Roman Space Telescope
Optical System:

Status and Test

SPIE Mirror Tech Days
November 15, 2023
Huntsville, AL

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Roman Optical Systems Lead
Goddard Space Flight Center
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)
- Spacecraft Bus
- Avionics Panels
- Communications Module
- Propulsion Module
- SCI PA
- Integrated Payload Assembly (IPA)
- Spacecraft Bus
- OSD (OBA/SASS/DAC)
  - Deployable Aperture Cover (DAC)
  - Solar Array Sun Shield (SASS)
  - Outer Barrel Assembly (OBA)

Observatory Description

November 15, 2023
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
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

LEGEND
Optic
Flight Compensator
Focal Plane
Mechanism
Optical Path
Optical Pupil

OTA Imaging Optics Assembly (IOA)
F1
(Tip/Tilt/Focus)
F2
TM
WFI AOM
8 Filters
1 Grism
1 Prism
1 Cold Dark
18 H4RG detectors
10 μm pixel size
288 Megapixels
λ = 0.48 to 2.3 μm
0.28 deg² active area
110 mas/pixel
f/7.9
WFI CSM

FOA
PMA
SMA
(5 DOF)
CGI TCA

Pick-off Mirror
Mirror 1
Mirror 2
Mirror 3
Mask
HLC
SPC

LOCAM
FPAM

EXCAM
DM2
DM1

EWA
DM (Focus)

ACM
(6 DOF)
MPA

IWA = 3 λ/D
OWA = 20 λ/D
1k x 1k detectors
λ = 546 to 980 nm

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SPIE Mirror Tech Days, Roman Optical System: Status and Test
## Optical Compensators

<table>
<thead>
<tr>
<th>Compensator</th>
<th>Degree of Freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM Focus Drives (FD)*</td>
<td>Defocus</td>
</tr>
<tr>
<td>SM Alignment Drives (AD)*</td>
<td>Decenter (x)</td>
</tr>
<tr>
<td></td>
<td>Decenter (y)</td>
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<tr>
<td></td>
<td>Defocus</td>
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<tr>
<td></td>
<td>Tip</td>
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<tr>
<td></td>
<td>Tilt</td>
</tr>
<tr>
<td>AOM Fold Mirror 1 (FM1)</td>
<td>Defocus</td>
</tr>
<tr>
<td></td>
<td>Tip</td>
</tr>
<tr>
<td></td>
<td>Tilt</td>
</tr>
<tr>
<td>WFI Alignment Compensation Mechanism (ACM)*</td>
<td>Defocus</td>
</tr>
<tr>
<td></td>
<td>Tip</td>
</tr>
<tr>
<td></td>
<td>Tilt</td>
</tr>
<tr>
<td>TCA Tip/Tilt Fold (TTF)</td>
<td>Tip</td>
</tr>
<tr>
<td></td>
<td>Tilt</td>
</tr>
</tbody>
</table>

*Heritage actuators from previous program
†Heritage JWST actuators

- **Compensate Wavefront Error (WFE)** Errors Common to Each Channel
- **Compensate Focus & Pupil Shear in WFI Channel**
- **Compensate Pupil Shear in CGI Channel**
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.

Scrapers on SM and support tubes limit reflections from blankets

PM Baffle prevents direct view of FM1 from sky

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

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

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.
- **Scrappers** on SM and support tubes limit reflections from blankets.
- **PM Baffle** prevents direct view of FM1 from sky.
- **Entrance aperture plates** limit out-of-field light in each instrument (WFI shown).
- **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.

Scrapers on SM and support tubes limit reflections from blankets

PM Baffle prevents direct view of FM1 from sky

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

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)

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

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

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

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)

Assembly Level

Mission Level

L3Harris
Ball Aerospace & JPL
GSFC
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

**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)

Assembly Level

**Instrument Carrier**
1. Metrology @Ambient
2. Cooldown with Photogrammetry @Cold

Mission Level

- L3Harris
- Ball Aerospace & JPL
- GSFC

November 15, 2023
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

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

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

Assembly Level

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

Mission Level

L3Harris
Ball Aerospace
& JPL
GSFC
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
- Instrument Carrier
  - (1) Metrology @Ambient
  - (2) Cooldown with Photogrammetry @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)

**Assembly Level**
- IFA
  - (1) Post-integration Metrology @Ambient

**Mission Level**
- L3Harris
- Ball Aerospace & JPL
- GSFC

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**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

**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

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

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

### Mission Level

- L3Harris
- Ball Aerospace & JPL
- GSFC
Optical Alignment & WFE Verification Summary

Component Level

Primary Mirror Assembly
1. Offner Null & g-offload @Ambient
2. CGH Null & g-offload @Ambient & 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

Assembly Level

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)

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

L3Harris
Ball Aerospace & JPL
GSFC

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### Optical Alignment & WFE Verification Summary

#### Component Level

<table>
<thead>
<tr>
<th>Primary Mirror Assembly</th>
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<tbody>
<tr>
<td>(1) CGH Null &amp; g-offload @Cold</td>
</tr>
<tr>
<td>(2) Offner Null &amp; g-offload @Ambient &amp; Cold</td>
</tr>
</tbody>
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#### Element Level

- **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

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

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

- **Instrument Carrier given to WFI and CGI to place latches and check alignment**

- **IC Simulator given to WFI and CGI to place latches and check alignment**

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

#### Assembly Level

<table>
<thead>
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<th>IPA</th>
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<tr>
<td>(1) Post-integration Metrology @Ambient</td>
</tr>
<tr>
<td>(2) Post-CGI Install Pupil Alignment Check @Ambient</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spacecraft Bus + IPA (SCIPA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) WFI pupil shear/clocking verification &amp; vignetting check with LED system @Cold</td>
</tr>
<tr>
<td>(2) CGI pupil shear/clocking verification with FSA fibers @Ambient &amp; @Cold</td>
</tr>
<tr>
<td>(3) WFI focal surface &amp; WFE x-check with double-pass sub-ap phase retrieval @Cold</td>
</tr>
</tbody>
</table>

#### Mission Level

- **L3Harris**
- **Ball Aerospace & JPL**
- **GSFC**

<table>
<thead>
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<th>Observatory</th>
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<tbody>
<tr>
<td>(1) Inspect vignetting and mirror coating @Ambient</td>
</tr>
<tr>
<td>(2) Analysis of 0-g on-orbit performance</td>
</tr>
</tbody>
</table>
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
A ring of LEDs are positioned within the clear aperture

1. Each LED is turned on individually 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
- LED Structure Alignment (1 DOF)
- Radial Support Arm
- LED Modules
- LED Structure Alignment (2 DOF)
- Mouse Holes for Photogrammetry tie-in points
- PG Tie-In Reference

Outer Barrel Assembly Simulator Top Deck
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

(6) Fiber sources
- Alignment characterized in Payload Coordinate System
- Imaged by interferometer at L3Harris or CGI at GSFC
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
WFI FOCAL SURFACE VERIFICATION /
WFE CROSS-CHECK
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 retro's 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 and LED ring
  - OLAFS ring and aperture
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!**