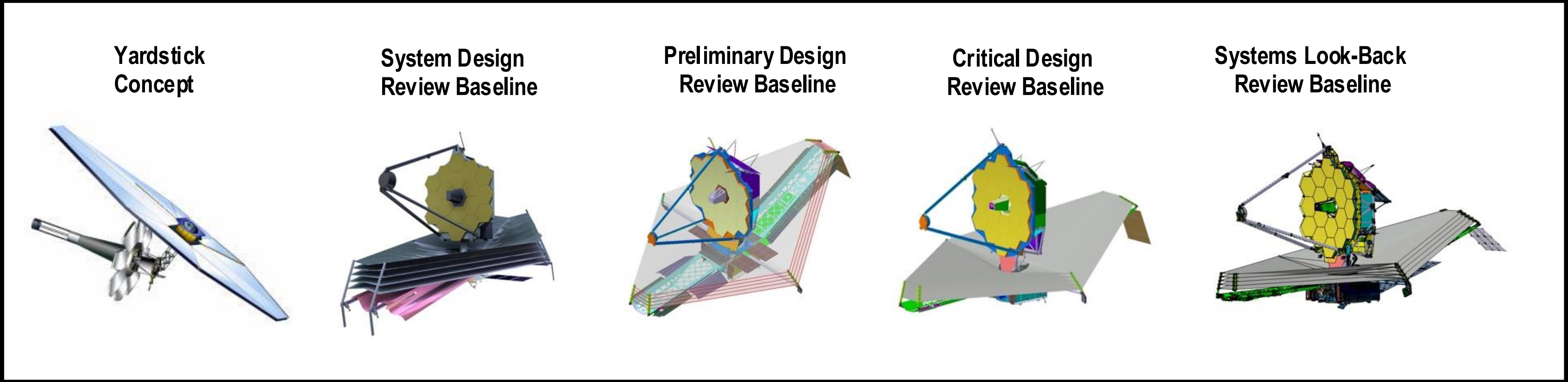


	Subsystems				
Subsytem Rating	Attitude Control	Propulsion	Thermal	Flight Software	Operations
Best	Option 1	Option 1	Option 1	Option 1	Option 1
	Option 2	Option 2	Option 2	Option 2	Option 2
	Option 3		Option 3	Option 3	
			Option 4	Option 4	
Worst			Option 5		

Option Combination Best for the System

Trade Studies

- **Over 70 system level trade studies were performed.**
- **About 40 of them were done as part of formulation. Most of these were done concurrently.**
- **Other trades were performed to address problems that arose during development / detailed design.**
  - Mass and Thermal recoveries.
  - Straylight recovery.
- **JWST evolved considerably as a result of these trades as shown below.**



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

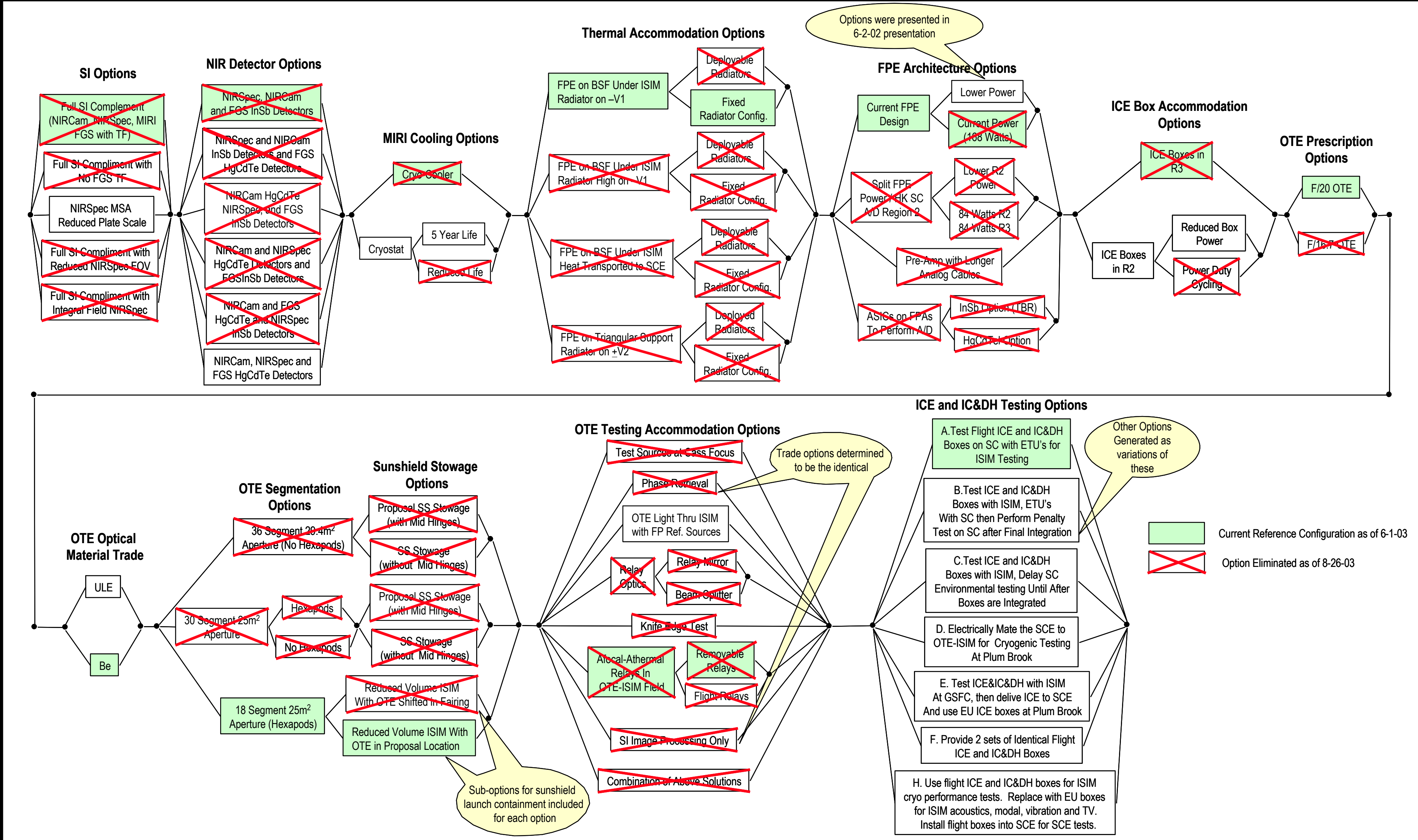
Verification / I&T Trades
- Plum Brook vs JSC Trade
- OTE / ISIM Metrology Trade
- OSIM Trade
- Observatory Transportation Trade
- OTE / ISIM Test Trades
- Electrical End-to-End Testing Trade
- Contamination Control Trades

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

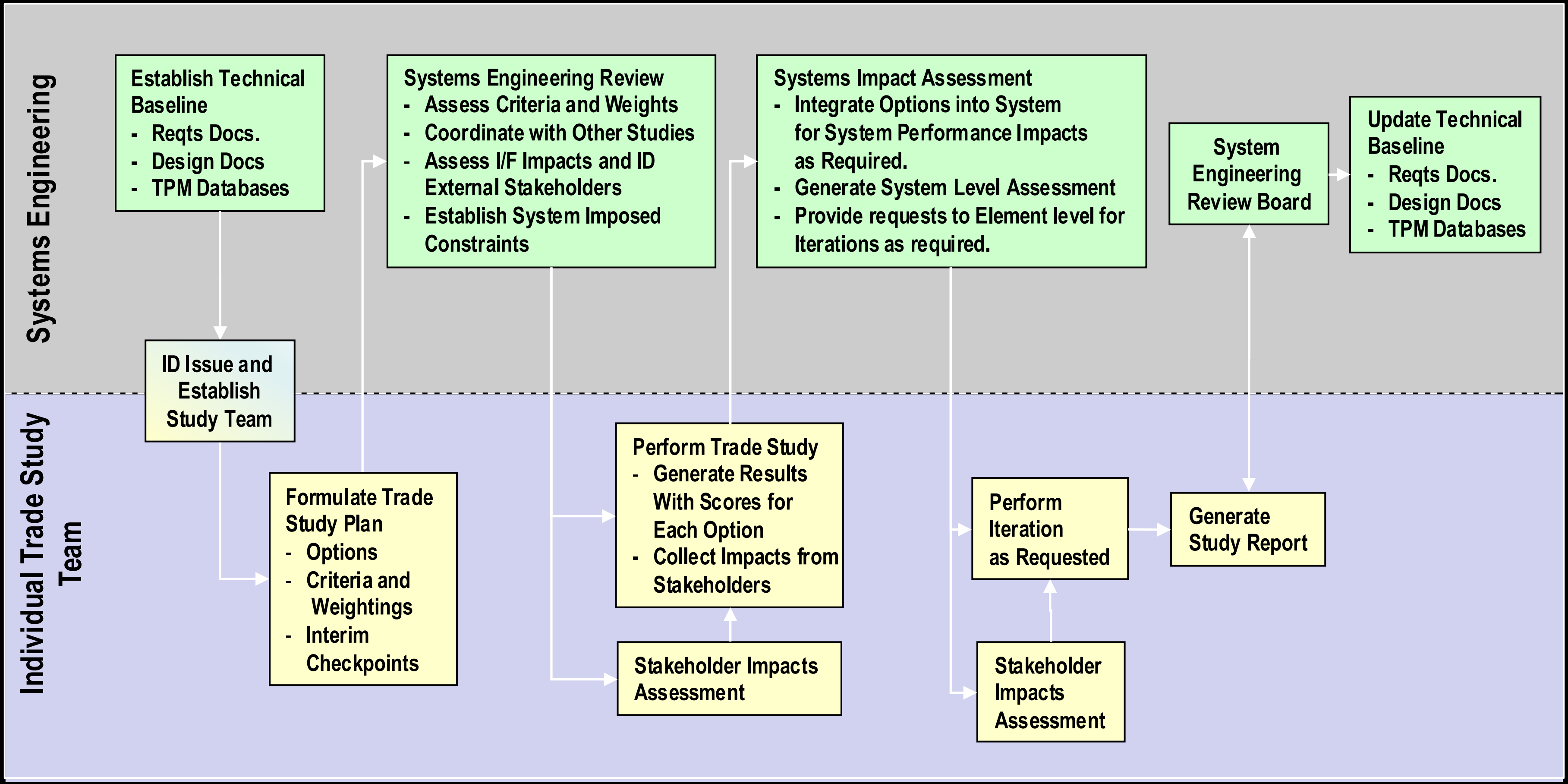
SCE Trade Studies
- Monopropellant vs Bi-Propellant Trade
- Spacecraft Structure Trade
- Solar Array Drive Trade
- Lithium Ion Battery Trade

Systems Engineer Trade Space Oversight



Mission Systems Engineering was the Air Traffic Controller for Concurrent Trade Studies

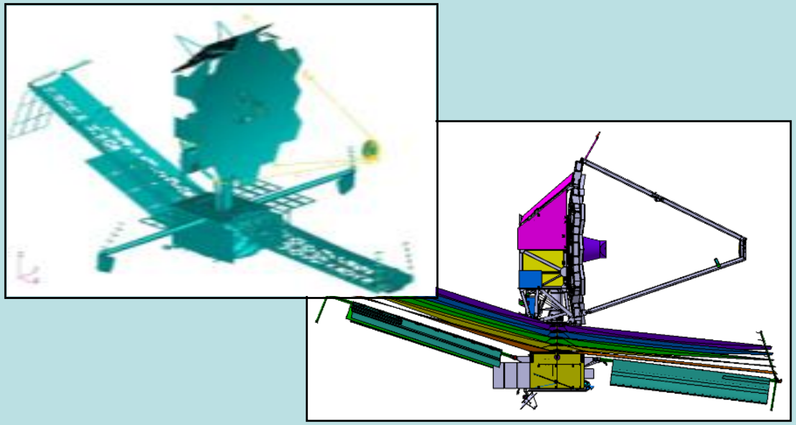
System Design Process for Trade Studies



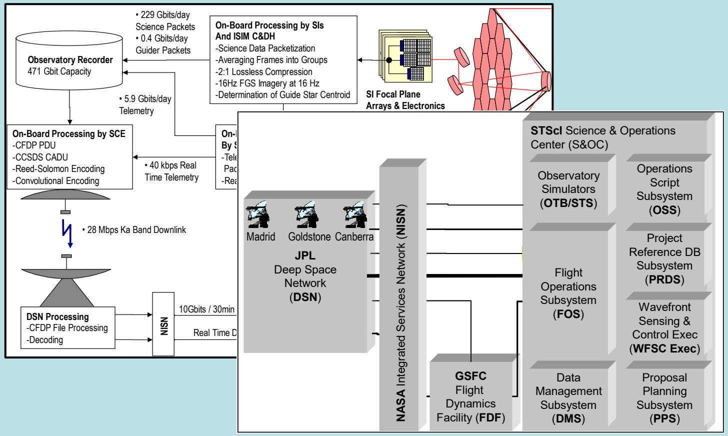
- **Segment, Element and lower level trades are formulated by responsible organizations, and reviewed by systems engineering for their compatibility with overall system goals**
  - SE ensures all stakeholders are identified for their inputs into the trade
  - SE determines data critical to systems performance assessments that should be produced as part of this trade
- **Trade results are reviewed and assessed by SE to determine their impact to overall systems performance**
- **Systems Engineering updates system baseline as required**

Maintain a System Baseline as a Point of Departure for Design Trades

Physical Configuration and Models



System Schematics /Interface Diagrams



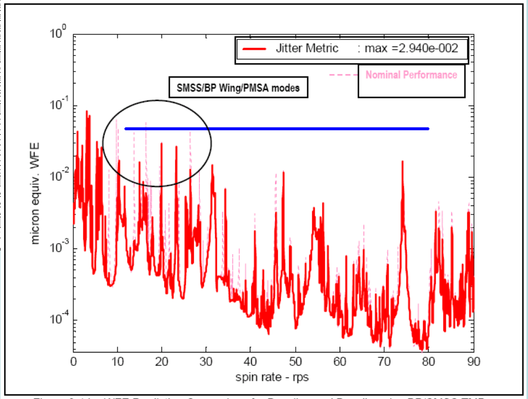
System Budgets / Resource Allocations

		Overhead Activity	Requirement / Allocation (hrs/5 years)	Estimate for Monograph 5 (hrs/5 years)
Observatory Segment	OTE	WFSC		720
		OTE Subtotal	1415	720
	ISIM	ICDH Safe Mode		120
		Guide Star Identification		73
		Guide Star Acquisition		177
		Guide Star Failure		78
		FGS Safe Mode		120
		Science Observation Overhead		
		Internal Calibrations		
		ISIM Subtotal		
	SCE	HGA Steering		
		S/C Safe Mode		
		Repointing Slew		
		Small Angle Maneuver		
		Station Keeping		
		Momentum Management		
		Spacecraft Subtotal		
	Observatory Subtotal			
Ground Segment	Observation Planning Scheduling			
	Target of Opportunity Scehduling			
	Anomaly Recovery			
	Ground Produced Anomaly			
	DSN Outage			
	Network (NISN) Outage			
	SOC Outage			
	Engineering Tests			
	Ground Segment Subtotal			
System Level Reserve (7%)				
System Totals (hrs / 5 years)				
System Efficiency (%)				

Item No.	Parameter	Value	Adv. Delta	Estimate Basis, Notes
	TRANSMIT			
1	TWTA Transmitt power	17.40 dBw		Minimum from 55-60W TWTA, See Detail for Item #1
2	Tx Passive Loss	-4.28 dB	-0.47 dB	TWTA located on -S2 Panel, Rotary Joint; See Detail for Item #2
3	HGA Antenna Gain	46.08 dBi		Ideal Value given assumed efficiency; See Detail for Item #3
4	HGA Pointing Loss	-2.29	-0.20 dB	See Detail for Item #4
5	Spacecraft EIRP	56.90 dBw		EIRP = P+G-L (Sum of Items 1 through 4)
	CHANNEL			
6	Free Space Loss	-245.84 dB	-0.35 dB	At 10.0 degree Elevation Angle; See Detail for Item #6
7	Atmospheric, Rain, Scintillation	-3.54 dB		Nominal uses IRCD Spec. for D2 Region; See Detail for Item #7
8	DSN RIP	-192.48 dBw		RIP = ERIP - Loss; RIP is at antenna Interface; (Sum of Items 5 through 7)
	RECEIVE			
9	DSN G/T	50.00 dB/K		Value spec'd in IRCD as TBR (assumes 34m ant.)
10	DSN Pointing Loss	-0.50 dB	0.38 dB	See Detail for Item #10
11	Polarization Loss	-0.10 dB	-0.05 dB	See Detail for Item #11
12	Boltzman's Constant	-228.60 dBHzK/W		
13	Receive C/No	85.52 dB-Hz		C/No = RIP + G/T -k - Loss; (Sum of Items 8 through 11, minus 12)
14	Bit Rate, Rb	73.89 dB		CCSDS formatted information bit rate; See Detail for Item #14
15	Signal distortion	-1.00 dB	-0.50 dB	IRCD Section 3.1.5.3, Tx distortion (TWTA I/Q imb., etc.)
16	Receiver Implementation Loss	-2.00 dB		IRCD Section 3.1.5.3, Rx distortion component
17	Available Eb/No	8.63 dB		Eb/No = C/No - Rb - Loss; (Sum of Items 13, 15, 16, minus 14)
	REQUIRED			
18	Theoretical Uncoded Eb/No	11.31 dB		IRCD Section 3.1.2.6: Uncoded SQPSK BER = 10^-7;
19	Reed-Solomon Coding Gain	-5.10 dB		CCSDS 700.0-G-3, R-S(255,223) outer code
20	Convolutional Coding Gain	-2.80 dB		CCSDS 700.0-G-3 --CC(7,1/2) inner gain + R-S gain
21	Interleaving Gain	-0.96 dB		CCSDS 700.0-G-3; Interleave depth of 5 is approx. infinite
22	Required Eb/No	2.45 dB		(Sum of Items 20 though 23)
	MARGIN			
24	**Link Margin @ 56 Mcps**	**6.18 dB**	**5.30 dB**	Total Margin = Available Eb/No - Required Eb/No; (Item 17 minus Item 22)

System Performance Estimates

Performance / Resource Parameters	Capability / Requirement	Estimate or Predict	Comments
Sensitivity Parameters			
NIRCam Sensitivity @ 2 microns (nJy)	11.4	9.70	Predict from 3-2010 SI TPM Report
MIRI Sensitivity @ 10 microns (nJy)	700	620	Predict from 3-2010 SI TPM Report
Straylight (MJy/ster @ NIR 2 microns)	0.091	0.082	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0118)
Straylight (MJy/ster @ NIR 3 microns)	0.07	0.062	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0118)
Straylight (MJy/ster @ MIR 10 microns)	3.9	0.480	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0118)
Straylight (MJy/ster @ MIR 20 microns)	200	204	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0118)
OTE Transimission* Ap (@ 8 μm) m^2	22	23.542	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0123)
Image Quality Parameters			
Strehl (NIR 2 microns)	0.80	0.847	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0123)
NIRCam Wavefront Error (nm)	150	130	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0114)
NIRSpec Wavefont Error (nm)	238	224	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0114)
TF Wavefront Error (nm)	180	145	CDR+ Inte
MIRI Wavefront Error (nm)	421	341	CDR+ Inte
EE Stability at 2 microns Over 24 hours	2.00%	1.10%	CDR+ Inte
EE Stability at 2 microns Over 14 days	2.50%	1.60%	CDR+ Inte
Image Motion (mas)	6.6	4.9	CDR+ Inte
Operations Parameters			
Observing Efficiency	70%	77.0%	From "Ob
Slew Time for 90 Degree Slew (min)	60	54.2	CDR+ Inte
Momentum Accumulation LV1 (Nms/d)	22	20.4	CDR IM C
Momentum Accumulation LV4 (Nms/d)	23	20.4	CDR IM C
Thermal Parameters			
Cryo Radiator Margin (NIRCam)	50%	67.7%	NG CDR+
Cryo Radiator Margin (NIRSpec FPA)	50%	79.0%	NG CDR+
Cryo Radiator Margin (NIRSpec OA)	50%	95.4%	NG CDR+
Cryo Radiator Margin (FGS/TF)	50%	76.2%	NG CDR+
Cryo Radiator Margin (MIRI)	50%	62.3%	NG CDR+
Cryo-Cooler Line Load Margin	58%	28% / 24%	CDR Loac
Data and Link Parameters			
S-Band Uplink Margin (dB)	3.00	6.70	Adverse M
S-Band Downlink Margin (dB)	3.00	4.00	Adverse M
Ka-Band Downlink Margin (dB)	3.00	5.94	Adverse M
Observatory Resources			
Observatory Wet Mass (kg)	6530	5868	Estimate
Observatory Power (W)	1993	1613	Estimate



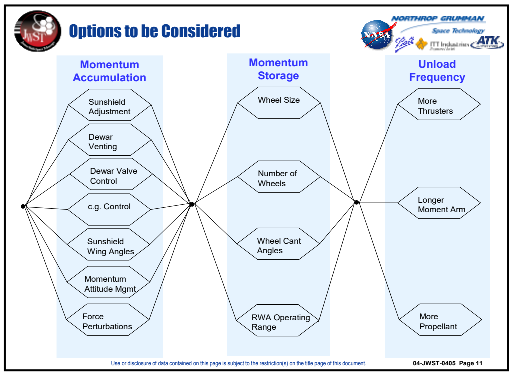
Trade Options Selected at the Systems Level For a Highly "Integrated System"

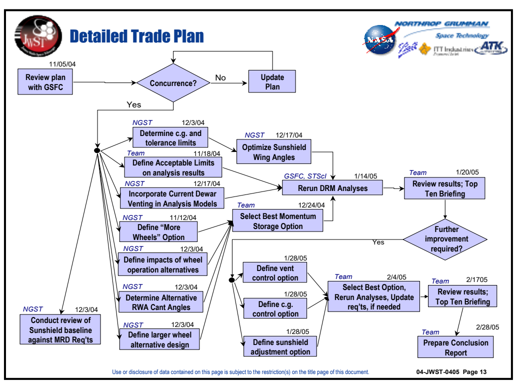
- **A set of optimized subsystems DOES NOT necessarily produce an optimized system!**
  - Possible IF requirements and interfaces are sufficiently defined, BUT this is rarely possible in the early periods of design.
  - Even in later periods, such clean interfaces do not usually result in high mass and resource efficiency.
  - Also, during early part of the design trades are going on simultaneously.
- **Solution: DO NOT close out subsystem trade at the subsystem level, rather have subsystems present their options and close out trades at the system level.**
  - This can present risk to the subsystems, that must be recognized by the Project and could have contractual implications.

	Subsystems				
Subsytem Rating	Attitude Control	Propulsion	Thermal	Flight Software	Operations
Best	Option 1	**Option 1** (green)	Option 1	Option 1	Option 1
	Option 2 (green)	Option 2	Option 2	**Option 2** (green)	**Option 2** (green)
	Option 3		Option 3	Option 3	
			Option 4 (green)	Option 4	
Worst			Option 5		
(green)	Option Combination Best for the System				

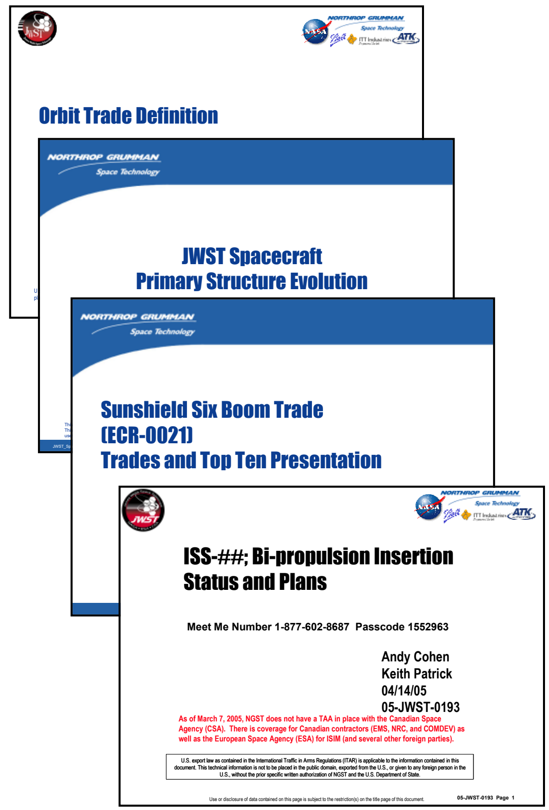
Example of Trade Study Process
Momentum Management Trade Study

Trade Study Plan Formulated And Presented Nov 4, 2004 04-JWST-0405



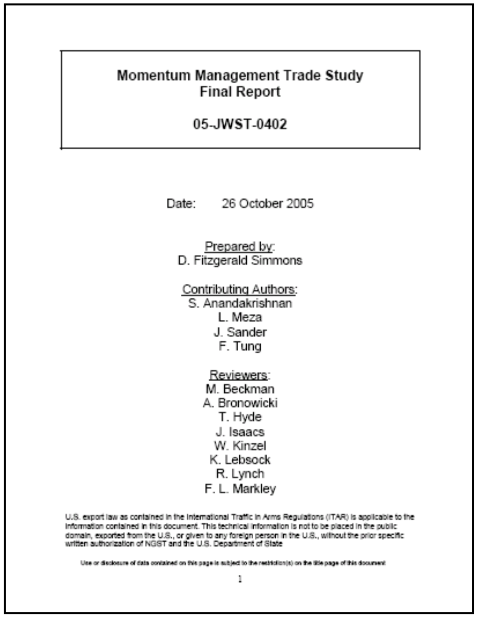


Systems Engineering Coordinates With Other Concurrent Trade Studies



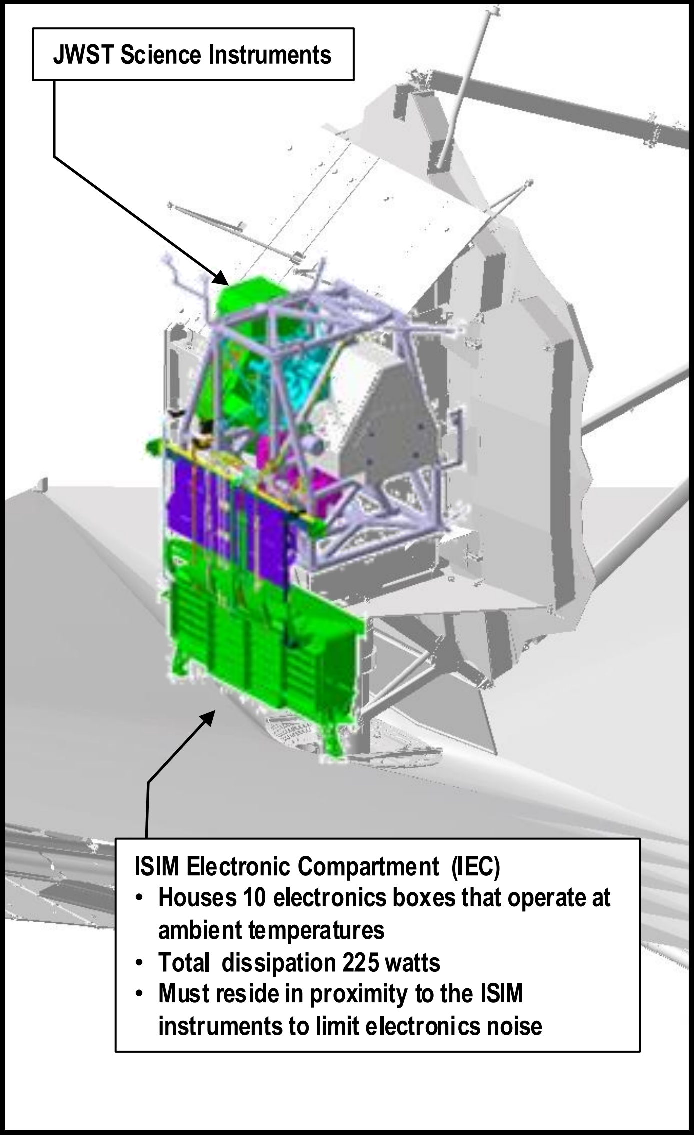
Final Results Presented to SE& PM

Report Generated & Reviewed by ERB



Trade Example: ISIIM Electronics Compartment Trade

- **The Optical Telescope Element (OTE) and the Integrated Science Instrument Module (ISIM) constitute more than 50% of the observatory mass (~3400 kg) and must be cooled below 55 K.**
  - The Primary Mirror must be below 55 K
  - The Near Infrared (NIR)Science Instrument detectors must be below 40 K.
  - The Mid Infrared Instrument detectors must be 6 K.
- **The bulk of this mass must be cooled passively using the sunshield as an insulator and cryogenic radiators viewing cold space to cool the detectors.**
  - The MIRI detector must use a dedicated cryo-cooler
- **Early architecture trades concluded that it was necessary to house the ambient instrument focal plane electronics and control boxes in proximity to the cold instruments.   Therefore on the COLD SIDE.**
  - Electrical noise allocations could not be met with cable lengths of roughly 10 meters.
- **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!**



Systems Engineering Functions:

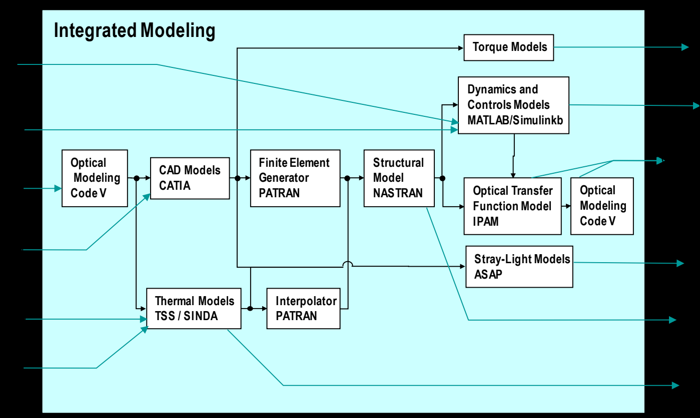
- Systems Analyses / Integrated Modeling
- Technical Performance Management

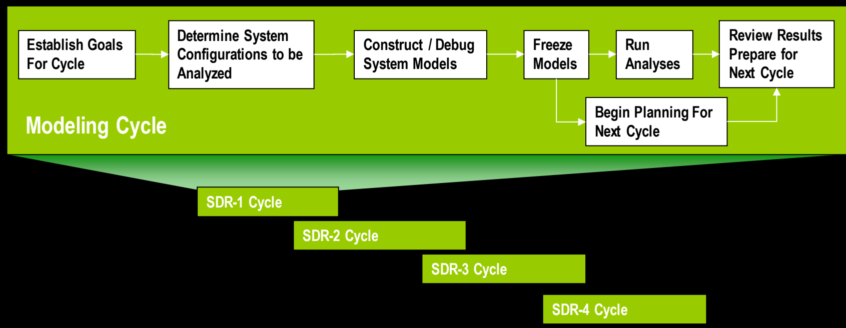
Systems Analysis

- **Systems Technical Performance Metrics (TPMs) are tracked to make sure the system is developing to meet its requirements.**
  - Select parameters to show the health of the system.
- **Systems level "Integrated Modeling" is performed to compute many of the more involved TPMs.**
  - Optical, CAD, Structural, Thermal and Control models from the individual elements or subsystems are integrated into a systems model.
  - Model interfaces and quality / consistency checks need to be specified.
- **Integrated Models are run in cycles which have specific purposes during different phases of development.**
  - Early runs are usually for problem identification. (Reconnaissance).
  - Subsequent runs support system level trades.
  - Later runs prove system compliance to requirements and verification of the "As Built" Systems.
    - Models will need to be validated and or correlated to actual hardware test results.
    - Independent model cross checks need to established.
  - **NOTE: Systems Modeling Does Not Prove Workmanship!**
- **Modeling must identify and quantify its inherent inaccuracies and or system sensitivities to establish necessary margin levels.**
  - Established by runs of the model to various parameter variations.
- **Fidelity of the models to the "To Be Built" or "As Built" system must be rigorously tracked and managed.**
  - A system of Threats and Liens lists should be established to track differences.
- **TPM margins should consider the Threats, Liens and Prediction Uncertainty.**

TPM	Status
Sensitivity	
Efficiency	
Data Volume / Link	
Momentum	
Commissioning Time	
Strehl, EE, OTE WFE	
WFE Stability	
Image Motion	
Stray Light Levels	
Cryogenic Thermal Margins	
Mass Margin	
Power Margin	

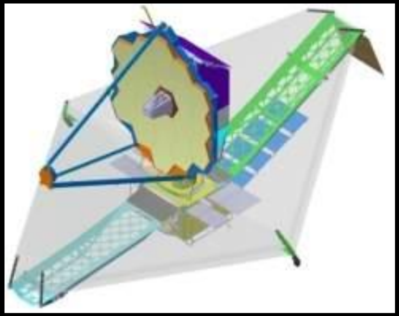
- Acceptable margins
- Requires improvement & improvement is likely
- High probability of not meeting requirements



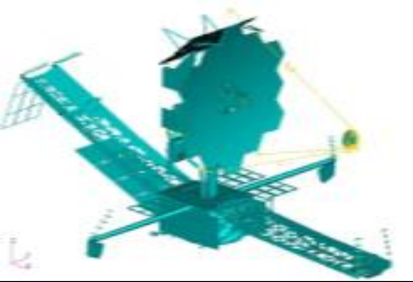


Integrated Systems Modeling was a Must for JWST's Success

- **The "integrated design" required system level analysis models to:**
  1. Support initial system trades and or issue resolution.
  2. Support reliable and accurate performance evaluation of Technical Performance Metrics
  3. Perform system level verification of the final "As-Built" observatory.

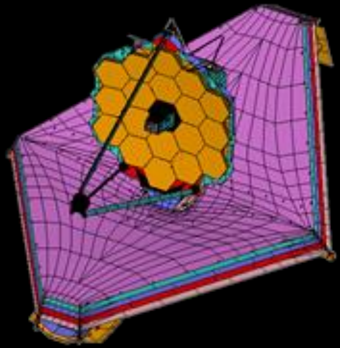


Observatory CAD Models

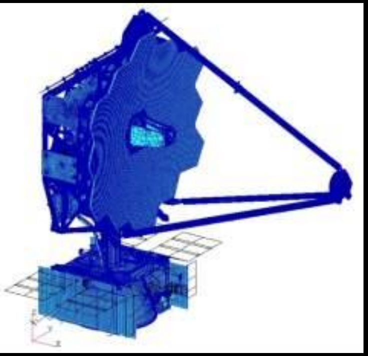


Observatory Dynamics Models

- **Systems Modeling Requirements:**
  - To be agile enough to support multiple concurrent trade studies.
  - To be managed to ensure interfaces between discipline models are controlled.
  - To have quantified uncertainties to support trade decisions and determine necessary performance margin allocations.
    - This includes sensitivity to workmanship errors.
    - To have plans for their correlation and validation
  - Configuration managed to ensure the models reflect the "As-Built" flight items.
    - Changes to either models or hardware must be coordinated.

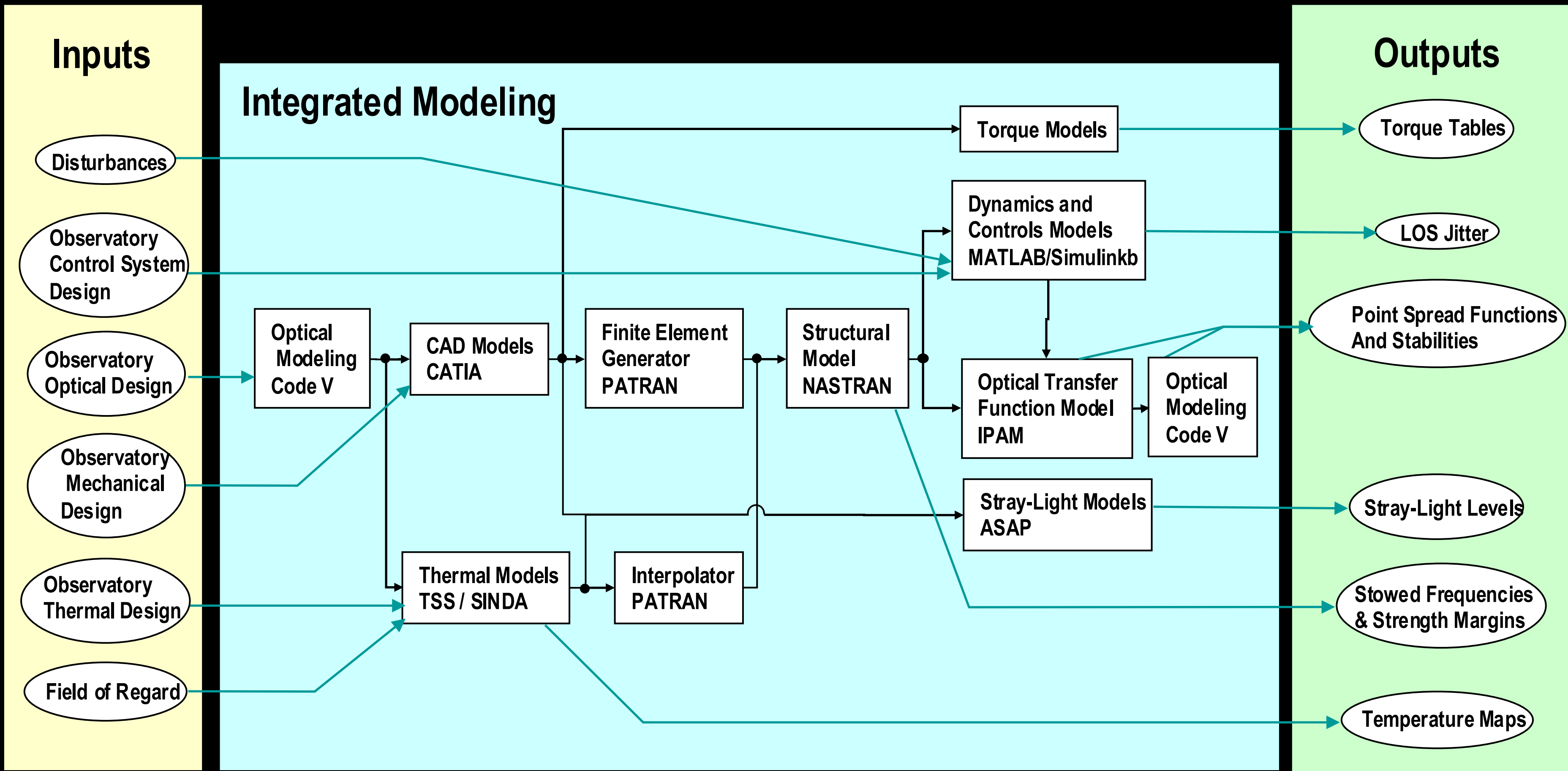


Observatory Thermal Models



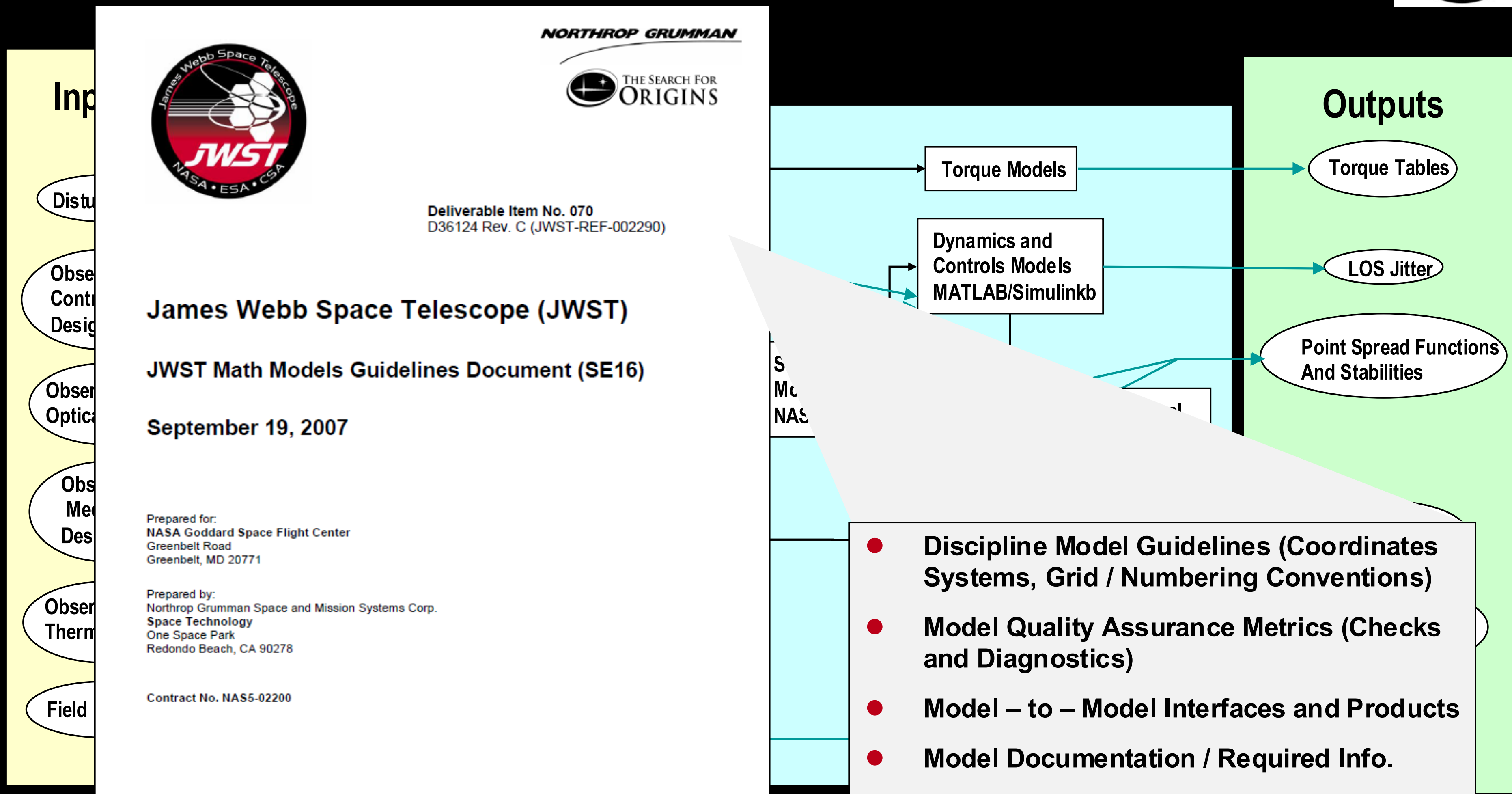
Observatory Thermal Distortion Models

Integrated Modeling System



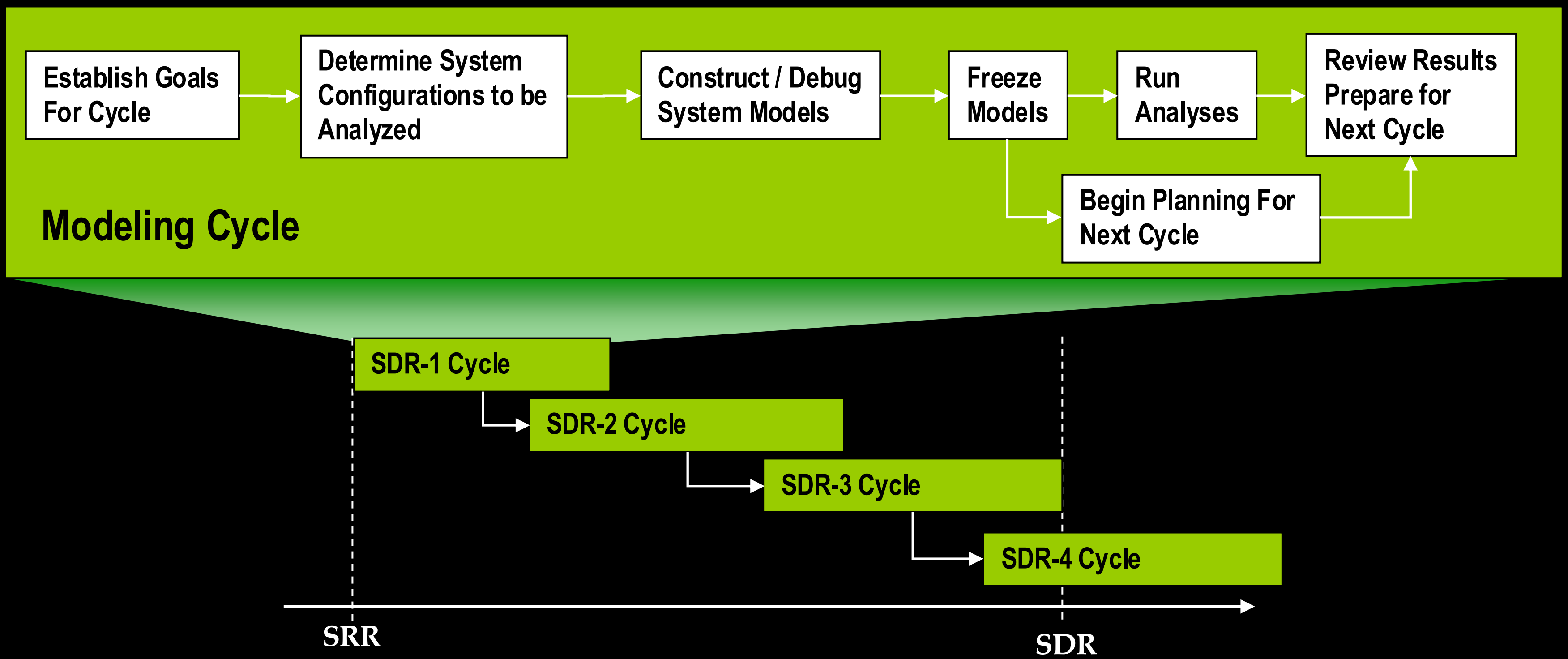
A system of models, interfaces and protocols to predict system performance.

Integrated Modeling System Guidelines



A system of models, interfaces and protocols to predict system performance.

JWST Integrated Modeling Cycles



- **Analytical models are run in cycles (much like the familiar "Load Cycles")**
  - Typically 3 to 4 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**

Technical Performance Parameters

- **Technical Performance Metrics (TPMs) are monitored at various frequencies from once a month to once every 4 months**
  - Mass and power are reported once per month.
  - WFE stability and image motion are products of integrated modeling cycles and are therefore updated at longer intervals.
  - Momentum accumulation parameters and stray light are relatively new issues and have recently been added to the list of TPMs.
- **Reaction limits for many of these TPMs are determined by engineering standards which include GSFC-STD-1000.**
- **MSE assessments of TPMs shown below. Details will be found in the various presentation packages.**

- Mission Level TPMs
  - Sensitivity
  - Efficiency
  - Data Volume / Link Margin
  - Momentum Accumulation Parameters
  - Commissioning Time
  - Strehl, Encircled Energy, OTE WFE
  - Wavefront Error Stability
  - Image Motion
  - Stray Light Levels
  - Cryogenic Thermal Margins
  - Mass Margin
  - Power Margin

TPM	Status
Sensitivity	
Efficiency	
Data Volume / Link	
Momentum	
Commissioning Time	
Strehl, EE, OTE WFE	
WFE Stability	
Image Motion	
Stray Light Levels	
Cryogenic Thermal Margins	
Mass Margin	
Power Margin	

	Acceptanble Margin
	Meets Requirement But With Insufficient Margin
	Does Not Meet Requirements

Technical Performance Metrics (TPMs)

Performance / Resource Parameters	Capability / Requirement	Estimate or Predict 10-21	Post Commissioning 7-2022
Sensitivity Parameters			
NIRCam SI Sensitivity @ 2 microns (nJy)	11.4	9.56	7.30
MIRI SI Sensitivity @ 10 microns (nJy)	700	513	462
Straylight (MJy/ster @ NIR 2 microns)	0.091	0.080	0.060
Straylight (MJy/ster @ NIR 3 microns)	0.07	0.065	0.040
Straylight (MJy/ster @ MIR 10 microns)	3.9	1.66	1.66
Straylight (MJy/ster @ MIR 20 microns)	200	178	178
OTE Transimission* Ap m2 Revised (TBR)	21.5	21.286	22.507
Image Quality Parameters			
Strehl (NIR 2 microns)	0.80	0.856	0.820
Strehl (MIR 5.6 microns)	0.80	0.962	0.962
NIRCam ChannelWavefront Error (nm)	150	126	96
NIRSpec Channel Wavefont Error (nm)	238	168	115
NIRISS Channel Wavefront Error (nm)	180	139	96
MIRI Channel Wavefront Error (nm)	421	174	140
EE Stability at 2 microns Over 24 hours	2.30%	0.41%	0.20%
EE Stability at 2 microns Over 14 days	3.00%	2.40%	0.53%
Image Motion rms for 15 sec Slidinging Window for NIRCam (mas)	6.6	5.7	1.0
Operations Parameters			
Observing Efficiency	70%	78.0%	78.0%
Slew Time for 90 Degree Slew with 5 RWAs (min)	60.0	59.6	50.0
Momentum Accumulation LV1 (Nms/d)	22	16.16	4.30
Momentum Accumulation LV4 (Nms/d)	23	16.44	4.90
Thermal Parameters			
Cryo Parastic Margin (NIRCam)	60%	79.7%	79.7%
Cryo ParasiticMargin (NIRSpec FPA)	60%	76.1%	76.1%
Cryo Parasitic Margin (FGS/NIRISS)	60%	80.4%	80.4%
Cryo-Cooler Line Load Margin (Pinch Point / Steady State)	83%	260%/288%	260%/288%
Cryo-Cooler OM Load Margin (Pinch Point / Steady State)	83%	245%/154%	245%/154%
Data and Link Parameters			
S-Band Uplink Margin (dB)	3.00	6.90	6.90
S-Band Downlink Margin (dB)	3.00	4.40	4.40
Ka-Band Downlink Margin (dB)	3.00	6.41	6.41
Observatory Resources			
Observatory Wet Mass (kg) as of 7-2016	6310	6161	6161
Observatory CG Offset (mm)	Area in DCI	38.0	38.0
Propellant Budget (kg)	300	251	251
Observatory Power Load (W)	1808	1802	1802
Observatory Power Generation (W)		2073	2073
Max Battery Discharge Time (Min)		458	458

All Technical Performance Metrics Predicted to be GREEN

Sensitivity Metrics

Image Quality Metrics. These predictions assume periodic Wave Front Sensing and Control (WFSC) Operations

Key Operational Metrics are those associated with efficiency.

Thermal Performance Metrics

RF Link Margins

Observatory Mass and Power Margins

TPM Tracking

Technical Performance Metrics 2008

Performance / Resource Parameters	Capability / Requirement	Estimate	Comments
Sensitivity			
SI Sensitivity (nJy @ NIR 2 microns)	11.4	1.02	ISIM PDR, Update in work
SI Sensitivity (nJy @ MIR 10 microns)	700	540	ISIM PDR, Update in work
Straylight (MJy/ster @ NIR 2 microns)	0.091	0.077	PDR-1 Integrated Modeling Cycle (08-JWST-0054)
Straylight (MJy/ster @ MIR 10 microns)	3.9	0.013	PDR-1 Integrated Modeling Cycle (08-JWST-0054)
Straylight (MJy/ster @ MIR 20 microns)	200	170	PDR-1 Integrated Modeling Cycle (08-JWST-0054)
OTE Transimission* Aperture (@ 2 microns) m^2	22	23.702	PDR-1 Integrated Modeling Cycle (08-JWST-0053)
Image Quality			
Strehl (NIR 2 microns)	0.80	0.915	PDR-1 Integrated Modeling Cycle (08-JWST-0053), Strehl at 14 days after slew
EE Stability at 2 microns Over 24 hours	2.00%	0.041%	PDR-1 Integrated Modeling Cycle (08-JWST-0053)
EE Stability at 2 microns Over 14 days	2.50%	0.793%	PDR-1 Intengrated Modeling Cycle (08-JWST-0053)
Image Motion (mas)	7.0	5.0	SDR4+ Report (07-JWST-0476) Image Motion predict 5.0 mas
Operations			
Observing Efficiency	70%	78.0%	From "Observation Efficiency Allocations Report JWST-RPT-004166, Revision D", May 2007
Momentum Accumulation LV1 (Nms/d)	22	19	
Momentum Accumulation LV4 (Nms/d)	23	20	
Thermal Margins			
Cryo Radiator Margin (NIRCam)	70% (Goal)	82%	
Cryo Radiator Margin (NIRSpec FPA)	70% (Goal)	96%	
Cryo Radiator Margin (NIRSpec OA)	70% (Goal)	64%	
Cryo Radiator Margin (FGS/TF)	70% (Goal)	78%	
Cryo Radiator Margin (MIRI)	70% (Goal)	112%	
Link Margins			
S-Band Uplink Margin (dB)	3.00	6.80	
S-Band Downlink Margin (dB)	3.00	5.30	
Ka-Band Downlink Margin (dB)	3.00	4.00	
Observatory Resources			
Observatory Wet Mass (kg)	6530	5589	
Observatory Power (W)	1998	1387	

Technical Performance Metrics 2010

Performance / Resource Parameters	Capability / Requirement	Estimate or Predict	Comments
Sensitivity Parameters			
NIRCam Sensitivity @ 2 microns (nJy)	11.4	9.70	Predict from 3-2010 SI TPM Report
MIRI Sensitivity @ 10 microns (nJy)	700	620	Predict from 3-2010 SI TPM Report
Straylight (MJy/ster @ NIR 2 microns)	0.091	0.082	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0118)
Straylight (MJy/ster @ NIR 3 microns)	0.07	0.062	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0118)
Straylight (MJy/ster @ MIR 10 microns)	3.9	0.480	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0118)
Straylight (MJy/ster @ MIR 20 microns)	200	204	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0118)
OTE Transimission* Ap (@ 8 μm) m^2	22	23.542	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0123)
Image Quality Parameters			
Strehl (NIR 2 microns)	0.80	0.847	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0123)
NIRCam Wavefront Error (nm)	150	130	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0114)
NIRSpec Wavefront Error (nm)	238	224	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0114)
TF Wavefront Error (nm)	180	145	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0114)
MIRI Wavefront Error (nm)	421	341	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0114)
EE Stability at 2 microns Over 24 hours	2.00%	1.10%	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0123)
EE Stability at 2 microns Over 14 days	2.50%	1.60%	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0123)
Image Motion (mas)	6.6	4.9	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0123) for NIRCam
Operations Parameters			
Observing Efficiency	70%	77.0%	From "Observation Efficiency Allocations Report JWST-RPT-004166, Revision F"
Slew Time for 90 Degree Slew (min)	60	54.2	CDR+ Integrated Modeling Results 3-15-10 (10-JWST-0119) with 6 RWAs
Momentum Accumulation LV1 (Nms/d)	22	20.4	CDR I
Momentum Accumulation LV4 (Nms/d)	23	20.4	CDR I
Thermal Parameters			
Cryo Radiator Margin (NIRCam)	50%	67.7%	NG C
Cryo Radiator Margin (NIRSpec FPA)	50%	79.0%	NG C
Cryo Radiator Margin (NIRSpec OA)	50%	95.4%	NG C
Cryo Radiator Margin (FGS/TF)	50%	76.2%	NG C
Cryo Radiator Margin (MIRI)	50%	62.3%	NG C
Cryo-Cooler Line Load Margin	58%	28% / 24%	CDR L
Data and Link Parameters			
S-Band Uplink Margin (dB)	3.00	6.70	Advers
S-Band Downlink Margin (dB)	3.00	4.00	Advers
Ka-Band Downlink Margin (dB)	3.00	5.94	Advers
Observatory Resources			
Observatory Wet Mass (kg)	6530	5868	Estim
Observatory Power (W)	1993	1613	Estim

Technical Performance Metrics 2014

Performance / Resource Parameters	Capability / Requirement	Estimate or Predict 4-14	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	0.089	Prediction from 4-7-14 Integrated Modeling Review
Straylight (MJy/ster @ NIR 3 microns)	0.07	0.066	Prediction from 4-7-14 Integrated Modeling Review
Straylight (MJy/ster @ MIR 10 microns)	3.9	0.74	Average of Non-Grey Only Case (12-16-13 AWG) and Worst Case R4 Estimate
Straylight (MJy/ster @ MIR 20 microns)	200	386	Average of Non-Grey Only Case (12-16-13 AWG) and Worst Case R4 Estimate
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	0.840	Strehl at λ = 2.0 μm 4-22-14 Integrated Modeling Review
Strehl (MIR 5.6 microns)	0.80	0.859	Strehl at λ = 5.6 μm computed by M. Menzel for WFE of 347 nm
NIRCam ChannelWavefront Error (nm)	150	131	4-22-14 Integrated Modeling Review
NIRSpec Channel Wavefont Error (nm)	238	220	4-22-14 Integrated Modeling Review
NIRISS Channel Wavefront Error (nm)	180	126	4-22-14 Integrated Modeling Review
MIRI Channel Wavefront Error (nm)	421	226	4-22-14 Integrated Modeling Review
EE Stability at 2 microns Over 24 hours	2.30%	0.80%	4-22-14 Integrated Modeling Review
EE Stability at 2 microns Over 14 days	3.00%	2.00%	4-22-14 Integrated Modeling Review
Image Motion rms for 15 sec Slidinging Window for NIRCam (mas)	6.6	5.4	Prediction from 4-7-14 Integrated Modeling Review
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	18.10	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	18.50	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%	69.1%	Predicts with Liens and Accepted Opportunities per 2014.04.07_Obs_v5.3h2_0R_P5P_v61.xlsx
Cryo ParasiticMargin (NIRSpec FPA)	60%	65.3%	Predicts with Liens and Accepted Opportunities per 2014.04.07_Obs_v5.3h2_0R_P5P_v61.xlsx
Cryo Parasitic Margin (FGS/NIRISS)	60%	58.9%	Predicts with Liens and Accepted Opportunities per 2014.04.07_Obs_v5.3h2_0R_P5P_v61.xlsx
ISIM Cavtity Temperature (K)	41K (TBR)	43.2	Area Average with Liens and Accepted Opportunities per 2014.04.07_Obs_v5.3h2_0R_P5P_v61.xlsx
Cryo-Cooler Line Load Margin (Pinch Point / Steady State)	83%	64%/69%	Cryo-Cooler Predicts from K. Banks and S. Thomson Feb 2014
Cryo-Cooler OM Load Margin (Pinch Point / Steady State)	83%	157%/69%	Cryo-Cooler Predicts from K. Banks and S. Thomson Feb 2014
Data and Link Parameters			
S-Band Uplink Margin (dB)	3.00	5.80	Adverse Margin From 2013.11.01 S-Band Link (SC CDR) .pdf (SC Omni at 2000 bps)
S-Band Downlink Margin (dB)	3.00	3.90	Adverse Margin From 2013.11.01 S-Band Link (SC CDR) .pdf (Both Omni's at L2 at 200 bps)
Ka-Band Downlink Margin (dB)	3.00	4.44	Adverse Margin From 2013.10.31 Ka-band Link (SC CDR).pdf (28 Mbps)
Observatory Resources			
Observatory Wet Mass (kg)	6620	6059	Estimate with Pendings From 4-10-14 Mass Report
Observatory CG Offset (mm)	Area in DCI	18.9	CG uncertainty ellipse to 5 mm margin Ariane Static Unbalance Domain with Pendings (4-10-14)
Observatory Power Load (W)	1808	1510	Estimate + Pendings, 4-10-14 Power Report vs SA at 6 years
Observatory Power Generation (W)		2055	Power Generation at 6 Years, 2-13-14 Power Report
I&T Parameters			
JSC Timeline (Days)	120	88	Partners Workshop Presentation 2-11

Resource and Performance Margins Approach

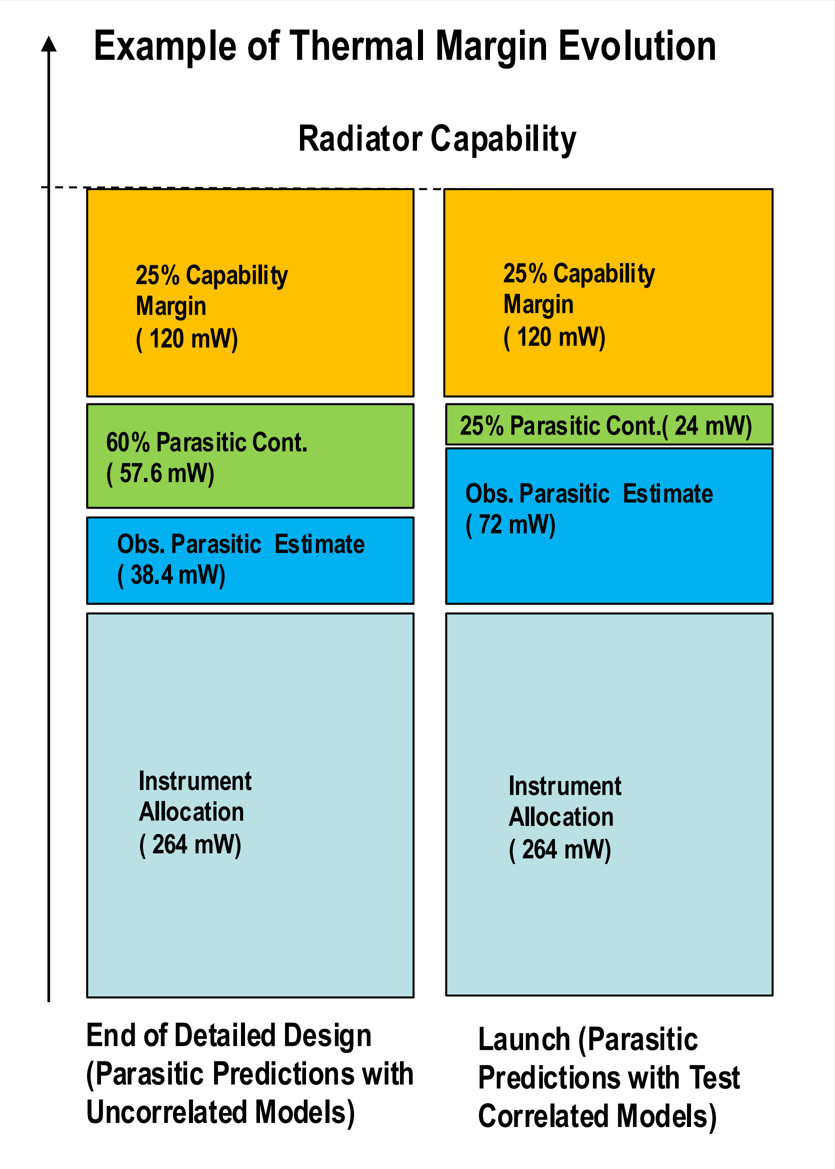
- **Minimum margins for resources are taken from the GSFC-STD-1000, the Golden Rules as a primary source. If guidance is not provided by this source then one of these are used:**
  - Interpolation / extrapolation of Existing Standards
  - Other Standard Aerospace Sources or common industry practice
  - JWST specific risk / uncertainty assessment
- **Table below cites JWST Margin Approach**
  - Margins are defined as (Requirement – Estimate) / (Estimate)
- **Cryogenic Thermal Rejection Margin = $(T^4_{Required} - T^4_{Predicted}) / T^4_{Predicted}$ where T is temperature measured at the cryogenic radiators**

Parameter	Min Margin Required for SDR	Rationale / Source
Mass	22%	Min Required from extrapolation of GSFC-STD-1000, rule 1.06. Uncertainty analysis by M. Menzel yielded a desired margin of 25%
Propellant	100%	Consumable sized for a 10 year mission
Power	25%	GSFC-STD-1000, rule 1.06
Link	3 db	GSFC-STD-1000, rule 1.06
Recorder Margin	100%	Industry practice to allow for one missed ground contact
Min Structural Frequency	15%	Industry Practice
Photometric Sensitivity	10%	MSE preliminary assessment pending studies of stray light based on SAT recommendatons
Wavefront Error	20%	MSE assessment
Cryogenic Thermal Rejection	70%	MSE uncertainty analysis. Margin is in terms of (Radiator Temperature)^4

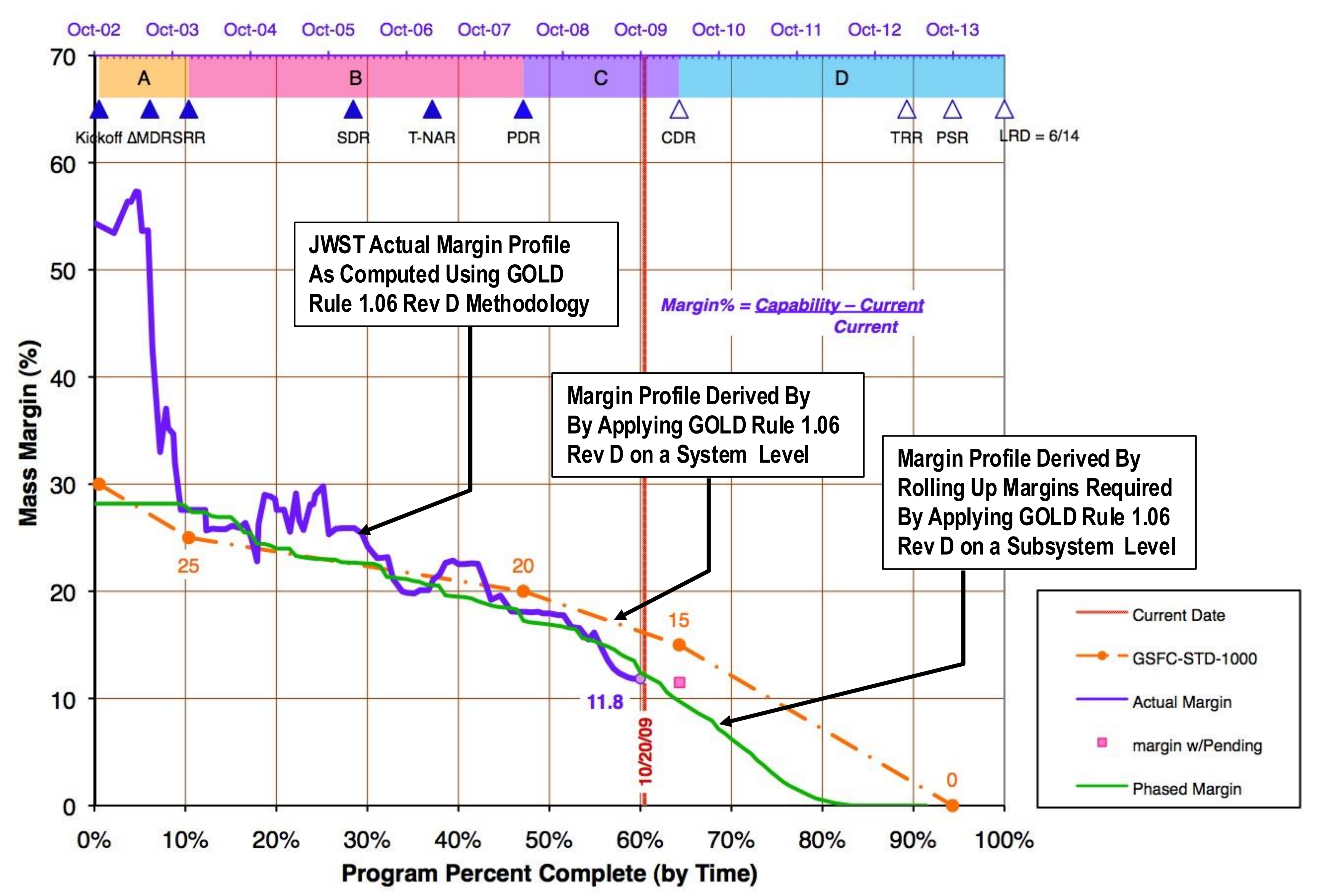
Technical Performance Metrics (TPM) and Margin Management (Cryogenic Margin)

- **Thermal loads are classified as:**
  - Deterministic, such as detector dissipations which are measured to a relatively high precision.
  - Parasitics which are verified by analytic models and are therefore less certain.
- **The key thermal TPM is radiator margin shown at a high level in the formula below. The more rigorous definition described in the back up charts, focuses specifically on radiator capability to provide margin for the more risky parasitic loads.**
- **The margin management plan requires:**
  - 25% margin on heat rejection capability at launch to account for unknown-unknowns.
  - 60% contingency on observatory level parasitics at the end of detailed design phase.
  - 25% contingency on observatory level parasitics at launch.
  - Instrument heat load allocations (which contain the dissipations) are treated as Not to Exceed values at the system level. No additional contingency is applied
  - Margin evolution is illustrated on the right.

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



Modification to Mass Margin Gold Rule



Budgets For Critical Performance and Resources

Baseline Mass Budget

James Webb Space Telescope 12-Mar-15 Description	Part Number	Quantity	Estimated Unit Mass	Estimated Mass	Contingency Percent	Contingency Mass	Predicted Mass
			kg	kg	%	kg	kg
JWST Observatory	327600-1	1	6047.1	6047.1	3.1%	185.5	6232.7
Optical Telescope Element (OTE)	327630	1	2318.0	2318.0	1.5%	34.6	2352.6
P		1	680.3	680.3	0.1%	0.4	680.7
S		1	22.4	22.4	0.5%	0.1	22.6
A		1	104.6	104.6	0.2%	0.2	104.8
P		1	973.2	973.2	0.5%	4.9	978.1
PMBA Hinges, Latches, and Mechanisms	157600	1	47.1	47.1	4.4%	2.1	49.2
SMSS Installation	173880-1	1	83.7	83.7	1.5%	1.2	84.9
Thermal Management Subsystem (TMS)	327682	1	247.3	247.3	8.5%	21.0	268.3
Deployable Tower Assembly (DTA)	D3040170100	1	58.9	58.9	3.5%	2.0	60.9
OTE Electronics		1	78.2	78.2	0.8%	0.7	78.9
IEC Flexures		1	3.1	3.1	4.4%	0.1	3.2
Mechanical Installation Hardware (MIH) - OTE		1	17.3	17.3	9.0%	1.6	18.9
Test & Fly Hardware - OTE		1	0.0	1.7	15.0%	0.3	2.0
Integrated Science Instrument Module (ISIM)	2070500	1	1263.7	1263.7	2.7%	34.4	1298.2
ISIM Region 1		1	913.1	913.1	3.0%	27.6	940.7
ISIM Region 2		1	301.9	301.9	1.5%	4.6	306.5
ISIM Region 3 (within S/C)		1	48.8	48.8	4.5%	2.2	51.0
Spacecraft Element (SCE) - Wet Mass	327627-1	1	2388.2	2388.2	4.8%	113.6	2501.8
Spacecraft (SC) Bus		1	1471.8	1471.8	5.6%	82.6	1554.4
Electrical Power Subsystem (EPS)		1	163.2	163.2	4.2%	6.8	170.0
Deployment Control Subsystem (DCS)		1	11.6	11.6	5.1%	0.6	12.2
Attitude Control Subsystem (ACS)		1	123.8	123.8	2.9%	3.6	127.4
Communications Subsystem (Comm)		1	19.5	19.5	3.8%	0.7	20.2
Command and Data Handling Subsystem (C&DH)		1	38.7	38.7	2.2%	0.8	39.6
Propulsion Subsystem	311420	1	68.6	68.6	11.0%	7.5	76.1
Structure Subsystem (SMS)	165850-1	1	651.0	651.0	3.1%	20.1	671.1
Mechanical Installation Hardware (MIH) - SC		1	23.5	23.5	14.9%	3.5	27.0
Thermal Control Subsystem (TCS)		1	98.8	98.8	9.9%	9.8	108.6
Observatory Wire Harness (OWH)		1	273.2	273.2	10.7%	29.1	302.3
Sunshield	165000 (Seq 114.0)	1	660.8	660.8	4.6%	30.6	691.4
Propellant / Pressurant		1	253.6	253.6	0.0%	0.0	253.6
Test & Fly Hardware - SCE		1	2.1	2.1	15.0%	0.3	2.4
Cryocooler	327648	1	71.1	71.1	3.4%	2.4	73.5
Cryocooler Accommodation		1	5.2	6.1	8.7%	0.5	6.6

Mass Liens / High Probability Threats ("Pendings")

PENDING - OTE Mass Changes

PENDING Item / Description	Date to MCB	Estimated kg	Cont. %	Cont. kg	Predicted kg	Yield %	Yield kg	Δ
Primary Mirror Segment Assembly (PMSA)							0.00	+0.00
								+0.00
								+0.00
Secondary Mirror Assembly (SMA)							0.00	+0.00
								+0.00
								+0.00
Aft Optics Subsystem (AOS)							0.00	+0.00
								+0.00
								+0.00
Primary Mirror (PMBSS)							0.00	+0.00
								+0.00
								+0.00
								+0.0
PMBA Hinges,							+0.36	+0.00
+V3 Wing Lif							-0.26	+0.00
PMBA Hinge							+0.50	+0.00
Additional NEA harness for (8) NEAs	Apr-15	0.10	15%	0.02	0.12	100%	+0.12	+0.00
Secondary Mirror Support Structure (SMSS)							0.00	+0.00
								+0.00
								+0.00
Thermal Management Subsystem (TMS)							0.00	+0.00
								+0.00
								+0.00
Deployable Tower Assembly							0.00	+0.00
								+0.00
								+0.00

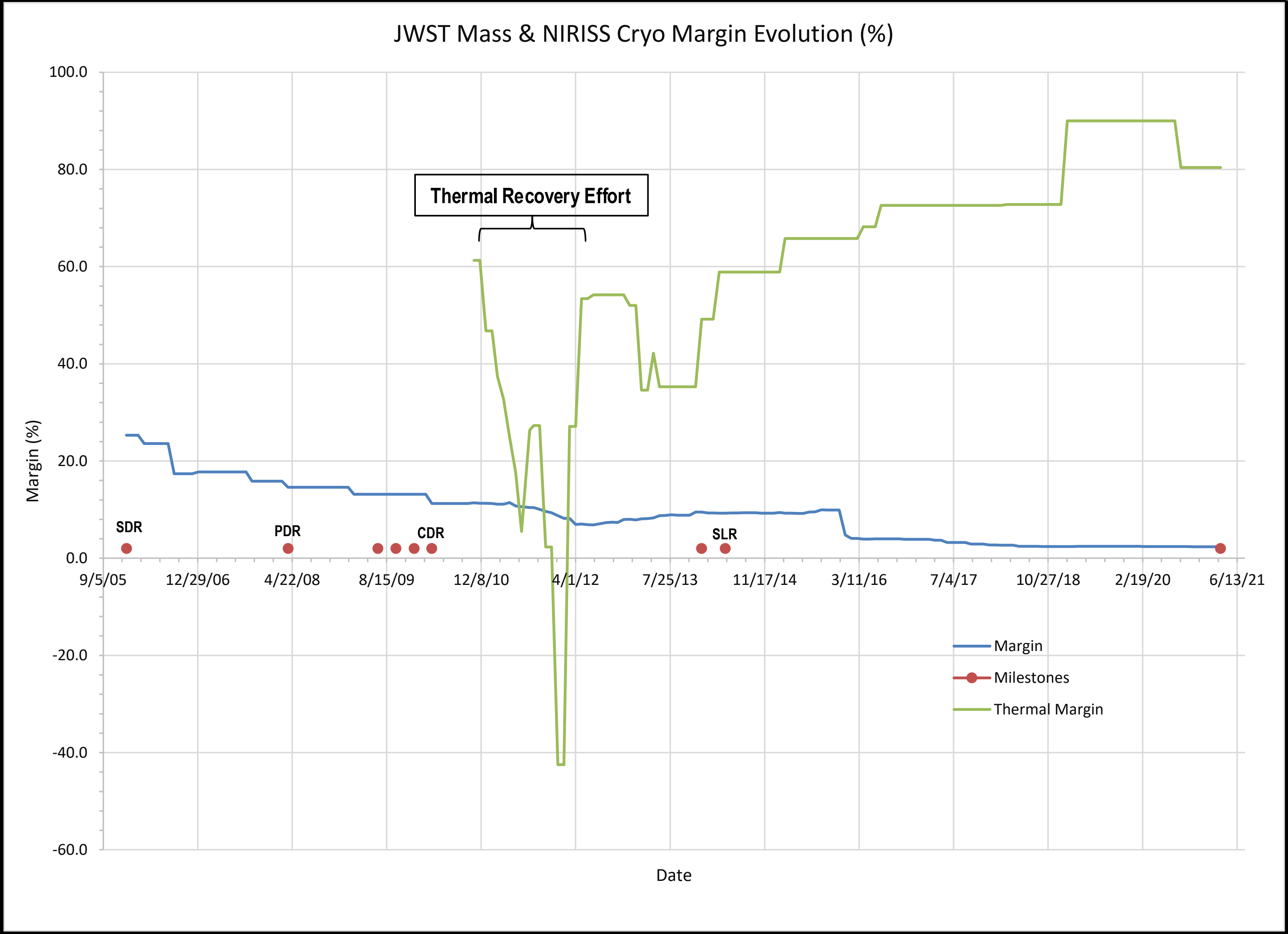
Mass Lower Probability Threats ("Potentials")

POTENTIAL - OTE Mass Changes

POTENTIAL Item / Description	Date to MCB	Estimated kg	Cont. %	Cont. kg	Predicted kg	Yield %	Yield kg
Primary Mirror Segment Assembly (PMSA)							0.00
Secondary Mirror Assembly (SMA)							0.00
Aft Optics Subsystem (AC							0.00
Primary Mirror Backplane							0.00
PMBA Hinges, Latches, ar							0.00
Secondary Mirror Support Structure (SMSS)							0.00
Thermal Management Subsystem (TMS)							+3.95
OTE Interface MLI Requirements, D58353	Aug-15	3.29	20%	0.66	3.95	3.95	+3.95
Deployable Tower Assembly							0.00
OTE Electronics							0.00
IEC Flexures							0.00
Mechanical Installation Hardware (MIH)							0.00
Test and Fly Hardare OTE							0.00
TOTAL POTENTIAL MASS:							+3.95

- **Budgets are frequently used to allocate and compute key performance metrics and resources:**
  - Radiometric Sensitivity / Optical Throughput / Noise and Stray light
  - Wavefront Error
  - Mass / Power / Data
- **In addition to nominal budgets, JWST also tracked the Liens and Threats for many of these.**

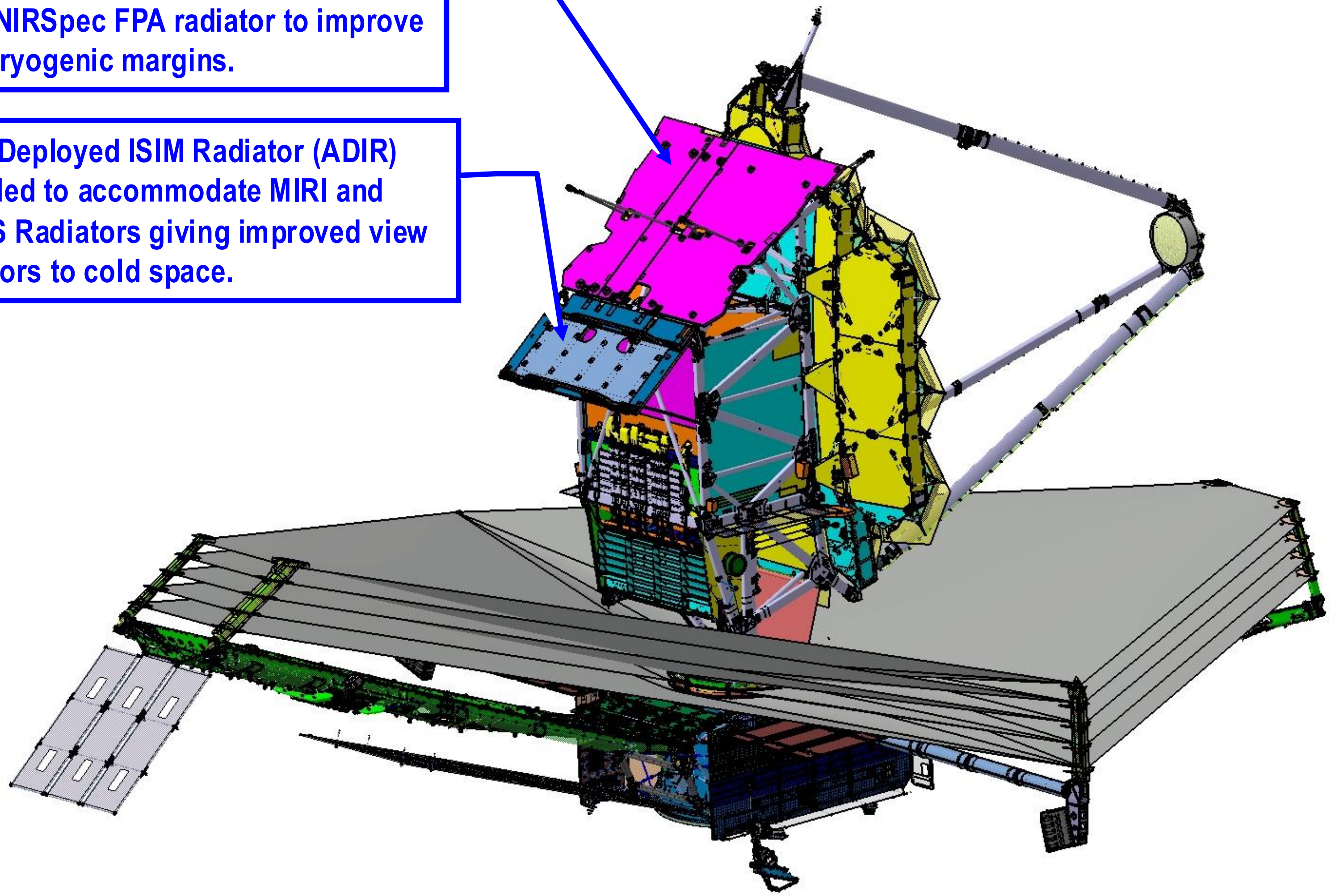
Mass and Thermal Margins



Final Thermal Recovery Solution

Fixed ISIM Radiators modified to "re-balance" area, giving more to the NIRSpec FPA radiator to improve its cryogenic margins.

Aft Deployed ISIM Radiator (ADIR) Added to accommodate MIRI and FGS Radiators giving improved view factors to cold space.



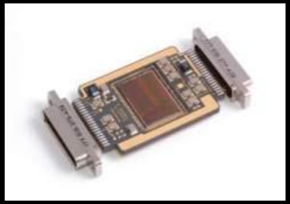
Systems Engineering Functions:

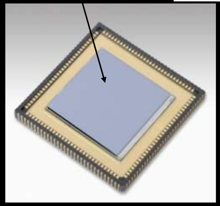
- Technology Development,
- Risk Management and Issue Resolution

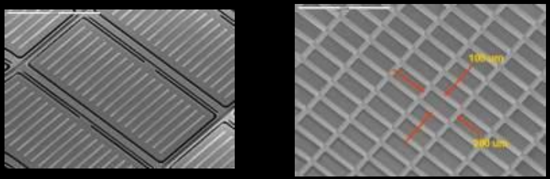
Critical Technology Development Items

- **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.

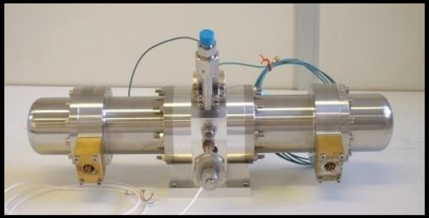

NIR Detector


Cryogenic ASIC


MIR Detector


Microshutter Arrays


Heat Switches


MIR Cryo-Cooler


Wavefront Sensing & Control


Large Cryogenic Composite Structures


Primary Mirror Segment


Sunshield Membrane Material

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

System/Subsystem Development

Technology Demonstration

Technology Development

Research to Prove Feasibility

Basic Technology Research

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)
TRL 7	System prototype demonstration in a space environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 5	Component and/or breadboard validation in relevant environment
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 2	Technology concept and/or application formulated
TRL 1	Basic principles observed and reported

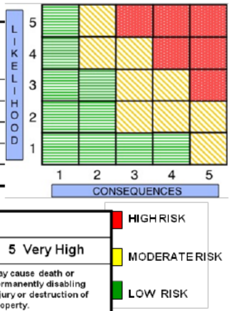
- **NASA Management Handbook requires that mission-enabling technologies reach *TRL 6* before the Project is confirmed**

Risk and Issue Management

- **Systems Engineering is responsible for communicating / informing Project Management of current and impending Risks and Issues. Risks have a formal system. Issue methods are more tailored to the Project. (See figures below).**
- **An Issue is something that is certainly a problem and MUST be solved.**
- **Risk is an uncertainty with a "bad" potential outcome. (Unlike Issues, some Risks can be accepted)**
  - Usually rated in two dimensions (Probability of Occurrence and Consequence) each on a scale of 1 to 5
- **Risks can be categorized as "Technical", "Cost" or "Schedule", and the clear distinction between them is often very blurry. Rating criteria for each are slightly different.**
- **Systems Engineering is a key participant in the Risk Management Process. (Program Management usually chairs the Risk Board)**
- **Risk mitigation plans are formulated to lower high risks to levels acceptable for flight. Plans usually consist of a combination of:**
  - Elimination
  - Transfer
  - Research (Technology Development can fall under this category)
  - Acceptance

GSFC Risk Matrix Standard Scale

Likelihood	Safety (Estimated likelihood of safety event occurrence)	Technical (Estimated likelihood of not meeting performance requirements)	Cost/Schedule (Estimated likelihood of not meeting cost or schedule commitment)
5 Very High	$(P_{SE} > 10^{-1})$	$(P_T > 50\%)$	$(P_{CS} > 75\%)$
4 High	$(10^{-2} < P_{SE} \leq 10^{-1})$	$(25\% < P_T \leq 50\%)$	$(50\% < P_{CS} \leq 75\%)$
3 Moderate	$(10^{-3} < P_{SE} \leq 10^{-2})$	$(15\% < P_T \leq 25\%)$	$(25\% < P_{CS} \leq 50\%)$
2 Low	$(10^{-5} < P_{SE} \leq 10^{-3})$	$(2\% < P_T \leq 15\%)$	$(10\% < P_{CS} \leq 25\%)$
1 Very Low	$(10^{-6} < P_{SE} \leq 10^{-5})$	$(0.1\% < P_T \leq 2\%)$	$(2\% < P_{CS} \leq 10\%)$



Consequence Categories

Risk	1 Very Low	2 Low	3 Moderate	4 High	5 Very High
Safety	Negligible or No impact.	Could cause the need for only minor first aid treatment.	May cause minor injury or occupational illness or minor property damage.	May cause severe injury or occupational illness or major property damage.	May cause death or permanently disabling injury or destruction of property.
Technical	No impact to full mission success criteria	Minor impact to full mission success criteria	Moderate impact to full mission success criteria. Minimum mission success criteria is achievable with margin	Major impact to full mission success criteria. Minimum mission success criteria is achievable	Minimum mission success criteria is not achievable
Schedule	Negligible or no schedule impact	Minor impact to schedule milestones; accommodates within reserves; no impact to critical path	Impact to schedule milestones; accommodates within reserves; moderate impact to critical path	Major impact to schedule milestones; major impact to critical path	Cannot meet schedule and program milestones
Cost	<2% increase over allocated and negligible impact on reserve	Between 2% and 5% increase over allocated and can handle with reserve	Between 5% and 7% increase over allocated and can not handle with reserve	Between 7% and 10% increase over allocated, and/or exceeds proper reserves	>10% increase over allocated, and/or can't handle with reserves

Code 300
GPR 7120.4D

Mission Systems Watch List (May 2010)

High Priority

- **Region 1 Thermal Dissipation (08-JWST-0365AI)**
  - NGST/GSFC model correlation (Core and 1/3 Scale Sunshield)
  - ASIC Thermal Dissipation
  - Thermal Liens List
- **Cryo-Cooler Pinch Point Margin, NG Line Loads**
  - Observatory Line Load Margins
- **Mass Margins (3/15/10 Mass Report)**
- **Verification**
  - Model Validation (Model Validation Peer Review Liens, 2-10-10)
  - JSC Jitter performance
  - JSC Timeline (10-JWST-0055)
- **Sine Vibe Test Levels vs LV Observed Load Levels (09-JWST-0391A)**
- **LV Ascent Thermal Issues**
  - Fixed Roll Predicts (09-JWST-0306I)
  - Post Cure (10-JWST-0305C)

Red Font indicates a degraded change in status
Blue font indicates an improved change in status

Medium Priority

- **Stray Light Levels (CDR+ IM Cycle Results)**
- **Observatory Deployment GSE (08-JWST-0101A, Top Ten 5/1/08)**
  - DTA Deployment
- **WFE and Alignment Margins (09-JWST-0047A)**
  - Liens and Threats List
- **OTE Stability**
  - CDR+ IM Cycle results (09-JWST-0380)
  - Independent GSFC STOP Analysis
- **Venting of IEC onto the Sunshield**
- **IEC Conformal Shield Design Integration**
- **Observatory Jitter performance degradation (**Trade Close Out 2-8-10)

Lower Priority

- **Sunshield Deployment Validation / Verification, Sunshield CDR Lien**
- **Sunshield Membrane Shape vs Thermal Sensitivity**
- **Recent finding of negative margins of the Backplane Cryo-Margins for "Bonded Joints"**
- **Sunshield Light-Line Tolerance**
- **MRE-1 Vapor Lock (SCE Re-Assessment Review**
- **NIRSpec POM Contamination Levels (Contamination Peer Review 2-2-10)**
- **Cryo Transition Harness Thermal Conductivities**
- **Launch Shock Verification Issues**
- **DTA Charging**
- **Composite Glow**
- **MIMF WFSC (Mission CDR Presentation**
- **Observatory Stowed Lateral Frequency Margins**

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Mission Systems Watch List

May 2010

High Priority

- Region 1 Thermal Dissipation (08-JWST-0365AI)
  - NGST/GSFC model correlation (Core and 1/3 Scale
  - ASIC Therma
  - Thermal Lien
- Cryo-Cooler Pi Line Loads
  - Observatory L
- Mass Margins (
- Verification
  - Model Valida Peer Review
  - JSC Jitter p
  - JSC Timeline
- Sine Vibe Test L Load Levels (09
- LV Ascent Ther
  - Fixed Roll Pr
  - Post Cure (1

Medium Priority

- Stray Light Levels (CDR+ IM Cycle Results)
- Observatory Deployment GSE (08

Lower Priority

- Sunshield Deployment Validation / Verification, Sunshield CDR Lien
- Sunshield Membrane Shape vs Thermal

August 2019

High Priority

- Verification
  - Observatory Deployment Test (MGSE Off-Loading, Seismic risks)
    - Overhead Deployment System Issues (Top Issues Meeting 5-16-19)
  - Observatory Sine for Ariane. (OTE
- Depressurization Issues Meeting 7-

Medium Priority

- Observatory Stray Light Levels
  - Threats List (TPM Report)
- Sunshield Deployment Test Concerns
  - Membrane Cable Management Status

Lower Priority

- Alignment Margins.
- Critical Clearances and Inspections (AWG 4-18-19)
  - Soft structure clearances

February 2021

High Priority

- Verification
  - Observatory Deployment Test (MGSE Off-Loading, Seismic risks)
- S-Band Transponder Anomalies (Top Issues Meeting 2-4-21)

Medium Priority

- Observatory Stray Light Levels (AWG 8-3-20)
- 1/8" NEA Anomaly (Top Issues Meeting 10-29-20)
- Verification Burn Up Plan (AWG 116-21)

Lower Priority

- Alignment Margins.
- Critical Clearances and Inspections (AWG 1-25-21)
- LV Ascent Thermal Issues (SAO Report 1-14-21)

June 2021

High Priority

- Verification
  - Observatory Deployment Test (MGSE Off-Loading, Seismic risks)

Medium Priority

- Verification Burn Up (NG PMR 6-23-21)

Lower Priority

- Alignment Margins.
- Critical Clearances and Inspections (AWG 5-24-21)
- SS Motor Temp Peculiarity
  - Thermal Analysis / Ops planning pending
- Water Migration During Commissioning (AWG 12-17-20)
- Sunshield Wind Motor Failure (NGAS FRB 10-4-19)
- Observatory Stray Light Levels (AWG 8-3-20)

Red Font indicates a degraded change in status
Blue font indicates an improved change in status

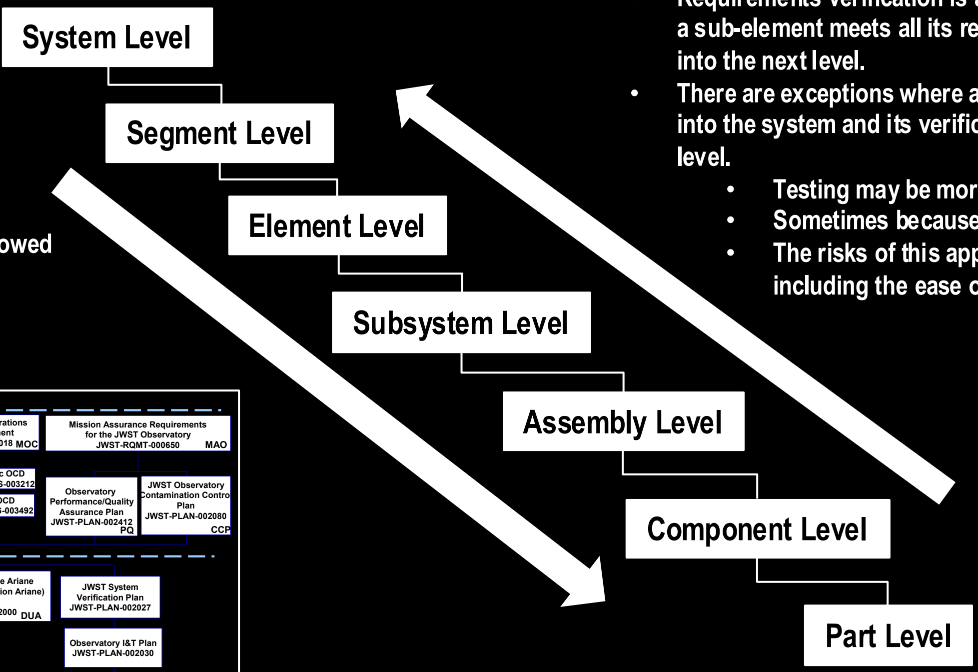
Systems Engineering Functions:

- Verification

Verification: Bottoms-Up Process

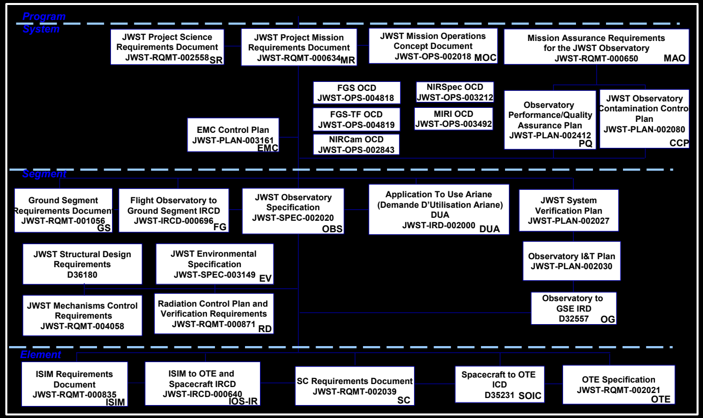
- Verification is the process that determines the "As-Built System" meets requirements and is ready to be deployed (Flight-Worthy)
- Verification is a "Bottom-Up" process. Verification of low level "child" requirements occurs first so that the part can proceed to the next level of integration. (Uses the requirements traceability as the "Trail of Breadcrumbs")

System Integration Levels



- Requirements verification is a bottoms up process that proves a sub-element meets all its requirements before it is integrated into the next level.
- There are exceptions where a sub-element may be integrated into the system and its verification performed at the higher level.
  - Testing may be more decisive at higher level
  - Sometimes because interface behavior is a driver
  - The risks of this approach must be considered, including the ease of de-integration.

- Requirements are decomposed and flowed the various levels of integration.
- Spec Trees are organized accordingly



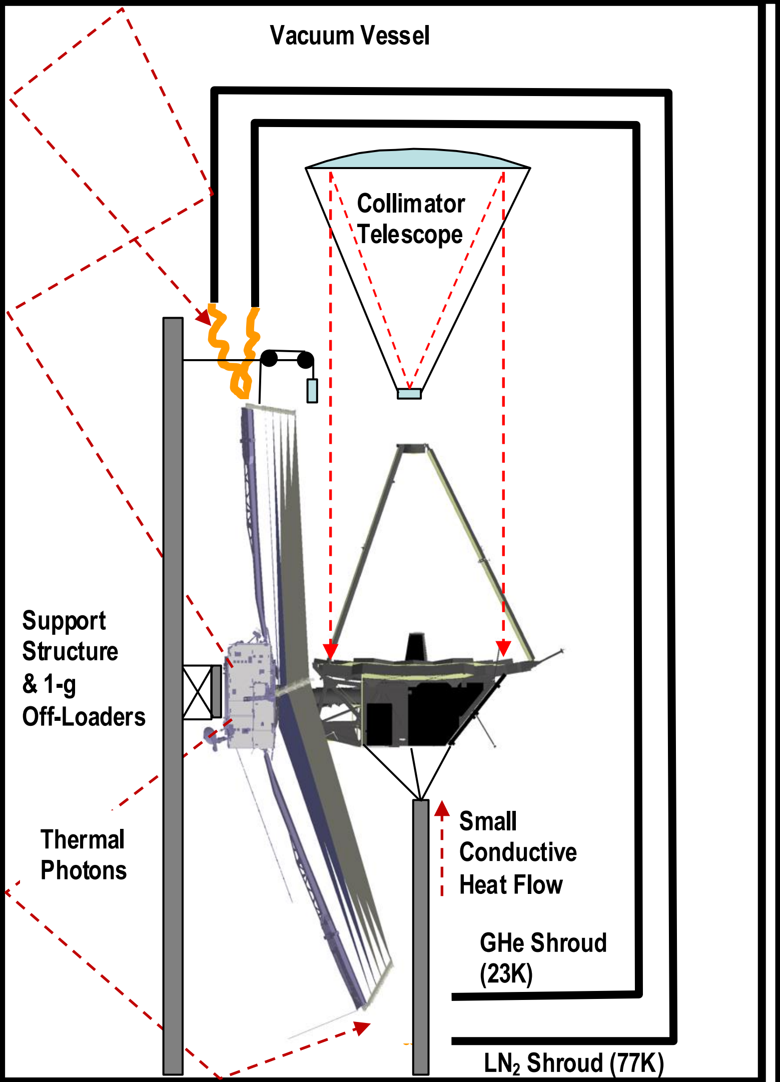
Verification Methods

- **Traditional verification methods: Test (T), Demonstration (D), Analyses (A), Inspection (I) Similarity (S).**
  - Test (aka Test as You Fly) is usually the most reliable method. But for complex systems test as you fly may be either impractical or introduce more uncertainty than analysis.
  - For these cases, a combination of Test and Analysis is employed:
    - Tests to ensure that the Analytical Models used for verification accurately depict the As-Built Hardware (HW) within the assumed uncertainties.
    - Analyses that analyze the system under predetermined flight conditions (Some set of nominal and or bounding cases)
    - Workmanship Tests that prove the system is put together correctly and within tolerances assumed by the analyses.
    - See following chart as an example.
- **Different types of requirements are usually handled with different methods or a combination of them. The most common combinations are shown in the table below.**
  - The documentation of these methods and their exact implementation is usually described in a Verification Plan and Verification Traceability Matrices

Requirement Type	Verification Method				
	T	A	I	D	S
Functional	X			X	
Performance	X	X	X		
Interface Requirements	X	X	X	X	X
Environmental Survivability	X	X			
Mechanical Tolerances / Alignment	X		X		
Lifetime	X	X			
Operational	X			X	

Verification of JWST by Systems Test

- **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 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 By Analysis

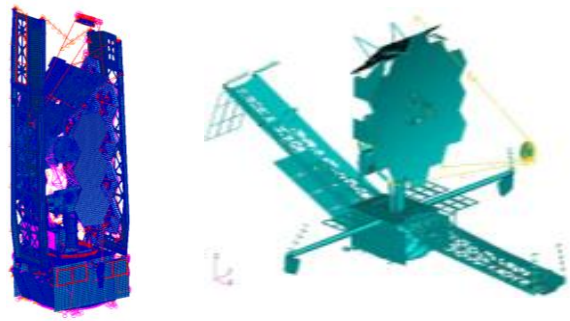
Optical Telescope Element
Test Configuration

Spacecraft Element
Test Configuration

- Testing at the OTE, ISIM, Sunshield and Spacecraft Bus levels are used to correlate / validate lower level analytical models.
- These lower level models are integrated into observatory models.
- Observatory analytical models are used to verify performance.

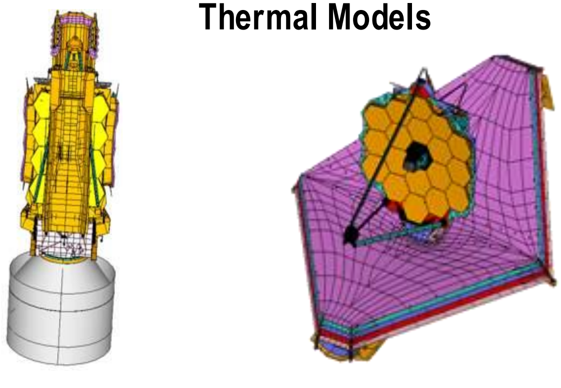
NOTE: Analyses cannot verify workmanship. Testing and or Inspections must be included along with Analyses.

Structural Dynamics Models



Stowed Deployed

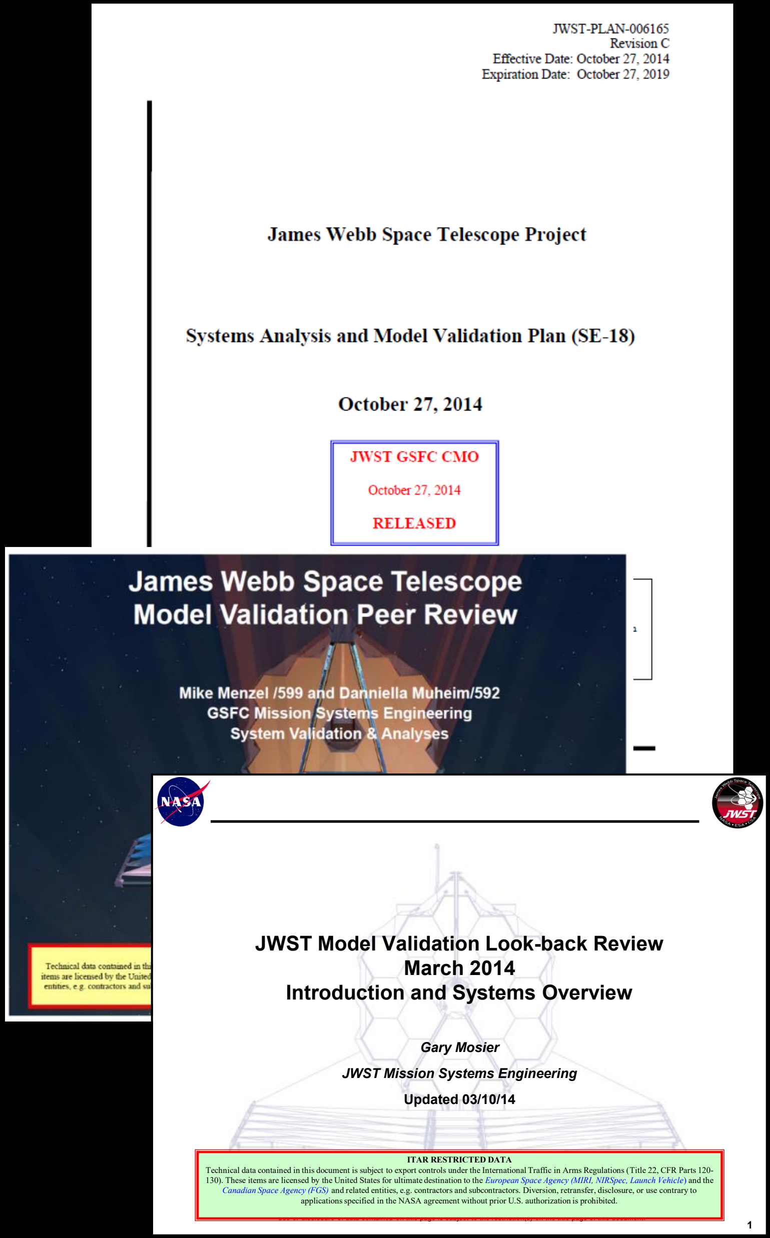
Thermal Models



Stowed Deployed

Model Validation

- **The system models must accurately represent what is being designed and what has been built.**
  - Small differences can matter.
  - Thermal blanket and stray light shield placement had significant consequences for JWST.
- **The validation / correlation of the systems models was planned in detailed and documented in a Systems Analysis and Model Validation Plan.**
  - Contents shown on the next chart
- **These plans were peer reviewed several times by independent experts.**
- **Before each major modeling cycle a Configuration Review was held to compare the model to the design.**



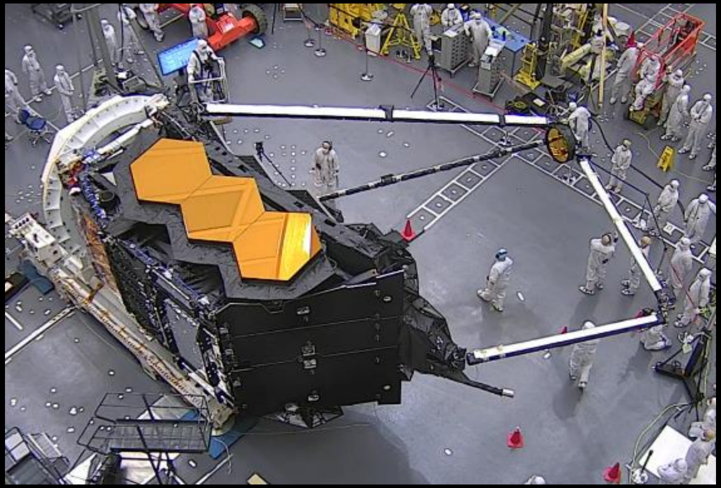
Deployment Testing

- **Large deployment tests are themselves challenging engineering efforts:**
  - Gravity Off-Loading with varying configurations
  - Wear and Tear on Flight Hardware
- **It should be realized that many of the most critical deployment tests were NOT to verify alignment or performance but to verify workmanship.**

Telescope Wing Deployment Test

Sunshield Folding Operations

Telescope Secondary Mirror Deployment Test

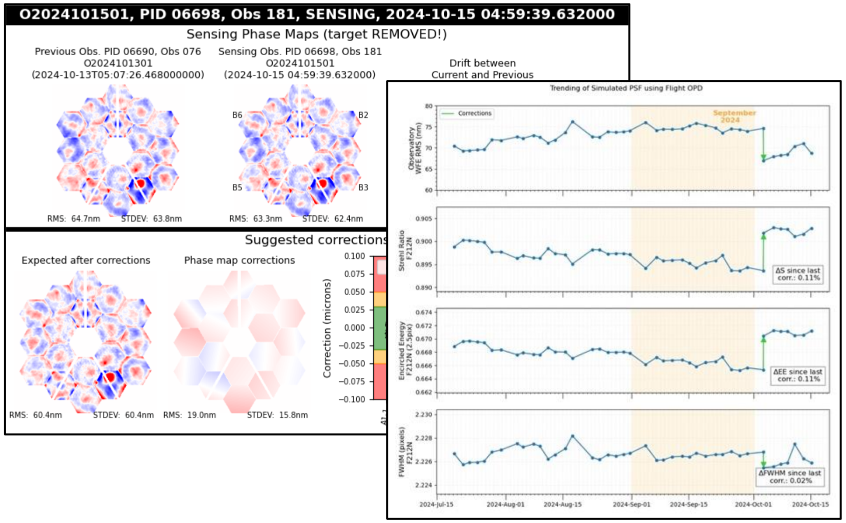


Systems Engineering Functions:

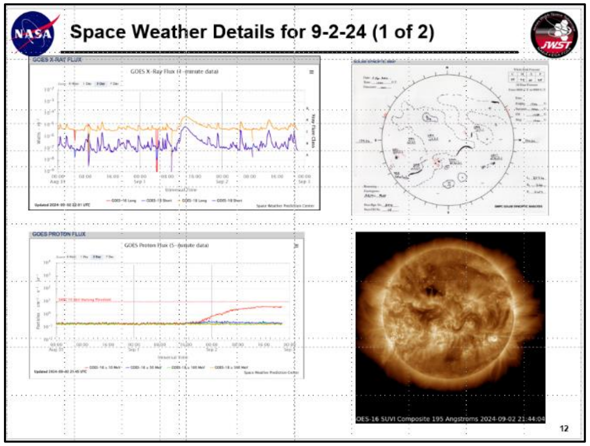
- Commissioning / Operations

Operations

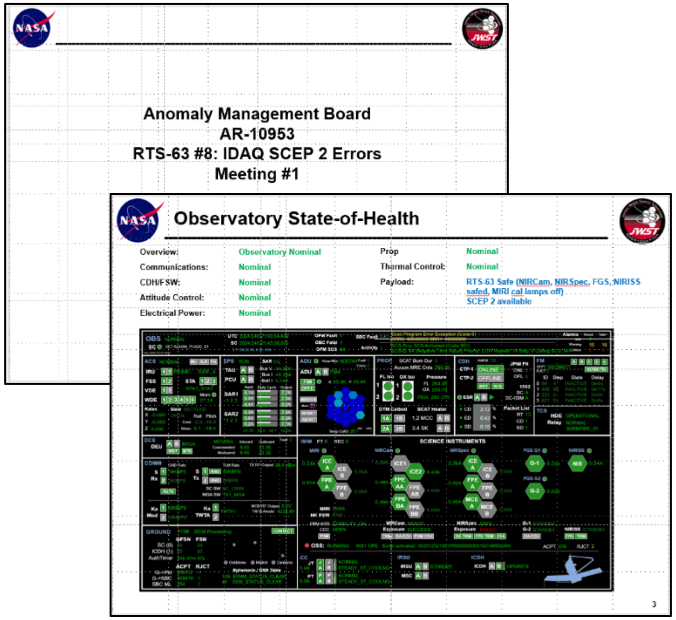
Trending Performance



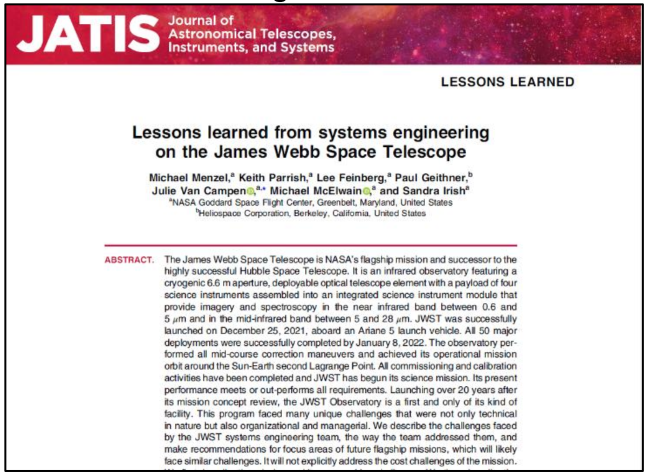
Monitoring Environments



Anomaly Resolution



Documenting Lessons Learned



JATIS Journal of Astronomical Telescopes, Instruments, and Systems

LESSONS LEARNED

Lessons learned from systems engineering on the James Webb Space Telescope

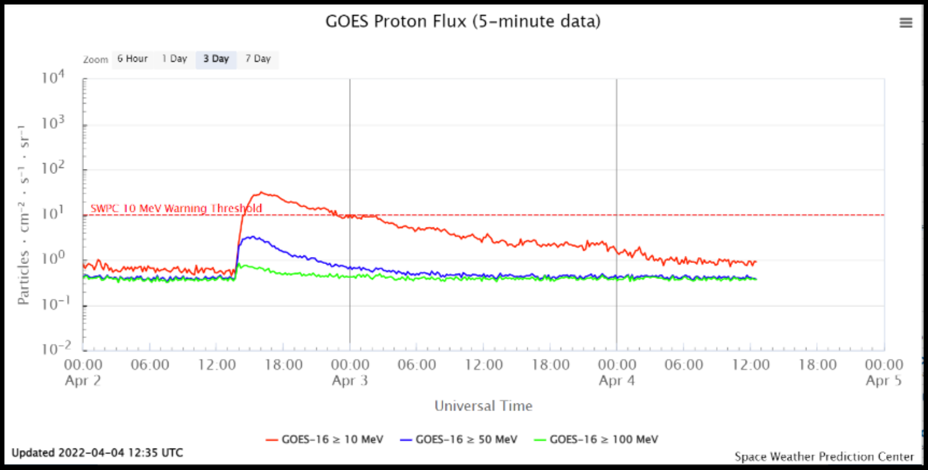
Michael Menzel,[a] Keith Parrish,[a] Lee Feinberg,[a] Paul Geithner,[b] Julie Van Campen,[a,*] Michael McElwain,[a] and Sandra Irish[a]
[a]NASA Goddard Space Flight Center, Greenbelt, Maryland, United States
[b]Heliospace Corporation, Berkeley, California, United States

ABSTRACT. The James Webb Space Telescope is NASA's flagship mission and successor to the highly successful Hubble Space Telescope. It is an infrared observatory featuring a cryogenic 6.6 m aperture, deployable optical telescope element with a payload of four science instruments assembled into an integrated science instrument module that provide imagery and spectroscopy in the near infrared band between 0.6 and 5 μm and in the mid-infrared band between 5 and 28 μm. JWST was successfully launched on December 25, 2021, aboard an Ariane 5 launch vehicle. All 50 major deployments were successfully completed by January 8, 2022. The observatory performed all mid-course correction maneuvers and achieved its operational mission orbit around the Sun-Earth second Lagrange Point. All commissioning and calibration activities have been completed and JWST has begun its science mission. Its present performance meets or out-performs all requirements. Launching over 20 years after its mission concept review, the JWST Observatory is a first and only of its kind of facility. This program faced many unique challenges that were not only technical in nature but also organizational and managerial. We describe the challenges faced by the JWST systems engineering team, the way the team addressed them, and make recommendations for focus areas of future flagship missions, which will likely face similar challenges. It will not explicitly address the cost challenges of the mission.

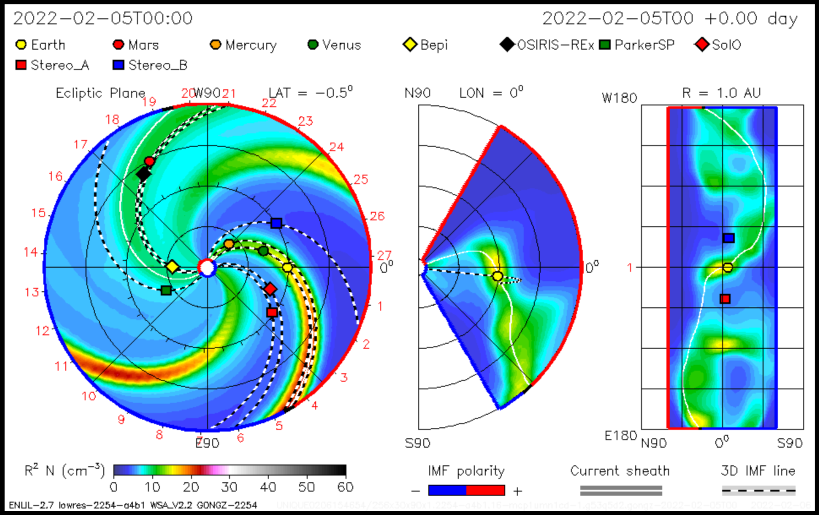
JWST Environments

- JWST has been in space for 1521 days
- Has as completed ~ 8.5 complete orbits around L2
- Has experienced the full variety of anticipated "typical" operational environments during commissioning:
  - Radiation Environments (Galactic /
  - Solar Proton Events (Upper Right)
  - Solar Flares (Lower Right)
  - Coronal Mass Ejections (Lower Left)
  - Geotail / Geomagnetic Substorms
  - Full Range of Micro-Meteoroid Environments

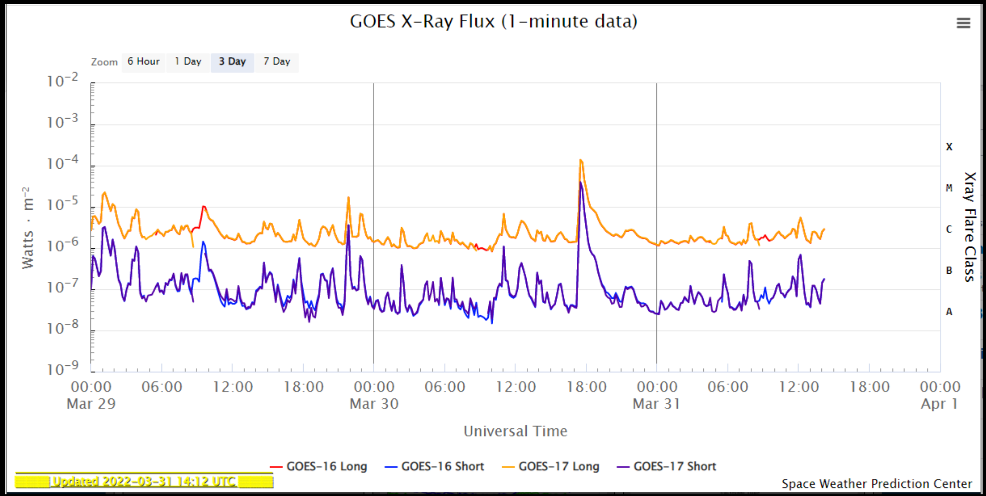
High Proton Flux on 4-2-22



Coronal Mass Ejections

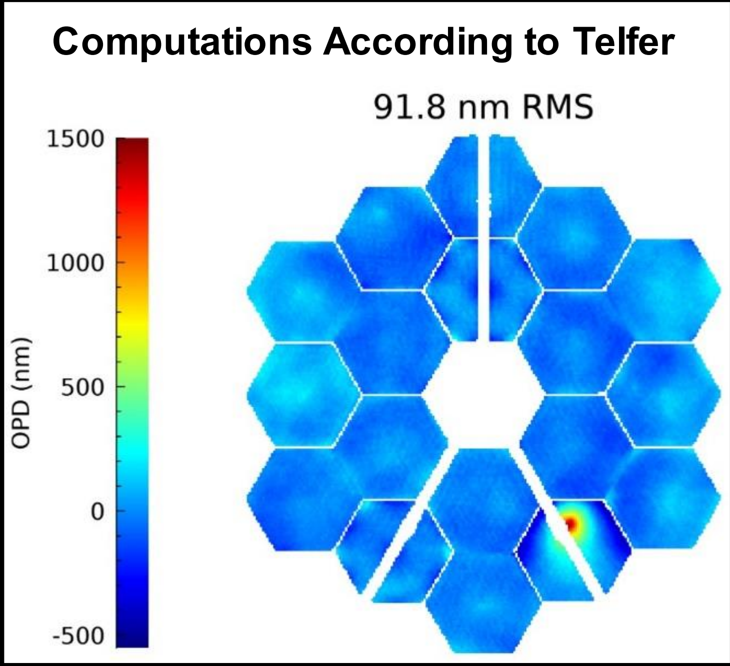


X1 Flare on 3-31-22



Primary Mirror Micro-Meteoroid Events

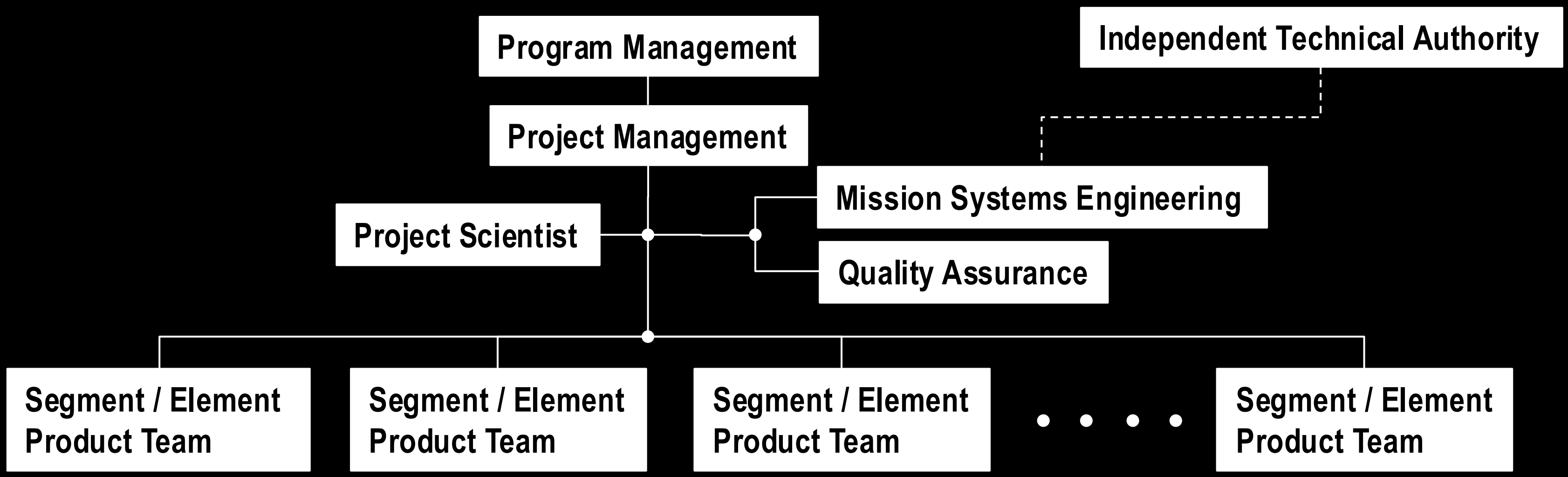
- **The cumulative WFE to date excluding the May 2022 event has been about 1 nm of WFE.**
- **As of February 2026 there have been 116 micro-meteoroid events that resulted in a measurable WFE on the Primary Mirror.**
  - The average rate of events is 2.6 events per month.
  - The histogram on the upper right shows the events counts.
- **With exception of an event that occurred in May 2022, all events have produced minor WFE,**
  - Total WFE contribution at the system level has been ~1 nm for these MM events.
  - Most of the resulting WFE's have been correctable.
  - Pre-launch allocation for MM induced WFE was 31 nm at 5.5 year life.



- **An impact was recorded on Segment C3 in the period between 5-22-22 and 5-24-22 that was significant.**
  - WFE map following impact shown on the upper right.
  - Change in Static WFE of the NIRCam-OTE was ~ 20 nm before correction.
  - A substantial portion of this WFE was correctable, but because of location on the C3 segment, a portion was uncorrectable.
  - After the full corrections, the system level WFE was reduced to ~ 9 nm.
- **Excluding the May 2022 event, analysis estimated that the measurable impacts correlate with MM lower threshold energies between 0.88J and 1.03J.**

Systems Engineering Organization and Planning

Systems Engineering in a Flagship Organization



- Systems Engineering (SE) is part <u>Product Team</u> in as much as their specific deliverables, (Specifications, IRDs, ICDs, Review Packages, Reports etc)
- It is also the <u>Technical Conscience of the Project</u>. As such it must have scope / responsibilities different from those of classical project teams.
- To execute these activities SE should be the <u>Technical Arm of Project Management</u>, but with the correct level of independence to fulfil role Independent Technical Authority.
- SE must have visibility into the technical efforts of the product teams. (Note: Not the ability to direct that is usually allocated to the COTRs / PM but the ability to monitor critical development activities sufficient to assess their risks or potential issues.)

Systems Engineering Organization

Lead Systems Engineer
Deputy
Admin

User Community Adviser

Engineering Review Board

Risk Manager

Configuration Control Manager

Mission Assurance
- Failure Modes and Effects
- Reliability
- Safety

Product Systems Engineering

- Segment 1 Systems Engineer
- • • • •
- Segment N Systems Engineer

Process Systems Engineering

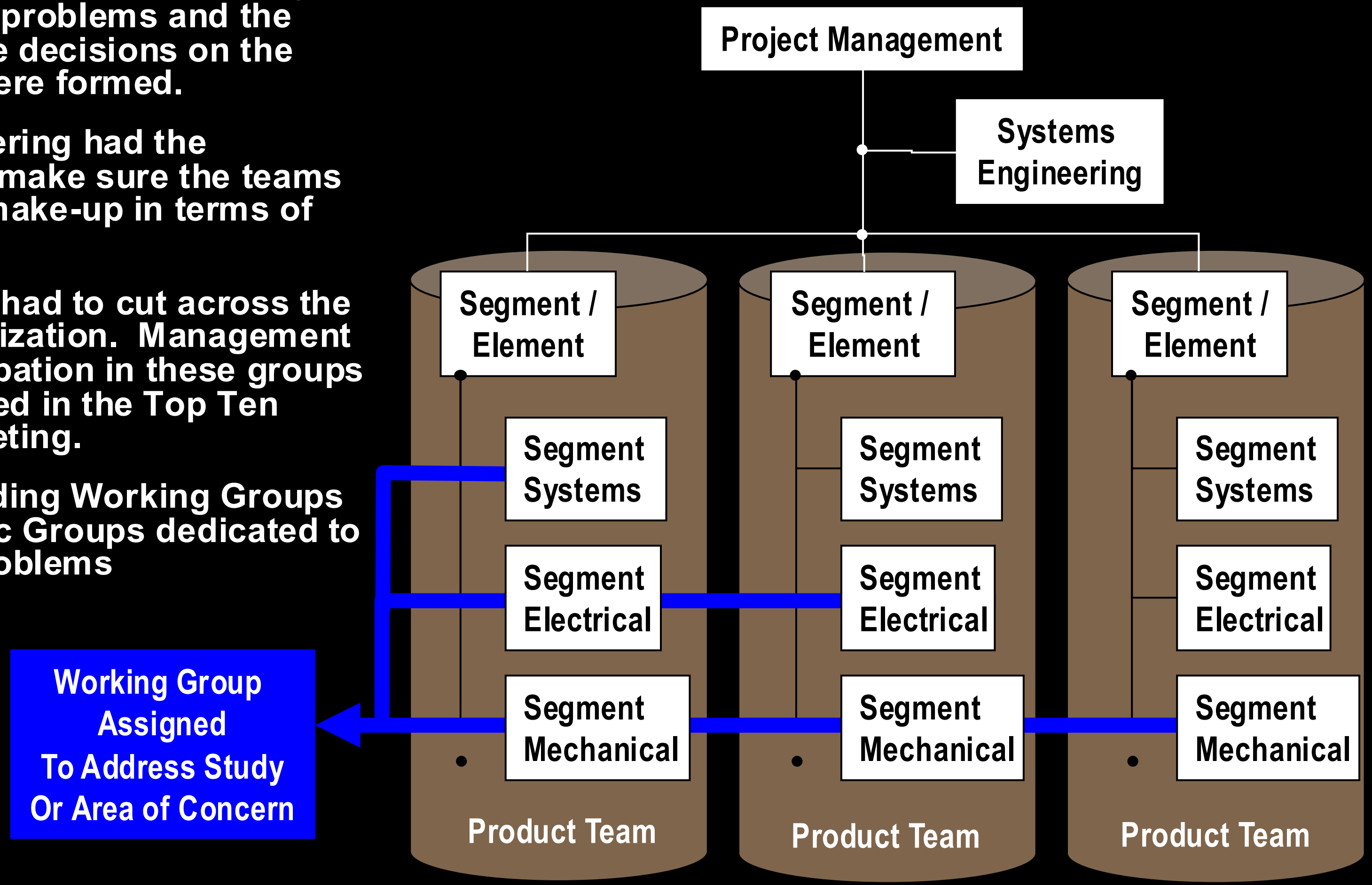
Process SE's
- Technology Development
- I&T
- Verification
- Requirements
- Critical Events
- Analytical Modeling
- Fault Management
- Contamination

Discipline Systems Engineering

Discipline SE's
- Mechanical
- Electrical
- Thermal
- Software
- Control Engineering
- Flight Dynamics
- Propulsion

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.
- There were Standing Working Groups as well as Ad Hoc Groups dedicated to solve specific problems



Systems Engineering Management Plan (SEMP)

- **Plans should generally address what needs to be done, when it needs to be done, how is it going to be done and what is needed to get it done.**
  - JWST SEMP contents shown on the right.

- **Therefore, a Systems Engineering Management Plan (SEMP) should address the following:**
  1. What tasks need to be done, and when they need to be done. (The SE functions already described)
     - The need dates should flow from the Integrated Master Schedule (IMS) of the Project
     - The products generated by these tasks (Reviews, Reports, Analyses etc.)
  2. The Systems Organization that will perform the tasks.
     - Organization chart, roles and responsibilities
     - Work Groups
     - Organizational interfaces to groups outside systems
     - Governance between external groups
  3. Resources necessary for SE to accomplish the tasks.
     - Funding profiles and labor skills
     - Necessary contracts
     - Facilities
  4. SE Methods and Tools that will be used.
     1. Applicable SE Standards and their tailoring, waivers and deviations
     2. Communication channels
     3. Issue resolution and adjudication methods
     4. Risk Management
     5. SE Tools

JWST Systems Engineering Management Plan JWST-PLAN-000872
Revision A

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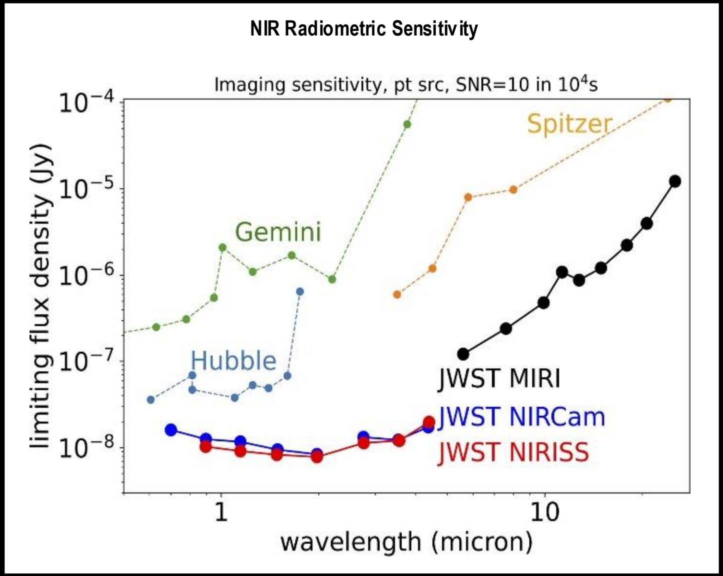
JWST Systems Engineering Management Plan JWST-PLAN-000872
Revision A

Summary

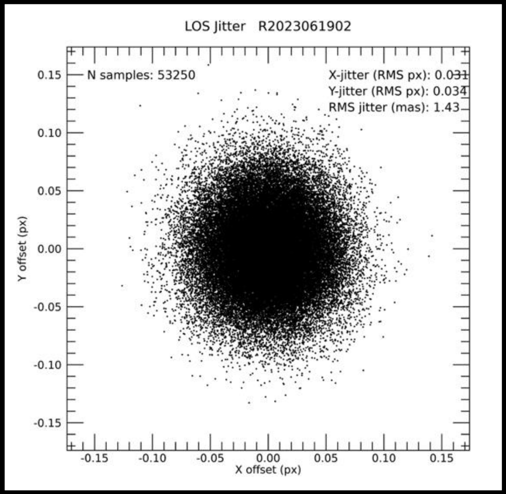
Science Performance: JWST is Exceeding all Performance Requirements

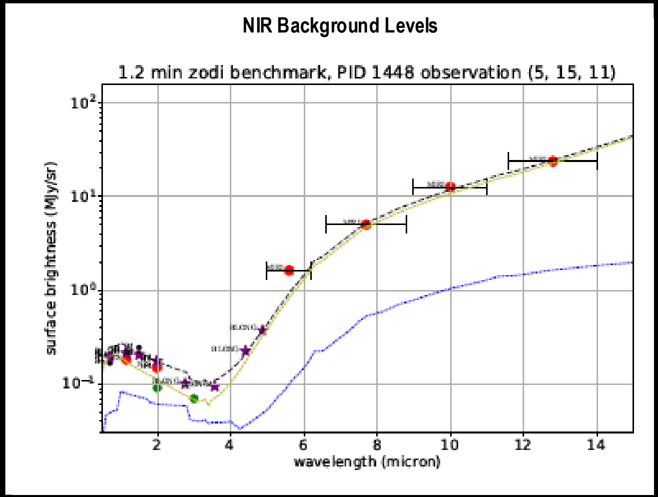
- **Radiometric Sensitivities, quantified by limiting flux density are at or better than pre-launch predictions. (Upper Right)**
- **Backgrounds: NIR and MIR backgrounds are below pre-launch predictions. (Lower Right)**
- **Image Quality: The max WFE of the observatory for December 2023 was 72 nm, versus a required WFE of 150 nm. Optical quality is ~2 times better than required.**
  - The observatory is diffraction limited at a wavelength of 1 μm versus its requirements for diffraction limited performance at 2 μm.
- **Line of Sight Stability is 0.001 arcsec versus allocation of 0.007 arcsec. (Bottom Center)**
- **All OTE temperatures and ISIM temperatures are within their specified levels. (Lower Left)**



Detector Temperature Temperatures

Instrument	Flight (K)	Target (K)
NIRSpec OA	35.57	35.5
NIRSpec FPA	42.80	42.8
FGS	38.48	38.5
NIRCam	38.52	38.5
MIRI	6.03	6.0
Cooler Load	Measured 119 mW	Predicted 118 mW

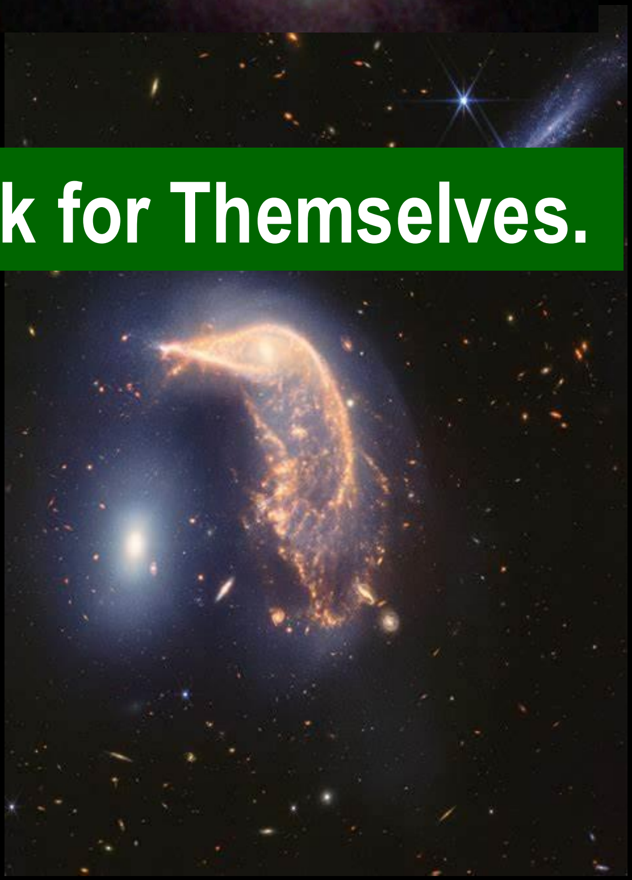




Summary

- **When a mission is successful, it is usually not apparent that SE was necessary. But when if it fails, the lack of proper SE can be very apparent.**
- **JWST can serve as a case study of how Systems Engineering (SE) was applied to a successful “First and Only of its Kind” space system.**
- **Traditional SE methods were applied and tailored to be as efficient and effective as possible.**
  - Resource limitations (manpower, funding etc.) had to be considered and respected.
- **JWST SE concentrated on timely identification of problems via rigorous performance monitoring and issue / risk tracking.**
  - An SE team with experience in the various system elements is a must.
  - SE had to proactively look for problems.
- **Addressing many of the more unique problems on JWST required some specific tailoring of SE processes and SE organization:**
  - Effective communication to decision makers with the data necessary to make decisions.
  - A highly “integrated system” (one with less than clean interfaces) requires organization structure that can avoid unnecessary stove-piping.
  - Effective systems modeling for trades, design, issue resolution and ultimately verification.

The Results Continue to Speak for Themselves.



My Other Telescope!