Roman Space Telescope Optical System:

Status and Test

SPIE Mirror Tech Days
November 15, 2023
Huntsville, AL

Matthew R. Bolcar
Roman Optical Systems Lead
Goddard Space Flight Center

• NASA GODDARD SPACE FLIGHT CENTER • JET PROPULSION LABORATORY •
• L3HARRIS TECHNOLOGIES • BALL AEROSPACE • TELEDYNE • NASA KENNEDY SPACE CENTER •
• SPACE TELESCOPE SCIENCE INSTITUTE • IPAC • EUROPEAN SPACE AGENCY •
• JAPAN AEROSPACE EXPLORATION AGENCY • LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE •
• CENTRE NATIONAL d'ÉTUDES SPATIALES • MAX PLANCK INSTITUTE FOR ASTRONOMY •

Observatory Description

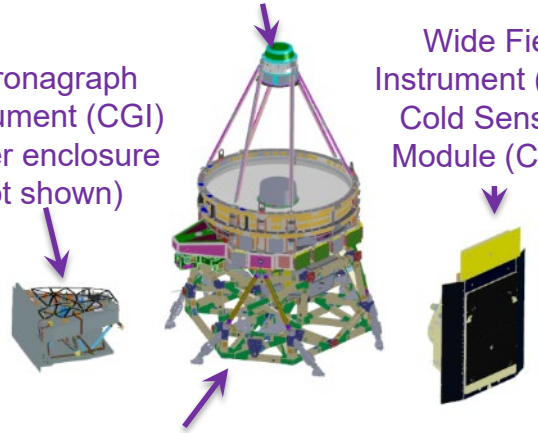
Observatory = Spacecraft + Integrated Payload Assembly

Imaging Optics Assembly (IOA)

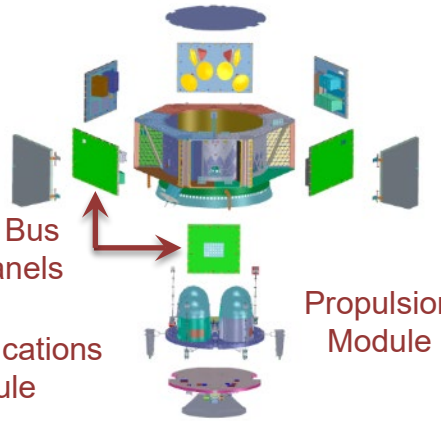
Coronagraph Instrument (CGI) (outer enclosure not shown)

Wide Field Instrument (WFI)

Cold Sensing Module (CSM)

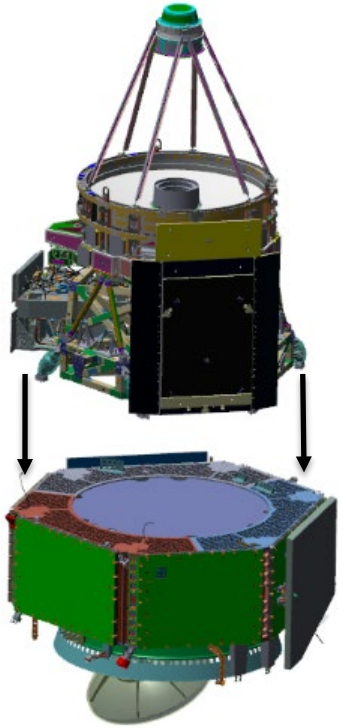


Instrument Carrier (IC)



SCIPA

Integrated Payload Assembly (IPA)



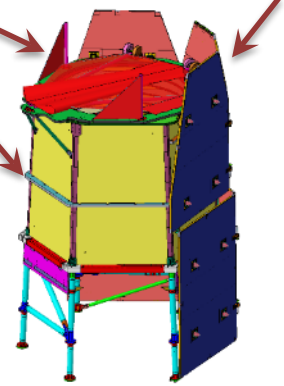
Spacecraft Bus

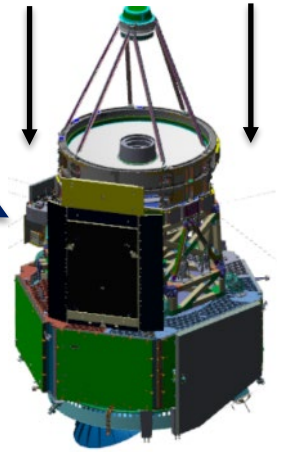
OSD (OBA/SASS/DAC)

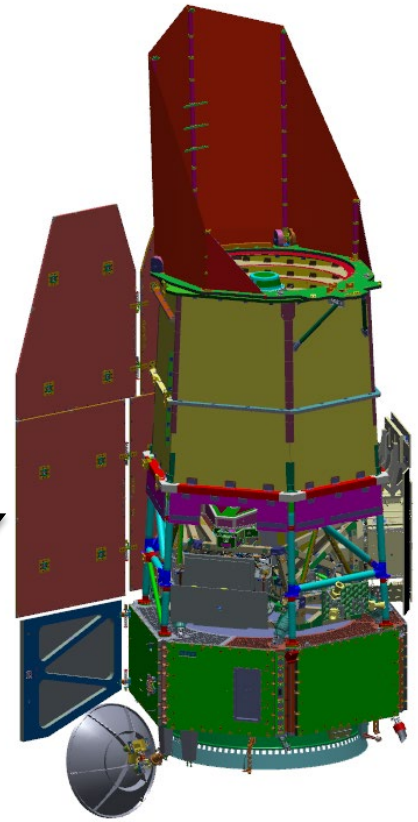
Deployable Aperture Cover (DAC)

Solar Array Sun Shield (SASS)

Outer Barrel Assembly (OBA)



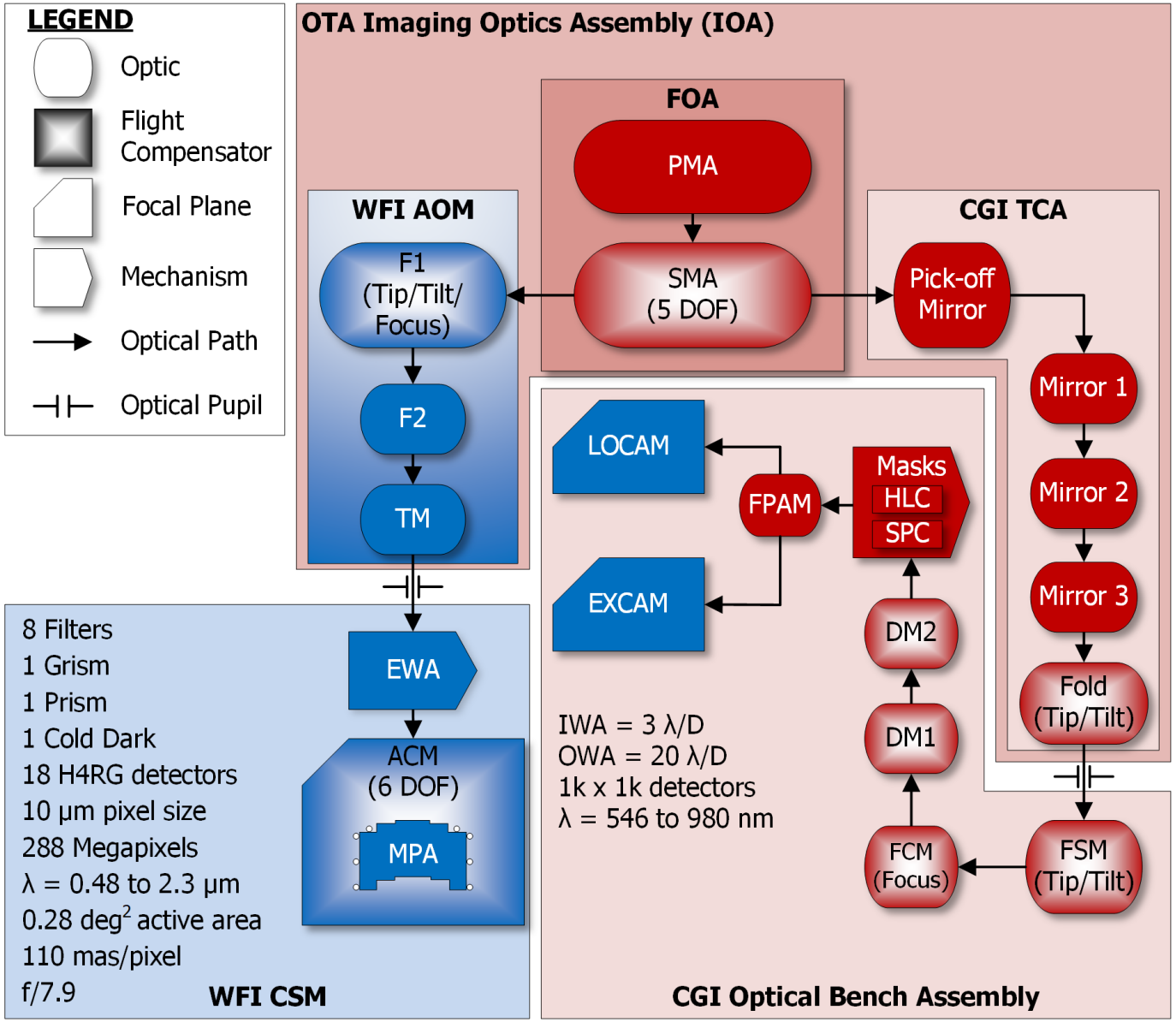




Observatory

OPTICAL SYSTEM OVERVIEW

Optical System Block Diagram



AOM = Aft Optics Module

ACM = Alignment Compensation Mechanism

CGI = Coronagraph Instrument

CSM = Cold Sensing Module

DM = Deformable Mirror

DOF = Degree of Freedom

EWA = Element Wheel Assembly

EXCAM = Exoplanet Camera

FOA = Forward Optics Assembly

FCM = Focus Control Mechanism

F1/F2 = Fold Mirror 1/2

FOA = Forward Optics Assembly

FPAM = Focal Plane Mask Precision Alignment Mechanism

FSM = Fast Steering Mirror

HLC = Hybrid Lyot Coronagraph

IOA = Imaging Optics Assembly

IWA = Inner Working Angle

LOCAM = Low Order Wavefront Sensing Camera

MPA = Mosaic Plate Assembly

OTA = Optical Telescope Assembly

OWA = Outer Working Angle

PMA = Primary Mirror Assembly

RCS = Relative Calibration System

SMA = Secondary Mirror Assembly

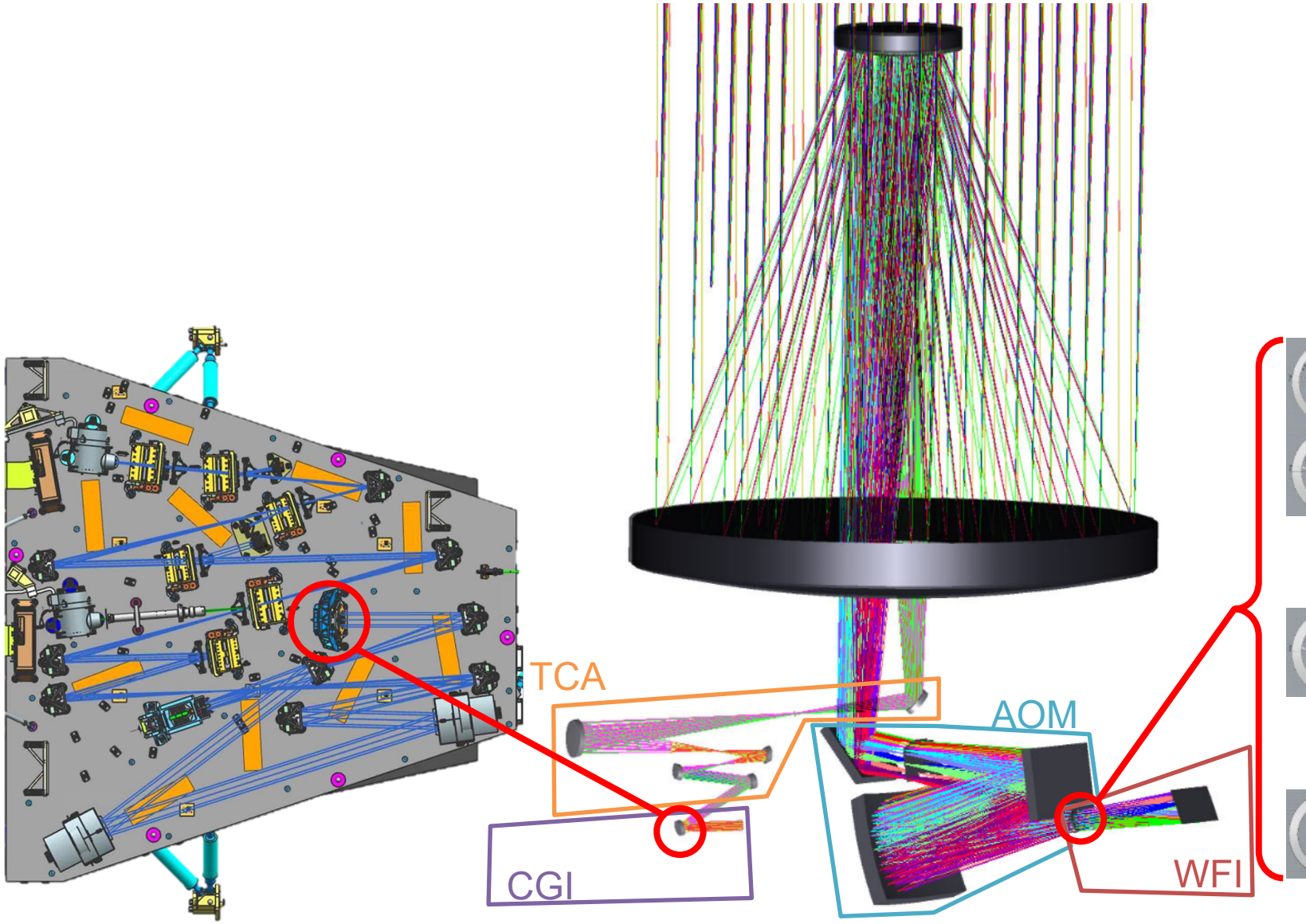
SPC = Shaped Pupil Coronagraph

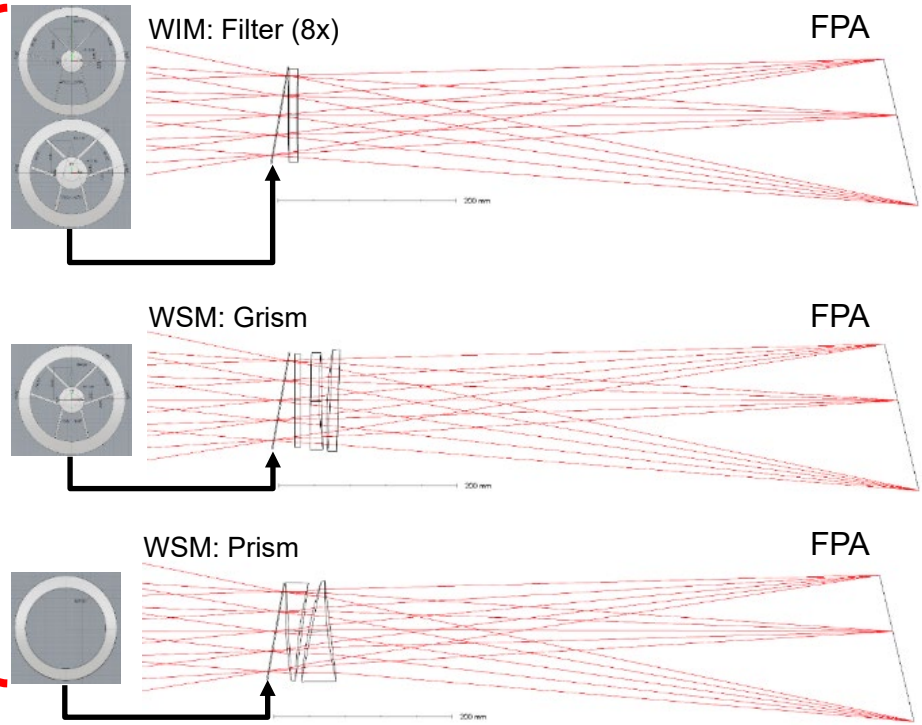
TCA = Tertiary Collimator Assembly

TM = Tertiary Mirror

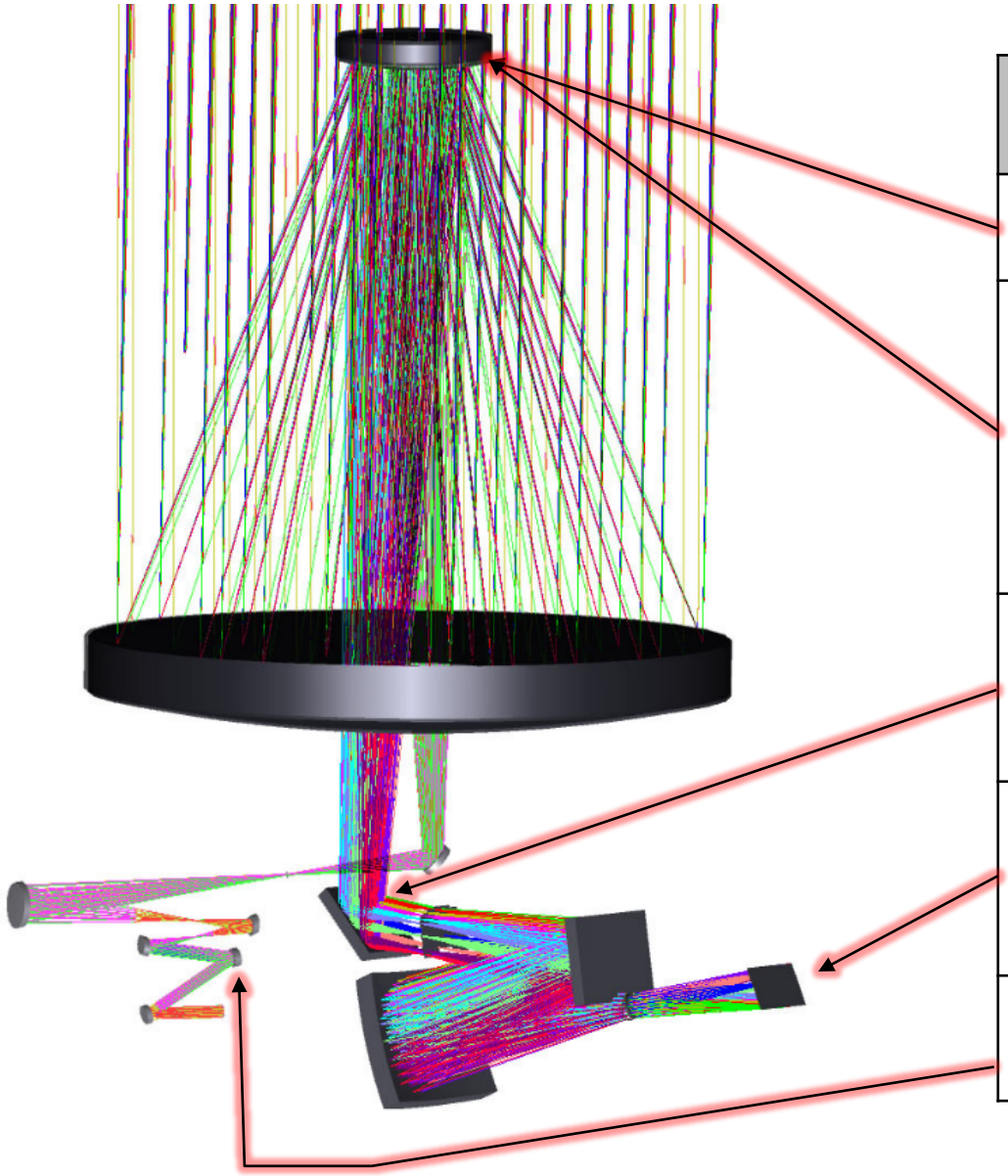
WFI = Wide Field Instrument

Optical Path





Optical Compensators



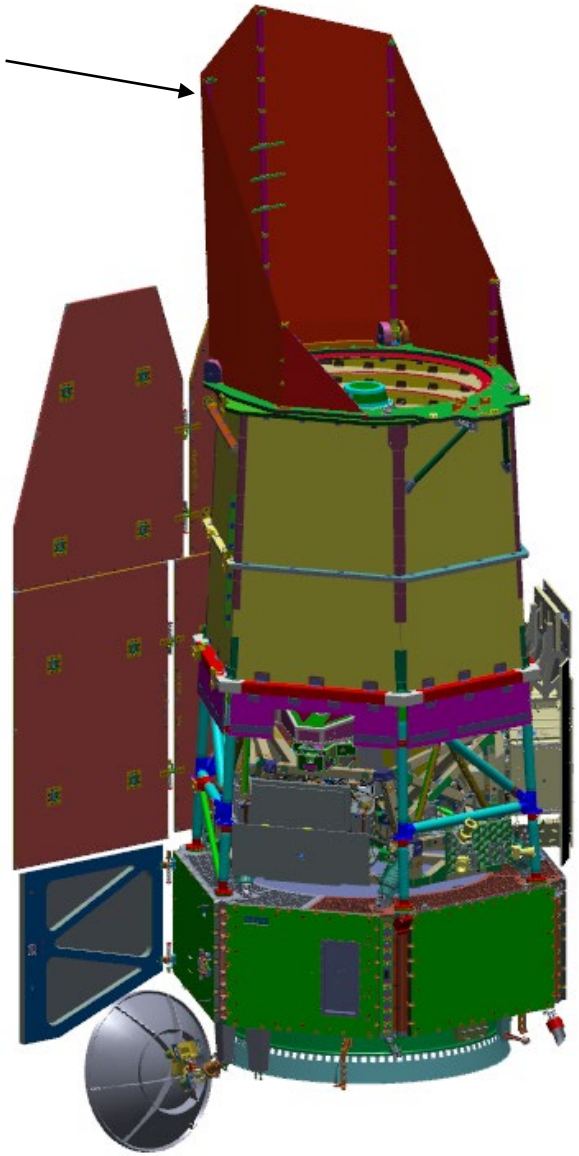
Compensator	Degree of Freedom	
SM Focus Drives (FD)*	Defocus	Compensate Wavefront Error (WFE) Errors Common to Each Channel
SM Alignment Drives (AD)*	Decenter (x)	
	Decenter (y)	
	Defocus	
	Tip	
	Tilt	
AOM Fold Mirror 1 (FM1)	Defocus	Compensate Focus & Pupil Shear in WFI Channel
	Tip	
	Tilt	
WFI Alignment Compensation Mechanism (ACM)†	Defocus	
	Tip	
	Tilt	
TCA Tip/Tilt Fold (TTF)	Tip	Compensate Pupil Shear in CGI Channel
	Tilt	

*Heritage actuators from previous program

†Heritage JWST actuators

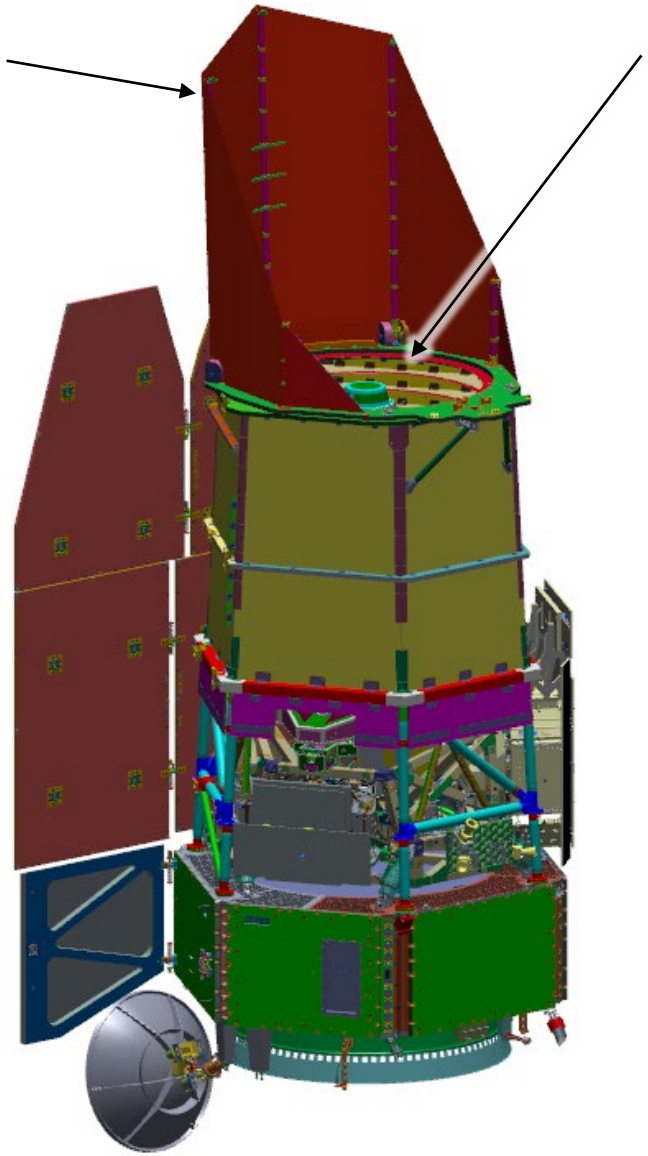
Stray Light Controls

Deployable Aperture Cover
keeps direct sun from entering
the Outer Barrel Assembly (OBA)



Stray Light Controls

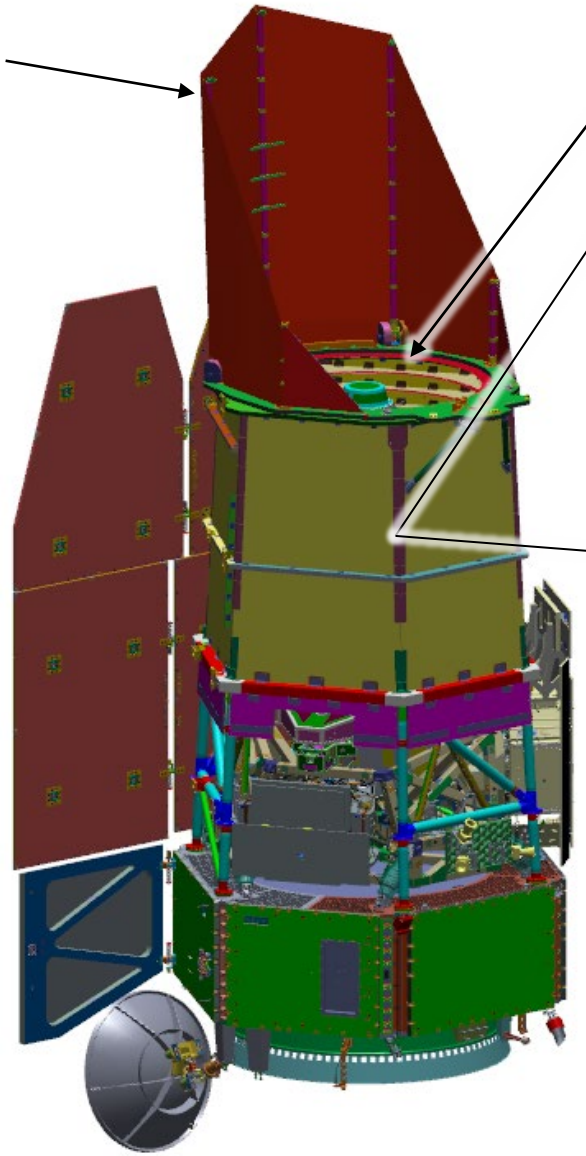
Deployable Aperture Cover keeps direct sun from entering the Outer Barrel Assembly (OBA)



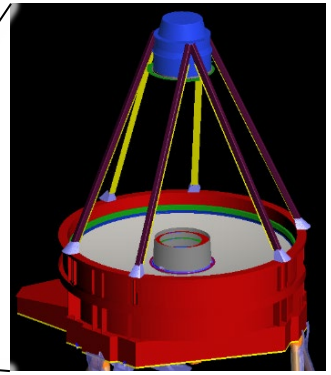
OBA Baffle Vanes limit view of OBA walls from sky & PM.

Stray Light Controls

Deployable Aperture Cover keeps direct sun from entering the Outer Barrel Assembly (OBA)



OBA Baffle Vanes limit view of OBA walls from sky & PM.



Scrapers on SM and support tubes limit reflections from blankets

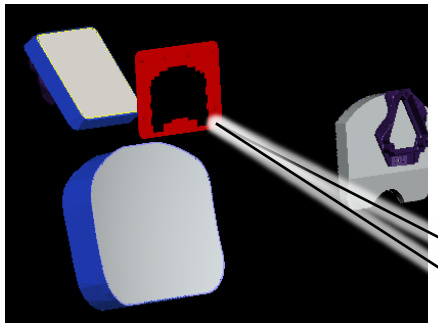
PM Baffle prevents direct view of FM1 from sky

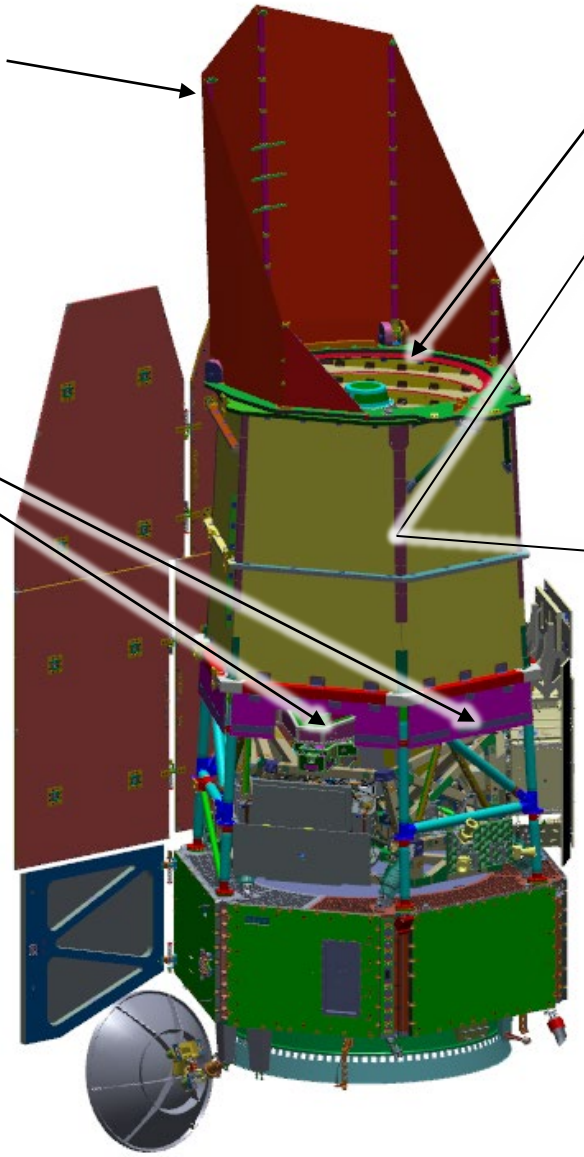
Stray Light Controls

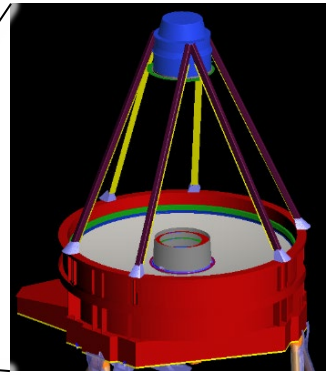
Deployable Aperture Cover keeps direct sun from entering the Outer Barrel Assembly (OBA)

OBA Baffle Vanes limit view of OBA walls from sky & PM.

Entrance aperture plates limit out-of-field light in each instrument (WFI shown)







Scrapers on SM and support tubes limit reflections from blankets

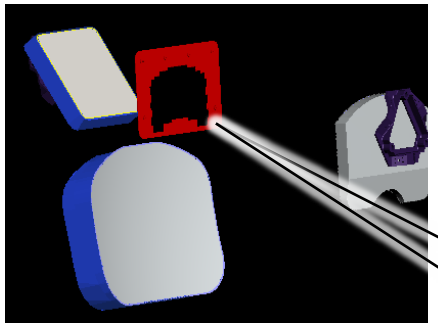
PM Baffle prevents direct view of FM1 from sky

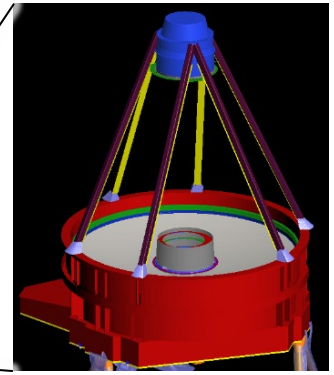
Stray Light Controls

Deployable Aperture Cover keeps direct sun from entering the Outer Barrel Assembly (OBA)

OBA Baffle Vanes limit view of OBA walls from sky & PM.

Entrance aperture plates limit out-of-field light in each instrument (WFI shown)

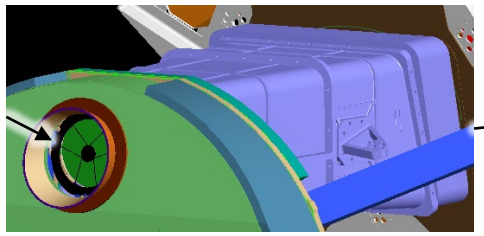


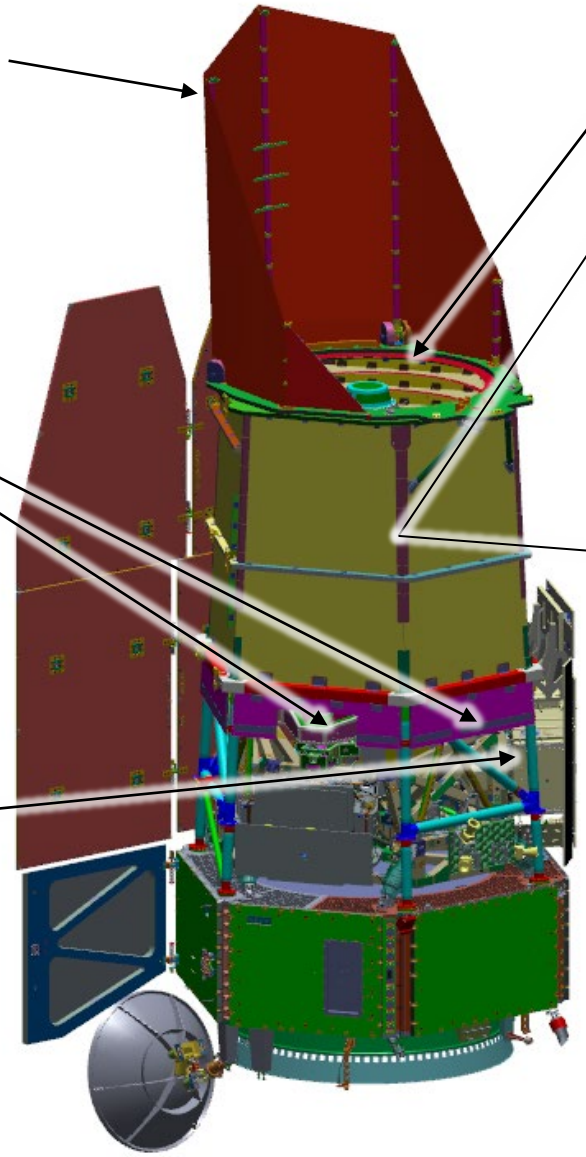


Scrapers on SM and support tubes limit reflections from blankets

PM Baffle prevents direct view of FM1 from sky

Stray light guards seal gap between instrument & IOA (WFI shown)

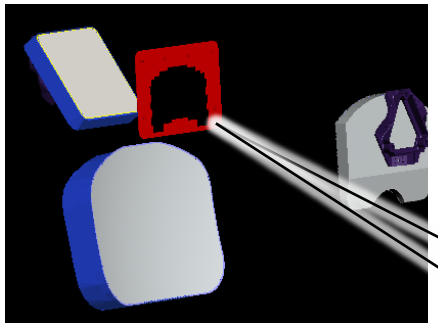




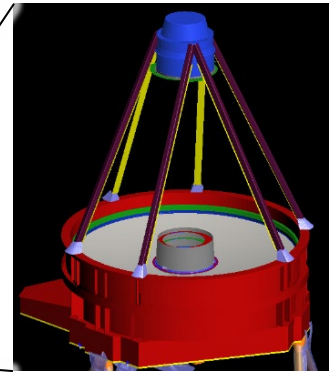
Stray Light Controls

Deployable Aperture Cover keeps direct sun from entering the Outer Barrel Assembly (OBA)

OBA Baffle Vanes limit view of OBA walls from sky & PM.

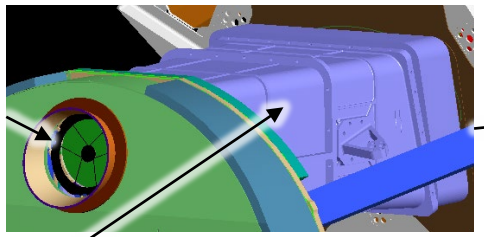


Entrance aperture plates limit out-of-field light in each instrument (WFI shown)

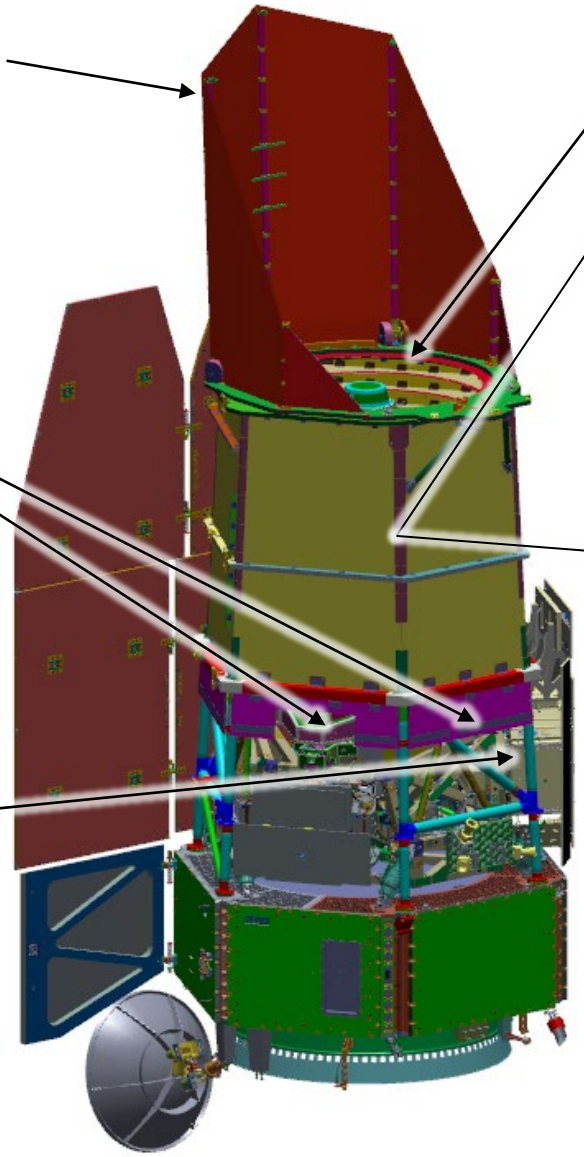


Scrapers on SM and support tubes limit reflections from blankets

PM Baffle prevents direct view of FM1 from sky



Stray light guards seal gap between instrument & IOA (WFI shown)



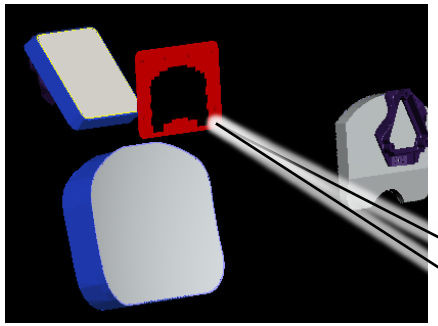
Cold Optics Baffle Assembly provides dark cold environment for WFI FPA
CGI Blanket prevents direct view of sky (not shown)

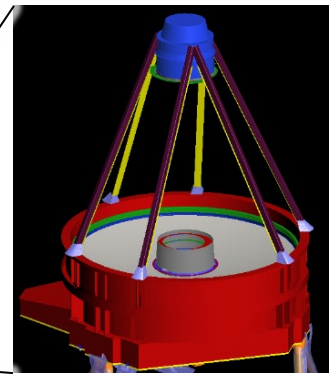
Stray Light Controls

Deployable Aperture Cover keeps direct sun from entering the Outer Barrel Assembly (OBA)

OBA Baffle Vanes limit view of OBA walls from sky & PM.

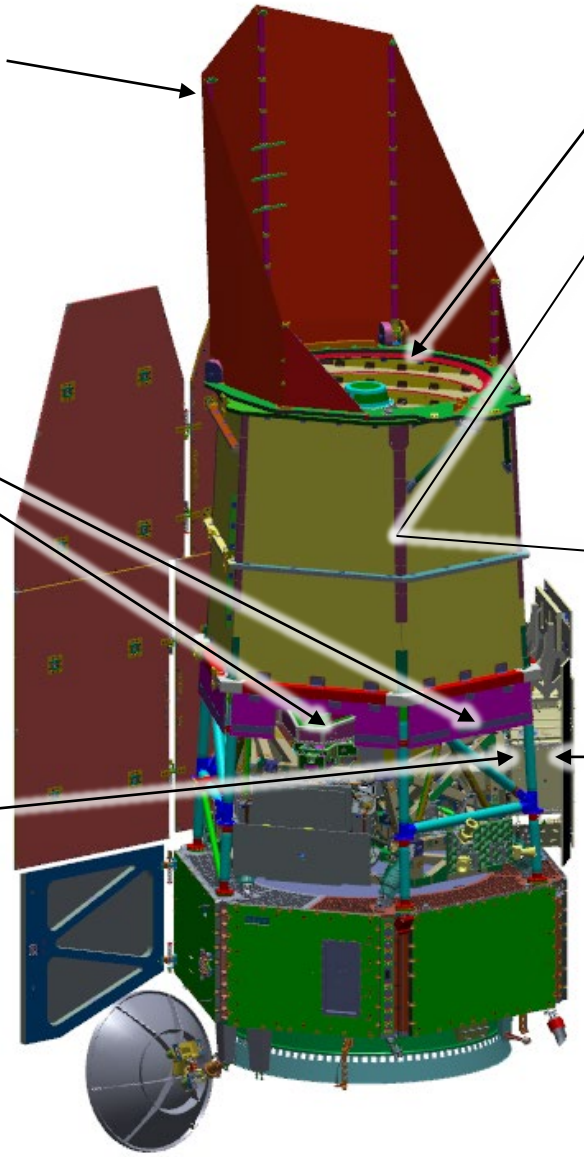
Entrance aperture plates limit out-of-field light in each instrument (WFI shown)



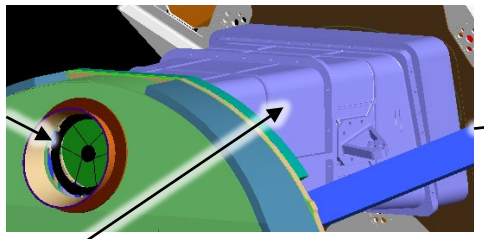


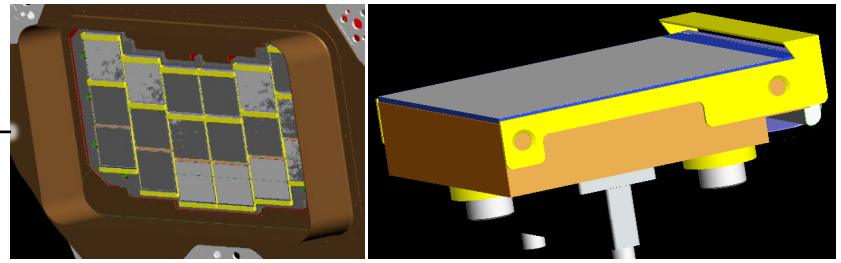
Scrapers on SM and support tubes limit reflections from blankets

PM Baffle prevents direct view of FM1 from sky



Stray light guards seal gap between instrument & IOA (WFI shown)





Labyrinth seal allows movement of the FPA while closing stray light paths

Cold Optics Baffle Assembly provides dark cold environment for WFI FPA
CGI Blanket prevents direct view of sky (not shown)

SCA Wirebond Shield blocks out-of-field light from shiny gold wires & bonds

TEST AND VERIFICATION SUMMARY

Optical Alignment & WFE Verification Summary

Component Level

Primary Mirror ✓
(1) Offner Null & g-offload @Ambient
(2) CGH Null & g-offload @Ambient & Cold

→

Primary Mirror Assembly ✓
(1) CGH Null & g-offload @Cold
(2) 1g CGH @Cold
(3) 0g x-check horizontal multi-orientation @Ambient

Other Optical Assemblies ✓
(1) Component & Assembly interferometry @Ambient
(2) Assembly interferometry @Cold (Tertiary mirror only)

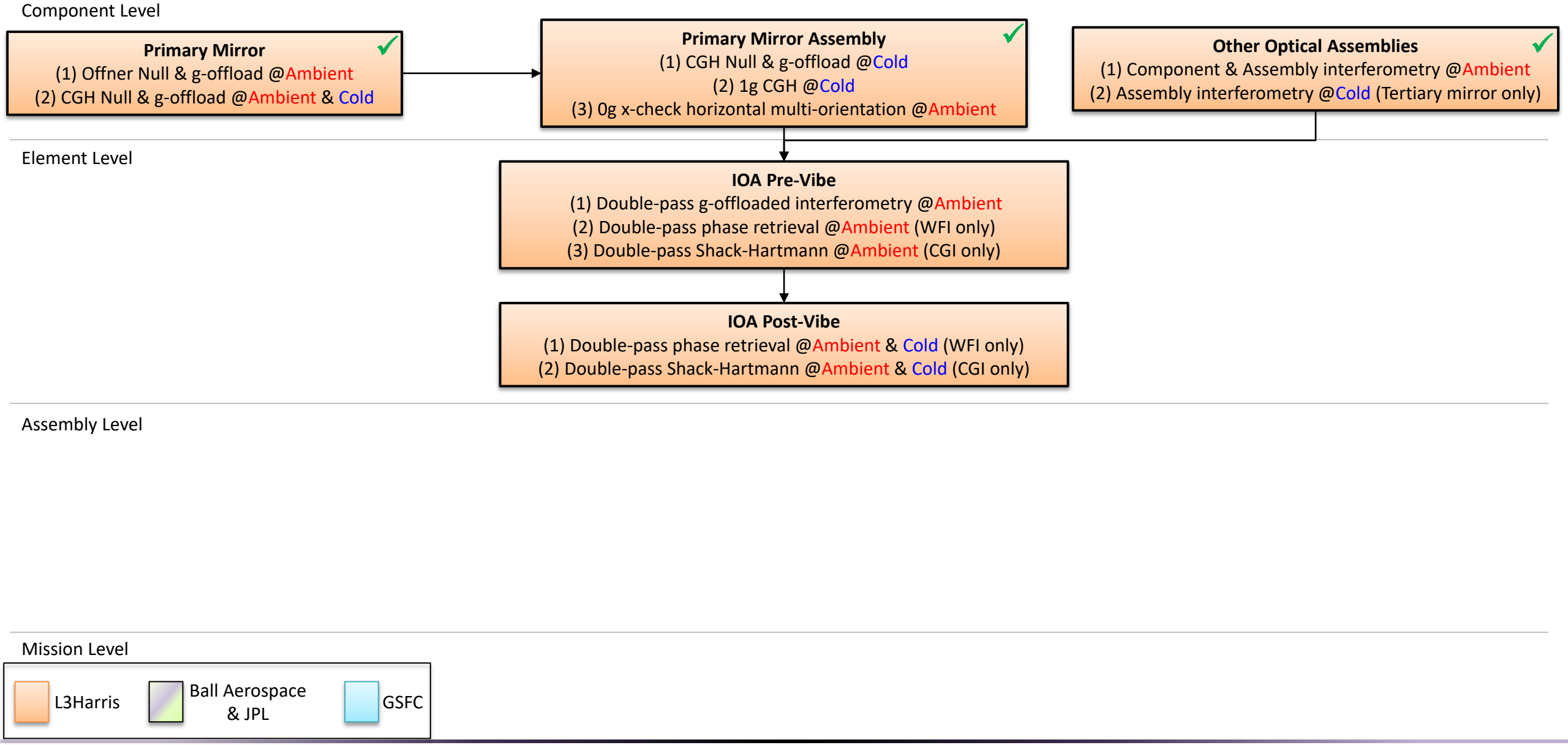
Element Level

Assembly Level

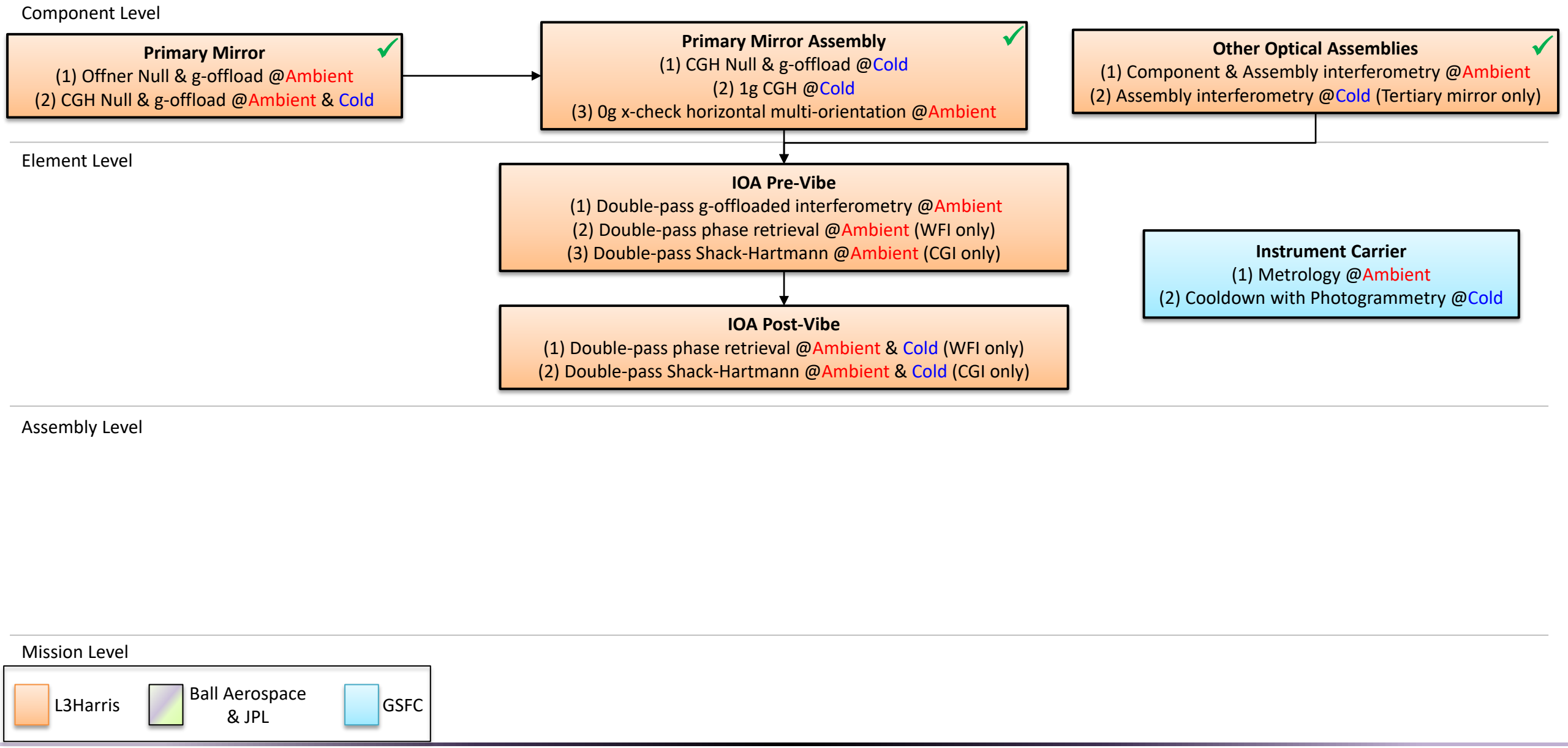
Mission Level

L3Harris | Ball Aerospace & JPL | GSFC

Optical Alignment & WFE Verification Summary



Optical Alignment & WFE Verification Summary



Optical Alignment & WFE Verification Summary

Component Level

Primary Mirror ✓
(1) Offner Null & g-offload @Ambient
(2) CGH Null & g-offload @Ambient & Cold

Primary Mirror Assembly ✓
(1) CGH Null & g-offload @Cold
(2) 1g CGH @Cold
(3) 0g x-check horizontal multi-orientation @Ambient

Other Optical Assemblies ✓
(1) Component & Assembly interferometry @Ambient
(2) Assembly interferometry @Cold (Tertiary mirror only)

Element Level

IC Simulator given to WFI and CGI to place latches and check alignment ✓

Instrument WFE & Alignment verification testing performed on GSE Interface @Ambient & Cold

IOA Pre-Vibe
(1) Double-pass g-offloaded interferometry @Ambient
(2) Double-pass phase retrieval @Ambient (WFI only)
(3) Double-pass Shack-Hartmann @Ambient (CGI only)

IOA Post-Vibe
(1) Double-pass phase retrieval @Ambient & Cold (WFI only)
(2) Double-pass Shack-Hartmann @Ambient & Cold (CGI only)

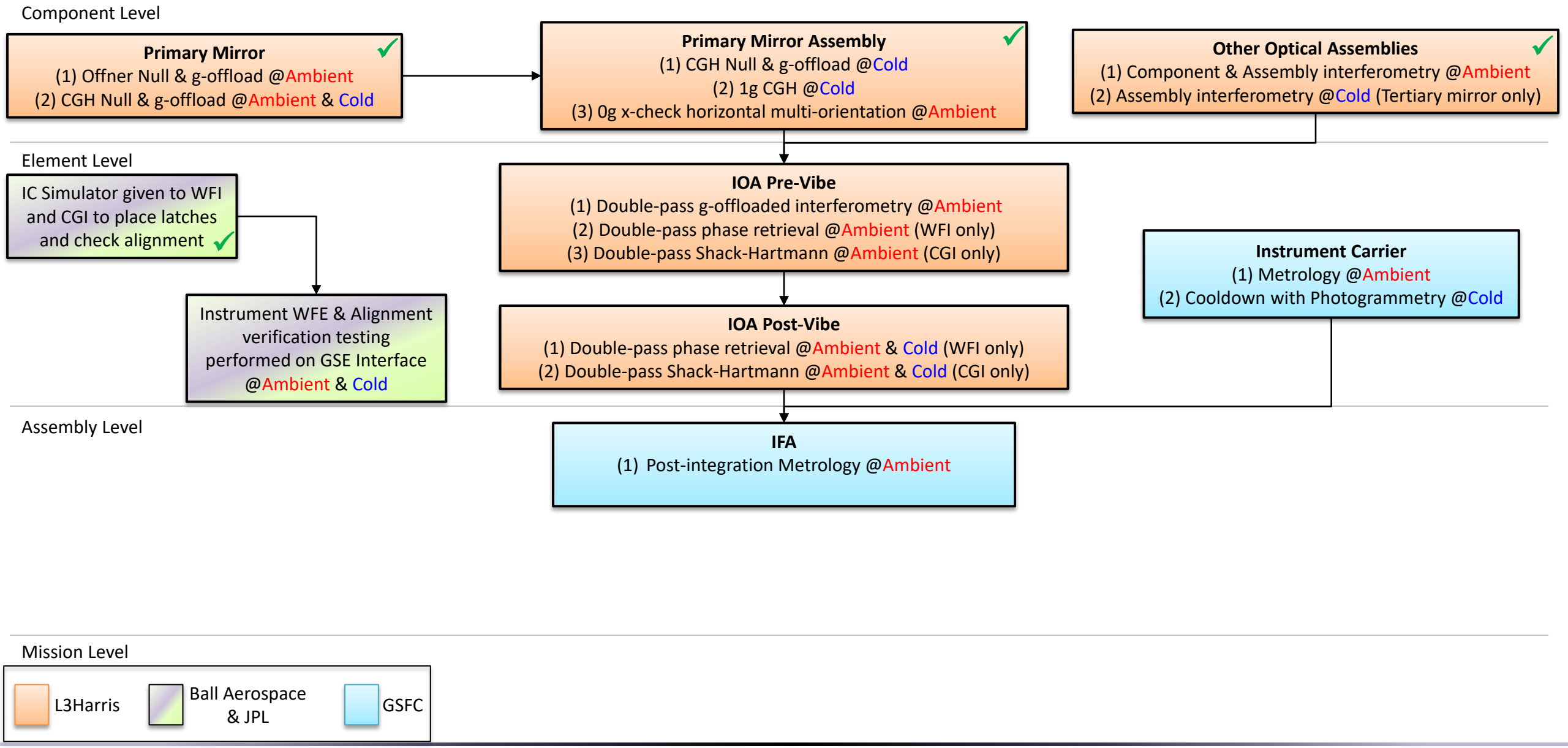
Instrument Carrier
(1) Metrology @Ambient
(2) Cooldown with Photogrammetry @Cold

Assembly Level

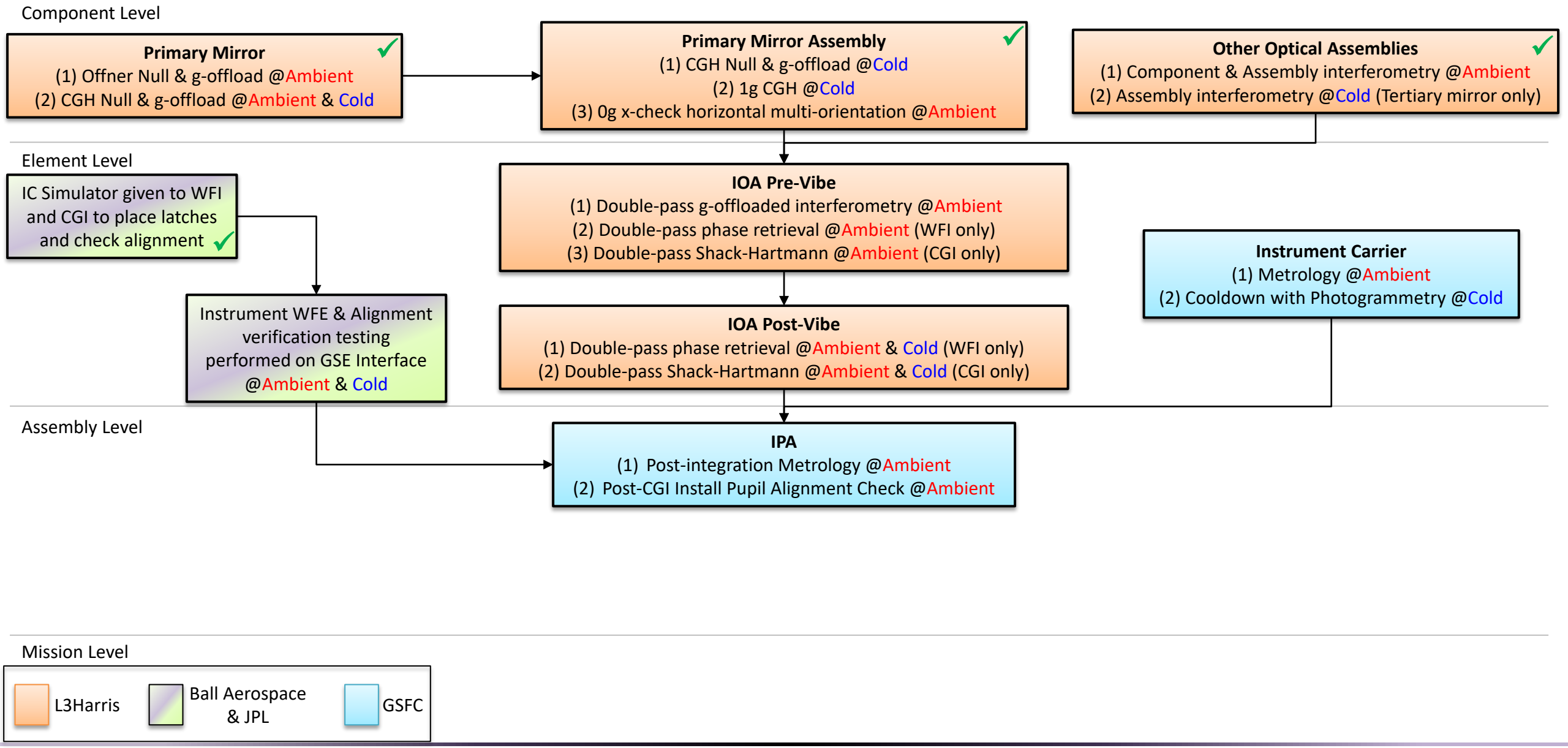
Mission Level

L3Harris | Ball Aerospace & JPL | GSFC

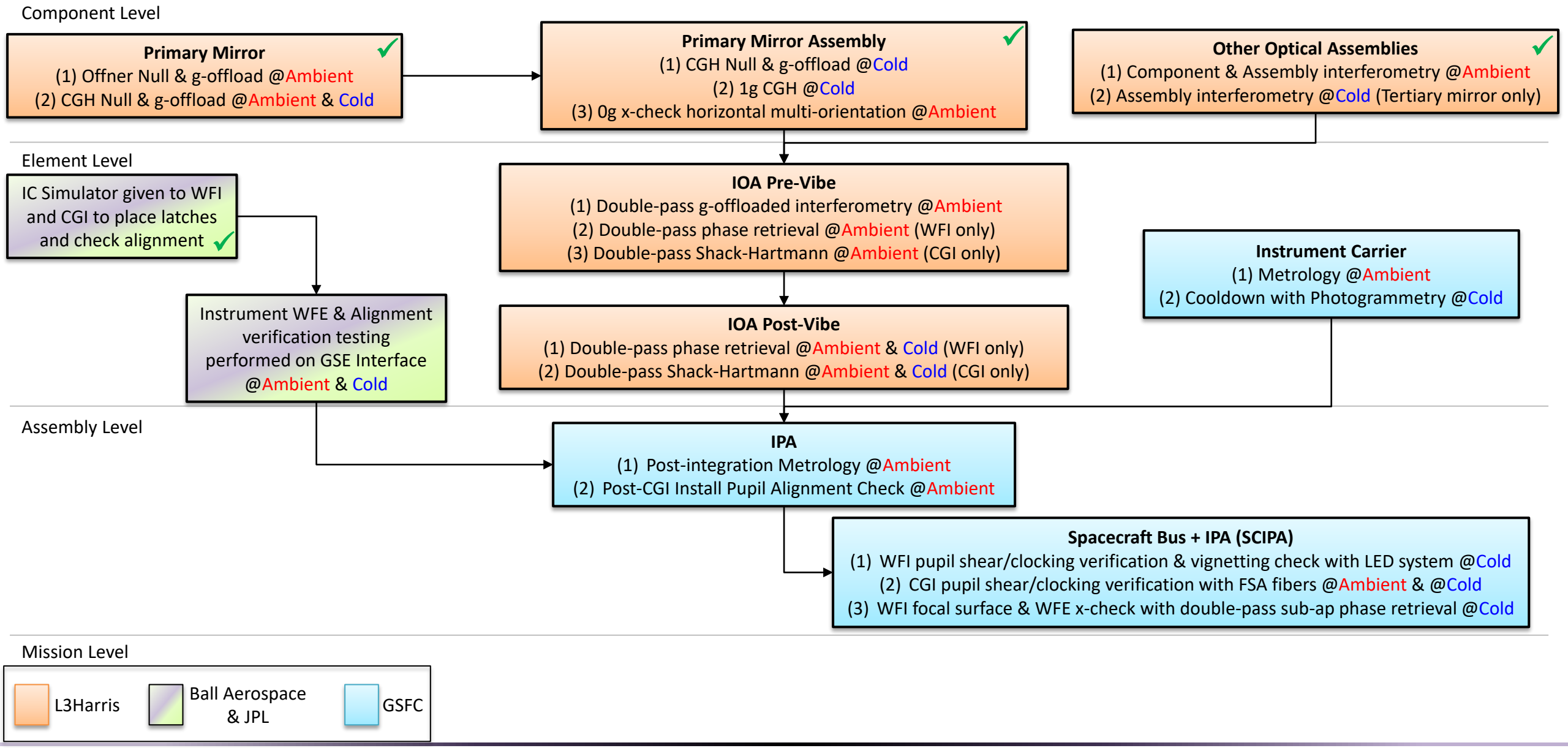
Optical Alignment & WFE Verification Summary



Optical Alignment & WFE Verification Summary



Optical Alignment & WFE Verification Summary



Optical Alignment & WFE Verification Summary

Component Level

Primary Mirror ✓
(1) Offner Null & g-offload @Ambient
(2) CGH Null & g-offload @Ambient & Cold

Primary Mirror Assembly ✓
(1) CGH Null & g-offload @Cold
(2) 1g CGH @Cold
(3) 0g x-check horizontal multi-orientation @Ambient

Other Optical Assemblies ✓
(1) Component & Assembly interferometry @Ambient
(2) Assembly interferometry @Cold (Tertiary mirror only)

Element Level

IC Simulator given to WFI and CGI to place latches and check alignment ✓

IOA Pre-Vibe
(1) Double-pass g-offloaded interferometry @Ambient
(2) Double-pass phase retrieval @Ambient (WFI only)
(3) Double-pass Shack-Hartmann @Ambient (CGI only)

Instrument Carrier
(1) Metrology @Ambient
(2) Cooldown with Photogrammetry @Cold

Instrument WFE & Alignment verification testing performed on GSE Interface @Ambient & Cold

IOA Post-Vibe
(1) Double-pass phase retrieval @Ambient & Cold (WFI only)
(2) Double-pass Shack-Hartmann @Ambient & Cold (CGI only)

Assembly Level

IPA
(1) Post-integration Metrology @Ambient
(2) Post-CGI Install Pupil Alignment Check @Ambient

Spacecraft Bus + IPA (SCIPA)
(1) WFI pupil shear/clocking verification & vignetting check with LED system @Cold
(2) CGI pupil shear/clocking verification with FSA fibers @Ambient & @Cold
(3) WFI focal surface & WFE x-check with double-pass sub-ap phase retrieval @Cold

Mission Level

Observatory
(1) Inspect vignetting and mirror coating @Ambient
(2) Analysis of 0-g on-orbit performance

L3Harris | Ball Aerospace & JPL | GSFC

Verification Plan Summary

- **IOA level:**
  - ***Ambient:*** ***Verify*** 0-g WFE with interferometry (both channels)
  - ***Ambient:*** ***Cross-check*** 0-g WFE with phase retrieval (WFI channel) and Shack-Hartmann (CGI channel)
  - ***Ambient:*** ***Verify*** alignment stability through dynamic environments with interferometry (both channels)
  - ***OpTemp:*** ***Verify*** WFE cold-shift with phase retrieval (WFI channel) and Shack-Hartmann (CGI channel)
  - ***OpTemp:*** ***Verify*** pupil shear and clocking with interferometer pupil imaging (both channels)
  - ***OpTemp:*** ***Cross-check*** pupil shear and clocking with FSA fibers (CGI channel only)
  - ***OpTemp:*** ***Verify*** focal surface placement with phase retrieval (WFI channel only)

- **Instrument Carrier level:**
  - ***OpTemp:*** ***Verify*** alignment and cooldown distortion using photogrammetry

- **WFI level:**
  - ***OpTemp:*** ***Verify*** instrument-level wavefront error, element confocality, and alignment with phase retrieval & pupil imaging

- **CGI level:**
  - ***Ambient:*** ***Verify*** instrument pupil alignment and alignment stability through dynamic environments with metrology
  - ***OpTemp:*** ***Verify*** instrument contrast performance with CGI Verification Stimulus

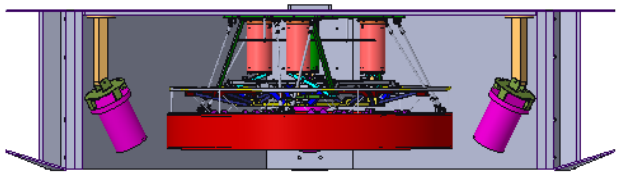
- **SCIPA level:**
  - ***OpTemp:*** ***Verify*** optical alignment with LED System and sub-aperture phase retrieval (WFI channel)
  - ***OpTemp:*** ***Verify*** no vignetting in WFI channel using LED System
  - ***OpTemp:*** ***Verify*** optical alignment with FSA fiber sources (CGI channel)
  - ***OpTemp:*** ***Cross-check*** optical wavefront error with sub-aperture phase retrieval (WFI channel only)

- **Observatory level:**
  - ***Ambient:*** Cross-check vignetting after dynamic environments using Imaging Inspection System

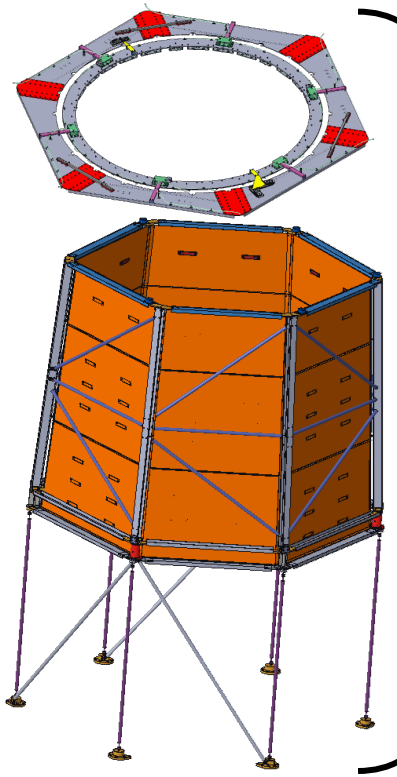
SCIPA TVAC TEST

SCIPA Test Configuration

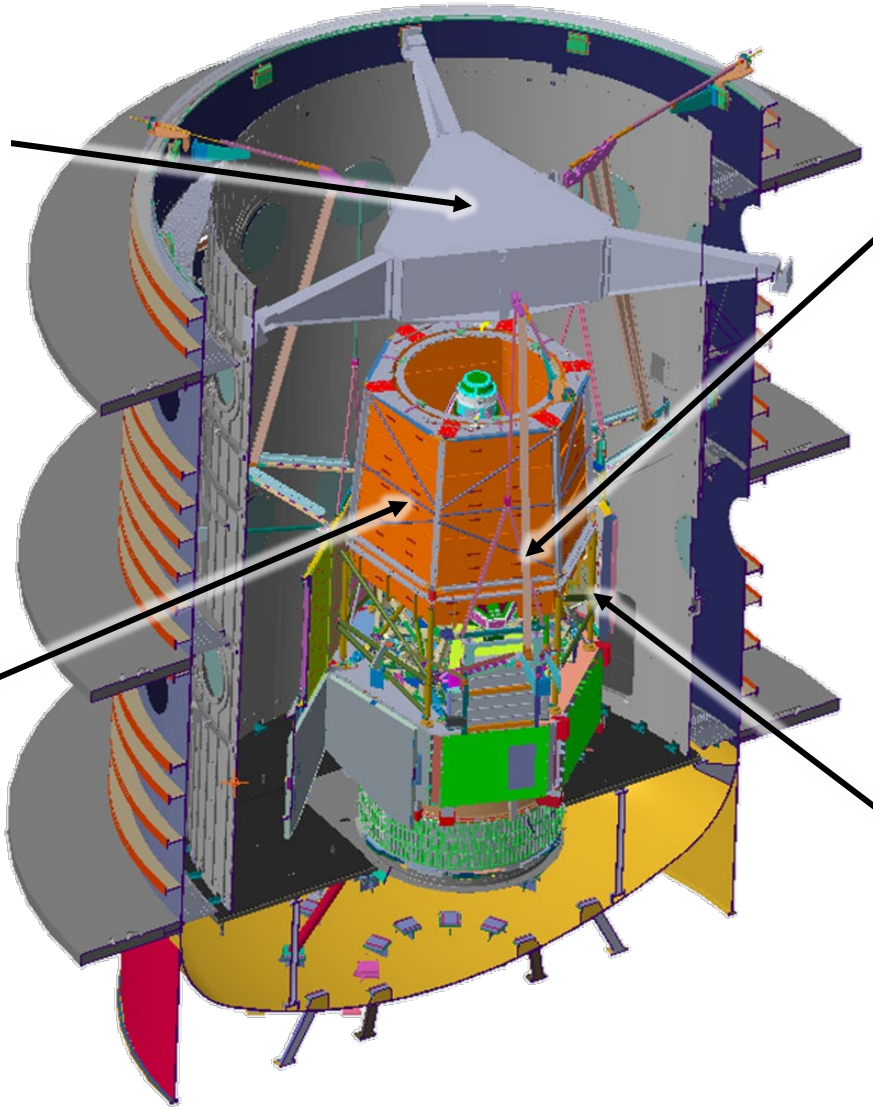
Upper Support Frame holds sub-aperture auto-collimating flat, photogrammetry cameras, and isolation system.

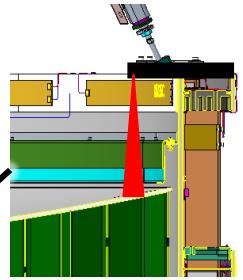


OBA-Sim top deck assembly supports LED System as well as photogrammetry targets



Outer Barrel Assembly Simulator (OBA-Sim) provides thermal environment and supports photogrammetry cameras for system alignment.





Non-flight fibers mounted around the perimeter of the primary mirror provide pupil sources for measuring CGI pupil alignment.

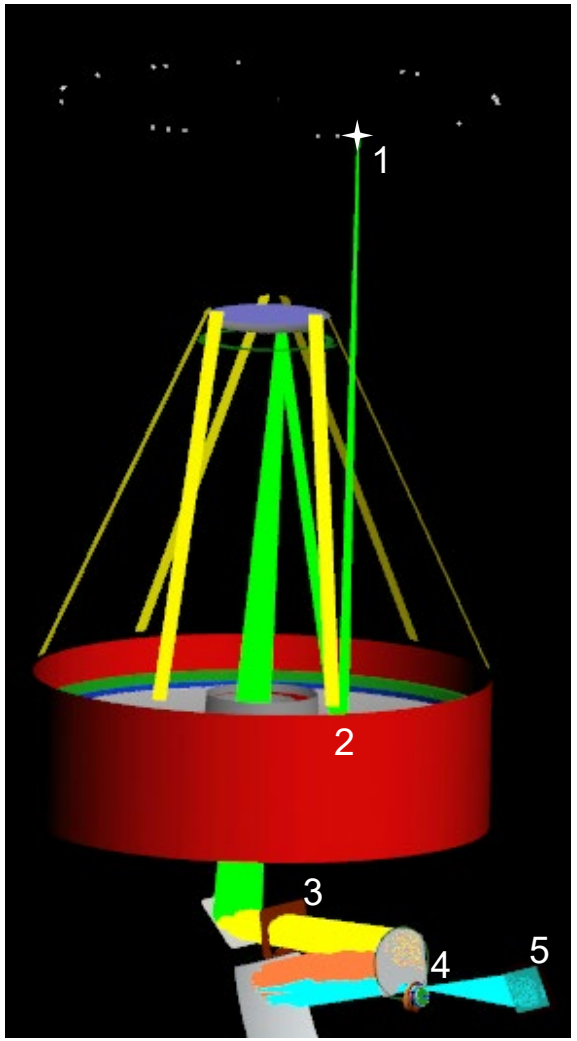
8 fibers mounted around the WFI focal plane array allow for double-pass testing of the system using focus-diverse phase retrieval.

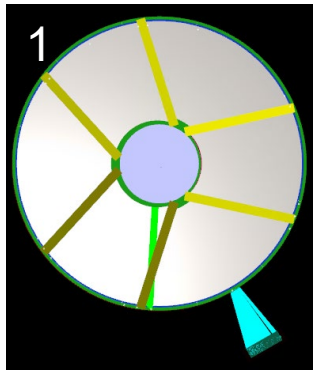
WFI PUPIL VERIFICATION / VIGNETTING CHECK

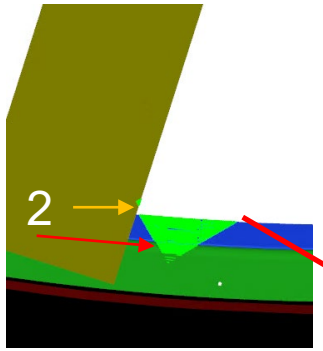
Pupil Alignment Overview

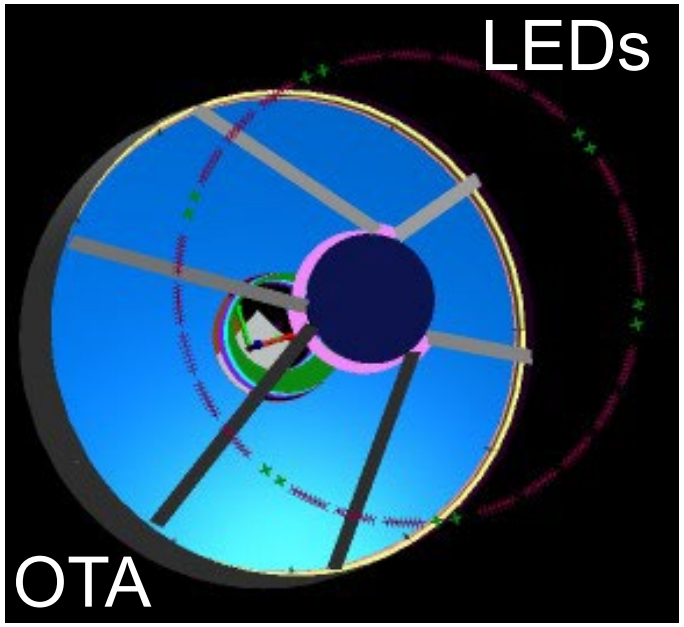
A ring of LEDs are positioned within the clear aperture

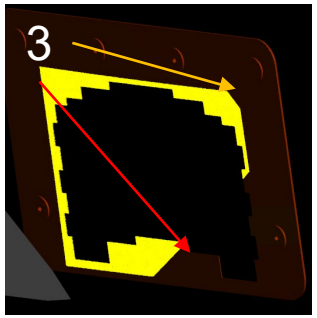
1. Each LED is turned on <u>individually</u> and floods the WFI field
2. Structure in the OTA pupil block ray angles associated with their location & direction with respect to the LED
3. These OTA features clip parts of the field; the entrance aperture plate limits the field-of-view otherwise
4. In pupil space, the same ray bundle can also be clipped by features in the WFI pupil mask
5. The features in the OTA pupil and the WFI pupil each cast shadows that are imaged at the WFI detector
6. **Positions of shadows on the WFI detector are related to the as built positions of the OTA and the WFI pupil mask**

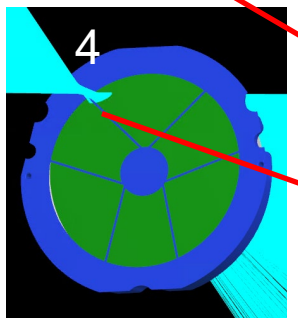


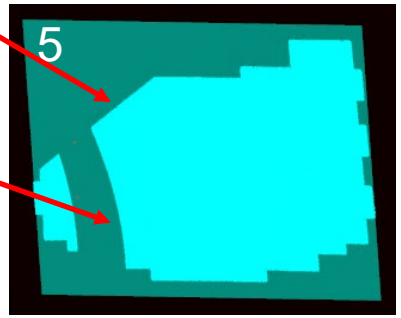








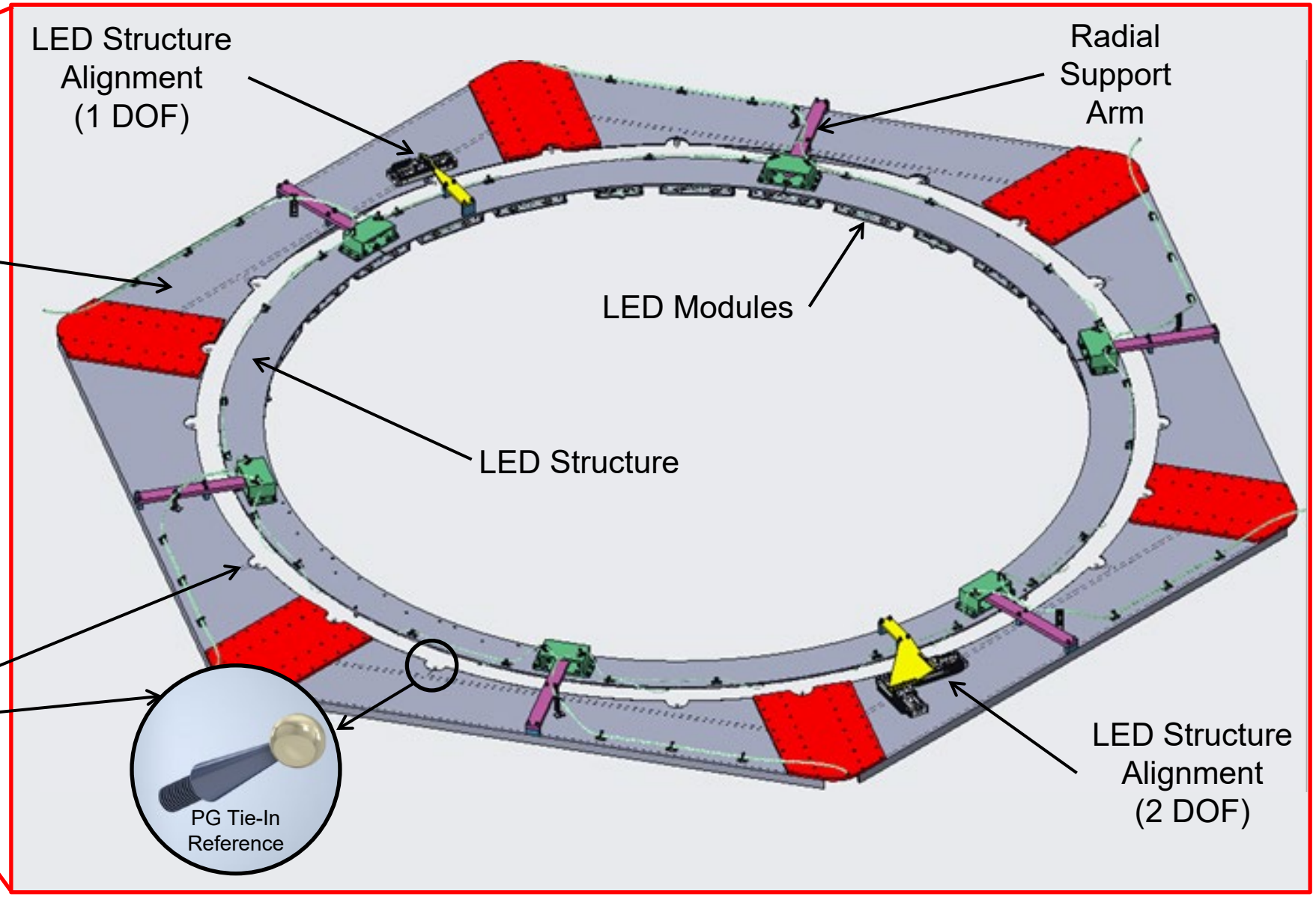




LED Structure

Outer Barrel Assembly Simulator Top Deck

Mouse Holes for Photogrammetry tie-in points



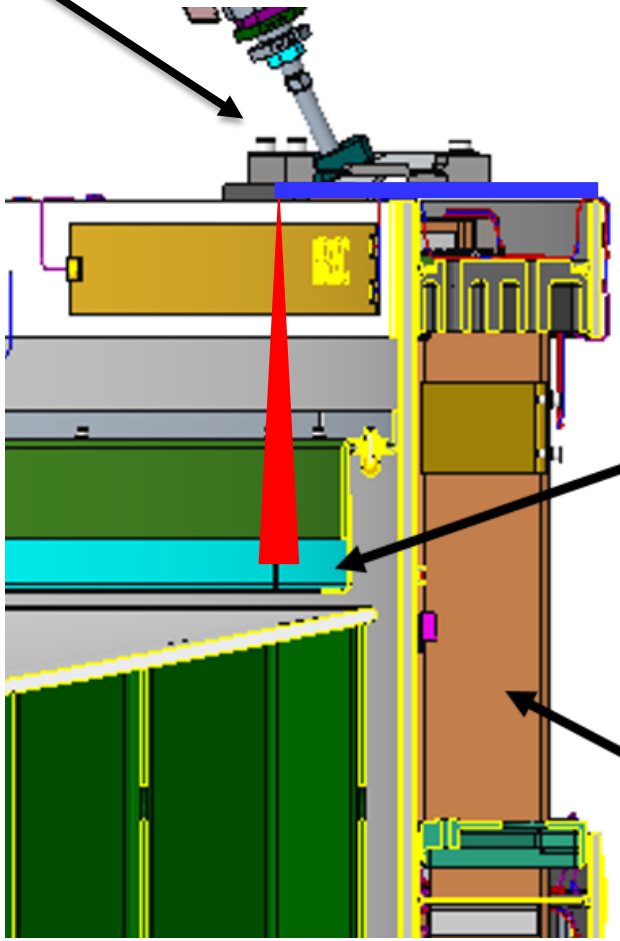
CGI PUPIL VERIFICATION

CGI / TCA Pupil Checks with FSA Fiber Sources

- **Six downward looking fiber sources mounted on diving boards attached to the Forward Structure Assembly (FSA) allow for a common pupil reference that can be seen at different levels of assembly**
  - First measured at IOA-level test using interferometer – establish baseline alignment of FSA fiber positions to pupil position measured by interferometer
- **After IPA integration CGI pupil imaging mode measures FSA fiber position three times:**
  - Ambient test after IPA integration and pre-SCIPA level vibe to allow check of integration accuracy and establish baseline alignment
  - Ambient post-vibe test to verify alignment stability
  - In TVAC to very at-temperature instrument alignment
- **Fiber sources**
  - Non-flight, mounted on metrologized diving boards above PM
  - Removed after TVAC test before outer-barrel assembly (OBA) integration

FSA Fiber Concept

Fiber optic on top of FSA

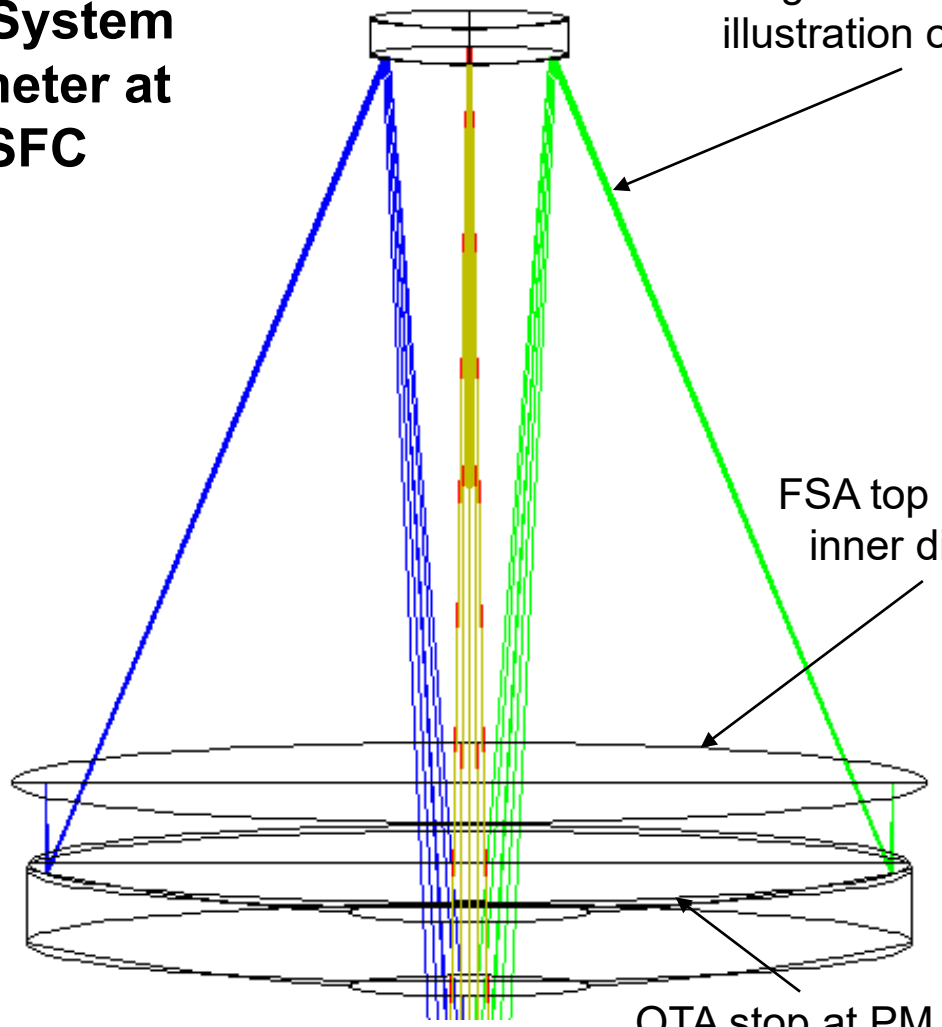


PM outer diameter scraper

Forward Metering Structure

(6) Fiber sources

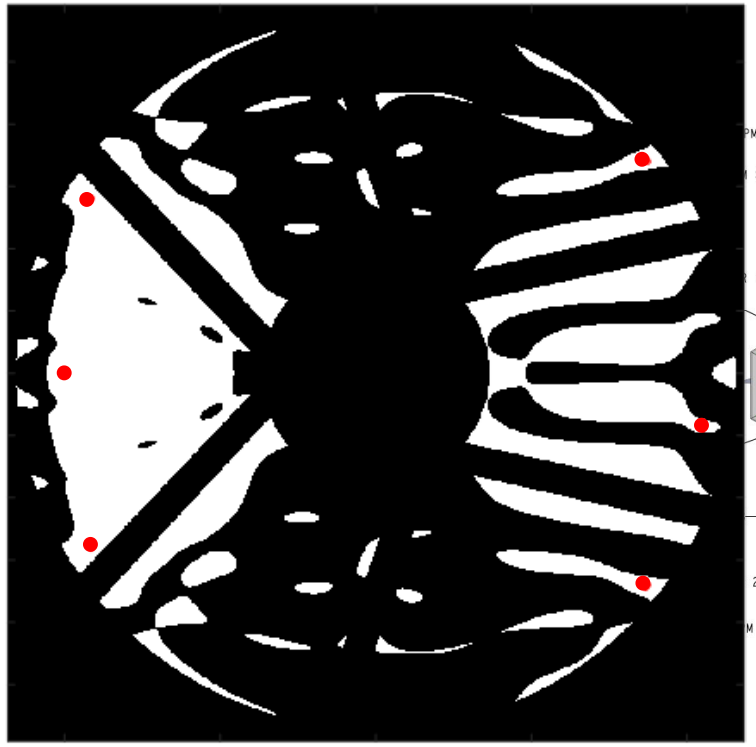
- **Alignment characterized in Payload Coordinate System**
- **Imaged by interferometer at L3Harris or CGI at GSFC**



CGI Reference Fibers Requirements

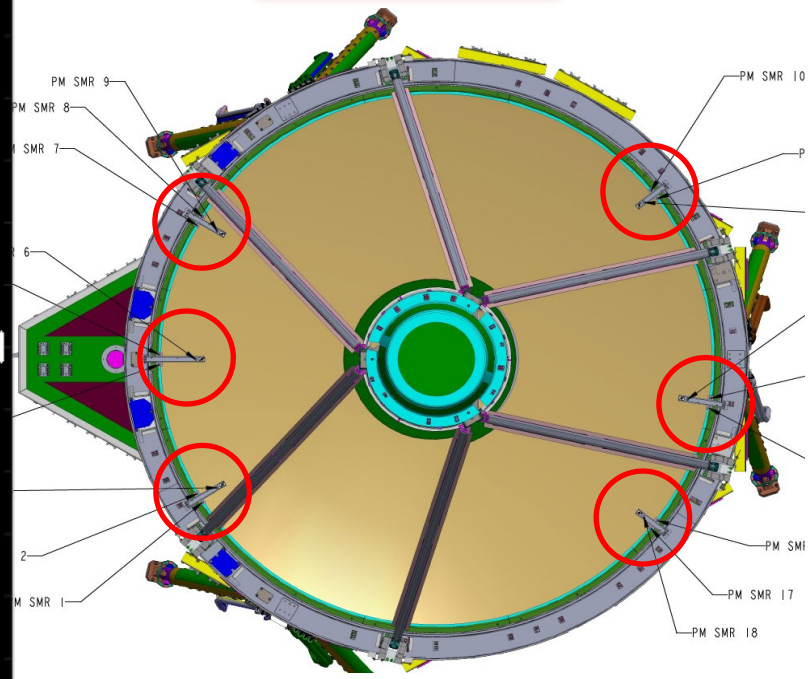
Design Requirements

- Removeable, operate cold @ vac during IOA & SCIPA TVAC
- Within clear aperture
  - 60-176.5 mm inside PM scraper
- Line of sight past SMST, blankets, ACF fiducials & CGI shaped pupil mask



CGI Shaped Pupil Mask

6 total locations around PM



WFI FOCAL SURFACE VERIFICATION / WFE CROSS-CHECK

Sub-aperture Double-pass FDPR

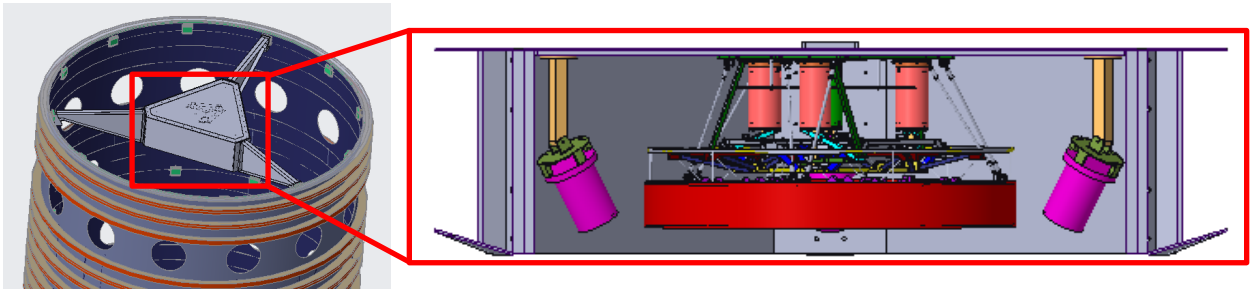
- **Use fibers located around the WFI Focal Plane Assembly (FPA) to create a collimated beam exiting the telescope pupil**

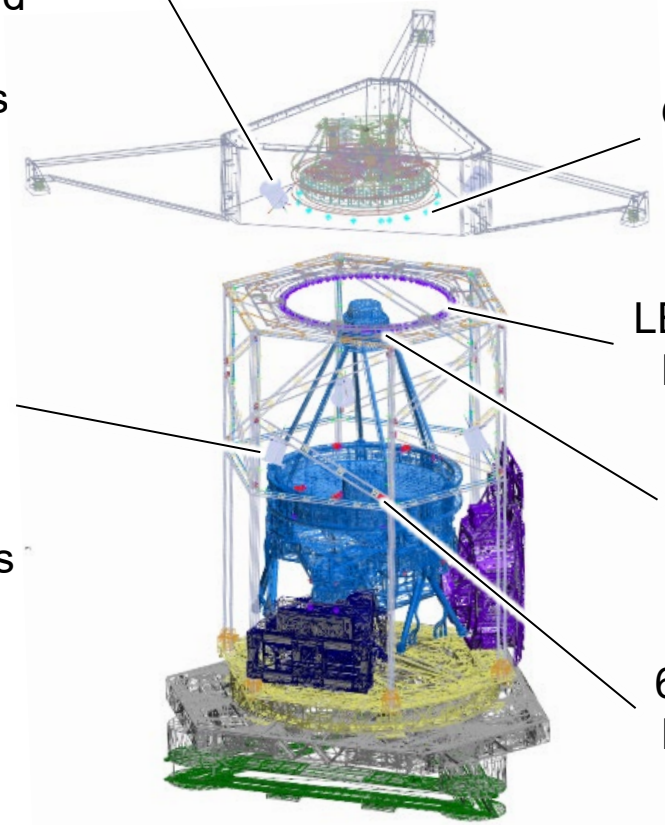
- **A sub-aperture optical flat (OLAFS) positioned above the telescope retros a portion of the collimated beam back through the system**
  - Small tip & tilt of the OLAFS can be used to steer the return beam through different field angles

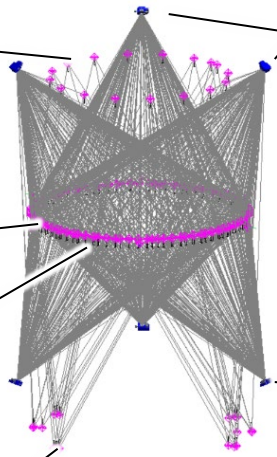
- **The optical system focuses the return beam onto the active area of the FPA**
  - Moving the FPA through focus with the alignment compensation mechanism (ACM) within WFI provide focus diversity for FDPR

OLAFS & Photogrammetry System

- **3 downward looking PG cameras see:**
  - Common spherical targets on OBA platform (tie-in points)
  - PG stickers on top of LED modules and LED ring
  - PG stickers on FSA fiber diving boards
- **3 upward looking PG cameras see:**
  - Common spherical targets on OBA platform (tie-in points)
  - PG stickers on bottom of LED modules LED ring
  - OLAFS ring and aperture







OLAFS PG Targets

Downward PG Cameras (3x)

LED Structure PG Targets

PG Tie-in Points

Upward PG Cameras (3x)

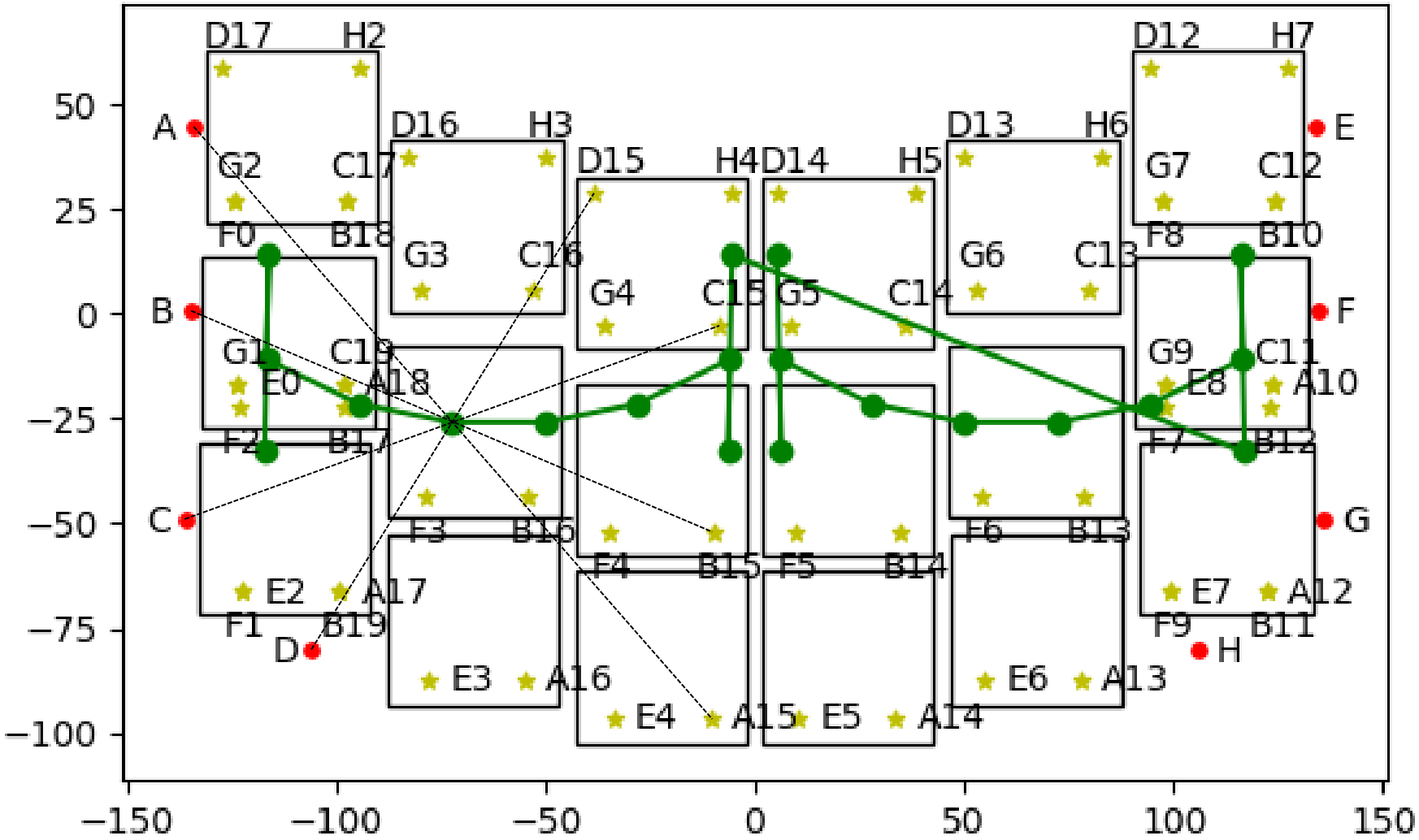
6 FSA Fiber PG Targets

Field Scan Points, aka “Full Moustache”

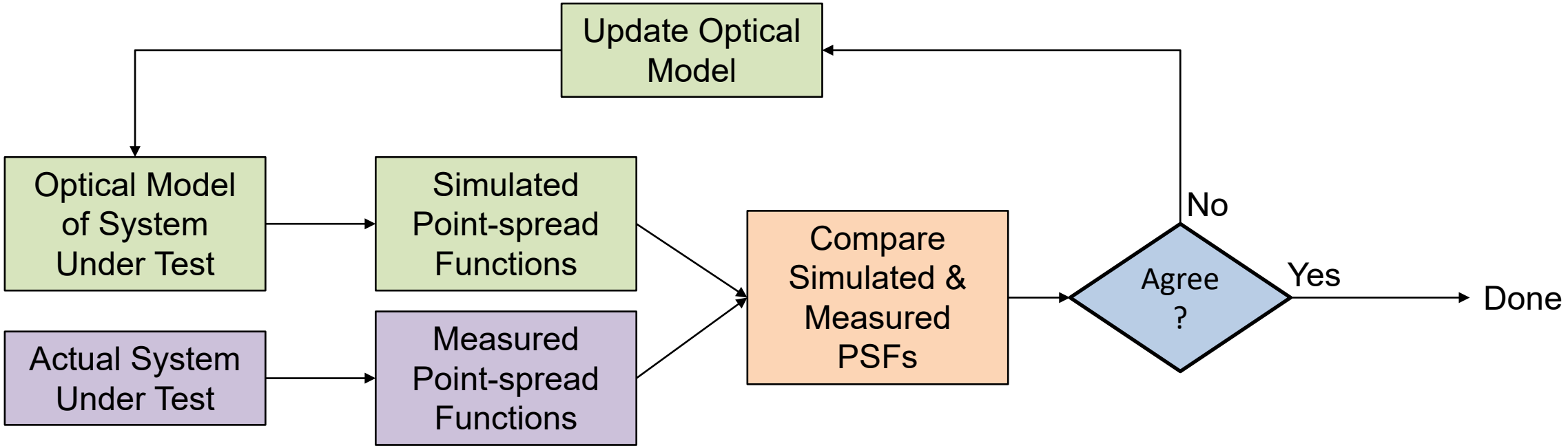
Red points are the FPA fiber positions

Green points represent individual OLAFS pointing angles in field space

Yellow stars represent images of a given illuminated fiber for a given OLAFS pointing



How Focus-Diverse Phase Retrieval (FDPR) Works



- **Issues:**
  - If optical model does not sufficiently represent the system under test, then FDPR will not converge to a solution
    - ***Knowledge*** requirements on system configuration
  - If system under test is changing during measurements, then FDPR can't find a self-consistent solution
    - ***Stability*** requirement during test

Conclusion

- **Integration and test of the Roman Space Telescope is well underway!**
  - Each Element is working through final integration now and preparing for thermal vacuum and dynamic environment testing later this year and early next year
  - Elements to be delivered to GSFC next spring and summer for payload integration

- **A comprehensive optical verification plan has been established**
  - All Elements are fully optically verified at operational temperature prior to delivery to payload integration
  - Final system alignment is verified at GSFC at operational temperature with additional cross-checks to ensure system integrity through I&T
  - Test verification budgets and test plans are in development

- **The Roman Space Telescope is on track for an October 2026 launch!**