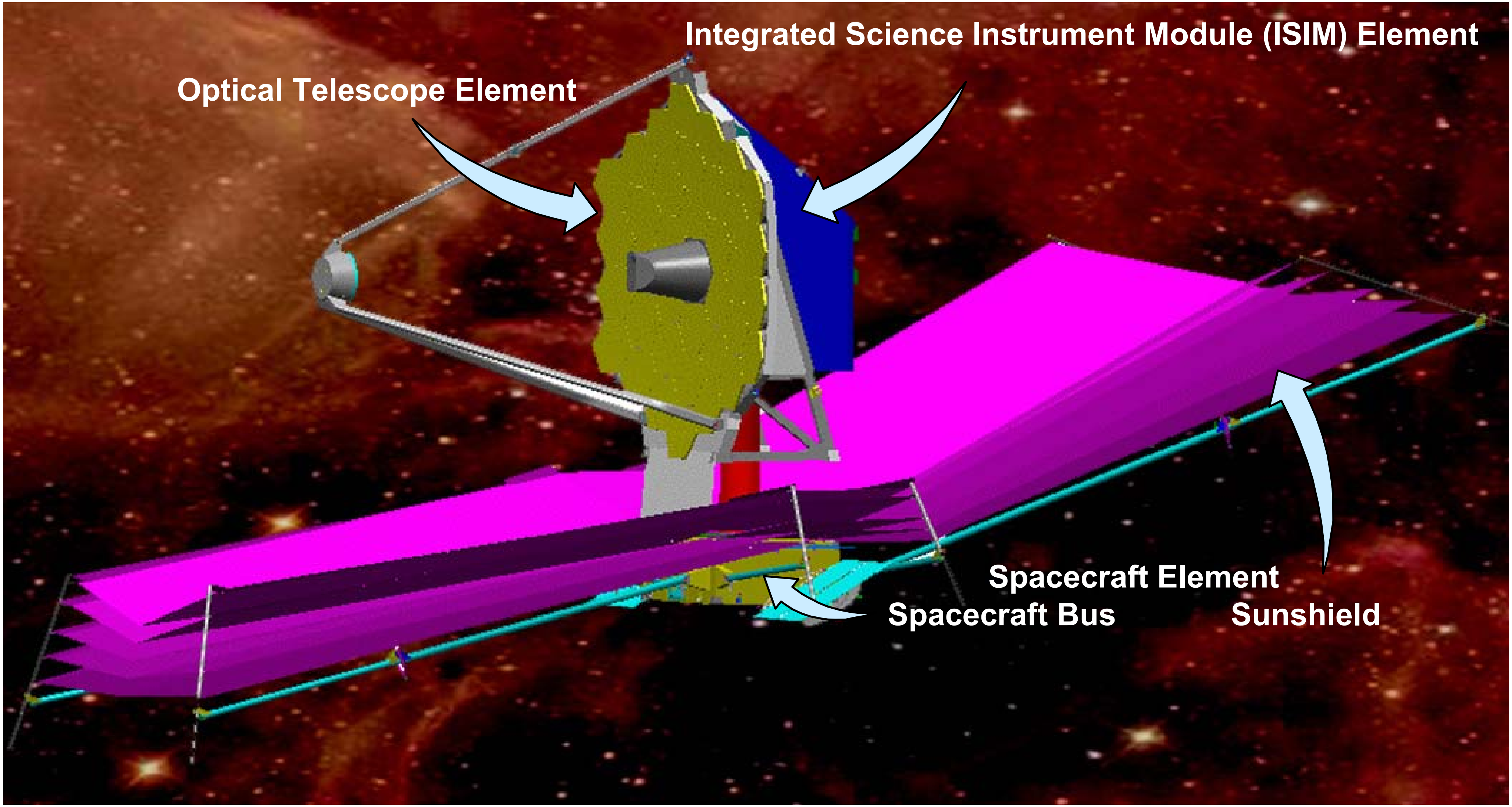
TRW

James Webb Space Telescope (JWST) Architecture and Overview

John Nella
JWST Kickoff Meeting
23 October 2002
02 JWST-0001

James Webb Space Telescope



Topics
JWST Observatory Architecture

- TRW's JWST Team
- Architecture Overview
- Compliance with Mission Requirements
- Deployment
- Design Features
- Interfaces
- Risk Mitigation
- Program Implementation
- Optical Verification
- Summary

Observatory Prime Contractor Team Brings Demonstrated Skills and Experience to JWST

TR W

NGST Prime Contractor

- Observatory performance, schedule, and cost
- Systems engineering and interfaces
- Spacecraft, Sunshield and all deployables
- Lead ground segment and operations support

Optical System Development

- OTE optical design and optics
- WFS&C design and algorithms
- Mirror segment cryogenic testing
- OTE and Observatory AI&T support

Telescope Integration and Test

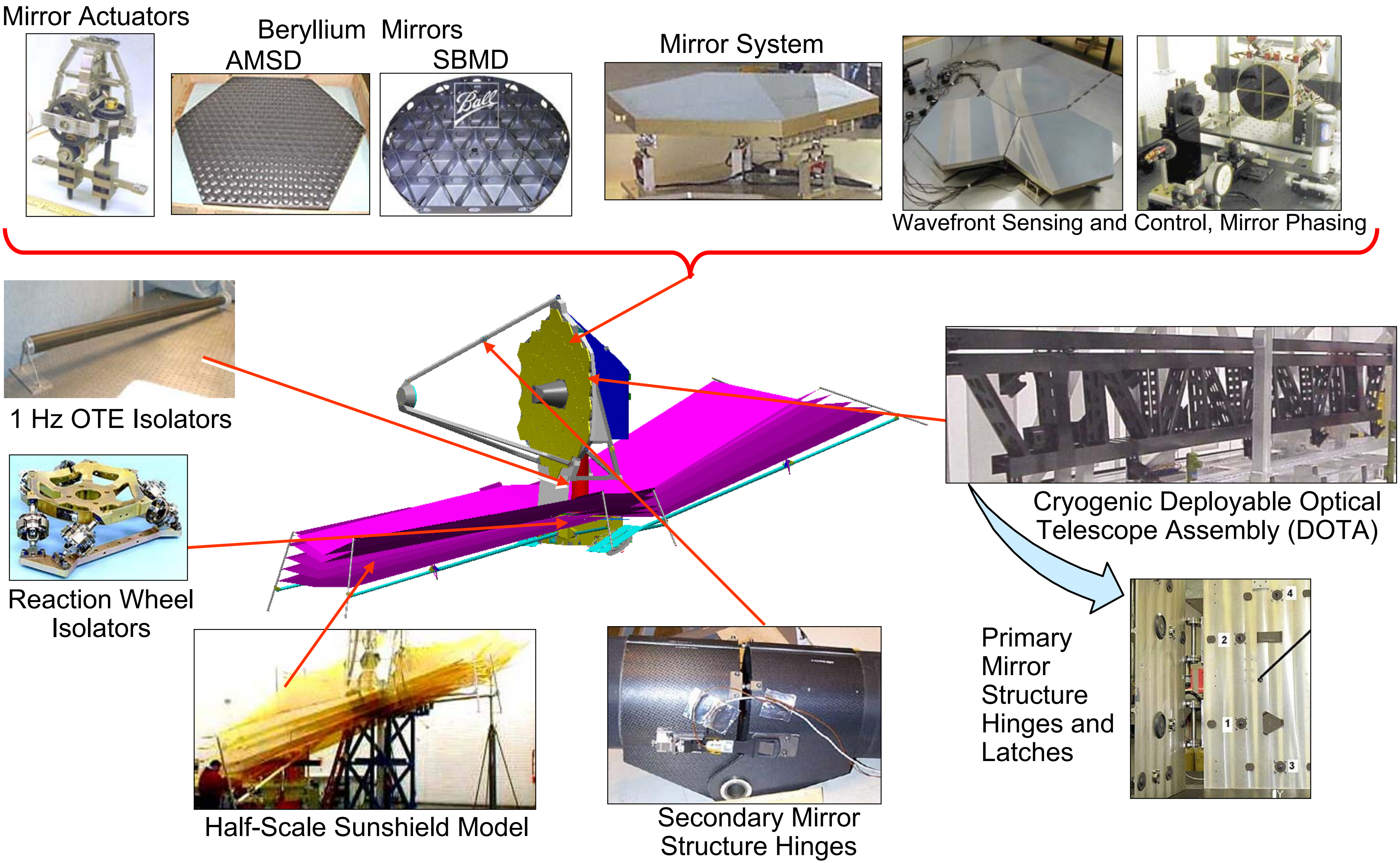
- OTE ground AI&T
- Plum Brook test configuration and interfaces
- Fabricate ULE mirrors (if option selected)

We Enter Phase 2 with a Mature Observatory Design

- Optical Telescope Element design
  - Proven hexagonal mirror segment architecture
  - Semi-rigid architecture - Be and ULE compatible, with few actuators
  - Wavefront sensing and control that is deterministic and testbed-proven
  - Primary mirror chord-fold deployment design simplicity
  - Observatory passive jitter and thermal control/isolation
- Sunshield design has deployment heritage, thermal margins, and tested materials
- Accommodates ISIM with simple interfaces
- Spacecraft design
  - Common command and data handling
  - High heritage spacecraft components
- Performance verification and risk reduction
  - Early use of pathfinders, testbeds, and simulators retire risks
  - Comprehensive ground end-to-end cryo testing at Plum Brook

By combining the right advanced technology with a simple approach, we have an Observatory with low cost, schedule, and performance risk.

Phase 1 Investments Have Reduced Risk and Make JWST Goals Achievable



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James Webb Space Telescope

JWST Observatory Architecture Is Reliable and Robust

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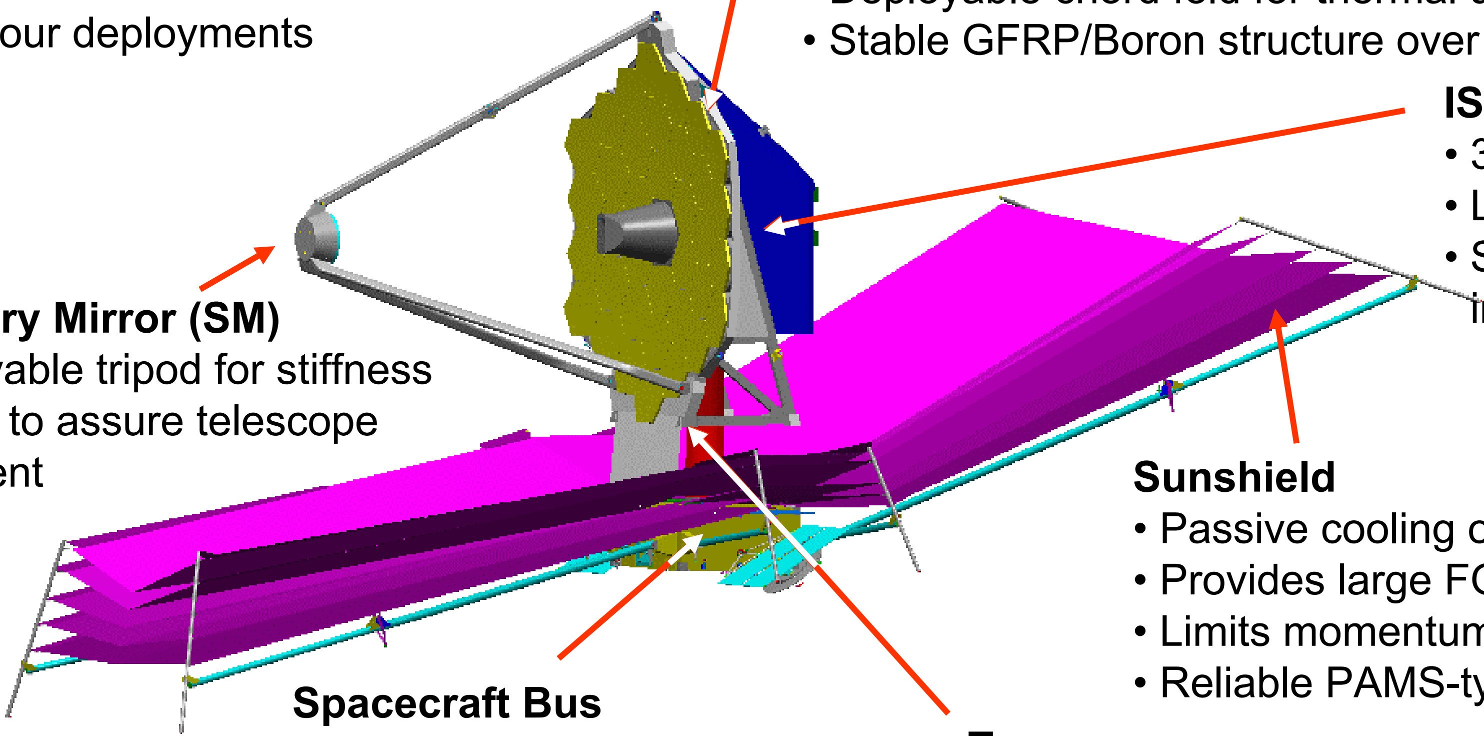
Optical Telescope Element (OTE)
- Stable over total field-of-regard
- Beryllium (Be) or ULE optics
- Performance verified on the ground
- Simple and low risk
  - Four deployments

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

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



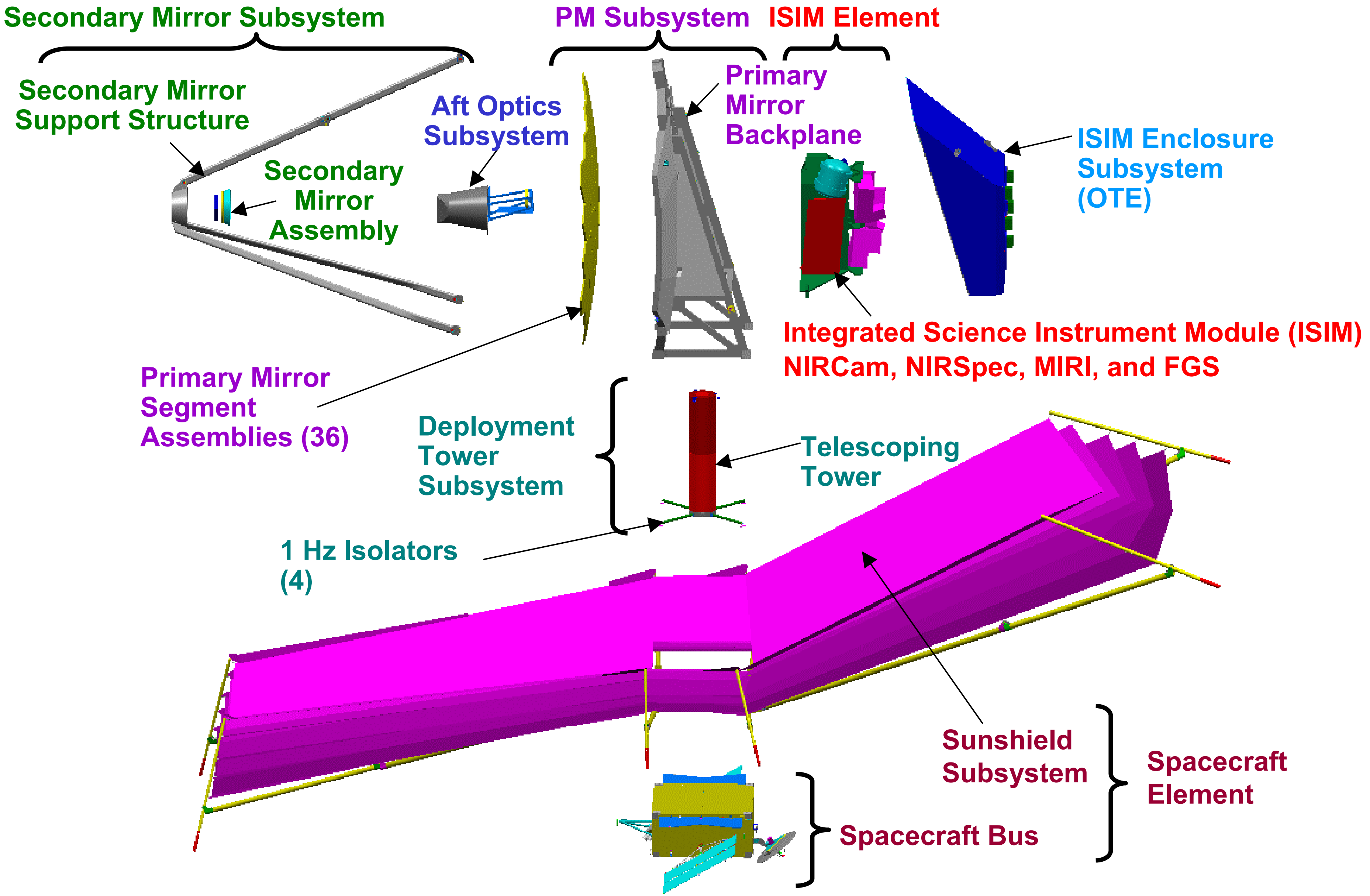
Secondary Mirror (SM)
- Deployable tripod for stiffness
- 6 DOF to assure telescope alignment

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

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

Tower
- Isolates telescope from spacecraft dynamic noise
- OTE rotation not required

Overview of the JWST Observatory



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Observatory Design Has Prudent Margin on the Driving Requirements

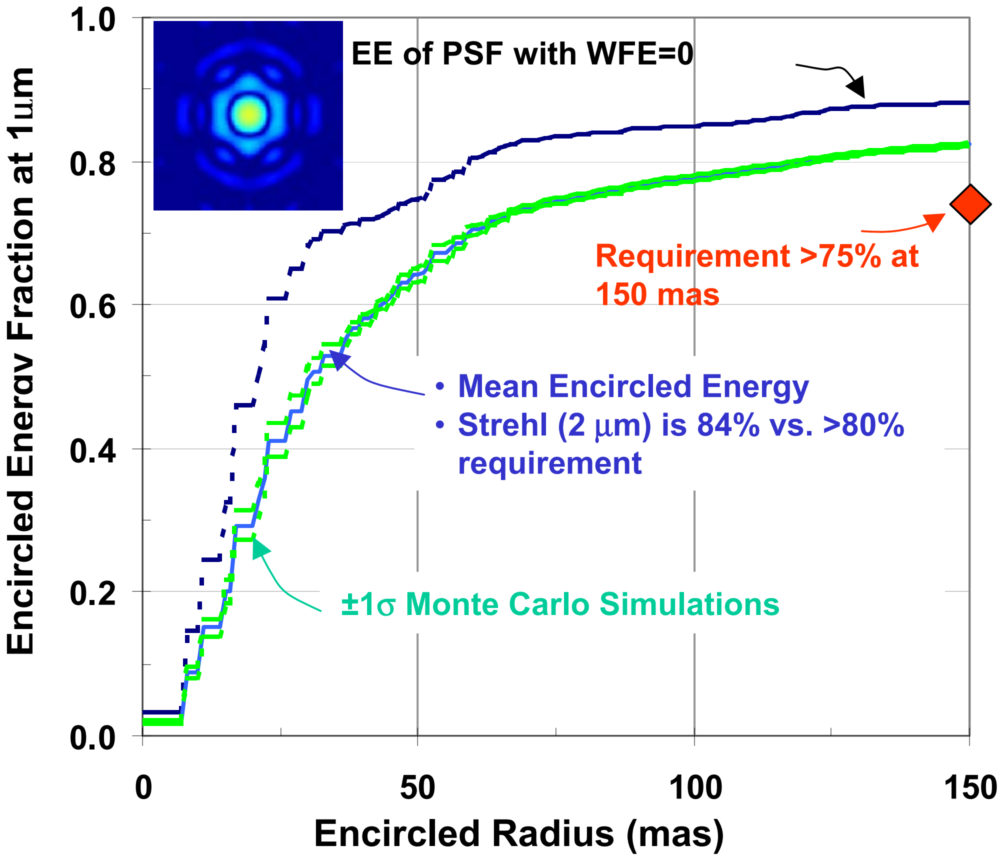
Requirement	Value	Estimated Performance
Aperture	>25 m^2 collecting area	29.4 m^2
Encircled Energy	>75% for 150 mas radius at 1 μm	82% (details in later chart)
PSF Stability	<2% RMS variation about mean over 24 hours at 150 mas radius at 1 μm	≤0.31% worst case over FOR
Sensitivity	Minimum target sensitivities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

Performance and design margins are ample to ensure meeting science needs as the design is matured.

Optical Performance Is Exceptionally Stable and Meets Science Needs

Encircled Energy

- Mid spatial frequencies WFEs, which significantly affect 150 mas EE, are polished in and verified with semi-rigid mirror architecture



Stability of Image Quality

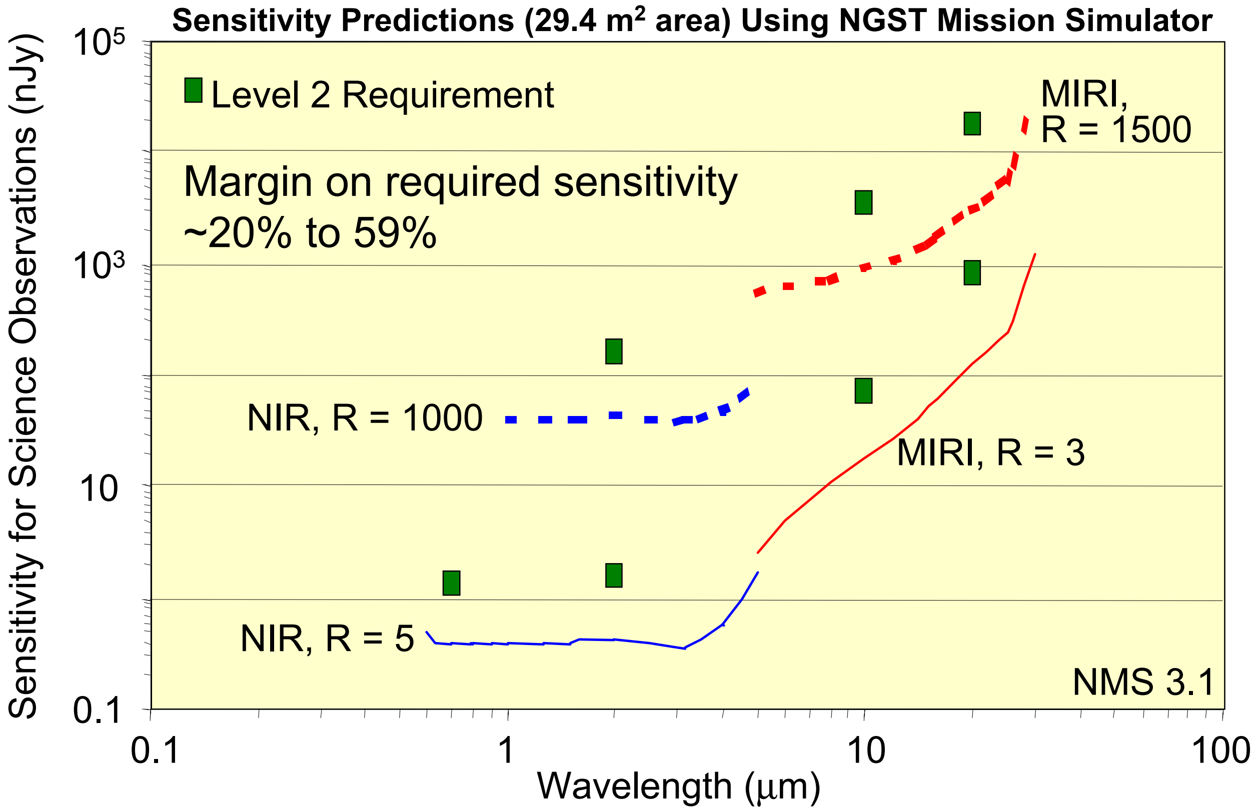
- Insensitive to average operating temperature
- Tolerant to slow changes in thermal environment
- Requirement is stability of EE at 150 mas < 2% rms about mean at λ=1 μm over 24-hour period

Sun Angle (Hot-to-Cold Case)	PSF Stability at 150 mas
-15° to -63°	≈0.31%

Observatory has margin in meeting image quality requirements without active control.

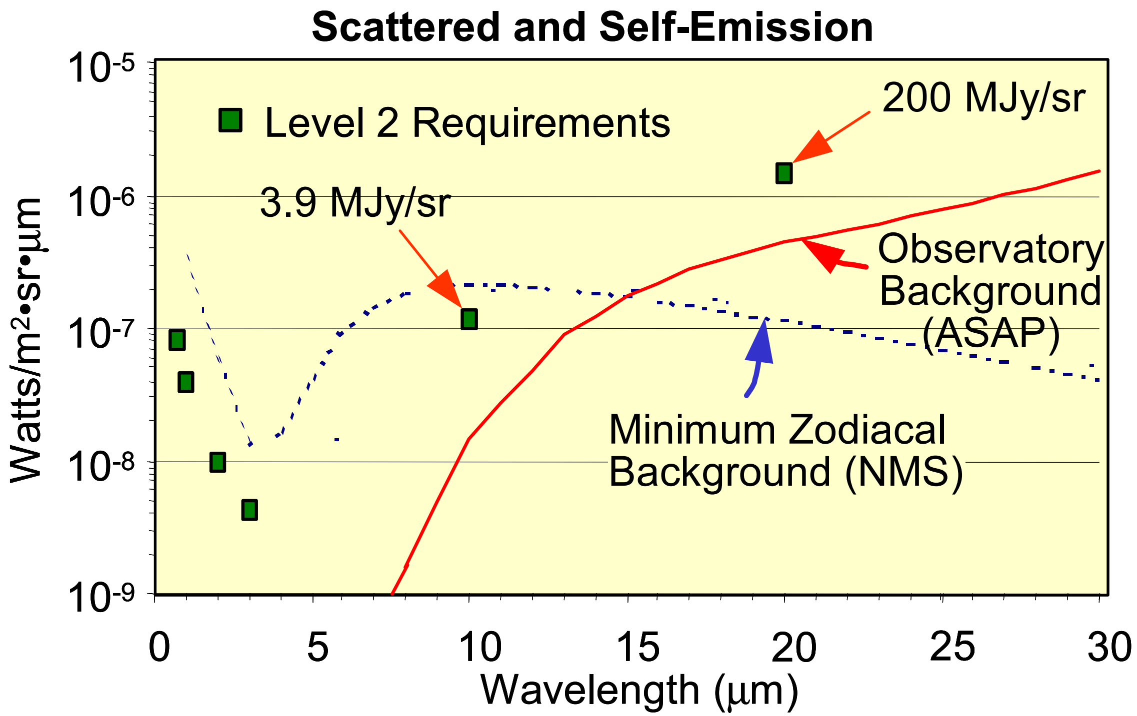
Observatory Sensitivity Provides Margin in the Worst-Case Scenario

- SNR = 10; 100,000 second integration; point target at North ecliptic pole
- End-of-life conditions, worst-case scattering
- ISIM performance from Appendix A of Level 2 Specification

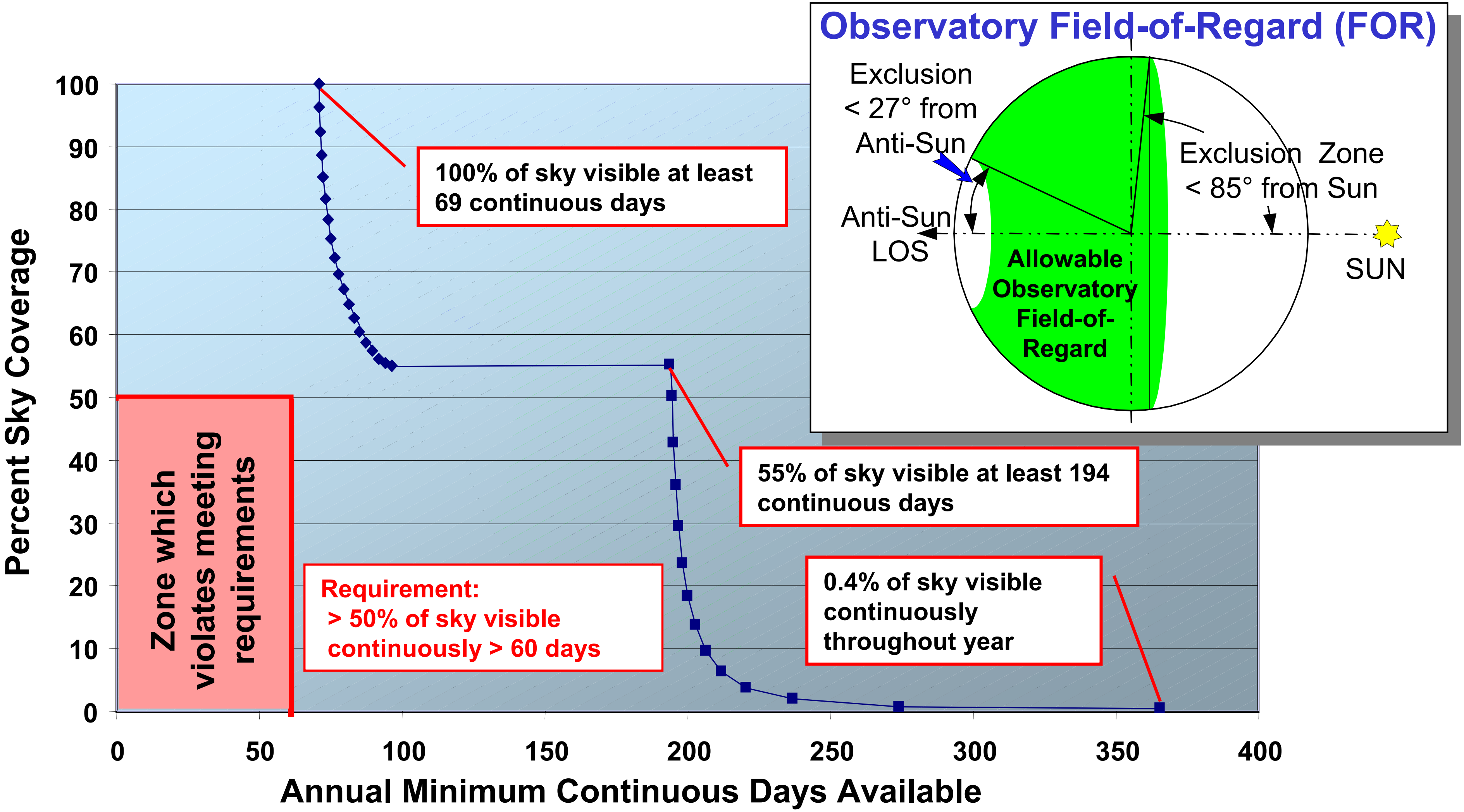


Elapsed time for design reference mission (DRM) predicted to be 2.54 years versus 2.5-year goal / 5-year requirement.

Observatory Background Brightness



Momentum Balanced Sunshield Provides a Large FOR Allowing Flexibility in Science Observations



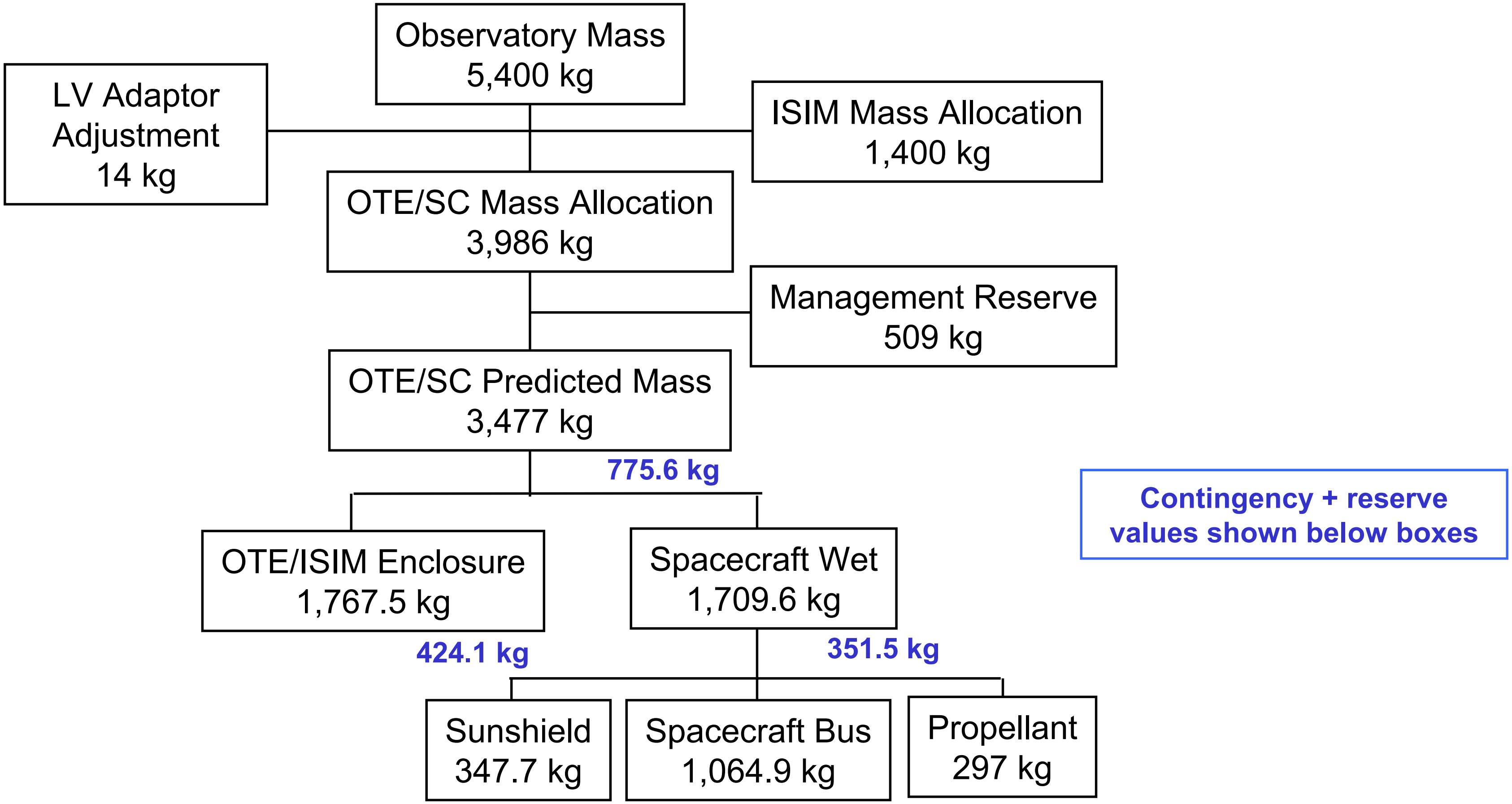
Benefits of momentum balanced sunshield include:
Large FOR, Simple mission operations, and Stable OTE temperature

Spacecraft Operations and Passively Stable OTE Provide Margin in Observing Efficiency

Overhead Activity	Activity Duration (days) to EOL (EOL = 5 years)
Slew, guide star acquisition, and settling	76
Small angle slews	14
Wavefront sensing and control	30
Momentum control	2
Stationkeeping	2
Thermal settling	0
Safe Mode	18
High Gain Antenna steering	0
Image quality monitoring	0
Sunshield reconfiguration	0
Predicted OTE/Spacecraft Overhead	142 days (7.8%)
ISIM Overhead Allocation	274 days (15%)
Observatory Efficiency (Requirement is >70%)	77.2%

Passive stability of Observatory enables science observation immediately after slewing.

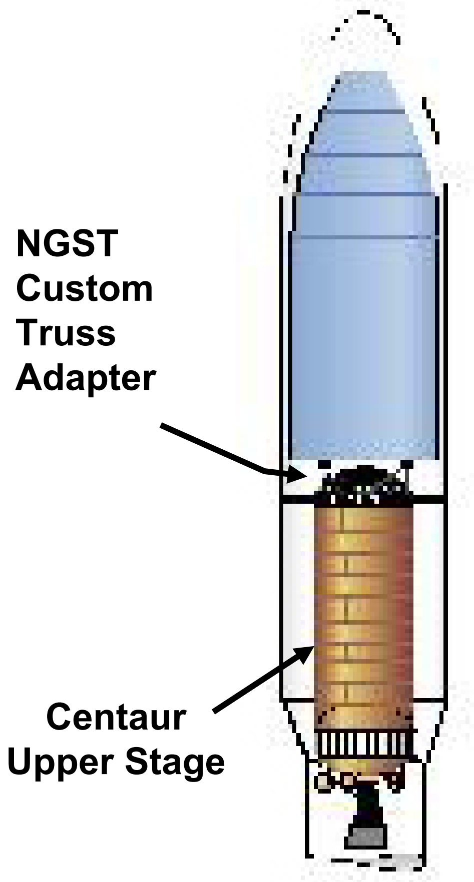
Observatory Has Ample Mass Margin for Atlas V EELV

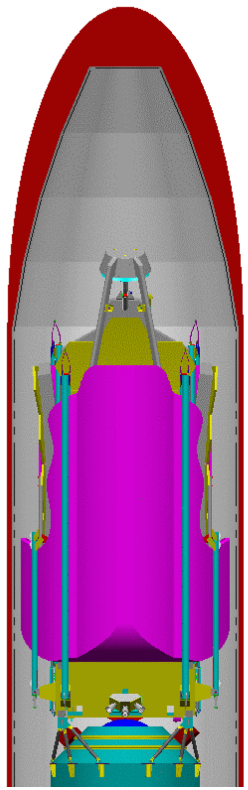


Mass margin protects against cost growth as the Observatory designs matures:

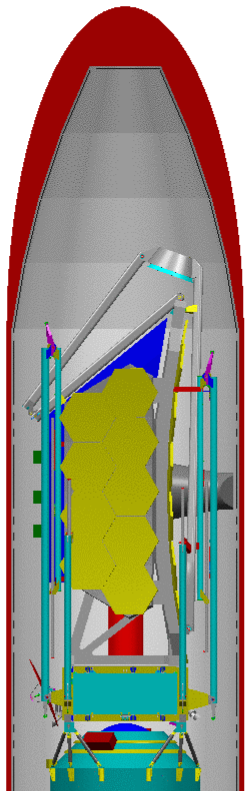
- ~42% margin (contingency plus reserve) against current mass estimates

Observatory Launch Configuration allows use of ATLAS V EELV with 5m Fairing



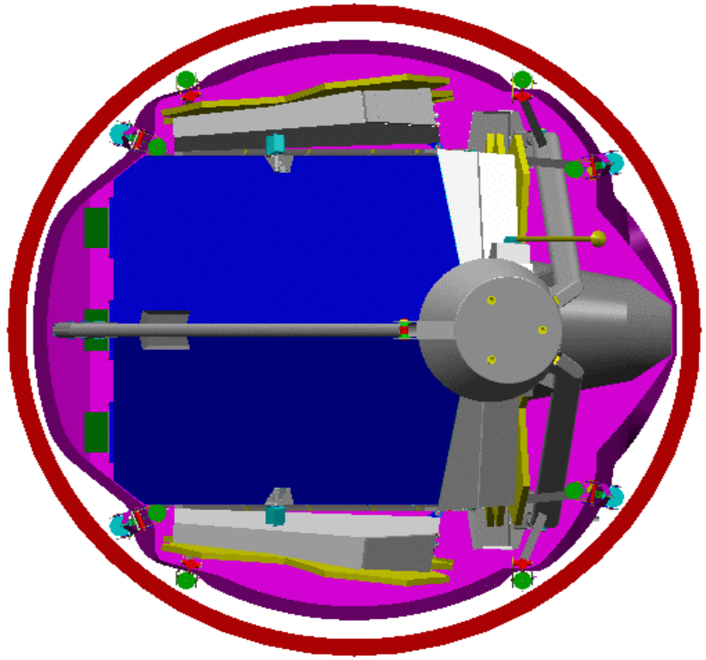


Stowed View



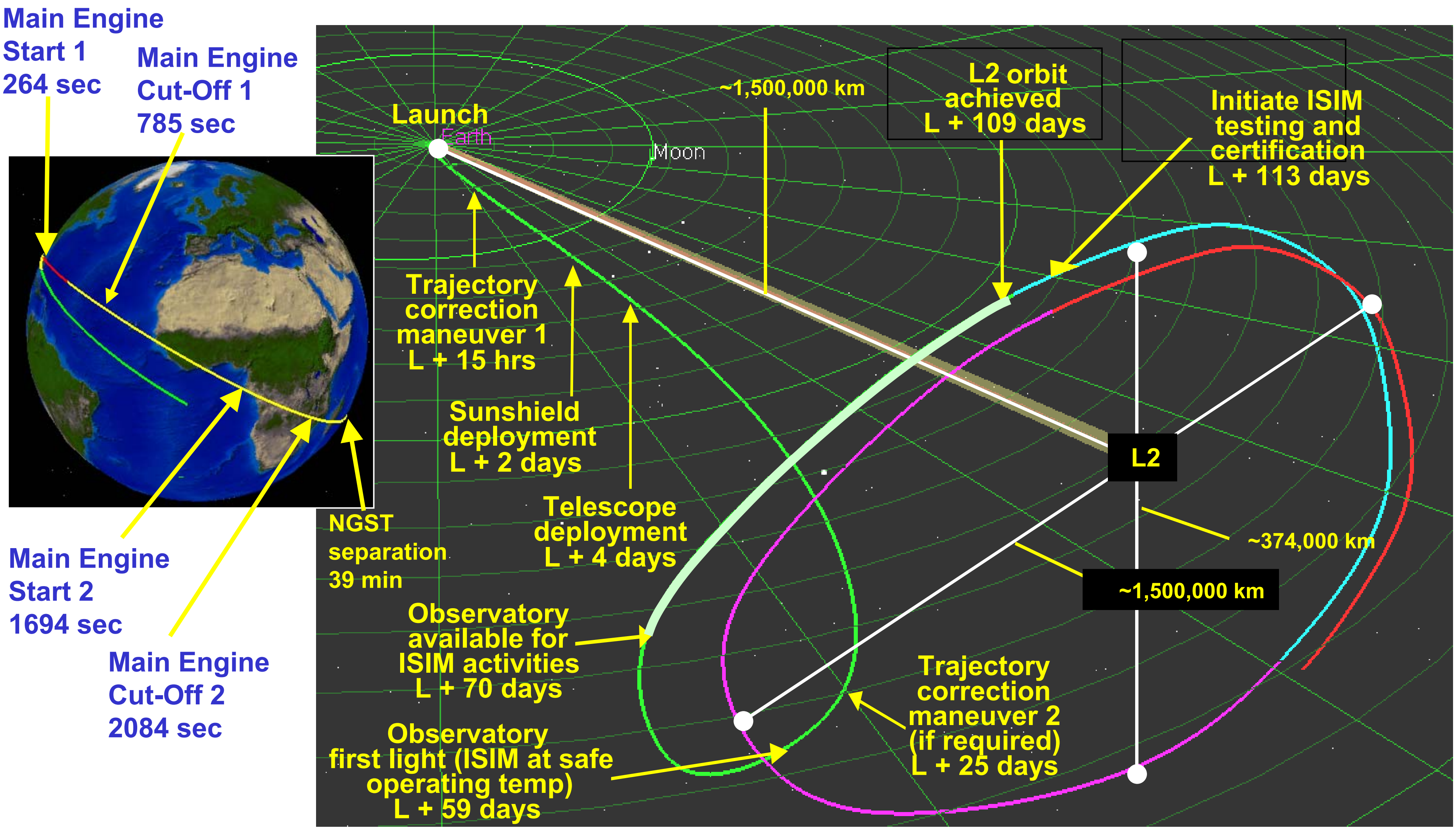
Without sunshield

Top View of Observatory stowed in 5m fairing



Observatory stows in Atlas V with a minimum clearance ≥ 25mm

Extensive Opportunities for Pre-Commissioning Activities Before Achieving L2 Orbit



Observatory Power Budget

Element	Estimated Power (W)	Growth Allocation (%)	Predicted Power (W)
Optical Telescope Element	**30**	**35**	**40.5**
OTE Nominal Power	30	35	40.5
ISIM Element	**130 (allocated)**	**0**	**130**
ISIM C&DH	65	0	65
FPE Boxes	65	0	65
Spacecraft Element	**665.9**	**20**	**796.5**
Attitude Control	131.6	11	146.6
Communications	176.0	20	211.2
Command and Data Handling	148.8	25	186.1
Thermal Control	30.0	25	37.5
Propulsion	83.6	22	101.8
Electrical Power	95.9	18	113.4
Observatory Total	**825.9**	**17**	**967**

Solar Array	**Capability (W)**	**Predicted Margin (W)**
5 year Capability @ 35° Sun Angle	1392.8	425.8
10 year Capability @ 35° Sun Angle	1381.0	414.0
15 year Capability @ 35° Sun Angle	1365.5	398.5

Growth allocation and Margin exist for > 10 year operation

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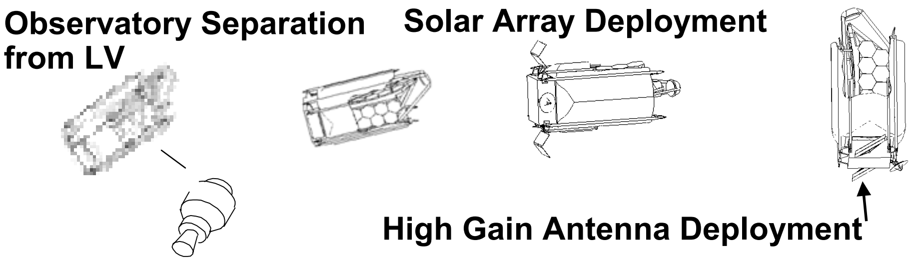
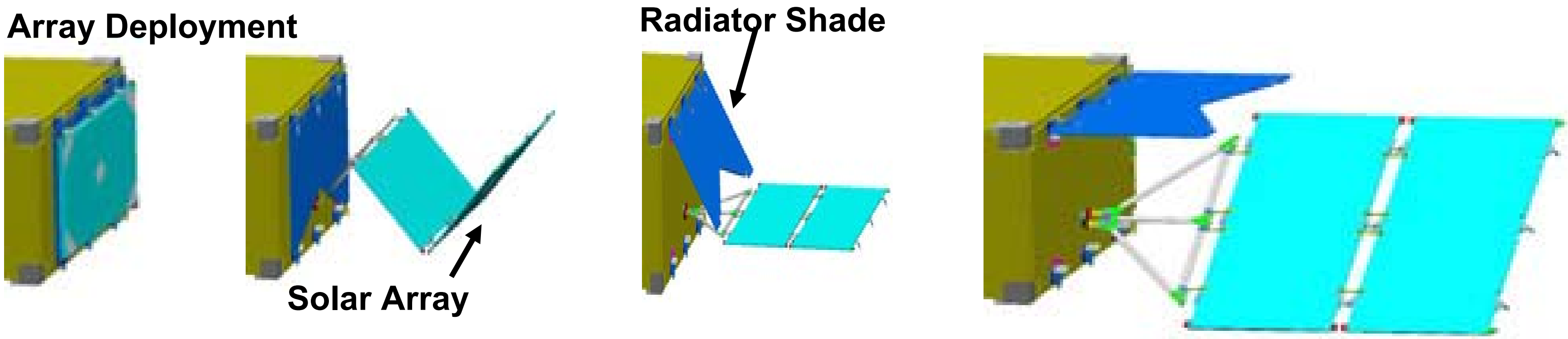
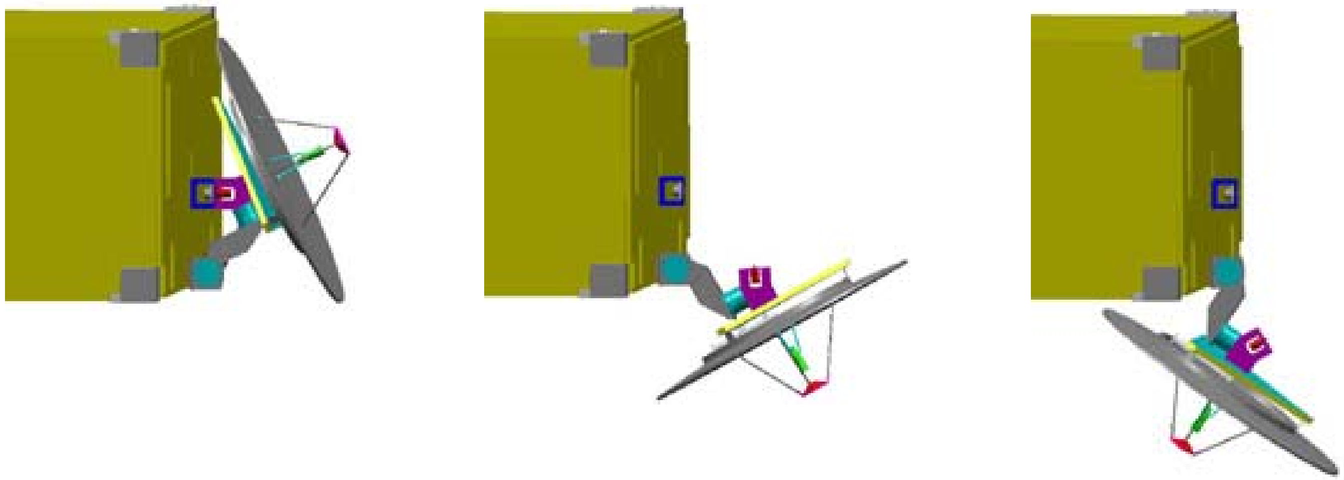
Power and Communications are the Initial Deployments



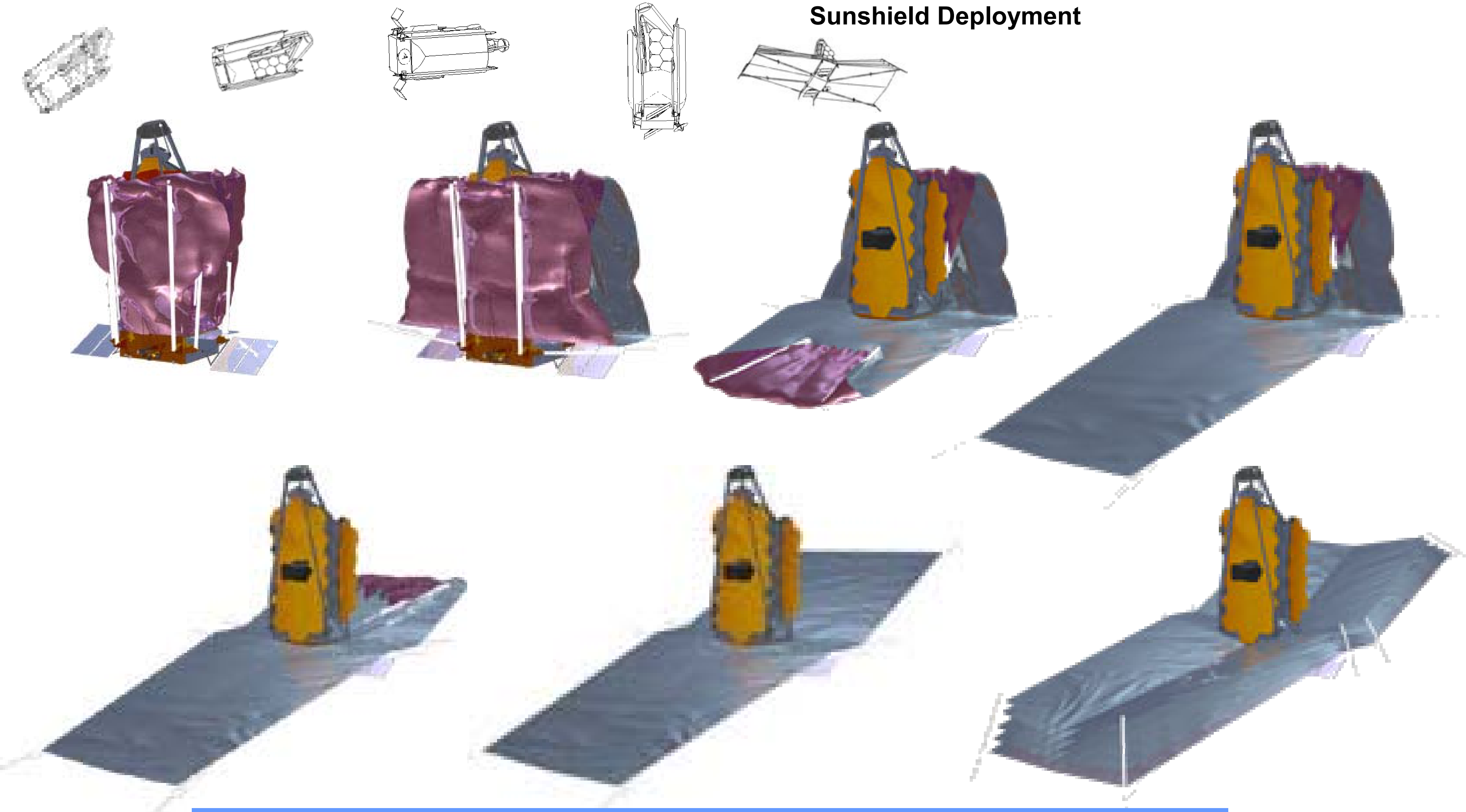
Solar Array Deployment



High Gain Antenna Deployment

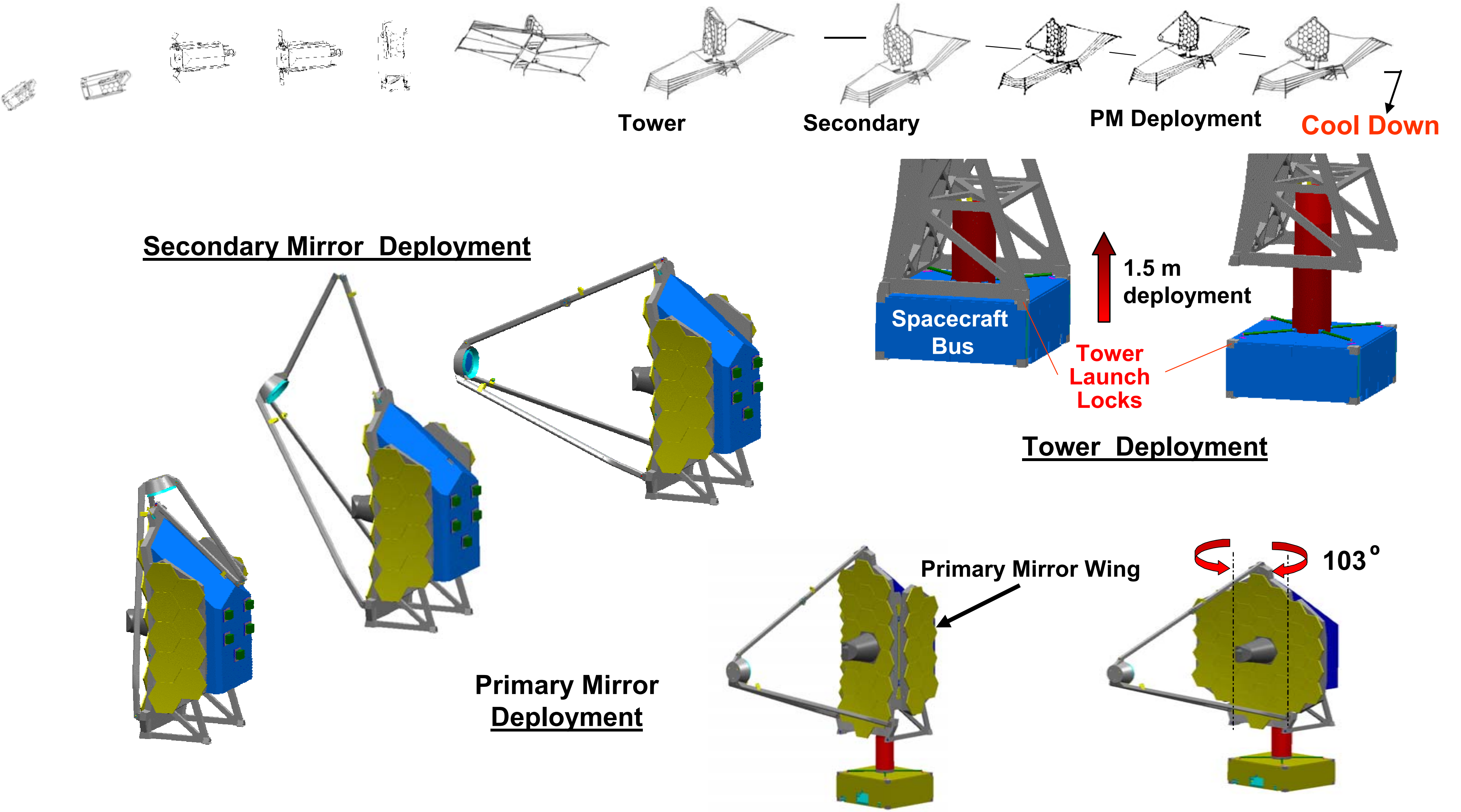


Sunshield Deployment



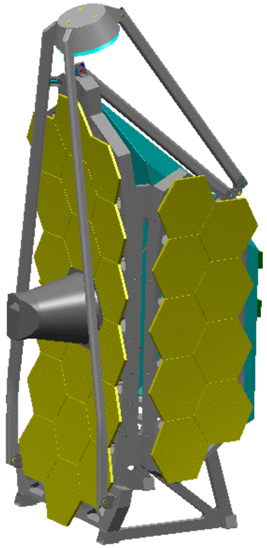
Flight-proven cable driven boom system provides a predictable and reliable deployment for the Sunshield

OTE Deployments

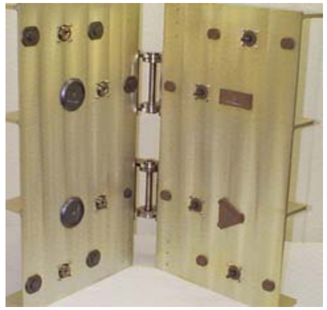


Primary Mirror Chord-Fold Architecture Is Simple, Tested, and Allows for Stable Optical Performance

- Enables passive PSF stability throughout mission
  - Allows thermal strapping between backplane chords and the mirror segments
  - Thermal uniformity and conductivity minimize primary mirror gradients without active control
- Simple and low risk deployment concept – full-scale hinge-line structure (DOTA) tested at temperature
  - Minimum number of actuators
- Allows using a stable SMSS tripod
- Limits optics view factor to particulate contamination
- Provides benefits to ISIM:
  - Simple and Stable interface to primary mirror
  - Large Volume for SI and FGS packaging,
  - Good thermal view factor to space
- Compatible with AMSD technologies



Hinge and Latches Tested for Repeatability



Full-Scale Test Structure (DOTA) Entering XRCF Test Chamber

Provides efficient packaging for launch vehicle and eliminates need for active thermal control of primary mirror.

Deployments Use Flight-Proven Technologies to Achieve Observatory Operation

- Based on proven TRW technologies and hardware used on numerous flight programs – over 672 deployable systems (1824 individual articulations) with 100% mission success
  - Sunshield based on PAMS
  - DOTA tested full-size chord-fold structure at temperature for stability
  - Hinges and latches tested for SMSS and PM deployments and repeatability
  - Sunshield deployment membrane management analyzed using 1/2 scale model
- Simplicity of design relative to past successes
  - TDRS flights A through F have 52 articulations each, were 100% reliable
  - NGST has 39 articulations
- Preliminary FMEA, FTA, and PRA performed on deployment events
- Design torque margins for all hinges
- Heaters used to allow latches and hinges to operate at any time

Flight Demonstrated technologies and early risk reduction provide a highly reliable Observatory deployment.

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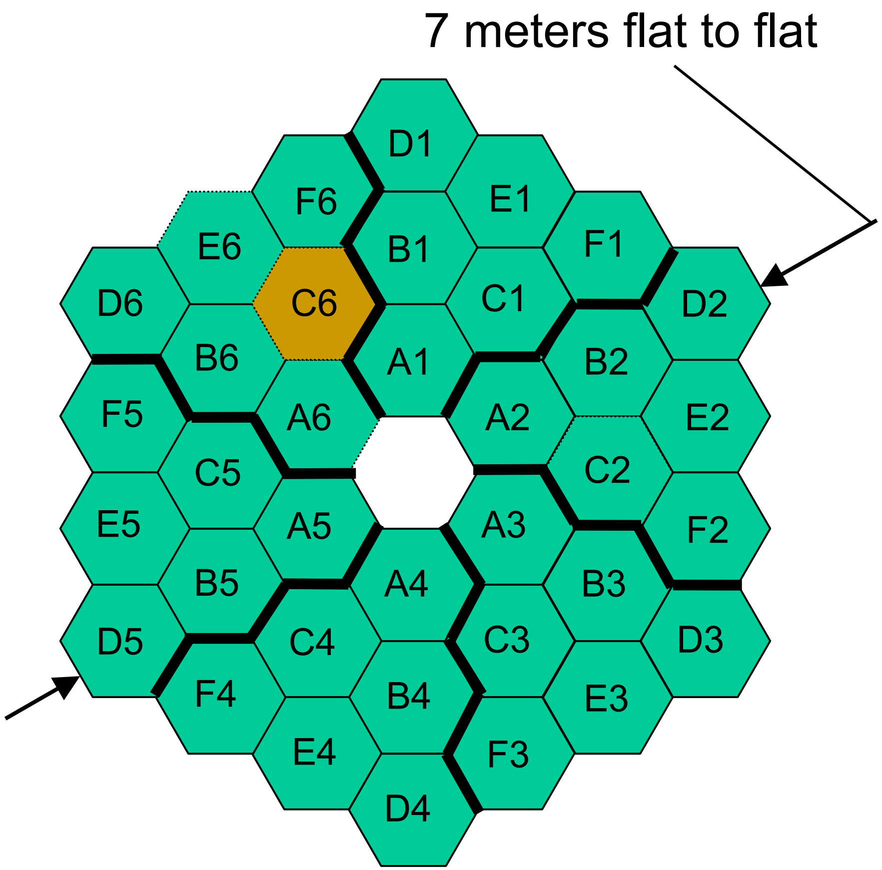
Segmented Primary Mirror Architecture Minimizes Cryogenic Testing and Cost



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

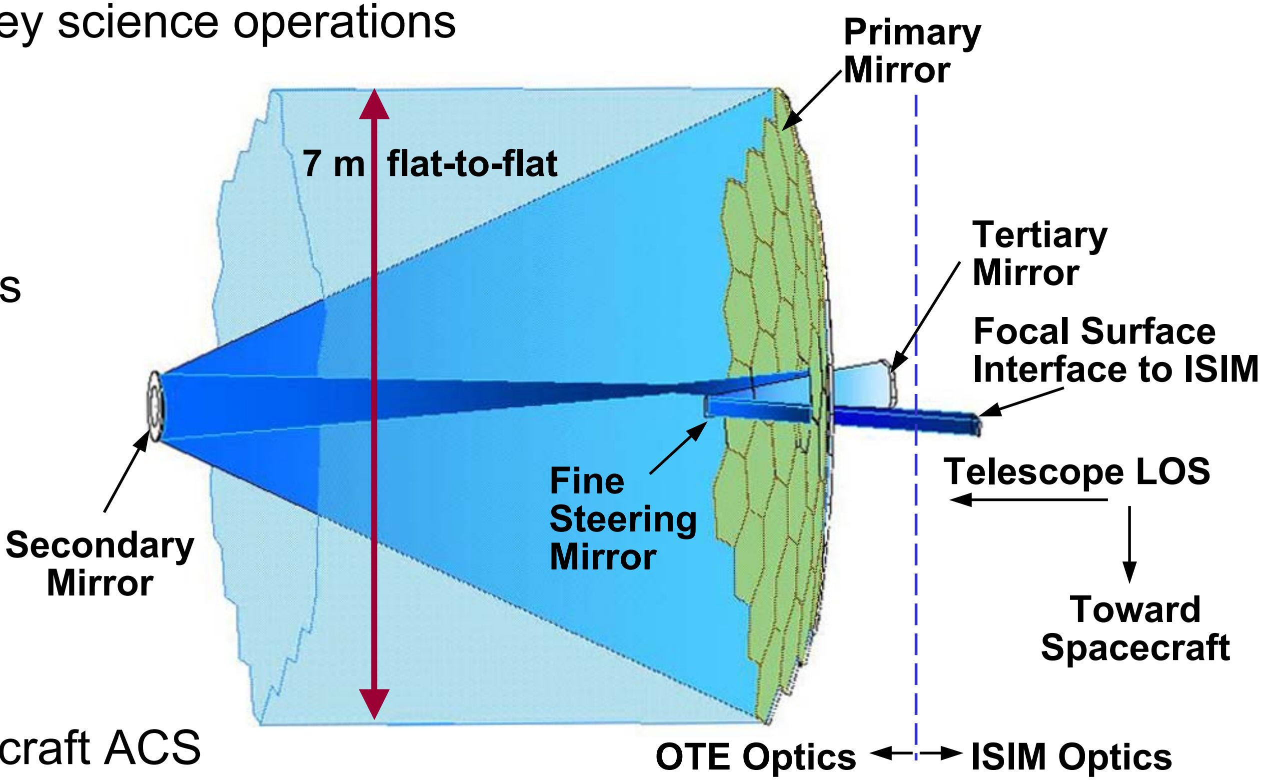
Segmented architecture allows us to minimize production time and cost.

Optical Design Provides Wide Field-of-View With Well Defined ISIM Interface

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

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

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

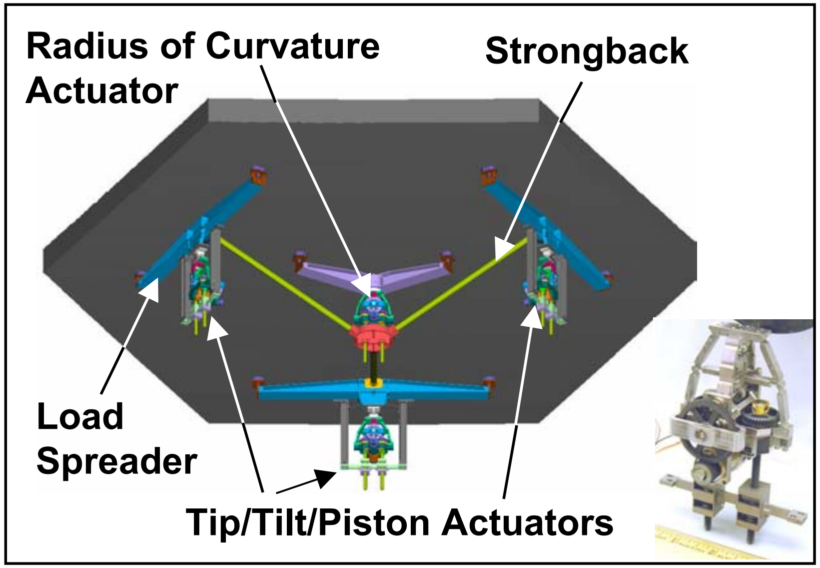


- Simple clean interface keeps costs low:
  - Reduces complexity of the interface
  - Simplifies AI&T and reduces independent verification cost

PM Semi-Rigid Hexagonal Segments is a Key Enabler of the Observatory Optical Performance

Simplifies WFS&C (144 actuators)

- Tip, tilt, piston, and ROC control
- Rigid body motion is independent of radius of curvature control
- Rigid body corrections do not induce surface distortions or stress



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

Final selection of mirror material will be made using AMSD results.

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Thermally Stable Backplane Structure Supports Optical Segments and Provides Margin for Optical Performance

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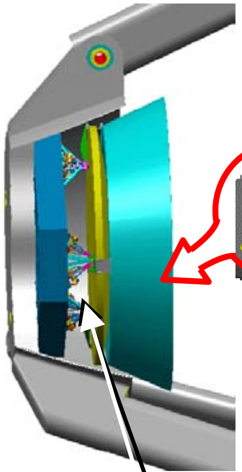
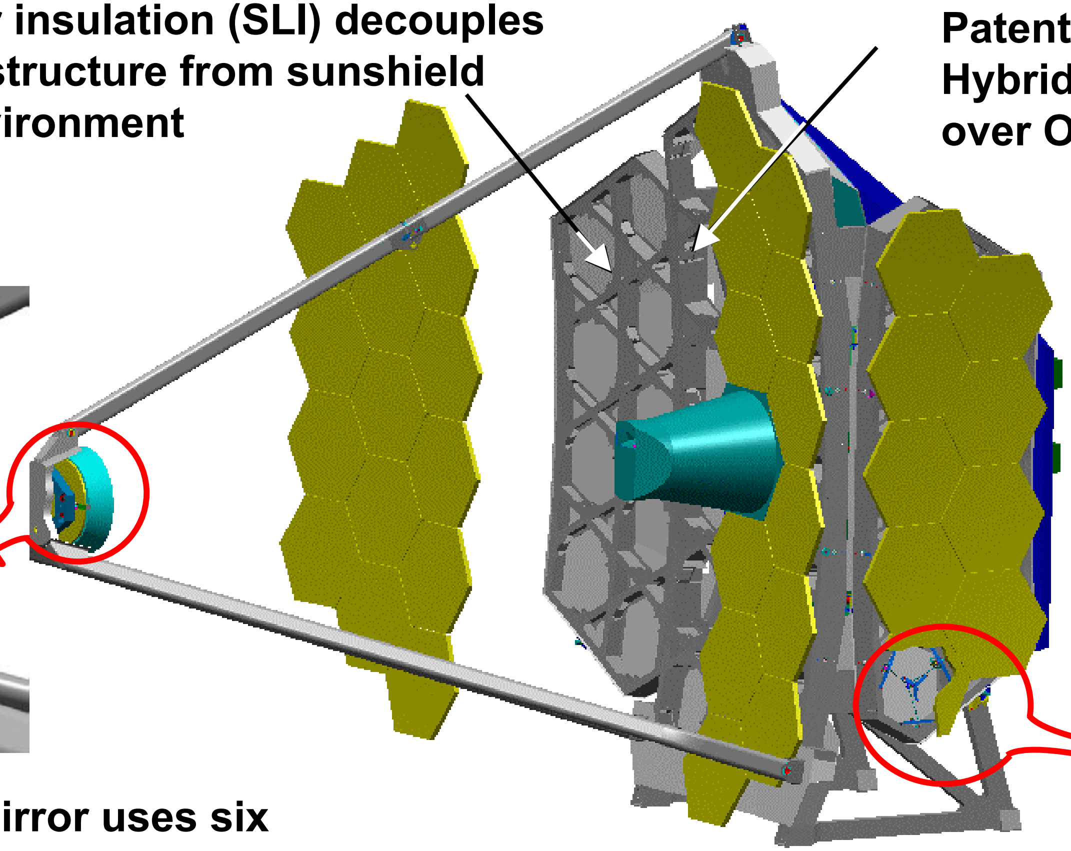
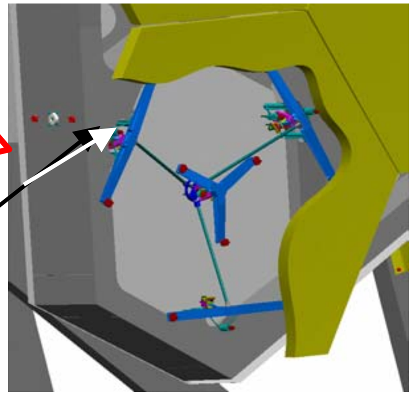
Single layer insulation (SLI) decouples backplane structure from sunshield thermal environment

Patent Pending Boron/M55J GFRP Hybrid backplane provides low CTE over OTE operating range





- Full scale test (DOTA) over operating range
- Beryllium Cost certainty – lower cost and risk
- Measured Stiffness and CTE properties at Temp (CTE< 0.1 ppm/K)



Secondary mirror uses six actuators in a hexapod configuration, provides positioning margin for WFS&C

Primary mirror segments attached to backplane using actuators in a simple three-point kinematic mount

Tested full-scale structure provides material property actuals for the design to reduce risk andincrease cost credibility.

TRW/Ball/Kodak Competition Sensitive/Proprietary

Telescope Commissioning Process Is Deterministic With Margin for Each Step

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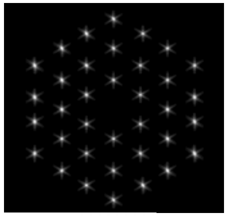
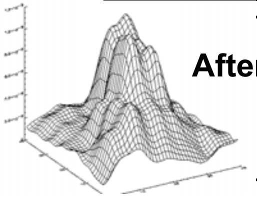
First light NIRCam

Primary/Secondary Mirror Deployment



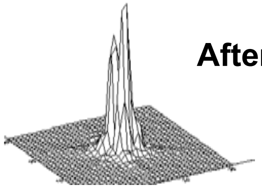
1. Coarse Alignment
   Secondary mirror aligned
   Primary RoC adjusted



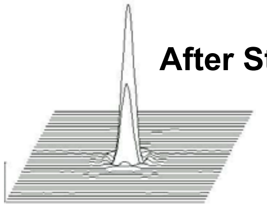
After Step 1

2. Coarse Phasing
   Fine Guiding

3. Fine Phasing



After Step 2



After Step 3

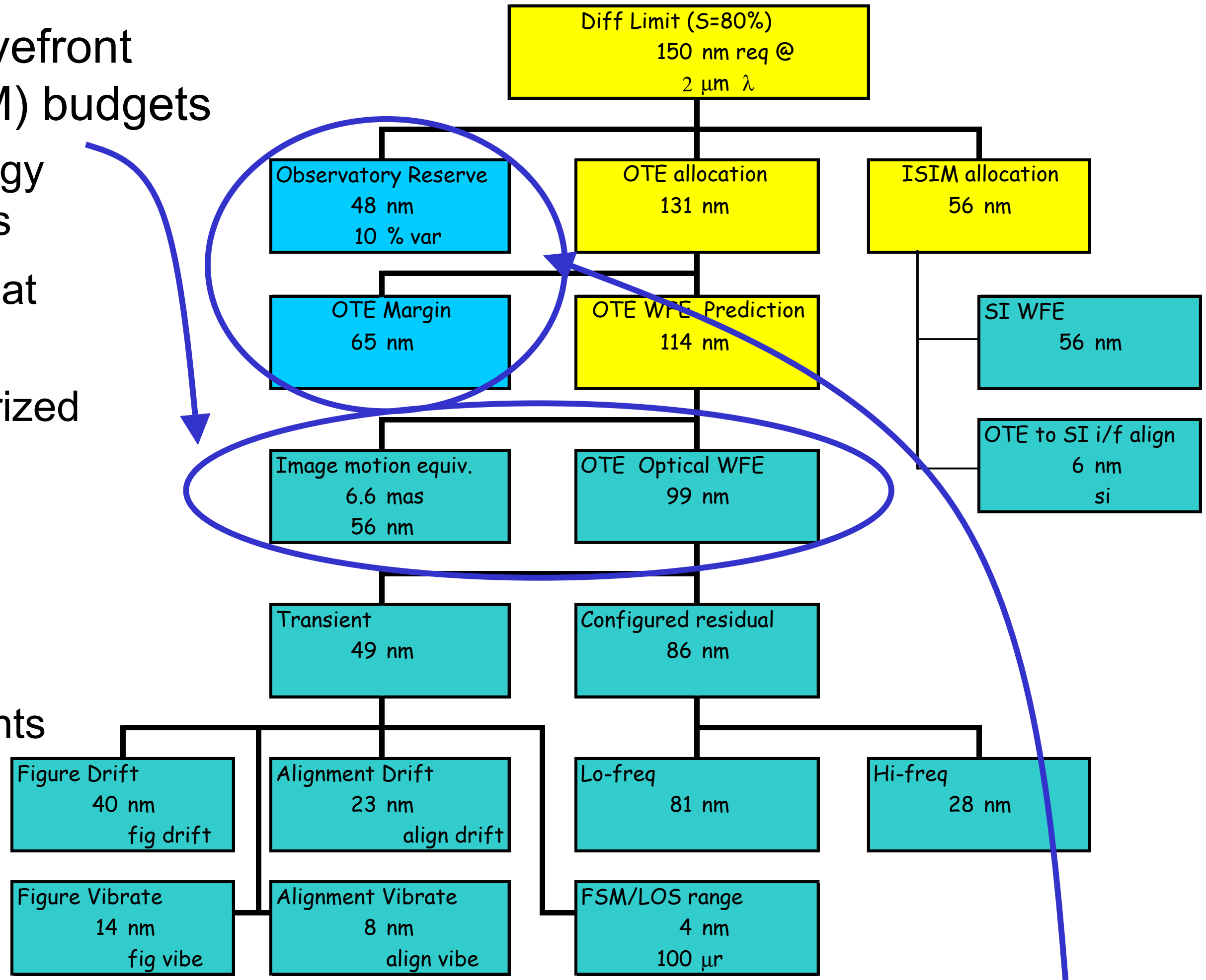
4. Image-Based
   Wavefront Monitoring

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

NASA's focus diverse phase retrieval algorithms are used as part of WFS&C architecture.

Comprehensive Budgets used to Manage Performance and Risk

- Image metrics partitioned into wavefront error (WFE) and image motion (IM) budgets
  - –Linked to Strehl and Encircled Energy requirements through PSF analyses
    - »Early verification of WFE and IM at subassembly and system level
  - –Spatial frequency content characterized for each WFE allocation



- WFE and IM allocations flowed into mechanical tolerances
  - – Design and fabrication requirements quantified for cost decisions

- Transient allocations linked to thermal mechanical and dynamic analysis
  - – Low-cost, passive thermal design and passive vibration isolation meet allocations with margin

Margins identified and managed to control cost.

ISIM Draft Allocations for Optical Budgets

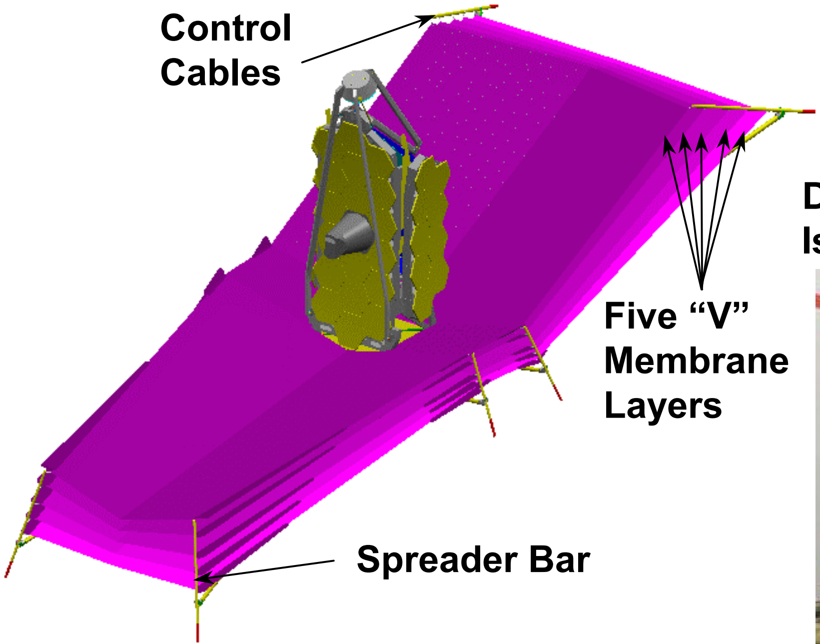
- Fine guiding draft allocations
  - Guide star noise equivalent angle not greater than 2.5 (TBR) mas (1σ per axis)
  - Centroid data latency < 64milliseconds (mid point of the FPA integration period until the end of the 32 Hz frame in which the data is available to the spacecraft)
  - Centroid update rate $\geq$ 16Hz
- Spacecraft role stability better than 1 arc-second (1σ)
- Separation between Guidestar and NIR target star to be less than 8 (TBR) milli arc-seconds – limit role induced jitter for WFE
- Other items: EE, Stability,etc.

Sunshield Design Based on Measured Data and Flight Proven Deployments

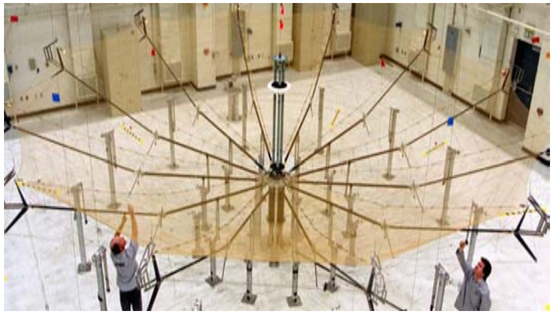
Thermo-physical properties of full-scale section of sunshield were measured and our models validated

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

Sunshield Material and Configuration tested at Cryogenic Temperature



Precision Adjustable Mesh System with numerous flight deployments



Deployment Membrane Management Issues Addressed in 1/2 Scale Model

Sunshield provides a thermal environment to the OTE that is insensitive to sun vector over the field-of-regard.

Sunshield Design Details Provide Margin for Daily Operations and Planning

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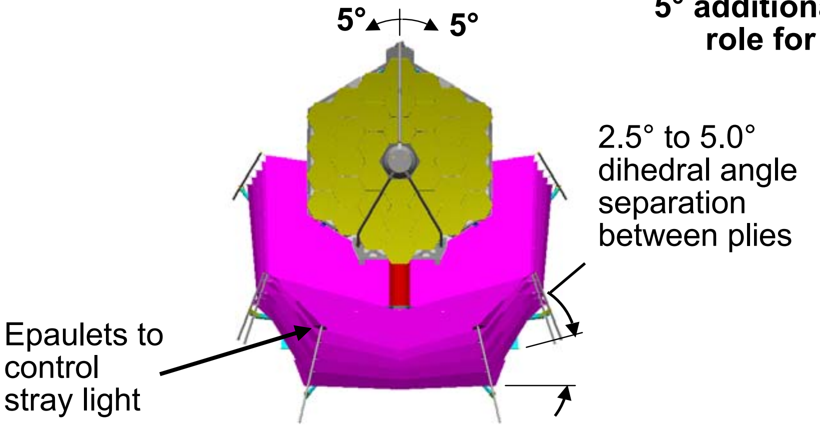
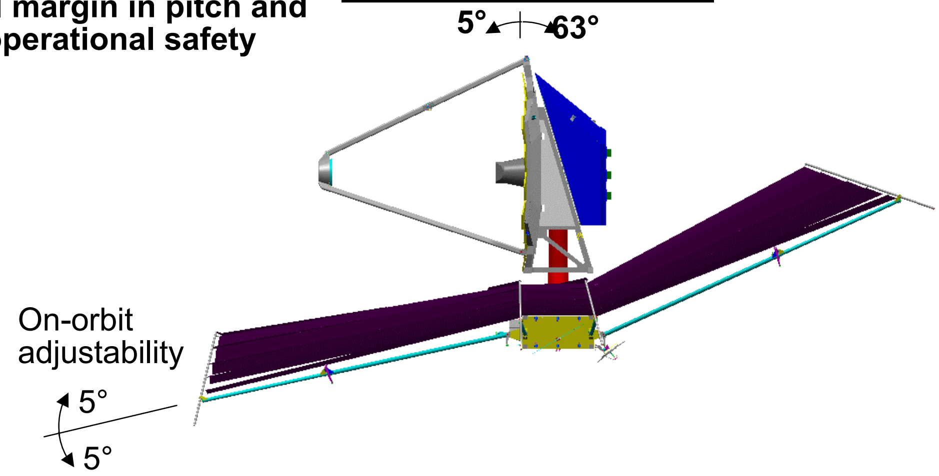
Roll Field of Regard

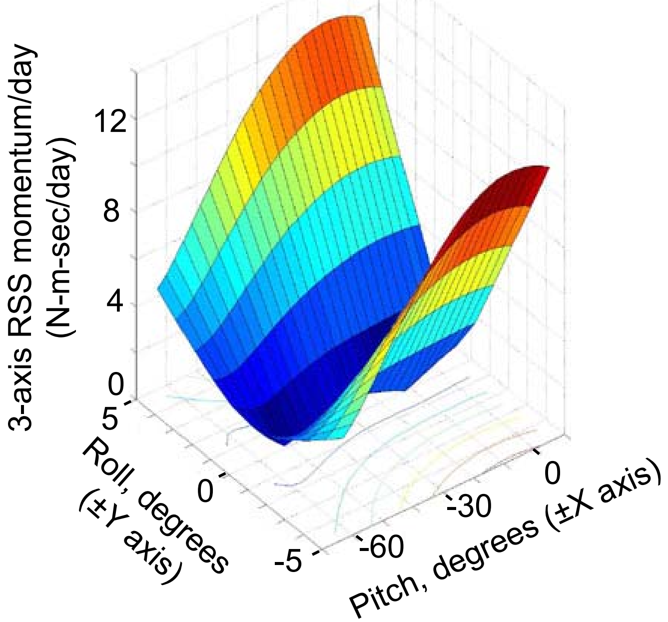


5° additional margin in pitch and role for operational safety

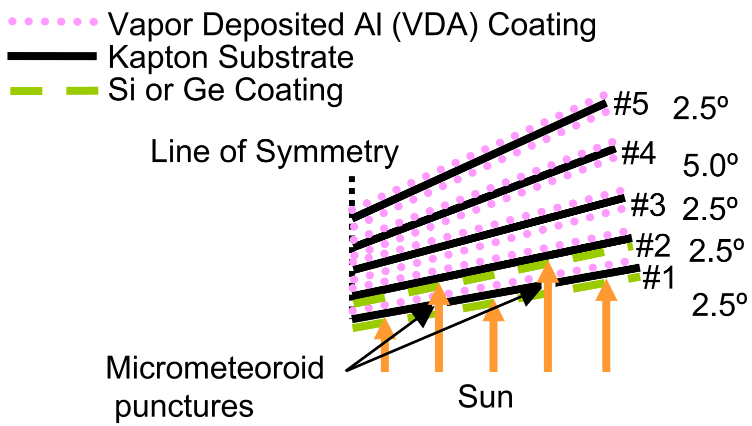
Pitch Field of Regard



Daily Momentum Buildup of 3-Plane Configuration



Dihedral Angles and Coating



Spacecraft Design Meets JWST Requirements Without Introducing Technology Risk.

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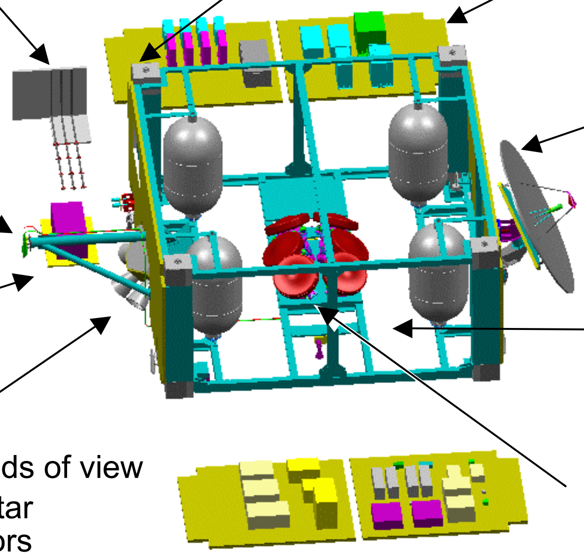
VIEW DURING AI&T (Removable Panels Are Shown Before Installation)

Battery Maintenance
Battery radiator panel for simple battery cooling inside fairing

Support OTE/ISIM Mass
Short graphite corner post design optimized for OTE design

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

L2 Orbit with Contamination Control
- Stationkeeping thruster on fixed boom provides ΔV in any direction
- Avoids heat or contamination source near OTE/ISIM



Dual Frequency High Gain Antenna
- Supports X-band and S-band communications
- Single hinge deploys and rotates from stowed configuration through 130° of operational pitch angles

AI&T Access
Battery access panel for easy access throughout launch processing flow

AI&T Access
- Multiple technician access for improved integration efficiency

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

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

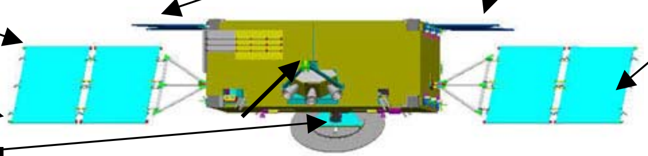
DEPLOYED VIEW

Attitude Determination and Control
- Coarse sun sensors (4, located on each outboard solar array tip)
- Provides full coverage for assured sun acquisition

(1 of 4)

(2 of 4)

Radiator Shading
Shades improve radiator effectiveness in presence of warm sun-facing sunshield layer

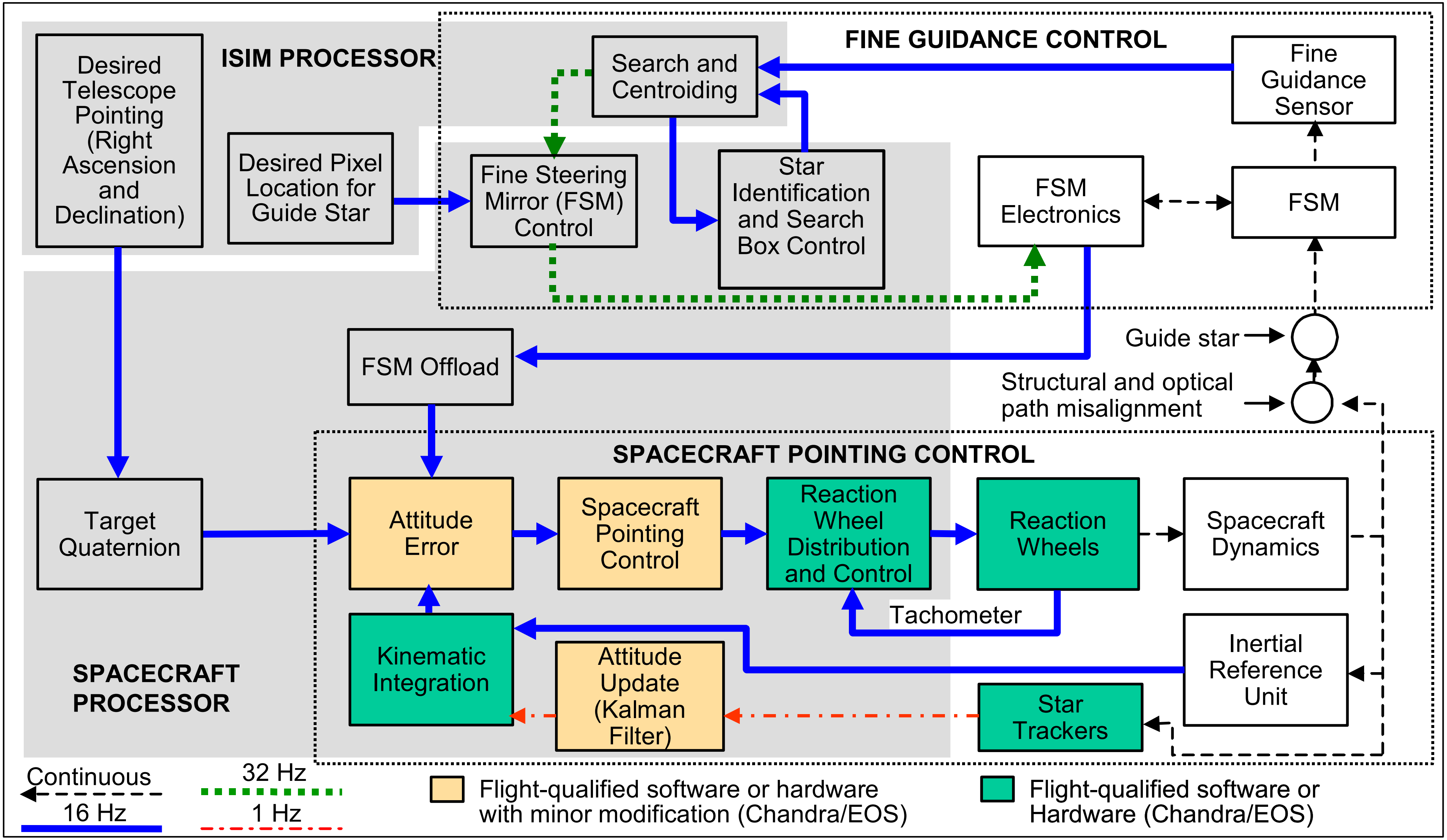


Power for Observatory
- Solar arrays fixed at center of operational pitch range for operational simplicity and reliability
- Solar cells face outward in stowed configuration to eliminate solar array deployment time constraint

Attitude Determination and Control
Fine sun sensor provides sun position monitoring through all operational attitudes

Solar Direction

Flight-Proven Chandra Pointing Control Approach Used on JWST



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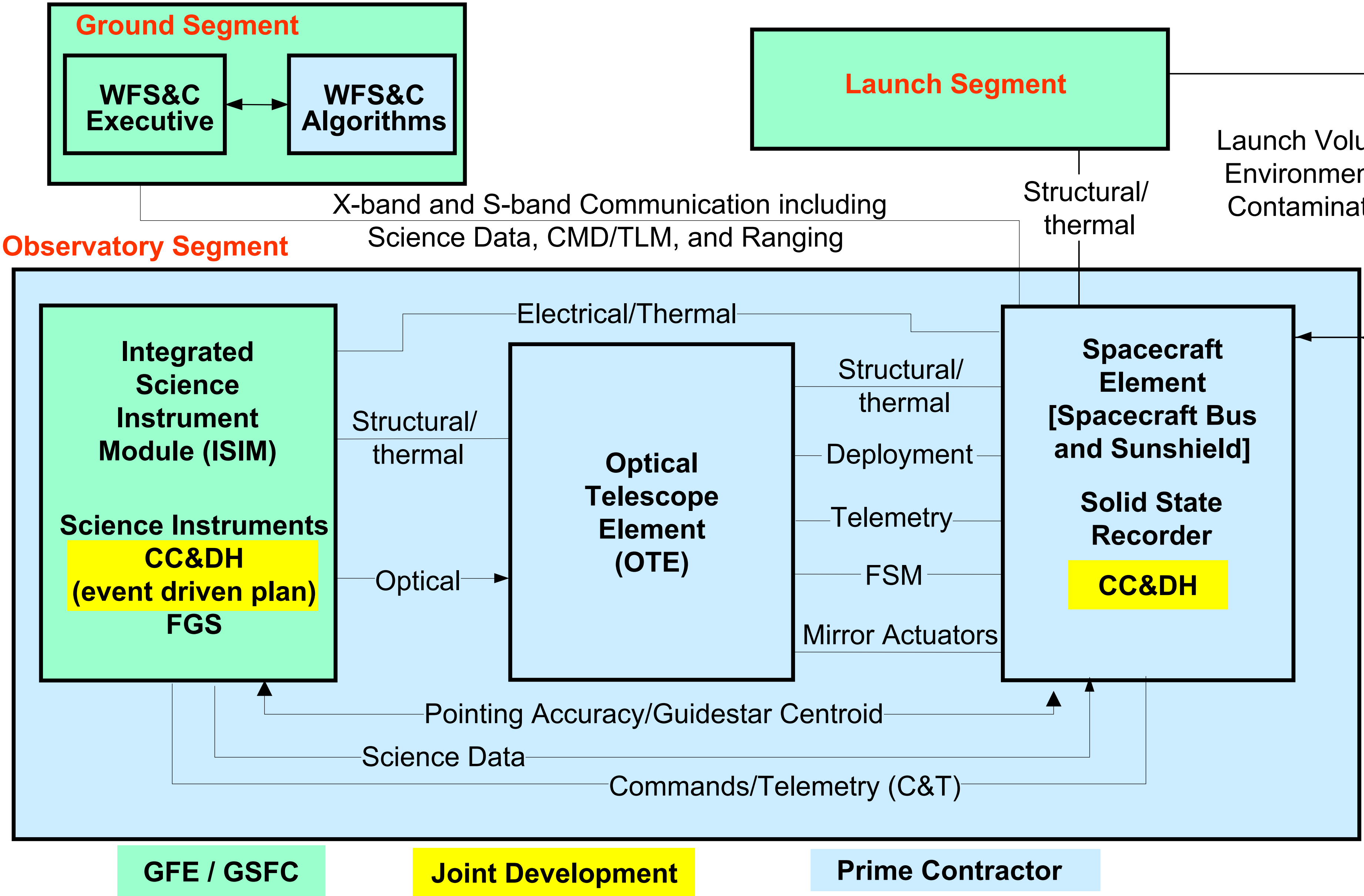
Observatory Partitioning and Interfaces Are Simple to Reduce Program AI&T Risk



Simple ISIM Interfaces Minimize Programmatic Risk as the SIs and FGS are Developed

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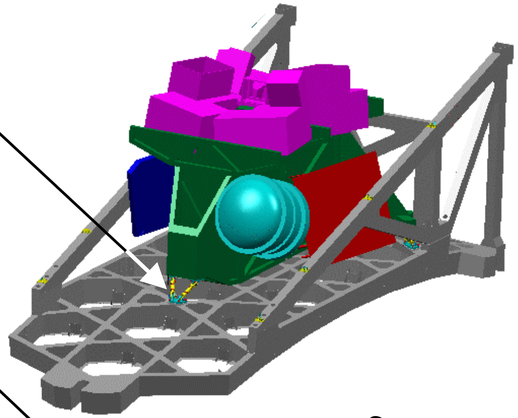
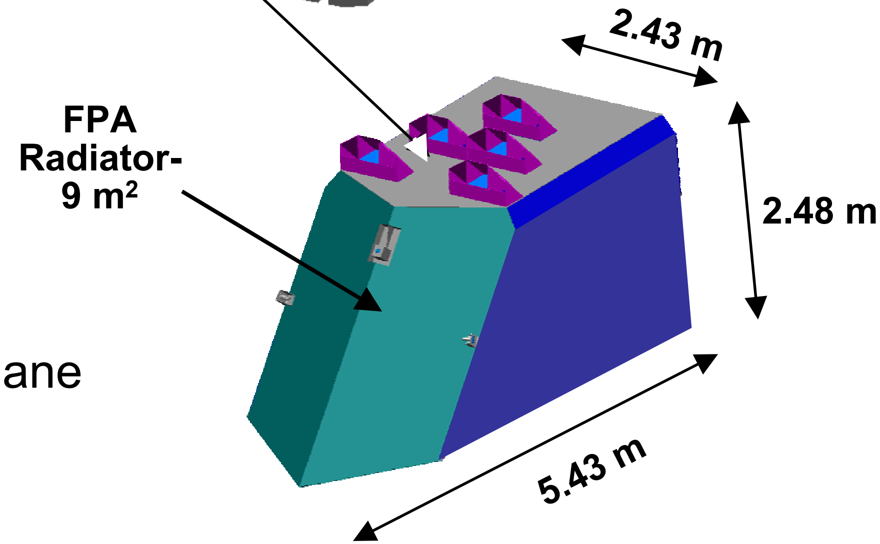
- **Mechanical interface**
  - Three-point kinematic mount to OTE
  - Significant mass margin at the Observatory level
- **Thermal interface**
  - Excellent view factor to space allowed by the two-chord-fold architecture
  - OTE under 40K
- **Packaging interface**
  - 23 cubic meters of volume
- **WFS&C interface**
  - Only items in NIRCam filter wheel, no pupil re-imagers
- **Optical interface**
  - Mounted to the OTE Primary mirror backplane
- **Electrical Interface**
  - 1355 data interface

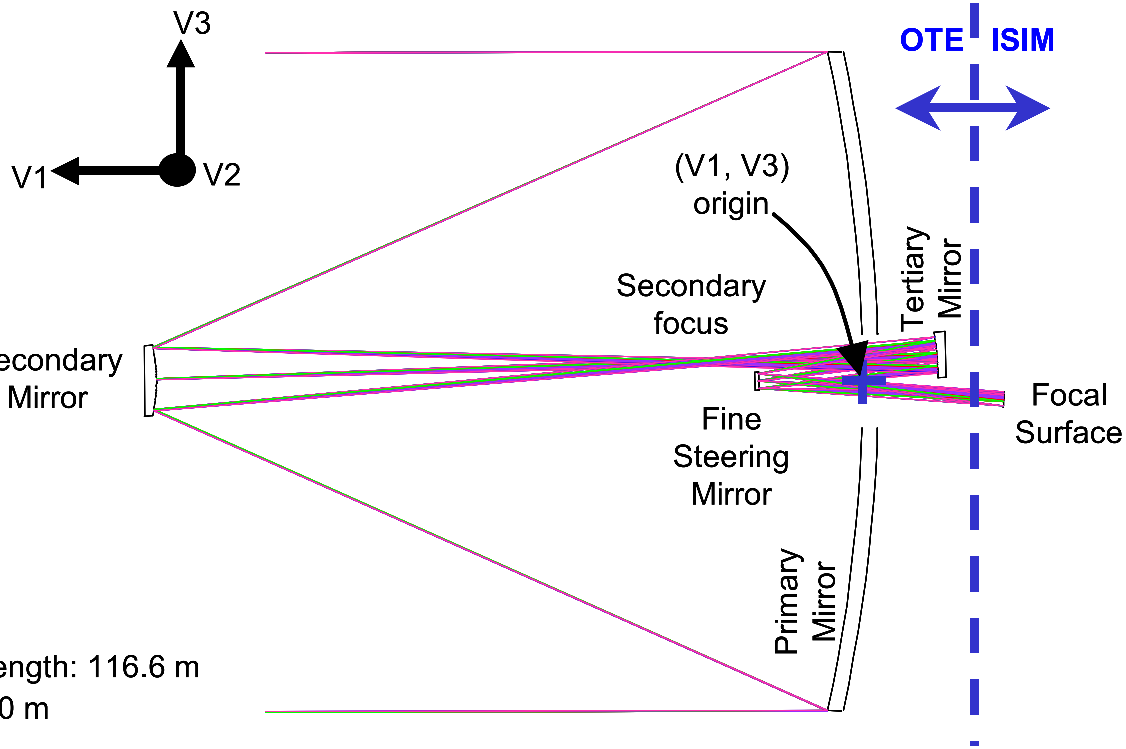




Keeping the interfaces simple gives GSFC greater design and schedule freedom, resulting in lower system cost and risk.

Observatory Optical Interfaces

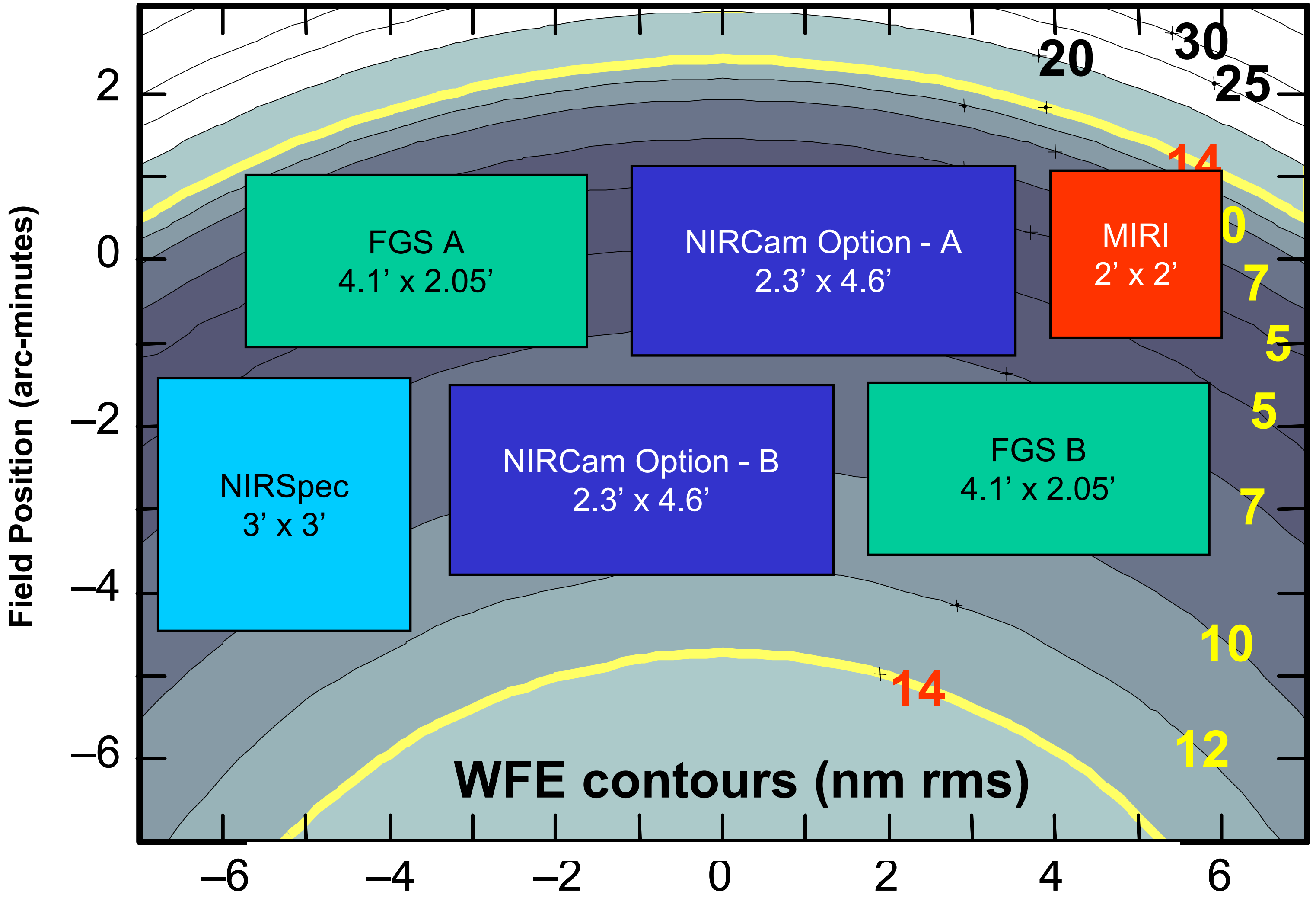
Component	ROC (mm)	Surface	K	V1 (mm)	V2 (mm)	V3 (mm)	Size (mm)
Primary	16000.0	concave	-0.995737	0.0	0.0	0.0	7000
Secondary	1895.7	convex	-1.716789	7187.9	0.0	0.0	814
Secondary focus			n-a	1515.5	0.0	182.3	230 X 92
Tertiary	3320.9	concave	-0.624719	-939.8	0.0	249.4	635 X 447
Fine steering mirror	infinity	flat	n-a	1100.0	0.0	0.0	200
Focal surface	3094.2	concave	n-a	- 1979.8	0.0	- 8.5	444 X 159



OTE
f/#: 16.7
Effective Focal Length: 116.6 m
PM diameter = 7.0 m

OTE f/# needs to be adjusted to provide final ISIM plate scale

Design Residual WFE Provides a Large FOV for Accommodating ISIM FPA Layouts



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

Population of FOV needs to be addressed relative to performance, packaging and spare FGS operations

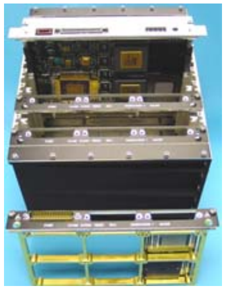
Spacecraft Interfaces Are Clearly Defined

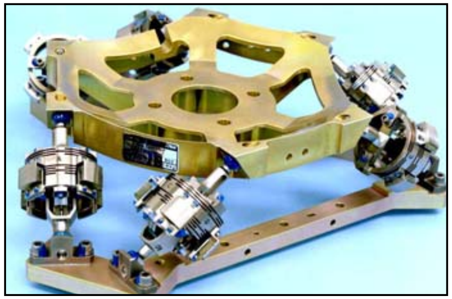
- Spacecraft is the primary interface to the Launch Vehicle
- Simple structural and electrical interfaces to the OTE and sunshield
  - Spacecraft will command all OTE deployments and actuators
  - No OTE software
- ISIM C&DH will be inside spacecraft (1355 interface)
- Avionics constituents of the spacecraft are primarily off the shelf
  - Flight-demonstrated heritage hardware
  - Upgrades as Integrated Avionics are available
  - Common C&DH is being jointly developed with GSFC

1-Hz Isolator

1-Hz Isolator in Test

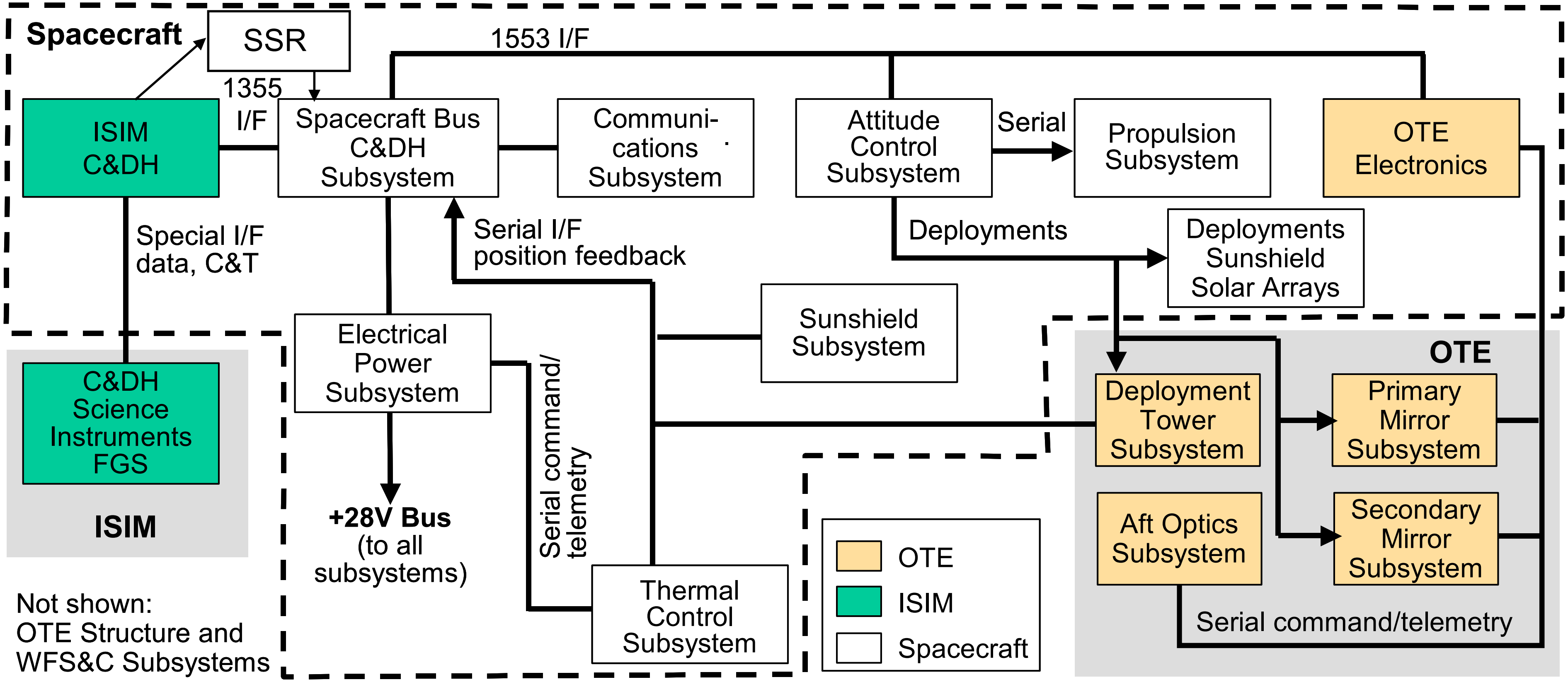
Integrated Avionics Unit





RWA Isolators Used on Chandra

Observatory Electrical Interfaces



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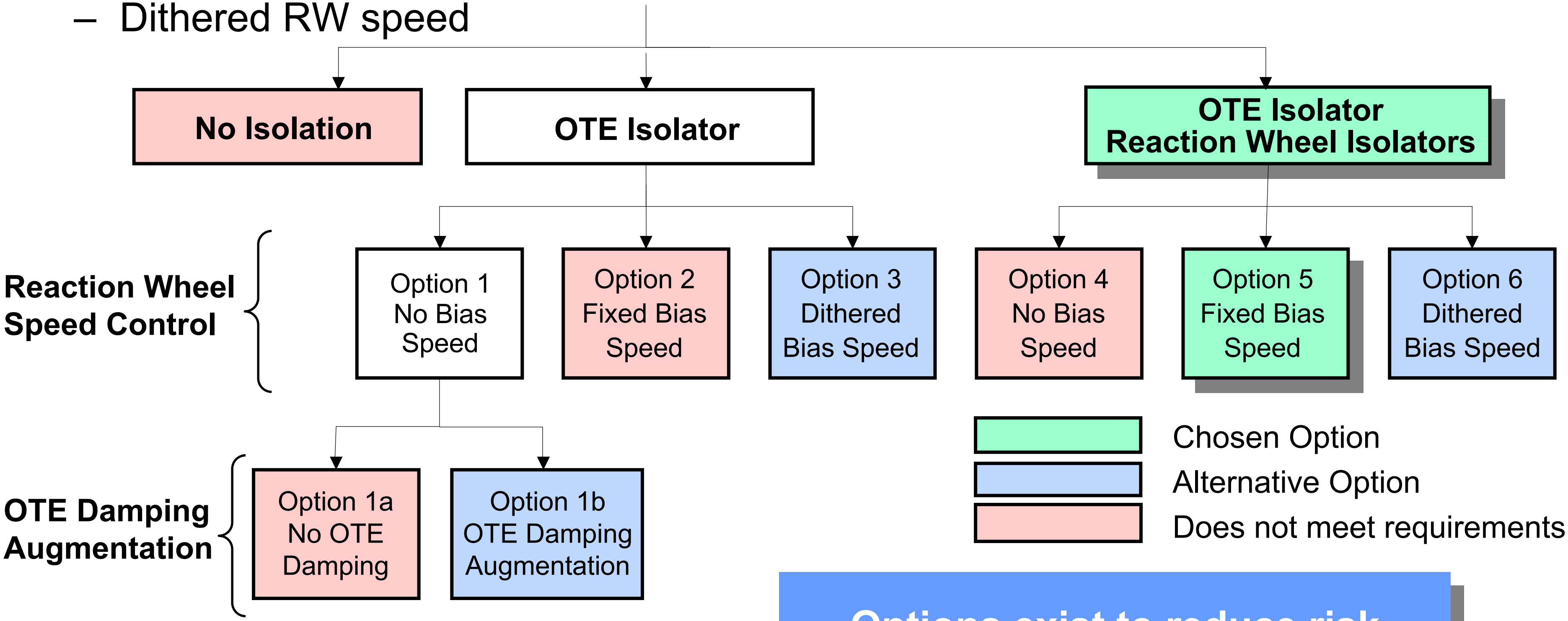
Chosen ACS/Passive Isolation System Architecture Has Margin for Ultra-Low Damping

- Two-stage isolator with six reaction wheels at fixed bias speed above 1200 rpm provides a robust performance even assuming worst case structural damping.
  - Reaction wheel isolator and fixed bias was used on Chandra
- Alternate passive isolation of the spacecraft dynamics
  - Reaction wheel (RW) passive isolators with alternatives
  - Augmented OTE damping
  - Dithered RW speed



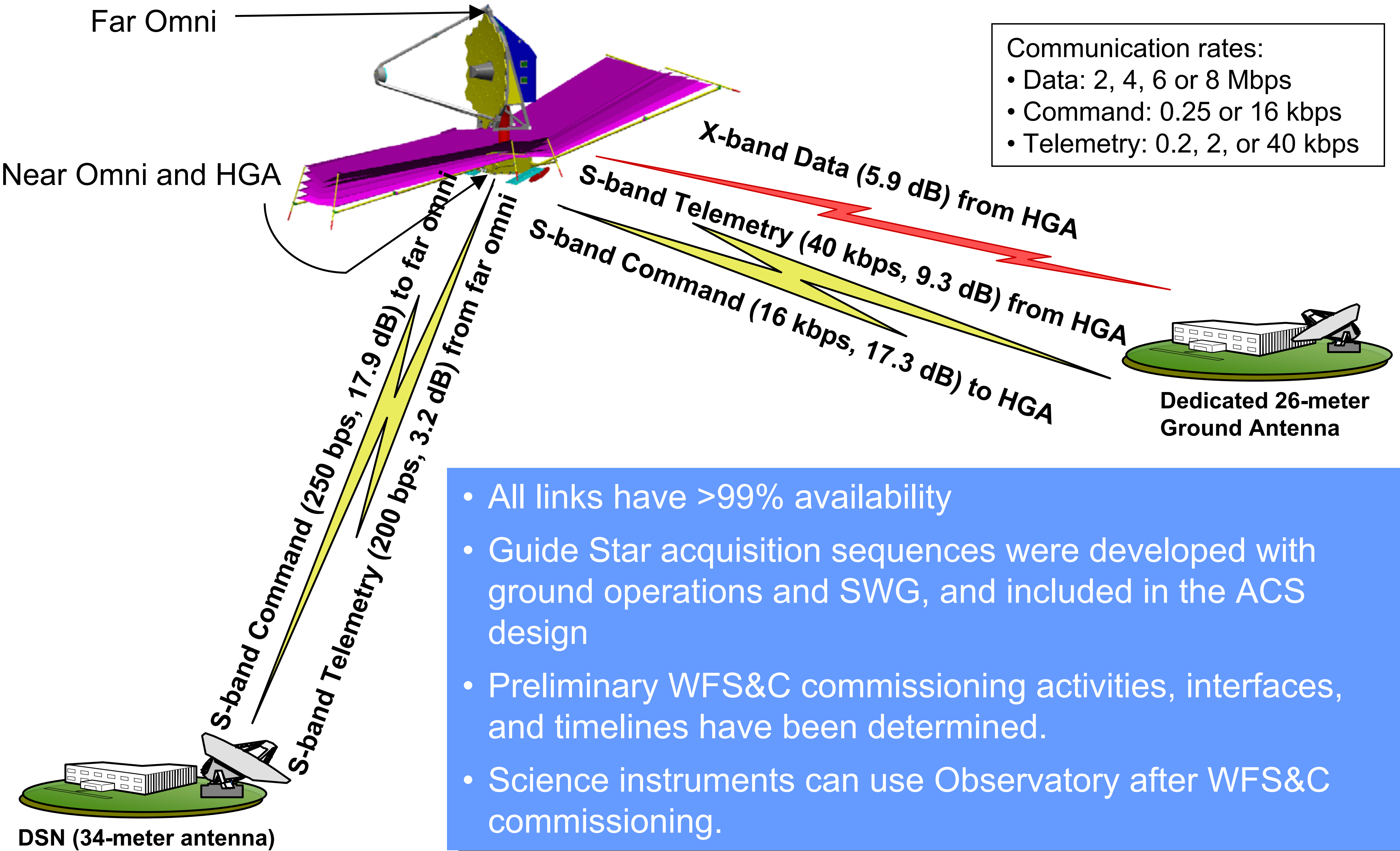
Options exist to reduce risk

Communication Link Budgets

Mode	Range (1000 km)	Spacecraft Antenna	Ground Station	Telemetry Rate bps	Telemetry Margin dB	Command Rate bps	Command Margin dB	X-band Rate Mbps	X-band Margin dB	Comments
Normal Operations										
Initial Capture	250	Far omni at 90 deg	Primary 26 mm	2k	4.37	2k	6.37	—	—	Spacecraft in any orientation
	500		DSN 34 m	2k	3.74	2k	19.32	—	—	
Nominal Orientation	500	Near omni at 70 deg	Primary 26 m	2k	5.44	2k	7.5	—	—	After orient spacecraft towards earth
	1000	HGA	DSN 34 m	2k	4.77	2k	20.51	—	—	
Commissioning/ Normal Operations	L2 (1,680)	HGA	Primary 26 m	40k	10.03	16k	15.22	8	6.55	Margin for 10 Mbps is 5.58 dB
Contingency										
Emergency	L2 (1680)	Far omni at 90 deg	DSN 34 m	200	3.28	2k	8.86	—	—	Use DSN for emergencies
			DSN 70 m	2k	3.61	16k	6.91	—	—	
Backup	L2 (1680)	Near omni at 70 deg	Primary 26 m	200	4.98	250	6.07	—	—	SC oriented towards earth in backup
			DSN 34 m	200	10.28	16k	6.99	—	—	
			DSN 70 m	2k	10.61	16k	14.08	—	—	

Significant Link Margins at a 10^{-7} BER provide assured communications for daily operations

Ground Interfaces Have Been Incorporated into Observatory Design and Operations



- All links have >99% availability
- Guide Star acquisition sequences were developed with ground operations and SWG, and included in the ACS design
- Preliminary WFS&C commissioning activities, interfaces, and timelines have been determined.
- Science instruments can use Observatory after WFS&C commissioning.

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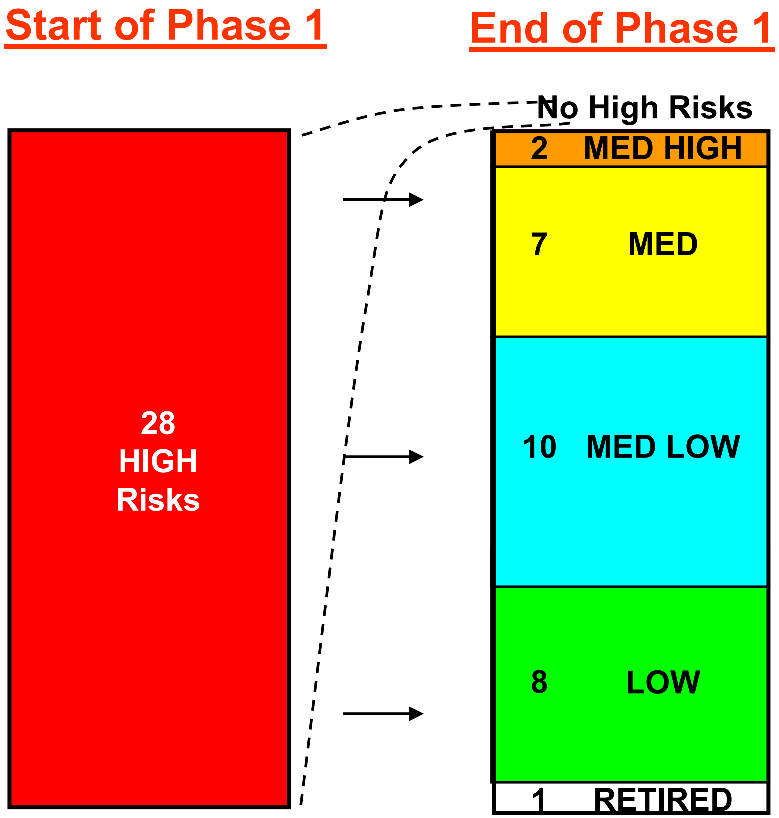
Phase 1 Significantly Reduced JWST Risk

- Observatory risk management focused activities on highest priority issues
  - Team trained in risk process, identified and analyzed risks at start and end of Phase 1
- Qualitative risk management process guided the risk reduction activity
  - Focused on highest risk technologies required for mission success
  - Phase 1 IR&D invested $25M in risk reduction in addition to the significant government risk reduction investment
- All high risks reduced to an acceptable level for entering Phase 2

Phase 1 activity eliminated known high risk performance items.



	Start Phase 1	End Phase 1
HIGH	28	0
MED HIGH	0	2
MED	7	9
LOW MED	0	16
LOW	0	11
RETIRED	0	-1
TOTAL RISKS	35	38

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James Webb Space Telescope

Our Observatory Plan Features Pathfinders for Early Risk Retirement

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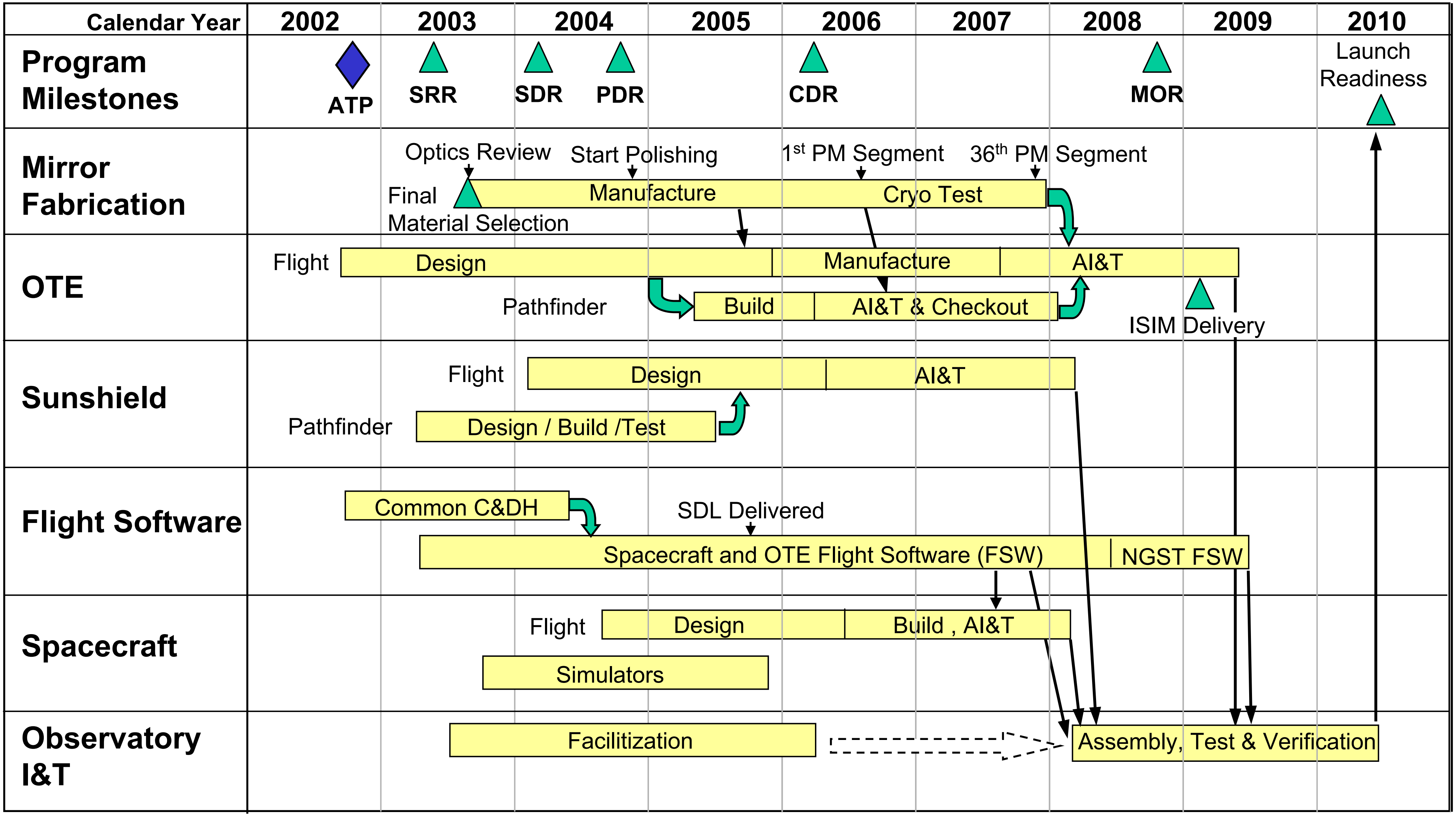
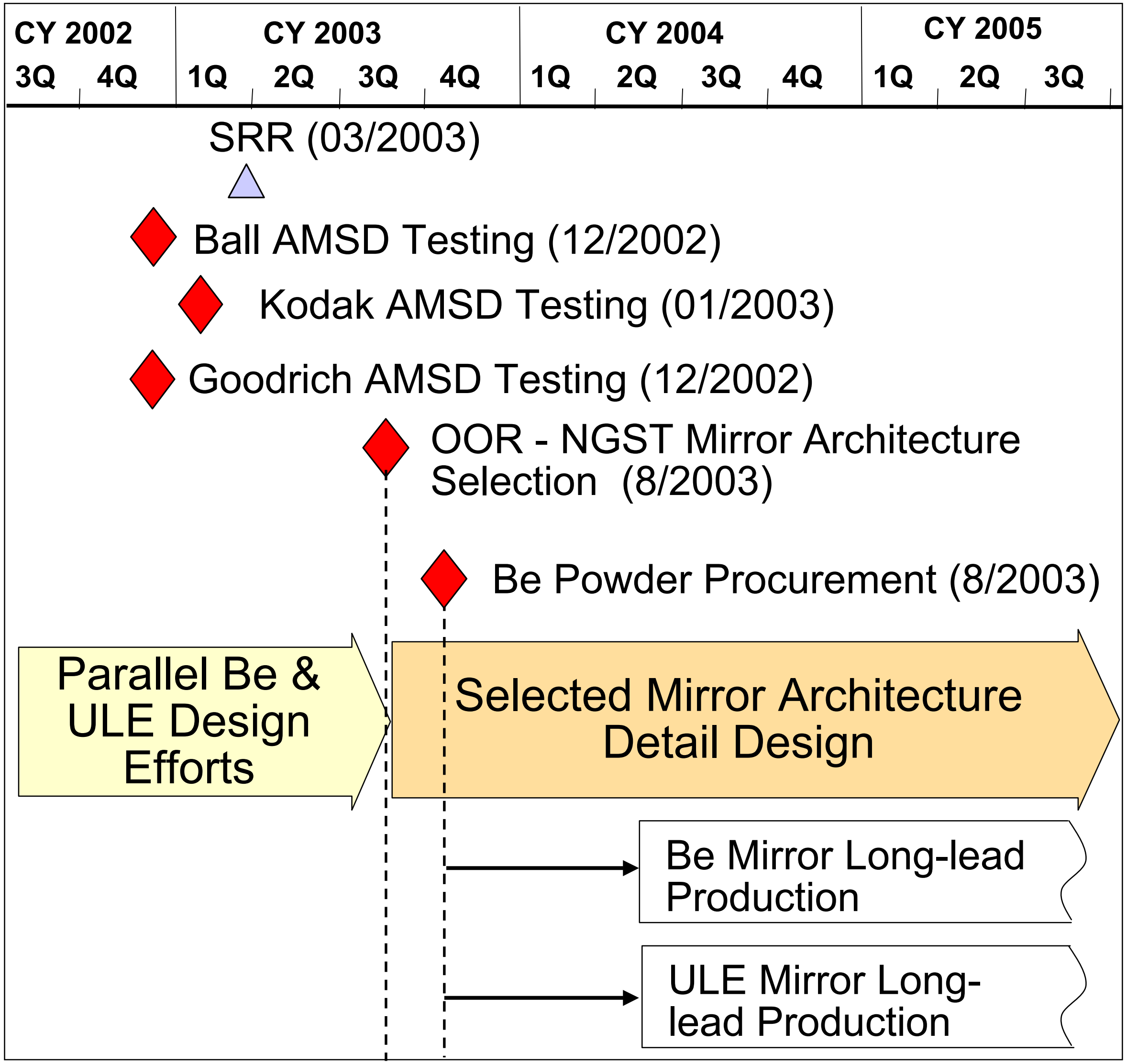
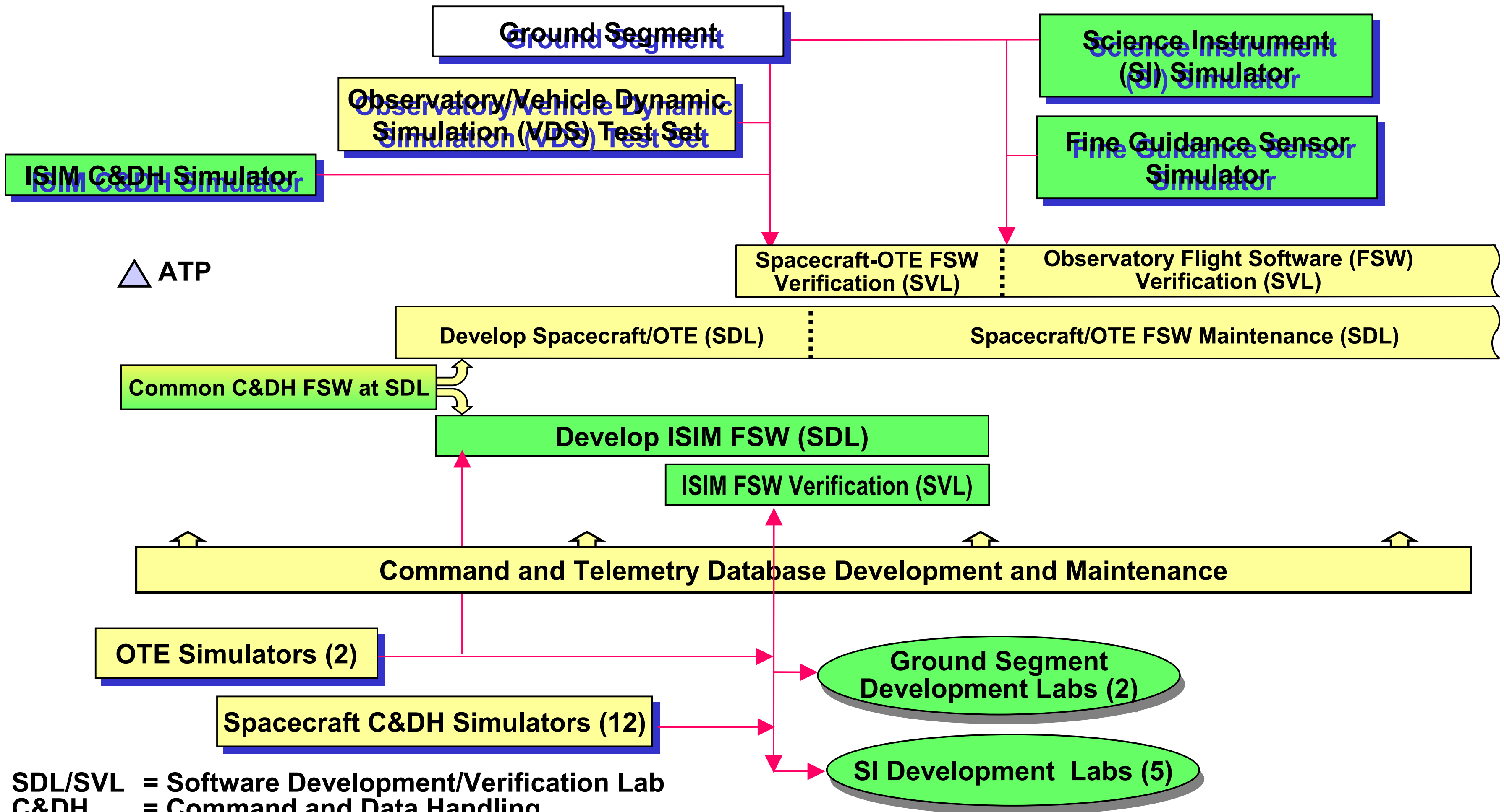


Schedule Allows Use of AMSD Cryogenic Test Data for Mirror Material Selection



Flight Software Development Facilities Integrated with ISIM and Ground Development to Reduce AI&T Risk



SDL/SVL = Software Development/Verification Lab
C&DH = Command and Data Handling
FSW = Flight Software

TRW

GFE/Non-prime facility

Schedule risk mitigated with multiple development labs and spacecraft interface testing prior to Observatory I&T.

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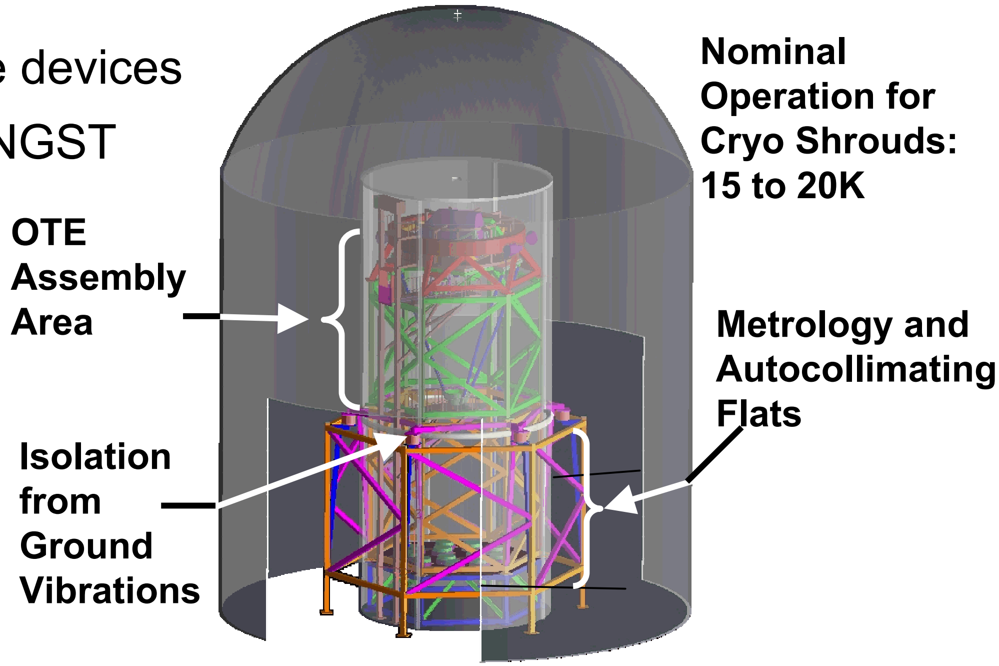
Architecture Allows for High Fidelity End-to-End Optical Performance Test During AI&T

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

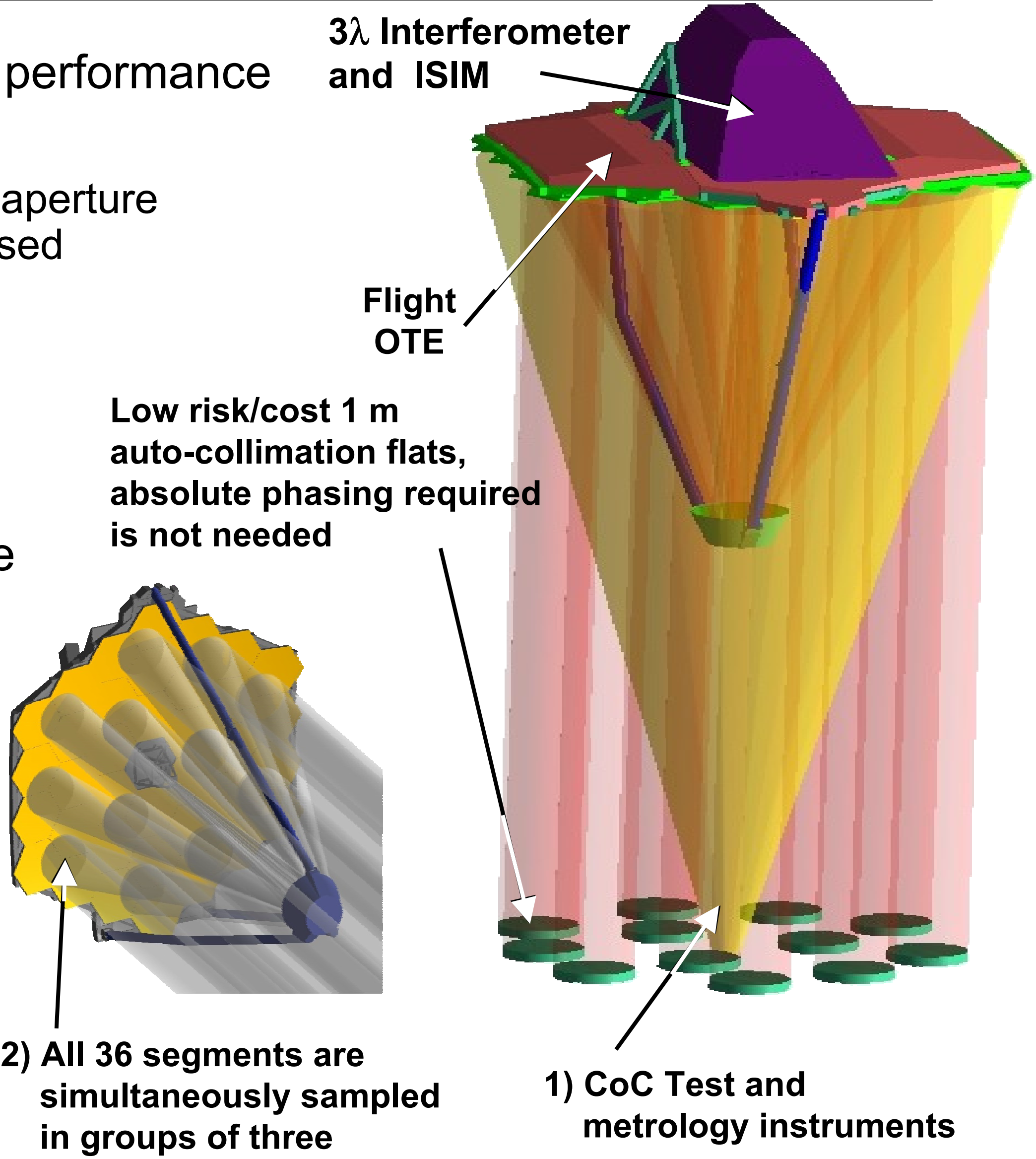


Plum Brook facility is the system solution.

Sampled Aperture Test Verifies End-to-End Optical Performance Prior to Launch

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

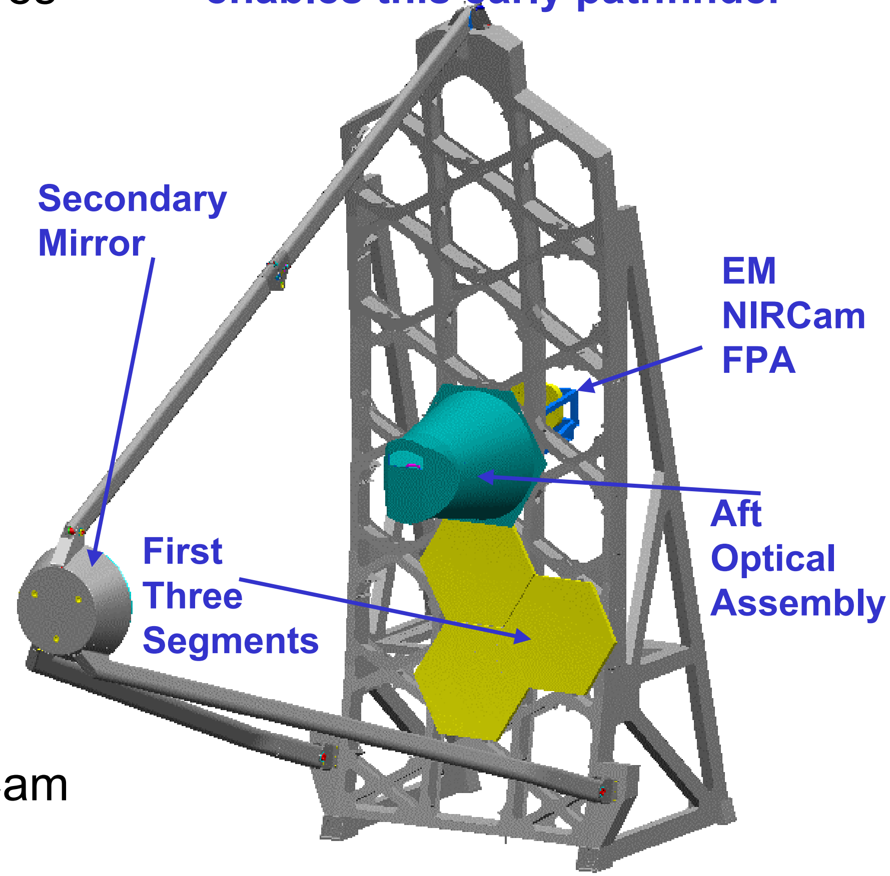
End-to-end optical performance is thoroughly verified prior to launch.



Demonstration of I&T and Performance Using OTE Pathfinder Reduces Downstream Schedule Risk

- Checkout of test facility, metrology, and procedures
  - Vibration isolation and damping at cryogenic temperature
- Dry run processes and test procedures
  - Hardware installation, offloading, and ISIM interface
  - Thermal and optical tests
- Provides 19 months to modify/upgrade test hardware and procedures
- Provides first system performance tests:
  - Entire OTE with thermal sensitivities
  - Thermal balance test
  - WFS&C using engineering model (EM) NIRCam FPA/FPE and flight optics on EM structure

Modularity of 36 segments enables this early pathfinder



Pathfinder mitigates the majority of OTE risks Nexus was envisioned to do, at an affordable cost.

Work During Blackout Period

- Phase 1 Contract Modification 20
  - Integrated Modeling Tasks – results will be part of the IM splinter
  - Support STScI in developing ground system architecture requirements – results to be discussed in ground splinter
  - OTE optical simulator approach and preliminary spec – OTE splinter
  - Wavefront Control analysis - OTE splinter
  - Preliminary flight software product plan – Flight Software Splinter
- Draft version of the Observatory Specification
- AMSD Progress – OTE splinter
- Cryogenic actuator development – OTE splinter
- Wavefront Sensing & control Process – OTE splinter
- Sampled Full Aperture Testing – OTE splinter
- Cryogenic multi-mirror testing – OTE splinter
- Integrated Avionics – Spacecraft splinter

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Summary

- Observatory meets technical requirements with margin and is cost effective
- Observatory architecture is simple and robust
  - Hexagonal segments can be implemented in Be or ULE
  - Primary mirror chord-fold coupled with sunshield provides a passive and thermally uniform telescope resulting in a stable PSF
  - WFS&C is simple and straightforward – solution is deterministic
- Observatory architecture is low risk
  - Beryllium is a demonstrated and proven cryogenic material – data on properties exists
  - Deployment is simple, has minimum components and is based on flight-proven concepts
  - Optical performance is known before launch – full unambiguous determination of end-to-end optical performance
  - OTE and Sunshield pathfinders reduce AI&T risk

We are Thrilled to be part of the
James Webb Space Telescope Team