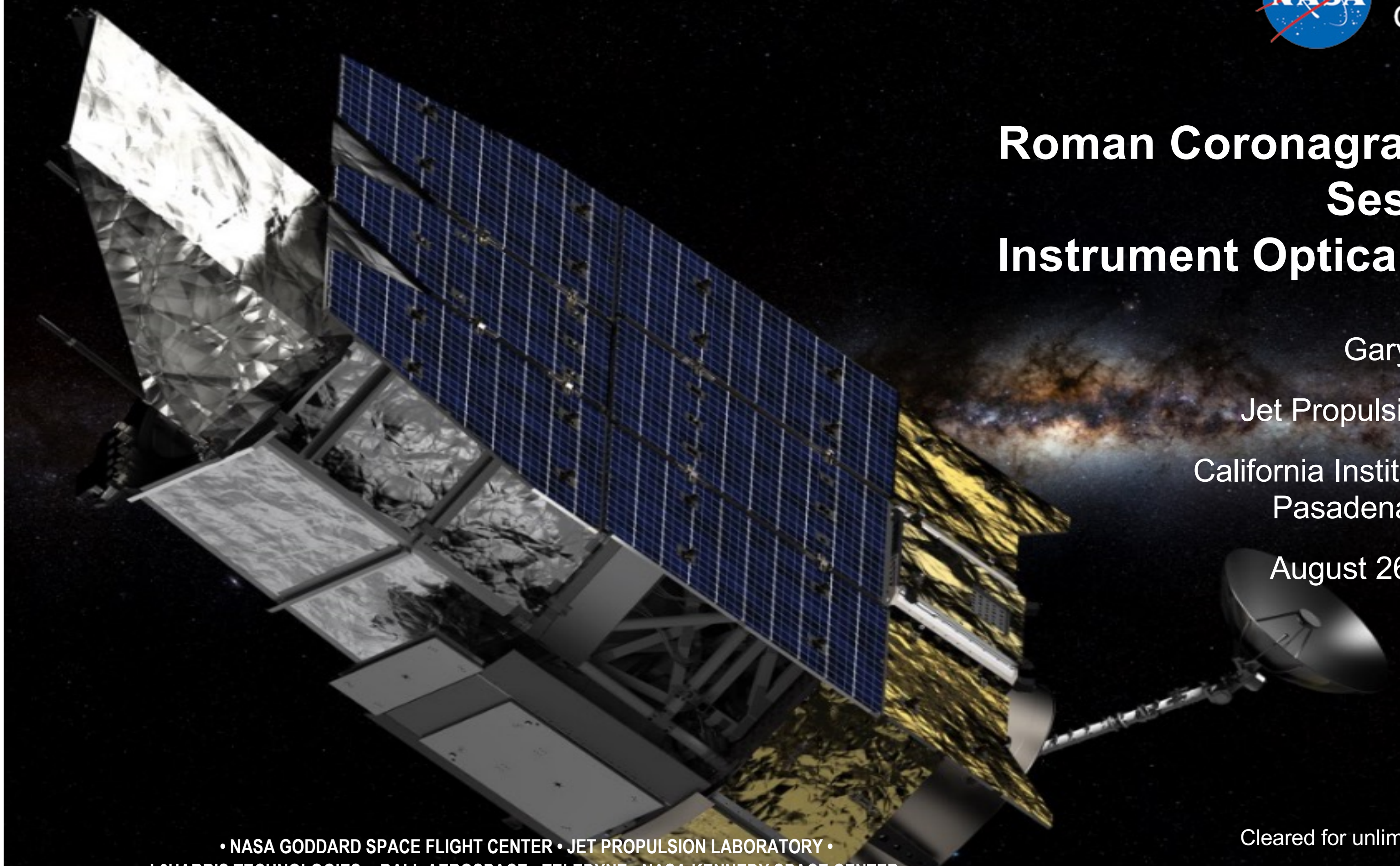
Jet Propulsion Laboratory
California Institute of Technology



Roman Coronagraph Test Results Info Session:
Instrument Optical Design Description

Gary Kuan

Jet Propulsion Laboratory

California Institute of Technology
Pasadena, CA 91109

August 26 – 27, 2024

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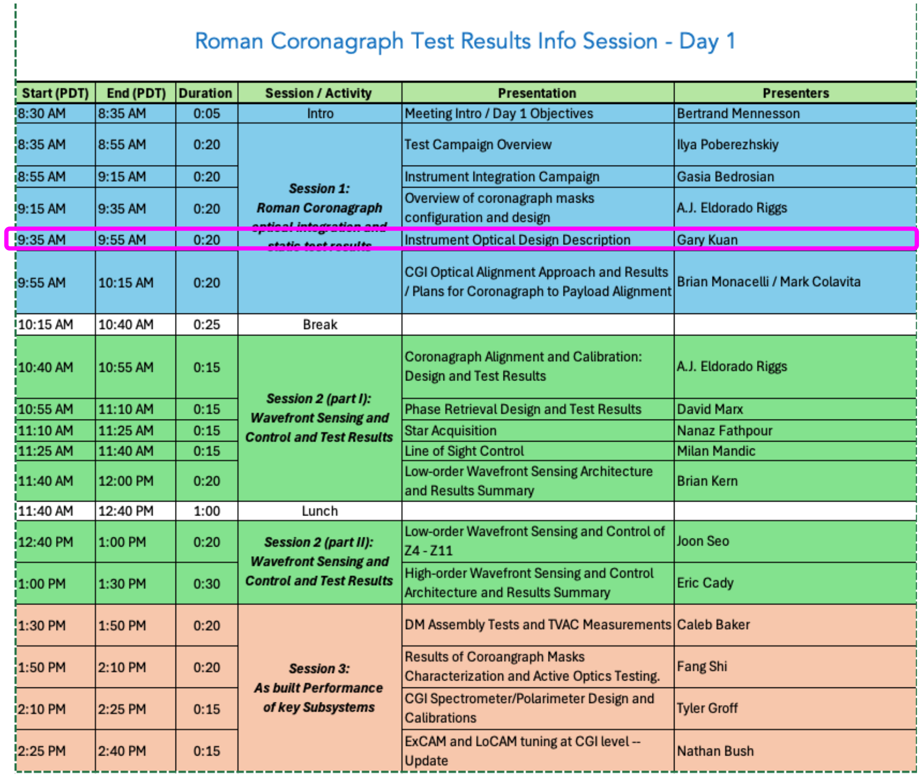
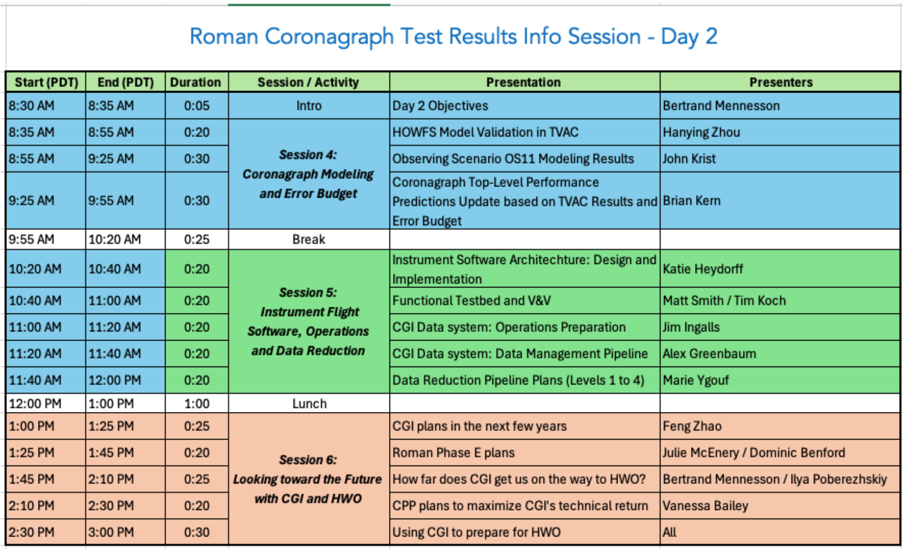
Workshop Schedule



Roman Coronagraph Test Results Info Session - Day 1

Start (PDT)	End (PDT)	Duration	Session / Activity	Presentation	Presenters
8:30 AM	8:35 AM	0:05	Intro	Meeting Intro / Day 1 Objectives	Bertrand Mennesson
8:35 AM	8:55 AM	0:20	***Session 1: Roman Coronagraph optical integration and static test results***	Test Campaign Overview	Ilya Poberezhskiy
8:55 AM	9:15 AM	0:20		Instrument Integration Campaign	Gasia Bedrosian
9:15 AM	9:35 AM	0:20		Overview of coronagraph masks configuration and design	A.J. Eldorado Riggs
9:35 AM	9:55 AM	0:20		Instrument Optical Design Description	Gary Kuan
9:55 AM	10:15 AM	0:20		CGI Optical Alignment Approach and Results / Plans for Coronagraph to Payload Alignment	Brian Monacelli / Mark Colavita
10:15 AM	10:40 AM	0:25	Break		
10:40 AM	10:55 AM	0:15	***Session 2 (part I): Wavefront Sensing and Control and Test Results***	Coronagraph Alignment and Calibration: Design and Test Results	A.J. Eldorado Riggs
10:55 AM	11:10 AM	0:15		Phase Retrieval Design and Test Results	David Marx
11:10 AM	11:25 AM	0:15		Star Acquisition	Nanaz Fathpour
11:25 AM	11:40 AM	0:15		Line of Sight Control	Milan Mandic
11:40 AM	12:00 PM	0:20		Low-order Wavefront Sensing Architecture and Results Summary	Brian Kern
11:40 AM	12:40 PM	1:00	Lunch		
12:40 PM	1:00 PM	0:20	***Session 2 (part II): Wavefront Sensing and Control and Test Results***	Low-order Wavefront Sensing and Control of Z4 - Z11	Joon Seo
1:00 PM	1:30 PM	0:30		High-order Wavefront Sensing and Control Architecture and Results Summary	Eric Cady
1:30 PM	1:50 PM	0:20	***Session 3: As built Performance of key Subsystems***	DM Assembly Tests and TVAC Measurements	Caleb Baker
1:50 PM	2:10 PM	0:20		Results of Coroangraph Masks Characterization and Active Optics Testing.	Fang Shi
2:10 PM	2:25 PM	0:15		CGI Spectrometer/Polarimeter Design and Calibrations	Tyler Groff
2:25 PM	2:40 PM	0:15		ExCAM and LoCAM tuning at CGI level -- Update	Nathan Bush



Roman Coronagraph Test Results Info Session - Day 2

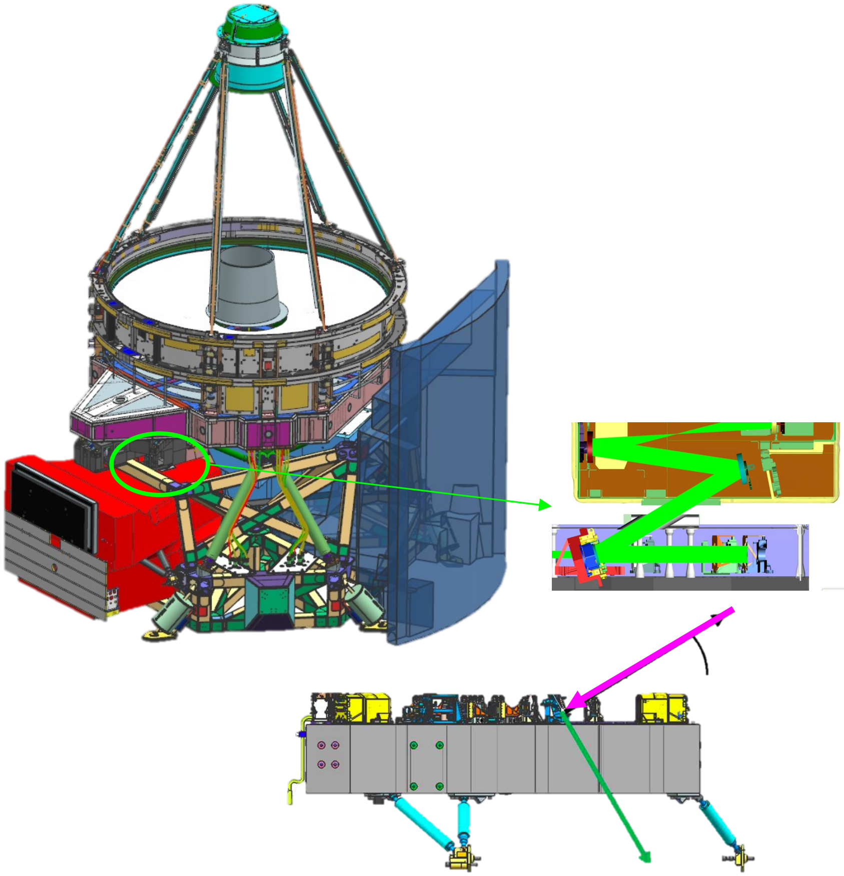
Start (PDT)	End (PDT)	Duration	Session / Activity	Presentation	Presenters
8:30 AM	8:35 AM	0:05	Intro	Day 2 Objectives	Bertrand Mennesson
8:35 AM	8:55 AM	0:20	***Session 4: Coronagraph Modeling and Error Budget***	HOWFS Model Validation in TVAC	Hanying Zhou
8:55 AM	9:25 AM	0:30		Observing Scenario OS11 Modeling Results	John Krist
9:25 AM	9:55 AM	0:30		Coronagraph Top-Level Performance Predictions Update based on TVAC Results and Error Budget	Brian Kern
9:55 AM	10:20 AM	0:25	Break		
10:20 AM	10:40 AM	0:20	***Session 5: Instrument Flight Software, Operations and Data Reduction***	Instrument Software Architechture: Design and Implementation	Katie Heydorff
10:40 AM	11:00 AM	0:20		Functional Testbed and V&V	Matt Smith / Tim Koch
11:00 AM	11:20 AM	0:20		CGI Data system: Operations Preparation	Jim Ingalls
11:20 AM	11:40 AM	0:20		CGI Data system: Data Management Pipeline	Alex Greenbaum
11:40 AM	12:00 PM	0:20		Data Reduction Pipeline Plans (Levels 1 to 4)	Marie Ygouf
12:00 PM	1:00 PM	1:00	Lunch		
1:00 PM	1:25 PM	0:25	***Session 6: Looking toward the Future with CGI and HWO***	CGI plans in the next few years	Feng Zhao
1:25 PM	1:45 PM	0:20		Roman Phase E plans	Julie McEnery / Dominic Benford
1:45 PM	2:10 PM	0:25		How far does CGI get us on the way to HWO?	Bertrand Mennesson / Ilya Poberezhskiy
2:10 PM	2:30 PM	0:20		CPP plans to maximize CGI's technical return	Vanessa Bailey
2:30 PM	3:00 PM	0:30		Using CGI to prepare for HWO	All

Outline

Interface to Observatory

- Collimated Beam
- Co-incident OTA+TCA exit pupil plane and CGI entrance pupil plane

- Key interface requirements:
  - ≦ 0.5mm pupil shear
    - Not hard stop; TTFold mirror has greater range of motion
  - ≦ 1.5 asec on-the-sky boresight alignment tolerance
    - Not hard stop; OTA Entrance Aperture Plate (field stop) has reserve allocation
  - ≦ 1.31 mrad pupil clocking
    - No mechanism to compensate for clocking
    - Less sensitive to optic displacements



Coronagraph Instrument Design Requirements

Category	Requirement
Instrument Interface	• 4asec vignetted FOV • 3asec unvignetted FOV • Receive 40mm dia beam at entrance pupil

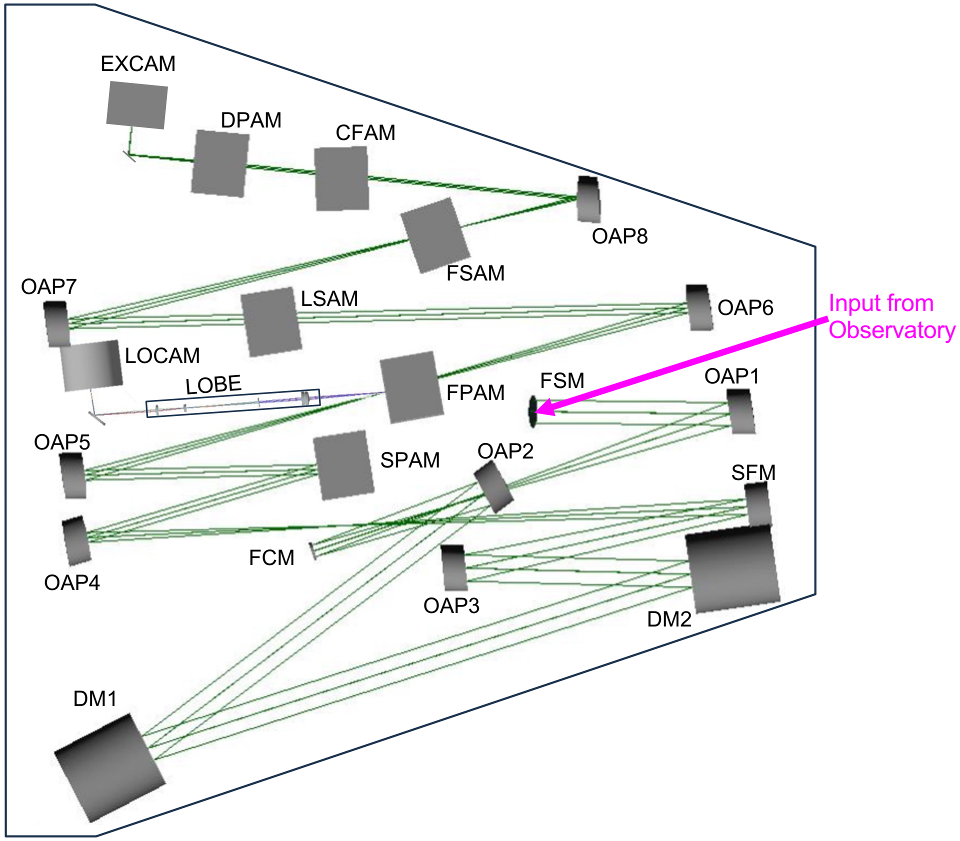
Instrument Design	• HLC Coronagraph
	• SPC Coronagraph
	• Direct Imaging Mode
	• Pupil Imaging Mode
	• Slit Spectroscopy Mode
	• Polarized Direct Imaging Mode
	• Observing Bands:
	  • Band1 (10% centered on 575nm) Imaging NFOV
	  • Band 2 (15% centered on 660nm) Spectroscopy
	  • Band 3 (15% centered on 760nm) Spectroscopy
	  • Band 4 (10% centered on 825nm) Imaging WFOV
	• Imaging plate scale: 0.022 asec/pixel

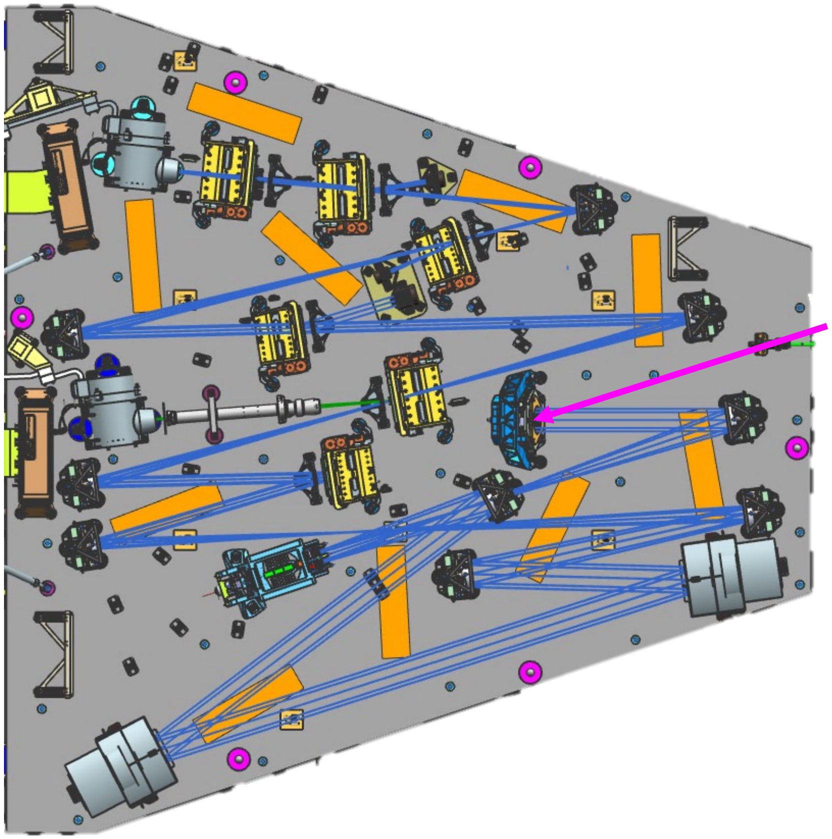
Control	• Fast Steering Mirror for Pointing Control (FSM) • Focus Control Mirror for defocus control (FCM) • Deformable mirrors (x2) for wavefront amplitude and phase control (DM1 & DM2)

Mode selection	• Mechanism to swap SPC masks (SPAM)
	  • Located before occulter focal plane
	• Mechanism to swap focal plane masks (FPAM)
	• Mechanism to swap Lyot stop masks (LSAM)
	  • Located at first pupil plane following occulter focal plane
	• Mechanism to swap field stops (FSAM)
	• Mechanism to swap color filters (CFAM)
	• Mechanism to swap imaging optics (DPAM)

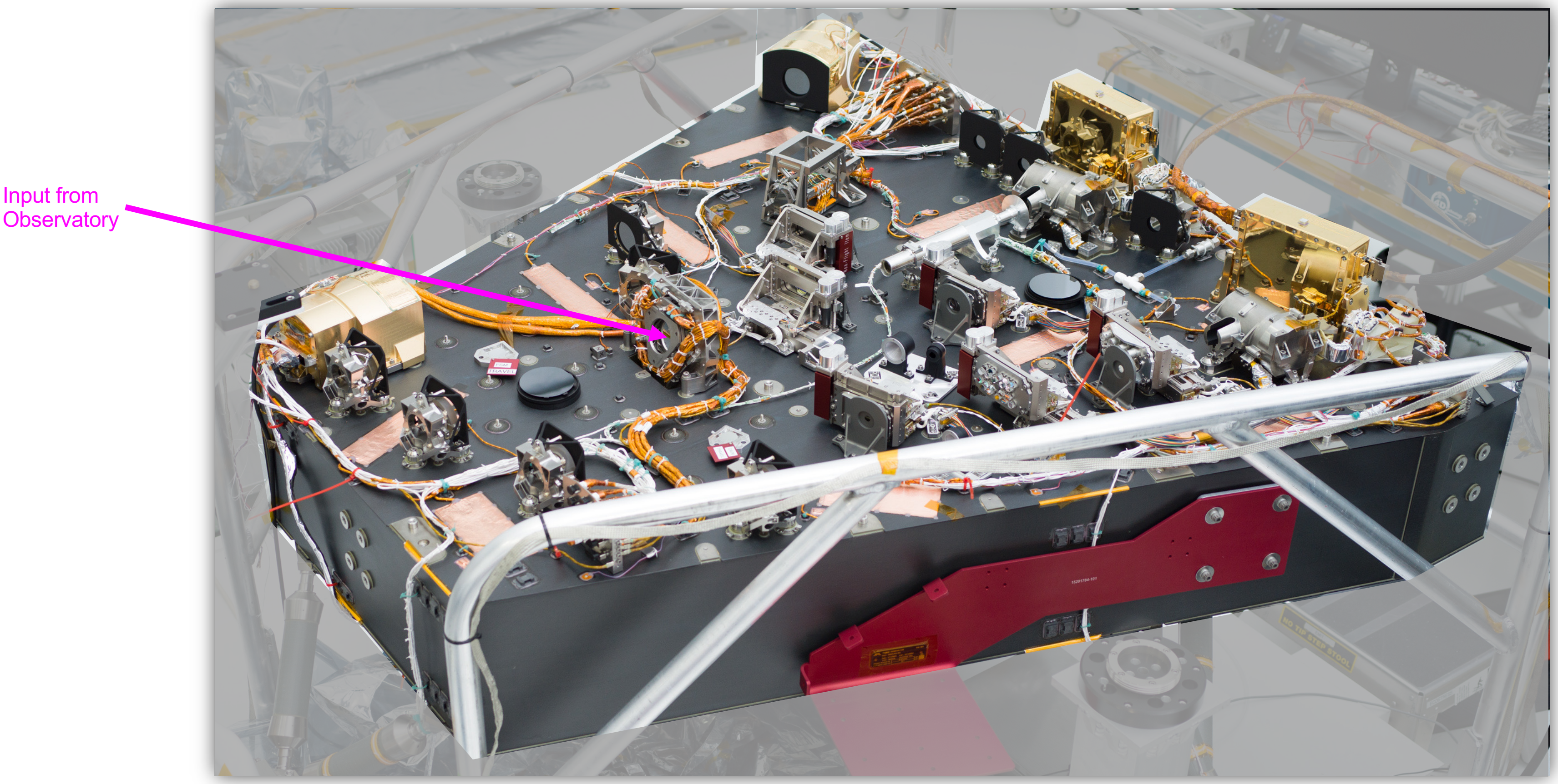
Deformable Mirrors	• Located before focal plane masks • Separated by 1m • Correct wavefront Zernikes 4-11
Low Order Wavefront Sensor	• Centered at 575nm • 128nm bandpass • Sense Zernikes 2-11

CGI Optical Subsystem





CGI Optical Subsystem – Fully Aligned



*CFAM baffle not yet installed

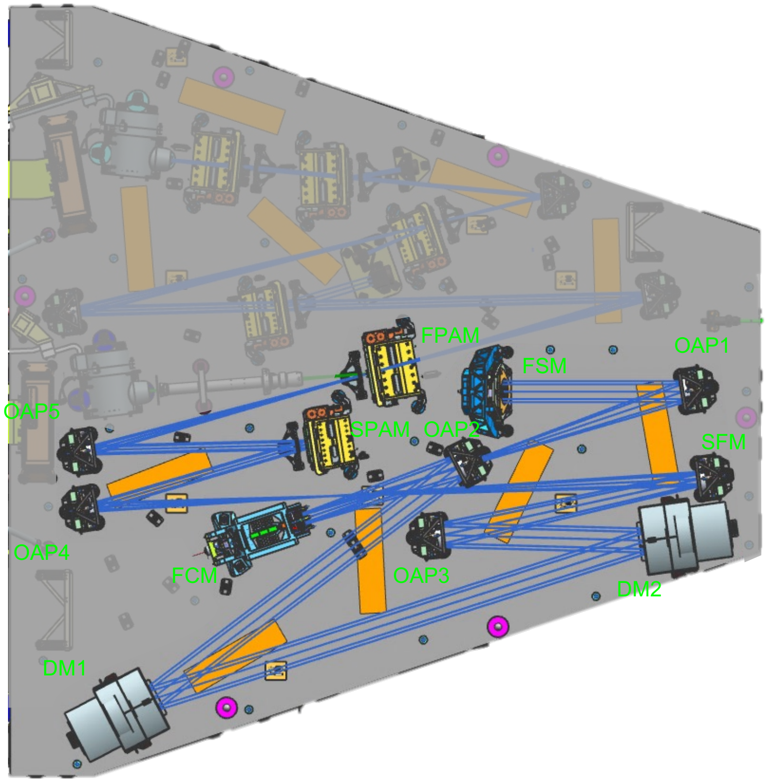
Front End

- The CGI front-end (FSM through FPAM) is where the majority of coronagraphic “magic” occurs.

- Key components include:
    - Fast Steering Mirror (FSM) for pointing control
    - Focus Control Mirror (FCM) for focus compensation
    - Deformable mirrors (DM1 & DM2) for wavefront amplitude and phase control
    - Shaped pupil coronagraph masks on a precision alignment mechanism (PAM)
    - Focal plane masks (a.k.a. occulters) on a PAM

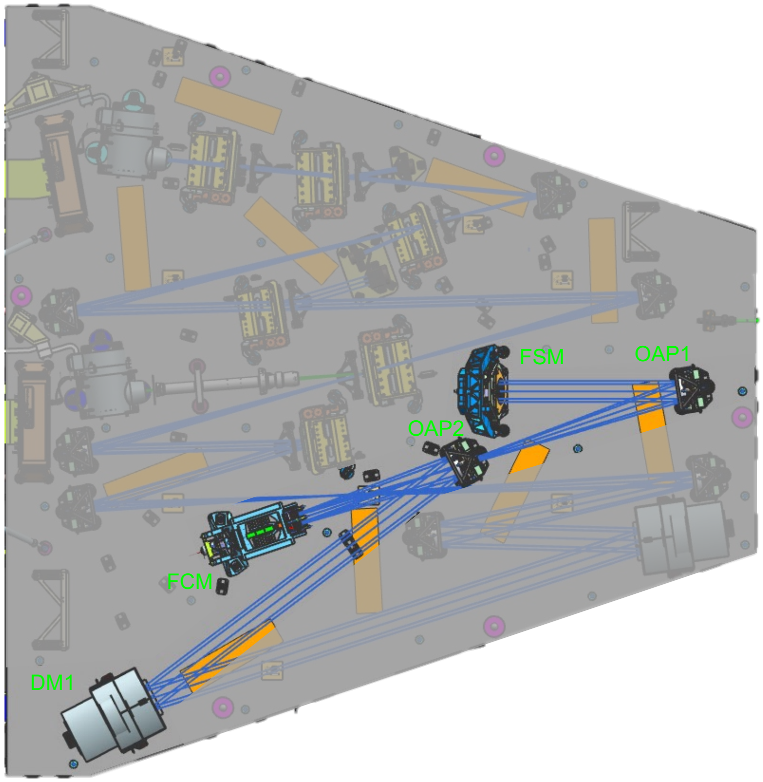
- Two OAP-pair relays produce two internal pupil planes.

- One OAP of the third relay produces the occulter focal plane and Low Order Wavefront Sensor pick-off



Relay 1

- The first OAP-pair relay produces an internal pupil plane for DM1. This DM performs phase correction of the wavefront.
- The FCM is located between the two OAPs such that piston of the mirror affects defocus with very little additional optical abberations.
- After reflecting from OAP1, the converging beam passes through the back-side of OAP2 by way of a through hole smaller than the central obscuration of the Roman telescope pupil.
- This allows the FCM surface normal to be parallel to the beam between the two OAPs.



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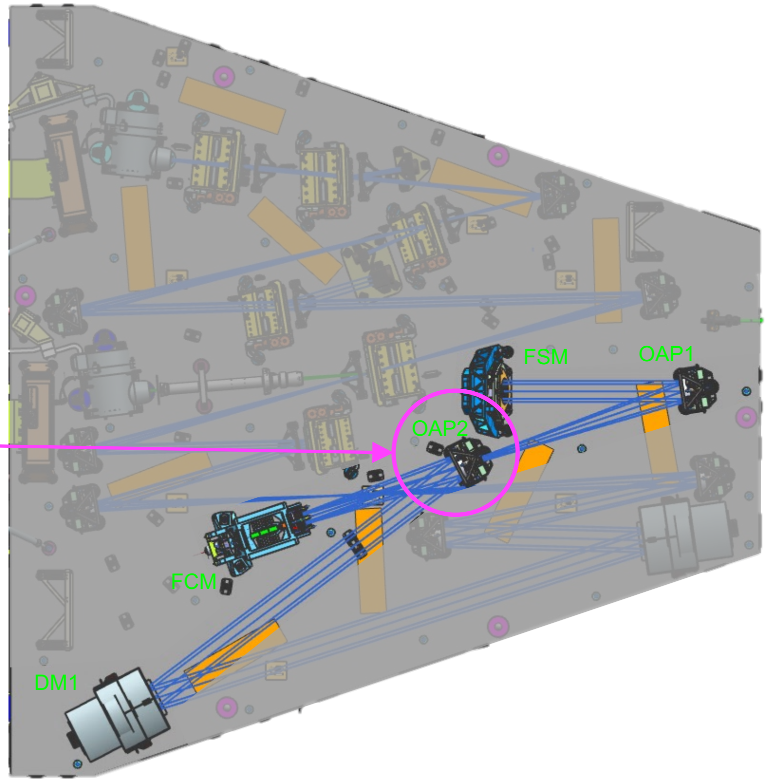
- This allows the FCM surface normal to be parallel to the beam between the two OAPs.

- *Note: the hole in OAP2 is 9mm diameter.*
    - It was a challenge to both accurately fabricate the OAP with a stepped hole in the center as well as aligning it within the relay.
    - It was especially challenging to displace OAP1 and OAP2 and the FCM to offset DM surface deformations under vacuum.



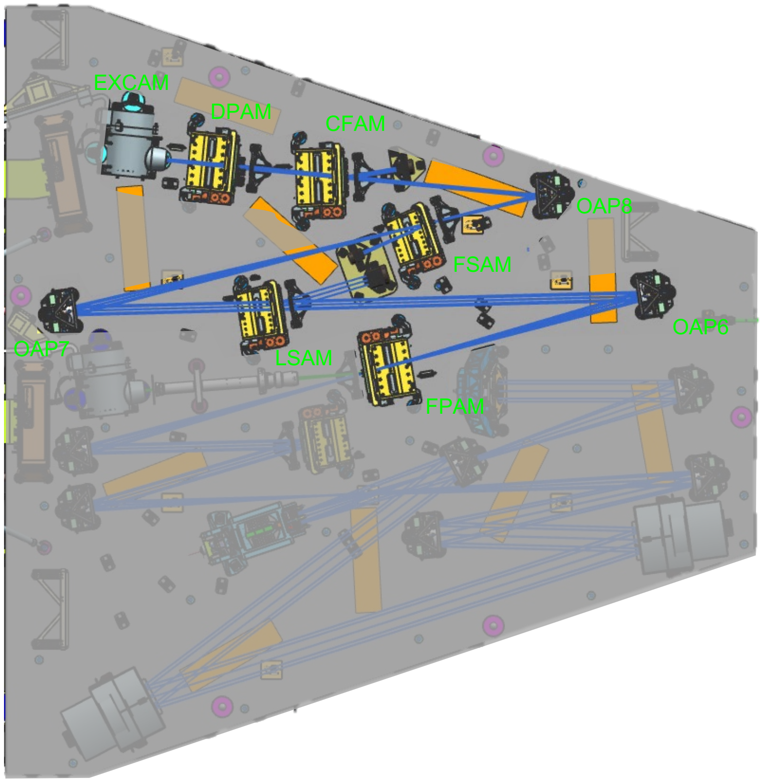
Back End

- The CGI Back-end (FPAM through EXCAM) provides additional coronagraphic support, color filters, and imaging modes.

- Key components include:
    - Lyot stop at a pupil plane
    - Field stops at a focal plane
    - Color filters
    - Imaging optics

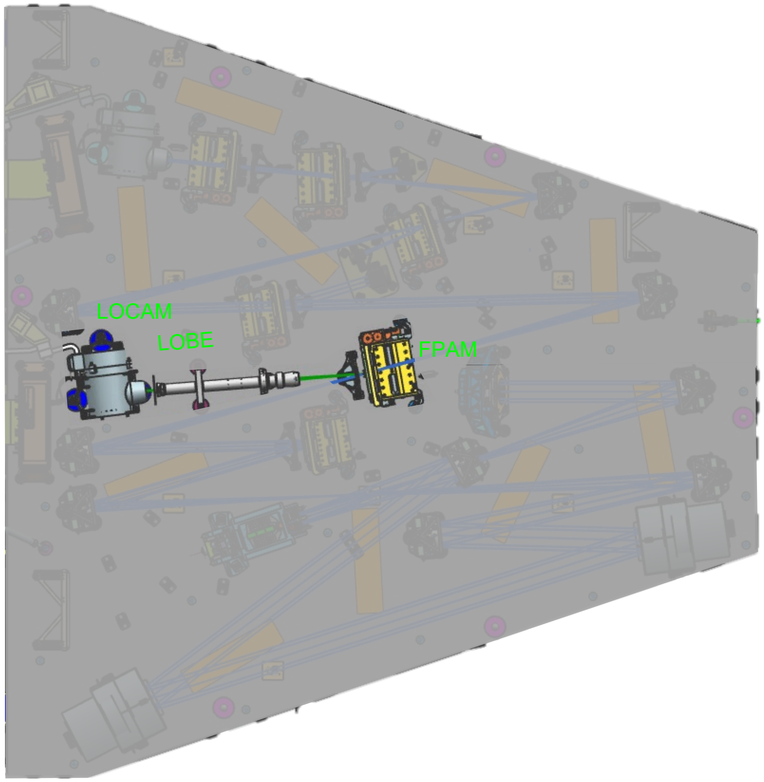
- The third OAP-pair relay produces a third pupil plane for the Lyot stop.

- The fourth OAP-pair relay produces a focal plane for the field stops and a collimated beam for the color filters and image lenses.

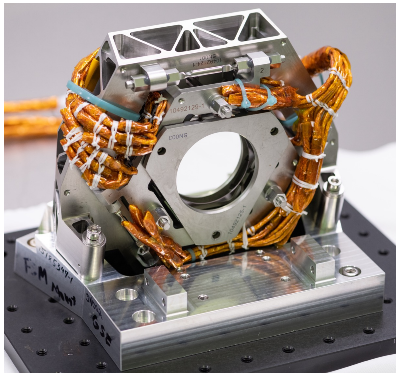


LOWFS

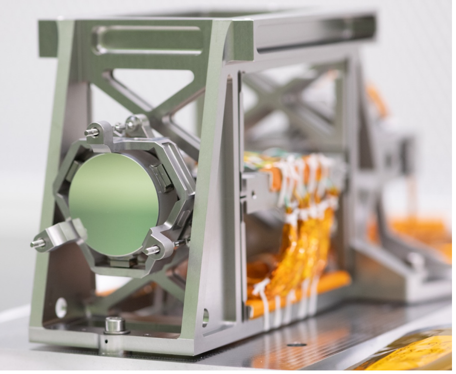
- A $\lambda/4$ phase dimple on each FPAM occulter allows for Zernike wavefront sensing of the starlight reflected.
- This allows the Low Order Wavefront Sensor (LOWFS) to sense wavefront Zernikes from Z2 through Z11.
- LOWFS provides pointing feedback to the CGI internal Attitude Control System (ACS).
- LOWFS also provides wavefront sensing for active wavefront compensation using the DMs.
- Note the optical design of the LOWFS Optical Barrel Element (LOBE) had originally accommodated a separate optical path for a starshade sensor and therefore is a non-optimal pupil relay especially for fields further off-axis.



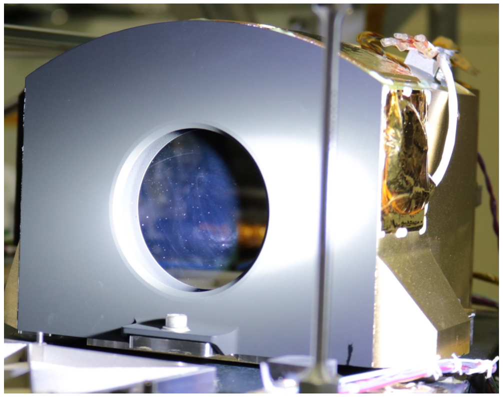
CGI Optic Mechanisms & Cameras



Fast Steering Mirror (FSM)



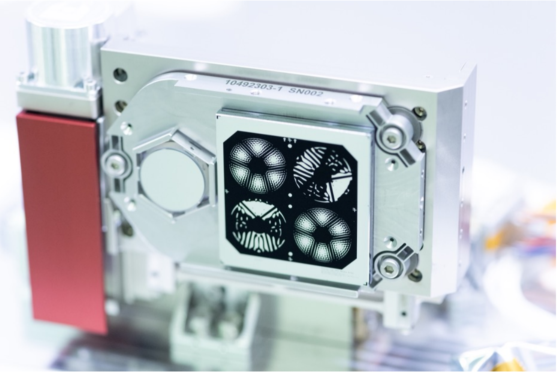
Focus Control Mirror (FCM)



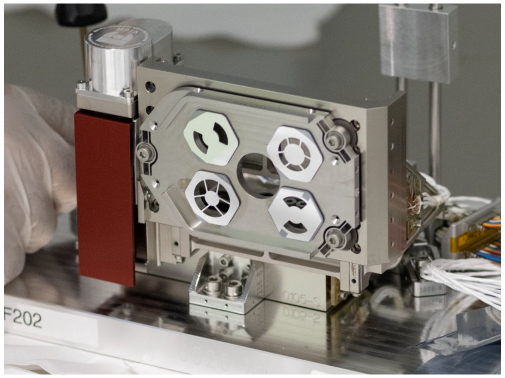
Deformable Mirrors (one shown)

Exoplanet Camera (EXCAM) (not shown)
Low Order Wavefront Sensing Camera (LOCAM)

Precision Alignment Mechanisms

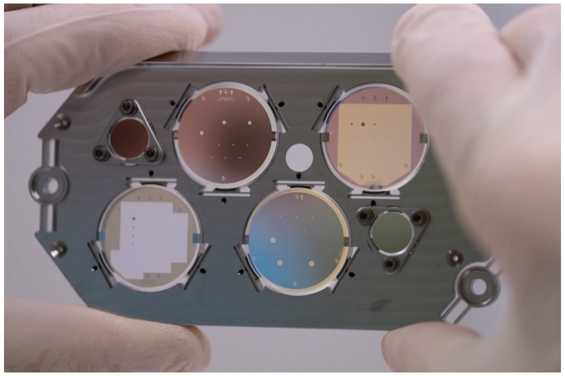


Shaped Pupil Alignment Mechanism (SPAM)



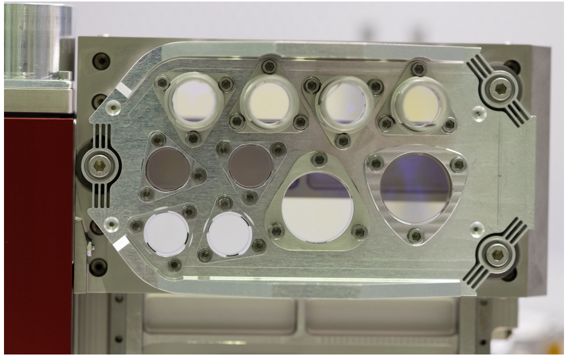
Lyot Stop Alignment Mechanism (LSAM)

Color Filter Alignment Mechanism (CFAM)



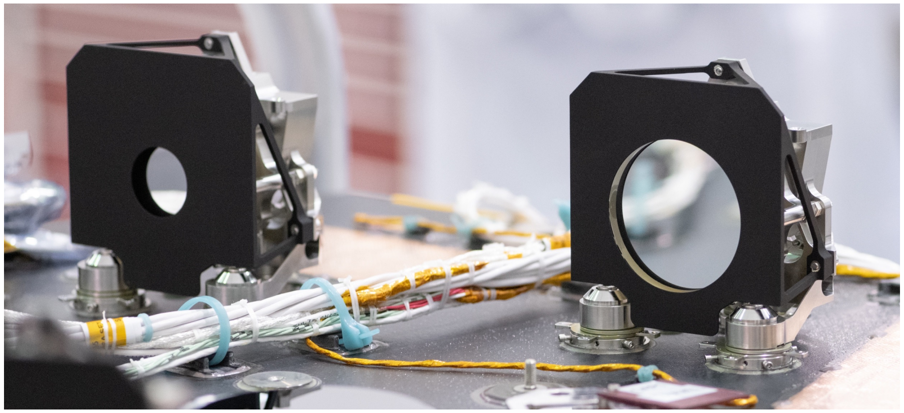
Focal Plane Alignment Mechanism (FPAM)

Field Stop Alignment Mechanism (FSAM)

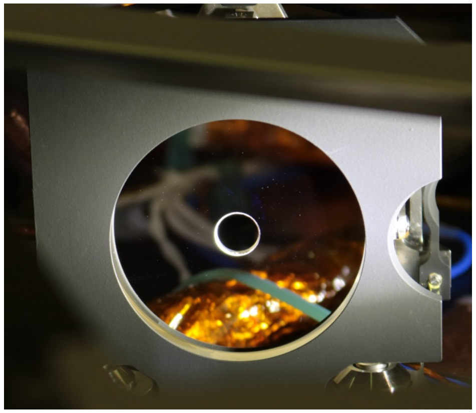


Direct Imaging and Polarization Alignment Mechanism (DPAM)

Static Optics



Off-axis Parabola (OAP) Mirrors

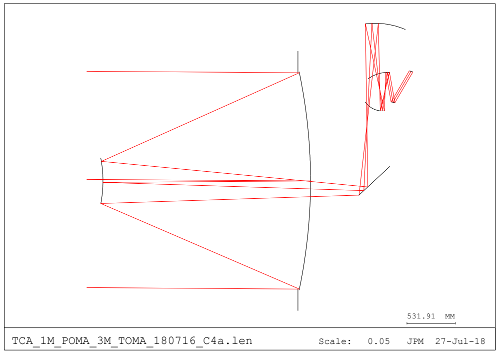


Off-axis Parabola (OAP) Mirror #2 (OAP2)
With through hole

LOWFS Optical Barrel Element (LOBE)

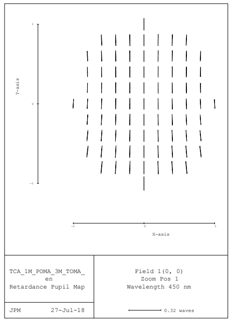
OTA+TCA Polarization Performance

- Polarization Retardance Analysis of OTA + TCA:
  - Optimal layout selected from a set of candidate options.

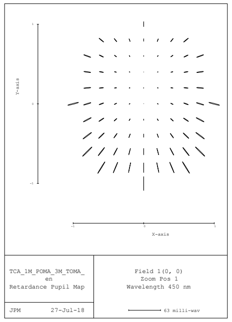


Retardance summary

```
Filename => TCA_1M_POMA_3M_TOMA_180716_C4a.len
                                                     Piston removed
                                Maximum      Minimum    Maximum
Zoom  Field    Wavelength     Magnitude    Magnitude  Magnitude        RMS
==========================================================
   1      1      950.000       0.09391      0.06653     0.01782      0.00710
   1      1      850.000       0.11877      0.08263     0.02474      0.00927
   1      1      750.000       0.10826      0.07263     0.02411      0.00902
   1      1      650.000       0.06509      0.04018     0.01591      0.00618
   1      1      550.000       0.01735      0.00473     0.00813      0.00292
   1      1      450.000       0.13953      0.09375     0.02753      0.01140
```

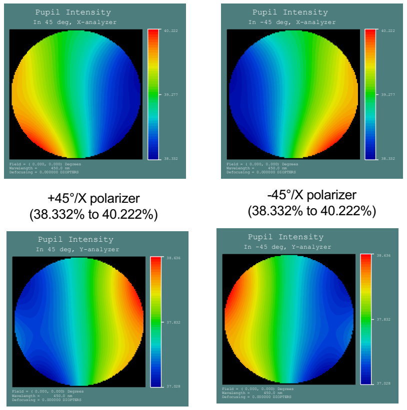


All retardance
0.140 max



Piston removed
0.028 max

Intensity at 450 nm (input polarized ±45°)



+45°/X polarizer
(38.332% to 40.222%)

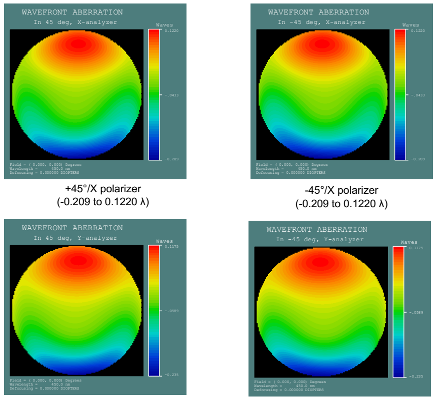
-45°/X polarizer
(38.332% to 40.222%)

+45°/Y polarizer
(37.028% to 38.636%)

-45°/Y polarizer
(37.028% to 38.636%)

Mirror symmetric

Phases at 450 nm ±45°



+45°/X polarizer
(-0.209 to 0.1220 λ)

-45°/X polarizer
(-0.209 to 0.1220 λ)

+45°/Y polarizer
(-0.235 to 0.1175 λ)

-45°/Y polarizer
(-0.235 to 0.1175 λ)

Mirror symmetric as expected. Largest component is polarization independent phase.

Analysis provided by Jim McGuire

Optical Performance – WFE

- An unexpected amount of defocus (Z4) and astigmatism (Z6) was present on the deformable mirror surfaces during TVAC testing.
- Self-flattening the deformable mirrors with actuator stroke would require significant wavefront control capacity.

- It was decided to deliberately displace OAPs 1-4 and the FCM to offset about 70% of this deformation while under dry nitrogen purge.

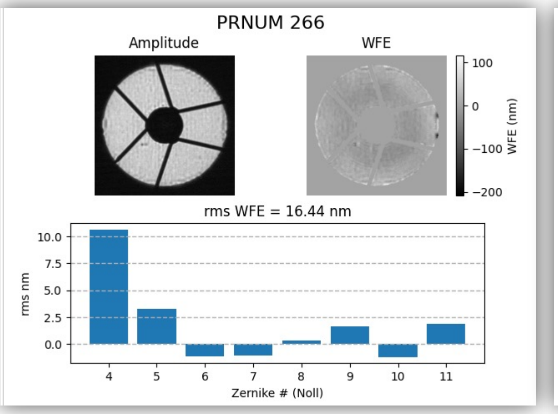
- Pre-DM installation WFE:
  - Front-end Z5+ WFE: 16.95 nm rms
  - Front-end Z4 WFE: 3.22 nm rms
  - Back-end Z4+ WFE: 24.1 nm rms

- Post-DM installation WFE (expected; DMs introduce wavefront aberrations):
  - Front-end Z5+ WFE: ~72 nm rms
  - Front-end Z4 WFE: ~50 nm rms
  - Back-end Z4+ WFE: no change

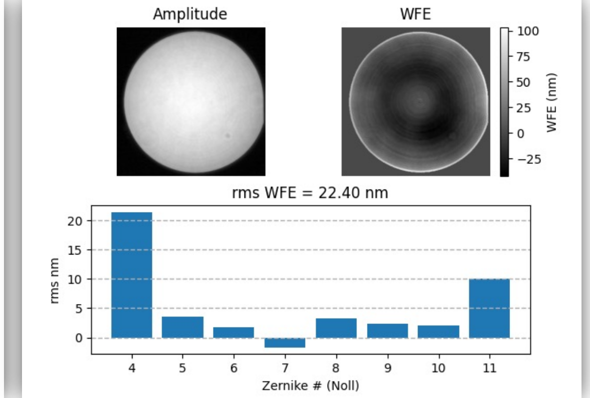
- Post-wavefront flattening prior to EFC (PRNUM 266, includes back-end):
  - Z4+: 16.44 nm rms
  - Z4 : 10.3 nm rms
  - Z5+: 12.8 nm rms

- Back-end WFE only (measured with pinhole at FPAM, full circular aperture):
  - Z4+: 22.40 nm rms
  - Z4 : 21.42 nm rms
  - Z5+: 6.55 nm rms

Front-end + Back-end, Post-Flattening



Back-end Only

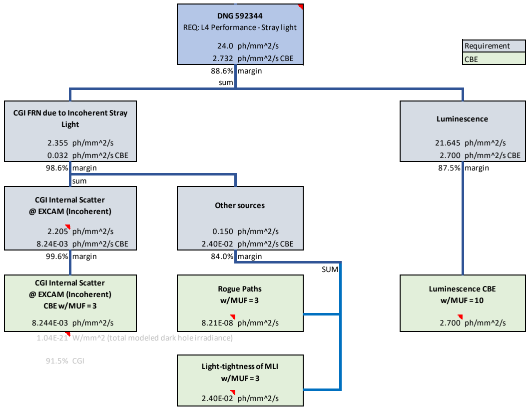


Stray Light Control

- Stray light control is critical to a coronagraph.
- Methods include:
  - High quality optical surfaces
  - Color filters
  - Baffles (stand-alone and integrated)
  - Beam dumps
  - Bladed stray light guard at entrance
  - Light-tight MLI enclosure
  - Contamination control

- 2.73 photons/mm^2/sec within the dark hole, verified by analysis
  - Includes MUF = 3,
  - MUF = 10 for radiation induced luminescence

As-built Stray Light Budget



DNG 592344
REQ: L4 Performance - Stray light
24.0 ph/mm^2/s
2.732 ph/mm^2/s CBE
88.6% margin
sum

Requirement
CBE

CGI FRN due to Incoherent Stray Light
2.355 ph/mm^2/s
0.032 ph/mm^2/s CBE
98.6% margin
sum

Luminescence
21.645 ph/mm^2/s
2.700 ph/mm^2/s CBE
87.5% margin

CGI Internal Scatter @ EXCAM (Incoherent)
2.205 ph/mm^2/s
8.24E-03 ph/mm^2/s CBE
99.6% margin

Other sources
0.150 ph/mm^2/s
2.40E-02 ph/mm^2/s CBE
84.0% margin
SUM

CGI Internal Scatter @ EXCAM (Incoherent) CBE w/MUF = 3
8.244E-03 ph/mm^2/s
1.04E-21 W/mm^2 (total modeled dark hole irradiance)
91.5% CGI

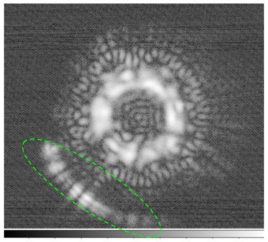
Rogue Paths w/MUF = 3
8.21E-08 ph/mm^2/s

Light-tightness of MLI w/MUF = 3
2.40E-02 ph/mm^2/s

Luminescence CBE w/MUF = 10
2.700 ph/mm^2/s

CFAM Baffle Stray Light Issue

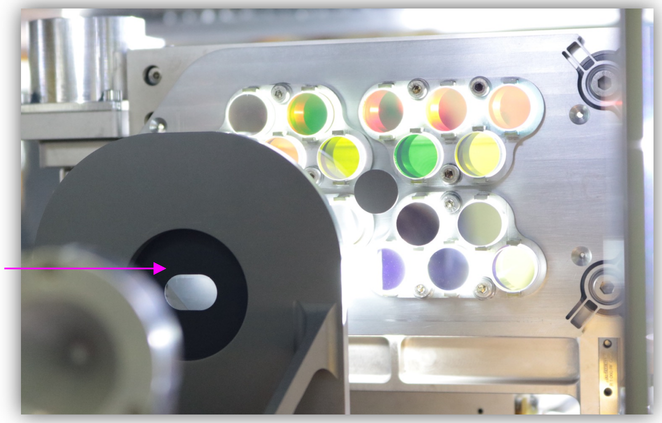
- A stray light leakage was found during TVAC.
- What occurred:
  - Out-of-band light diffracted into the field stop following EFC
  - This light bypassed the color filter and entered the dark hole.



Stray light leakage shown in a pupil image

- Cause:
  1. A design flaw in the color filter mount exposed a gap through which light could bypass the color filter.
  2. In addition, the original color filter baffle had been removed, after bench fabrication, to accommodate harnessing.
  3. Traditional stray light analysis had not modeled diffraction due to wavefront manipulation by EFC.
- Solution:
  - Model a diffracted beam at the field stop that overfills the color filter and determine the proper baffle aperture to ensure no gaps are illuminated.
  - Fabricate a new baffle aperture and re-install the baffle onto original interface to cover the gaps.

Back-lighting highlights gaps around color filters



Installed CFAM baffle

Optical Throughput

- The optical throughput of the CGI is a combination of mirror reflectivity, optic transmission, and residual transmission after contamination loss.
- Coronagraph mirror coatings are all high reflectivity protected silver, with the exception of bare aluminum on the DMs. This is OK for CGI.
- The table to the right captures the throughput of each as-built optic for each observation waveband and LOWFS.
- For the threshold observing waveband (Band 1), the total estimated throughput 15 months after launch, is 51%.

	Transmission Type (R/T/M)	Coating Material	Band 1	Band 2	Band 3	Band 4	LOWFS	Notes
FSM	R	Protected Silver	98.30%	98.38%	99.00%	99.48%	98.37%	8-8732R 8 deg
OAP1	R	Protected Silver	99.24%	98.61%	98.44%	98.74%	99.19%	6-8648R 8 deg
FCM	R	Protected Silver	98.18%	98.10%	98.54%	98.89%	98.23%	8-8380R 8 deg
OAP2	R	Protected Silver	99.24%	98.61%	98.44%	98.74%	99.19%	6-8648R 8 deg
DM1	R	Aluminum	91.12%	90.07%	88.60%	86.10%	91.08%	1MM48-009
DM2	R	Aluminum	91.10%	90.07%	88.60%	86.03%	91.07%	1MM48-008
OAP3	R	Protected Silver	99.24%	98.61%	98.44%	98.74%	99.19%	6-8648R 8 deg
SFM	R	Protected Silver	98.20%	98.10%	98.53%	98.88%	98.24%	8-8261R 8 deg
OAP4	R	Protected Silver	98.10%	97.79%	98.14%	98.57%	98.11%	6-8763R 8 deg
SPAM	R	Protected Silver	98.18%	98.10%	98.54%	98.89%	98.23%	8-8380R 8 deg
OAP5	R	Protected Silver	98.10%	97.79%	98.14%	98.57%	98.11%	6-8763R 8 deg
FPAM	T	Fused Silica w/AR coatings	98.46%					Corning 7980 fused silica grade substrate; from material product information, assume 99% transmission apply worst of Batches 1 and 2, Sides 1 and 2
OAP6	R	Protected Silver	98.10%	97.79%	98.14%	98.57%		6-8763R 8 deg
LSAM	M	N/A						mask
OAP7	R	Protected Silver	98.10%	97.79%	98.14%	98.57%		6-8763R 8 deg
LSAM	M	N/A						mask
OAP8	R	Protected Silver	99.24%	98.61%	98.44%	98.74%		6-8648R 8 deg
CFAM	T	Fused Silica w/filter + AR	91.59%					worst case avg from 5 measured regions
DPAM (DI Lens)	T		99.05%	99.56%	99.70%	99.72%		From Tyler Groff
Camera FM	R	Protected Silver	97.51%	98.16%	98.55%	98.68%	97.65%	8-8431R; both serial numbers are within 0.01% for band 1
Total Throughput			60.4%	63.7%	63.7%	62.9%	71.0%	

The average contamination throughput loss, 15 months after launch, is 14.8% or 85.2% transmission.

The total average Band 1 throughput 15 months after launch is 85.2% * 60.4% = 51%