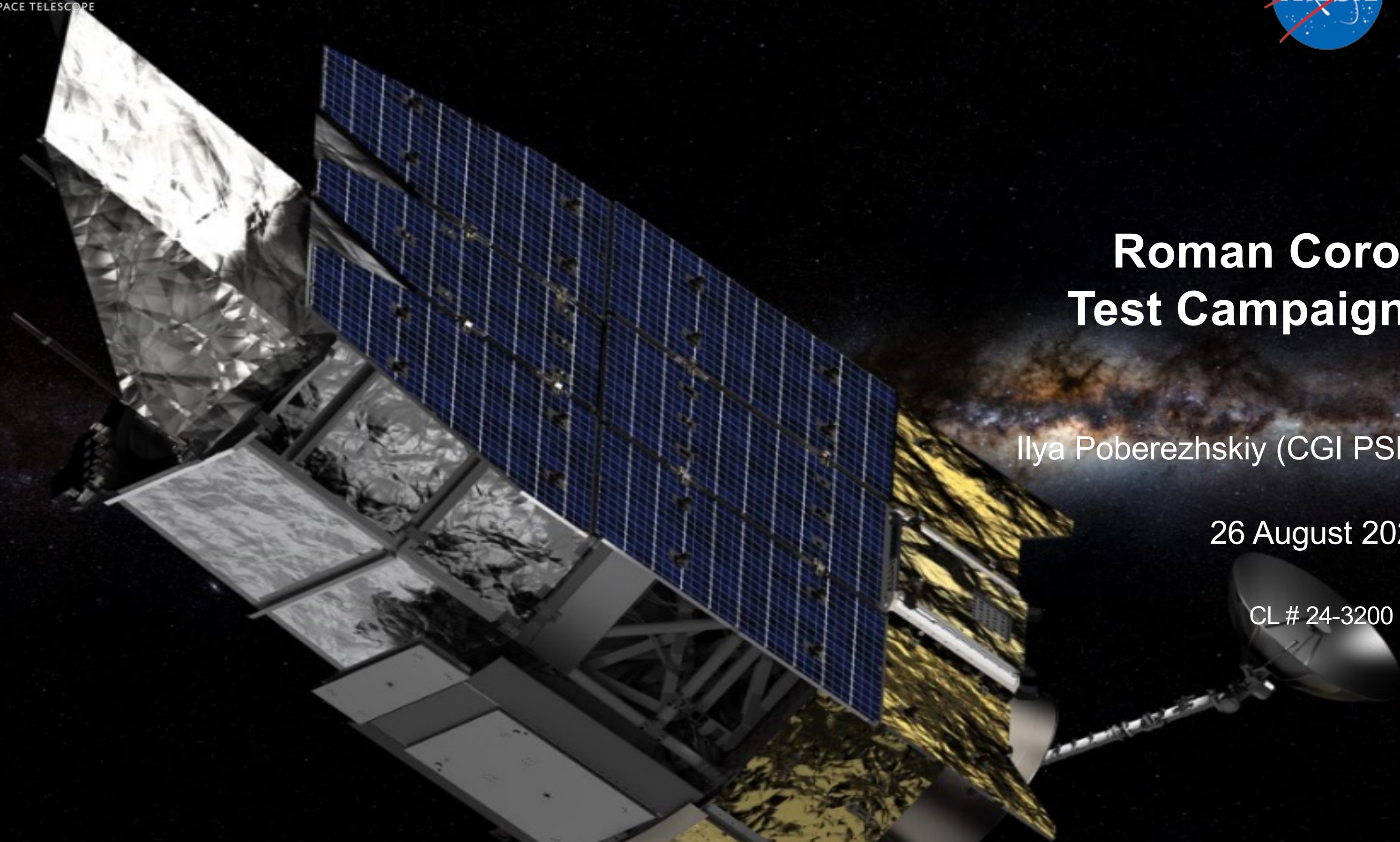
ROMAN SPACE TELESCOPE

Jet Propulsion Laboratory
California Institute of Technology



Roman Coronagraph Test Campaign Overview

Ilya Poberezhskiy (CGI PSE) for CGI Team

26 August 2024

CL # 24-3200

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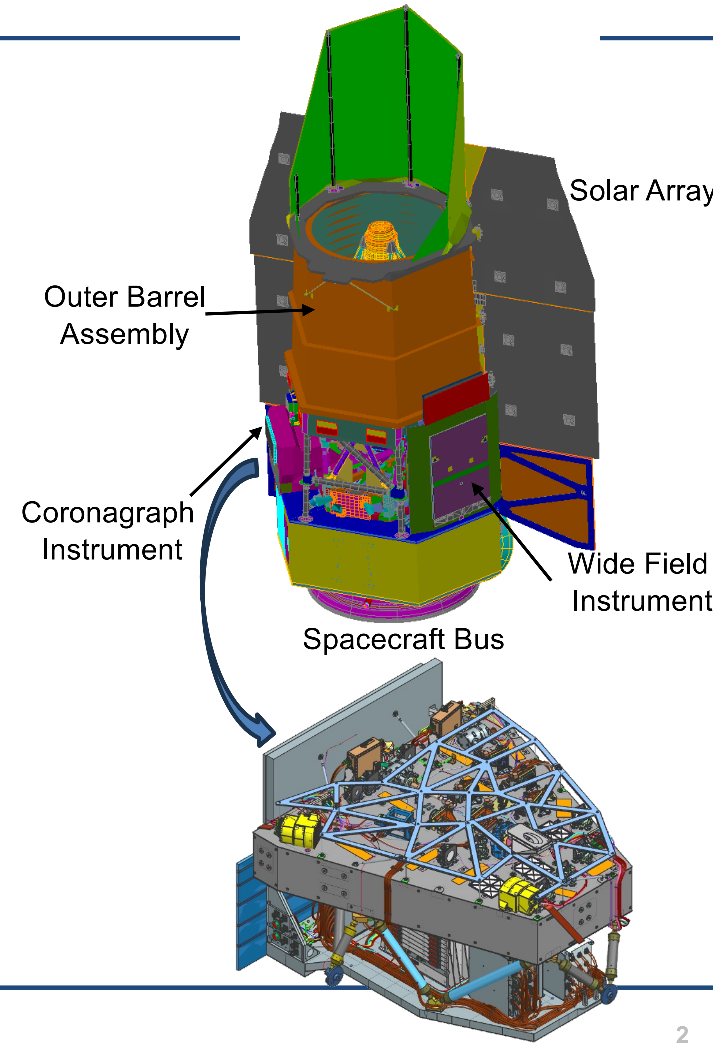
Project Overview

- Nancy Grace Roman Space Telescope (a.k.a. Roman or RST) is a flagship NASA observatory with a 2.4 meter diameter telescope and 2 instruments:
  1. Wide Field Instrument
  2. Coronagraph Instrument
- Managed by NASA Goddard Space Flight Center (GSFC)
- L2 Orbit; Launch planned NET Oct 2026

- Coronagraph Instrument will be the first coronagraph in space to employ active wavefront sensing & control, demonstrating technology for the future Habitable Worlds Observatory (HWO)
  - **High-Contrast Broadband Imaging**
  - High-Contrast Slit Spectroscopy
  - High-Contrast Extended Source Imaging and Polarimetry
- Coronagraph is:
  - Technology demonstration instrument, Risk Class D
  - Implemented by JPL, in partnership with GSFC, industry, international partners (MPIA, JAXA, ESA, CNES/LAM)



Coronagraph Instrument Overview

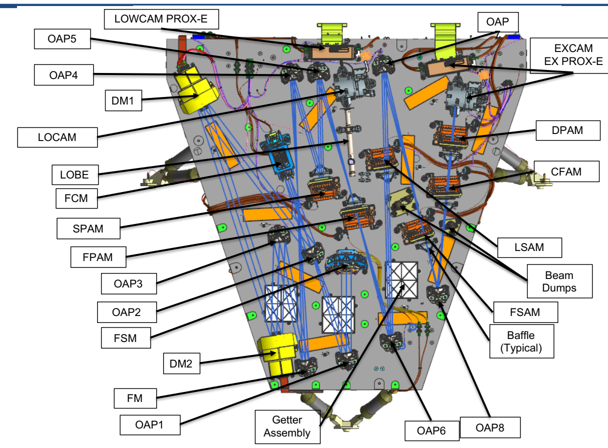
- Dimensions: 1.7 X 1.1 X 1.8 (m^3)
- Mass: 303 kg
- Power: 343 W operations
- Temperature: ~20°C optical bench

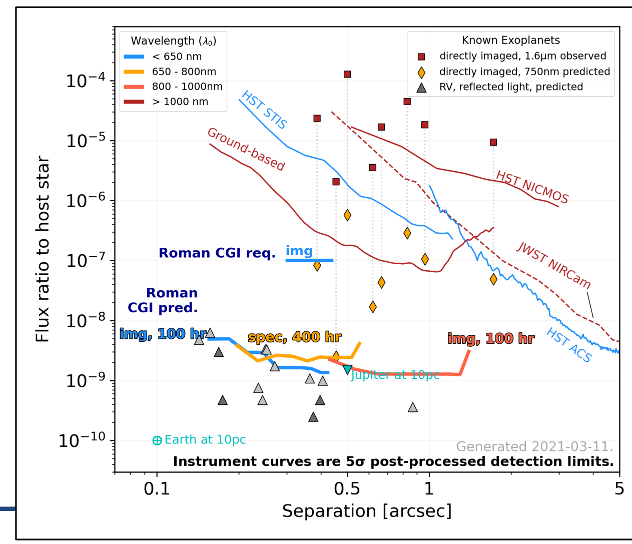
- Wavelength: 460-980 nm; 546-604 nm primary coronagraphic band
- Field-of-view: Ø7.2 arcsec unvignetted
- Pointing jitter: <1 mas post-correction with FSM (~10 mas pre-correction)
- Pupil imaging and phase retrieval capabilities

- EMCCD Camera #1: 1K X 1K pixels – EXCAM ("science" camera)
- EMCCD Camera #2: 50 X 50 pixels used – LOCAM (low-order WF sensing)
- EMCCD temperature: -88°C

- 2 48x48 AOA Xinetics deformable mirrors
- 6 X-Y Precision Alignment Mechanism
- Data rate: 8.9 Mbps; Data volume: 0.77 Tbits/day

- 49x electronics slices
- 9x unique FPGA designs
- Flight computer card (from GSFC): LEON4 processor + RTG4 FPGA
- >260,000 source lines of code (Flight SW, Ground SW, FPGA)
- Ground-in-the-loop iterative starlight suppression (HOWFSC)





CGI Integration and Test Progress since 2022 SPIE

Optical Bench Alignment
in parallel with
Electronics Pallet Integration
2022 – July 2023 ✓

→

Complete Integration
followed by
Full Functional Test
Aug – Nov 2023 ✓

→

EMI/EMC Test
Dec 2023 ✓

↓

Dynamics Tests
Jan 2024 ✓

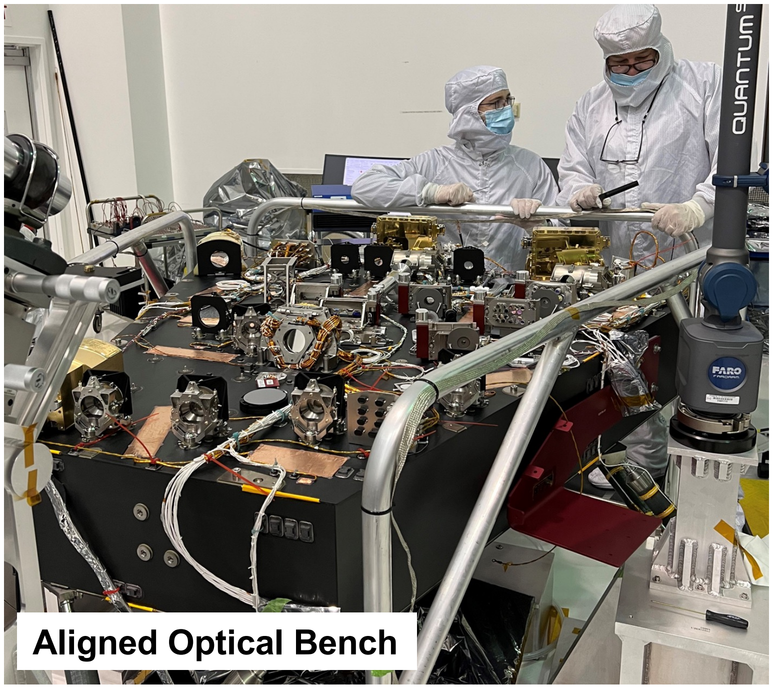
←

Thermal Vacuum Test and Performance V&V
Feb – April 2024 ✓

←

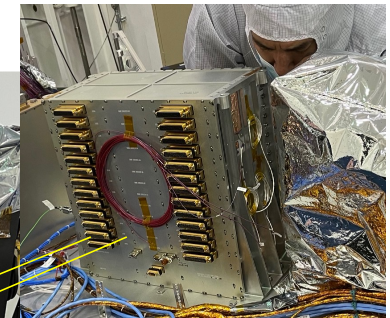
Delivery and Final Checkout at GSFC
May 2024 ✓

Optical Bench Alignment and Electronics Pallet Integration



Aligned Optical Bench

Complete Electronics Pallet being integrated to the Optical Bench



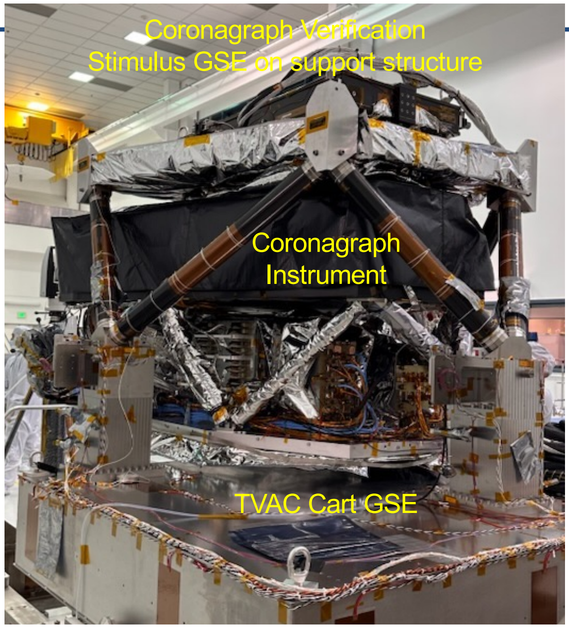
(2x) Deformable Mirror Electronics Assemblies

Completed Optical Bench alignment in May 2023, Electronics Pallet integration in July 2023
Optical Bench and Electronics Pallet integrated and cabled in August-Sept 2023

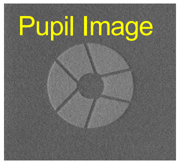
Full Functional Test (FFT): Oct-Nov 2023

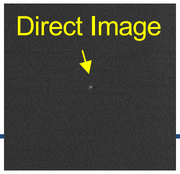
- First Coronagraph system-level test with flight hardware and software + flight-like optical stimulus
  - Coronagraph Instrument **in-air**, room temp cameras
  - Optical interface with Star and Telescope Simulator GSE (a.k.a. Coronagraph Verification Stimulus or CVS)
  - Power and data interface with Spacecraft Interface Simulator GSE

- Results
  - End-to-end CVS to CGI first light and alignment
  - Successfully tested device layer, verified majority of functional requirements
    - Tuned camera read-out sequences to improve performance
  - Executed alignment and calibration sequence: phase retrieval and DM wavefront flattening, alignment of boresight, masks and stops
  - Demonstrated line-of-sight sensing and control
  - Starlight suppression: demonstrated data flows but no meaningful dark hole
  - Found several hardware, flight software, ground software issues related to system-level emerging behaviors
    - Reason we test
    - Some issues fixed during FFT, others after

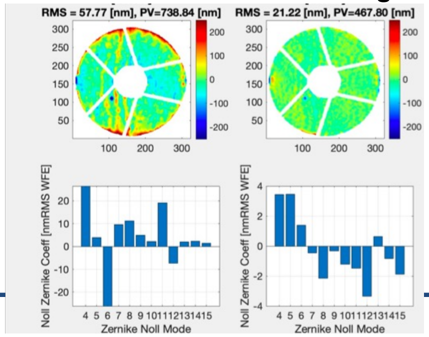


First light of CVS+CGI



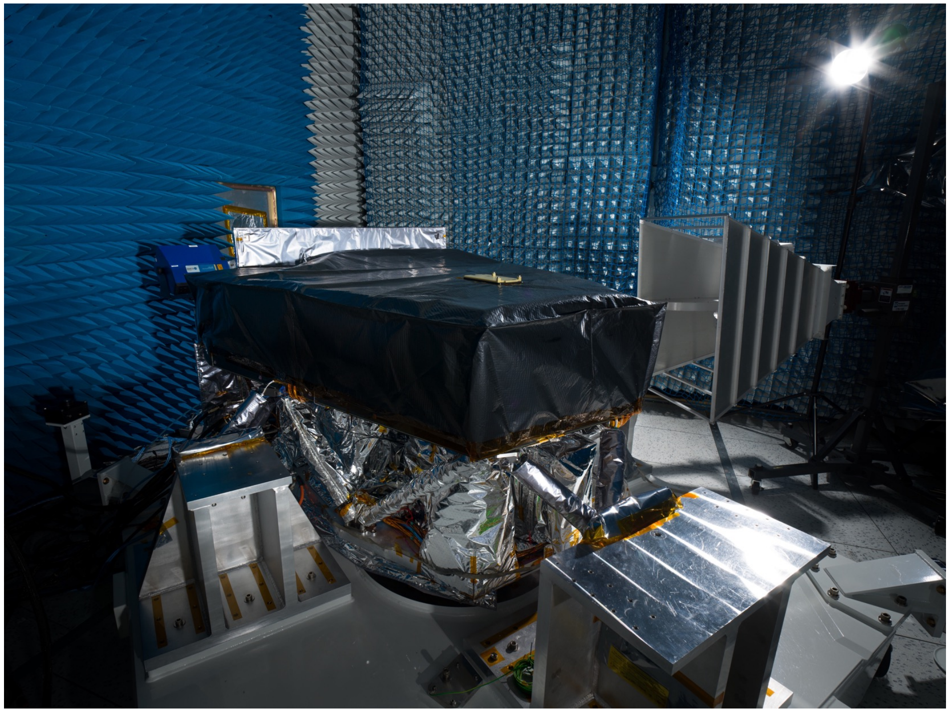


In-air Phase Retrieval before and after DM flattening



Full Functional Test met its objectives

EMI/EMC Test: Dec 2023



- ElectroMagnetic Interference (EMI) / ElectroMagnetic Compatibility (EMC) testing at JPL's anechoic chamber to Roman requirements
  - Radiated Emissions and Susceptibility
  - Conducted Emissions and Susceptibility
- No optical stimulus
  - Camera noise was the most sensitive susceptibility gauge
  - Electromagnetic self-compatibility verified in TVAC
- Close collaboration with Roman EMI/EMC lead, exceedances on both emissions and susceptibility rated as low risk

Coronagraph Instrument successfully completed EMI / EMC testing

Dynamics Tests: Modal, Sine Vibe, Random Vibe – Jan 2024

- Performed at JPL's Environmental Test Lab (ETL)
- Modal Test:
  - Verified >35 Hz first mode frequency
  - Characterized instrument modes up to 100 Hz
  - Produced model correlation report
- Completed vibration tests in X/Y/Z orientations
  - Sine Vibe: 5-50 Hz
  - Random Vibe: 20-2000 Hz
  - Measured Optical Alignment before and after vibe with alignment scope; changes deemed acceptable
- Acoustic by analysis only, test deferred to observatory level
- Further sine vibes as a part of Roman at GSFC

Test Mode No.	FEM Mode No.	Test Freq (Hz)	FEM Freq (Hz)	Freq Pct Diff	Cross Ortho
1	1	39.4	38.2	-3.0	99
2	2	40.0	38.8	-3.2	99
3	3	48.8	45.4	-7.0	97
4	4	51.9	46.9	-9.6	97
5	5	60.4	54.5	-9.7	95
6	6	68.9	65.5	-4.8	93
7	7	83.0	77.6	-6.5	97
8	8	94.7	82.8	-12.6	92

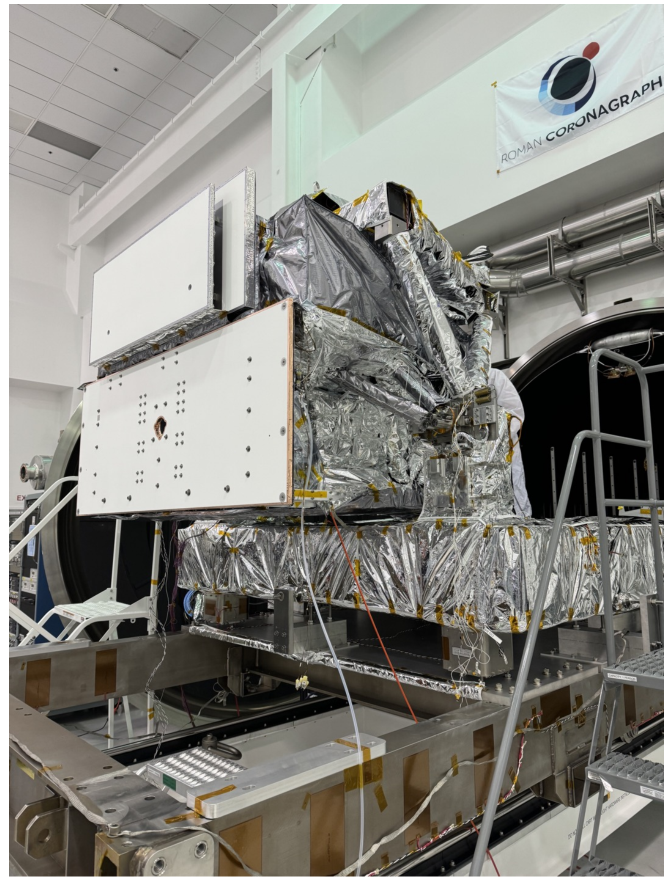
Coronagraph Instrument successfully completed modal and vibe tests

Thermal Vacuum (TVAC) Test: Feb-Apr 2024

TVAC Objectives

1. Thermal Verification and Validation (V&V):
    - Hot Operational, Cold Operational, and Survival thermal balance
    - Transient heater characterization test
    - Thermal stability tests
    - Collected data for thermal model correlation

2. Performance V&V and calibrations in flight-like environment:
    - Cold camera calibration w/ gain
        - -85 to -95C for EMCCD, +15 to +32C for prox-elex
    - Boresight, wavefront, mask alignment and calibration
    - Star acquisition
    - **Starlight suppression (HOWFSC)**
    - Line-of-sight sensing and control
    - Z4-Z11 sensing and control
    - Planet core throughput and tip/tilt sensitivities
    - Scenario (validation) tests
    - Spectroscopy and polarimetry calibrations

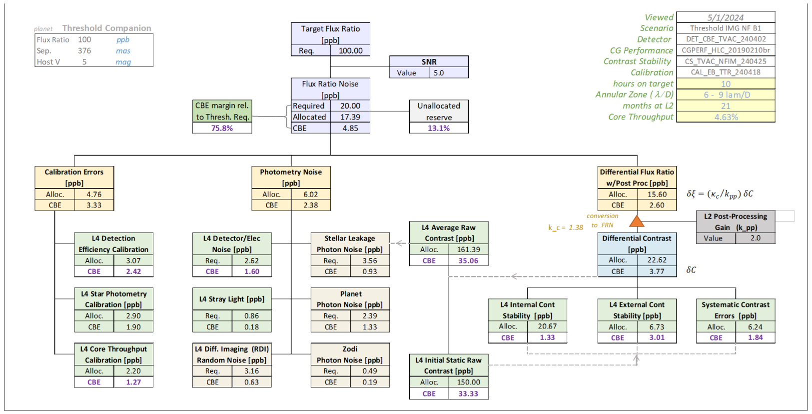


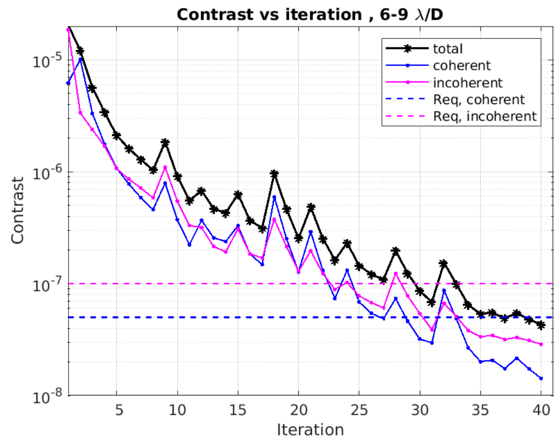
Thermal stability in TVAC exceeded tight requirements (note sub-mK DM stability)

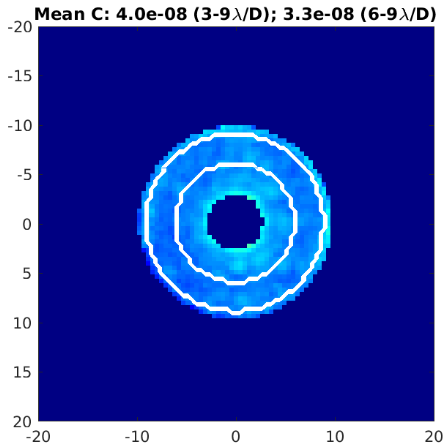
Subsystem	Requirement (mK)	Mean Stability (mK)	Delta Mean Stability(mK)
OBSA_BIP	10	8.1	2.9
OBSA_BNCH	10	2.0	0.2
OBSA_BIP_GRAD	30	8.0	4.1
OBSA_BNCH_GRAD	30	1.7	0.2
STATIC_OPT	50	6.6	4.4
FSM	20	0.8	0.4
FCM	20	0.6	0.6
PAM	50	2.4	1.5
DM_PUCK	10	0.2	0.3
DM_MNT	50	13.0	7.8
CAM_EMCCD	250	21.7	17.2
CAM_HSG	100	17.5	5.8
CAM_PROX	100	9.8	23.0
CTCE	100	1.7	1.8
DME	100	5.7	2.0

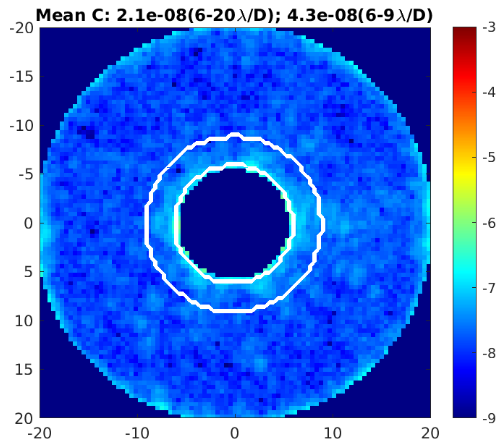
Coronagraph Instrument successfully completed TVAC

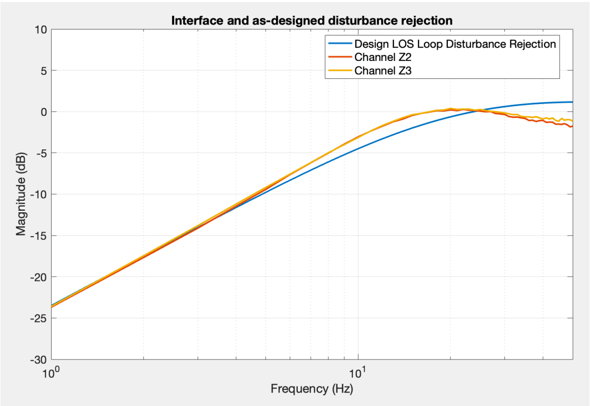
TVAC Results will be Reviewed in Detail during this Workshop





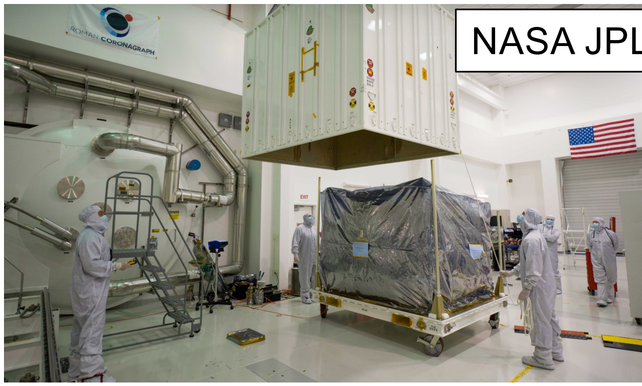




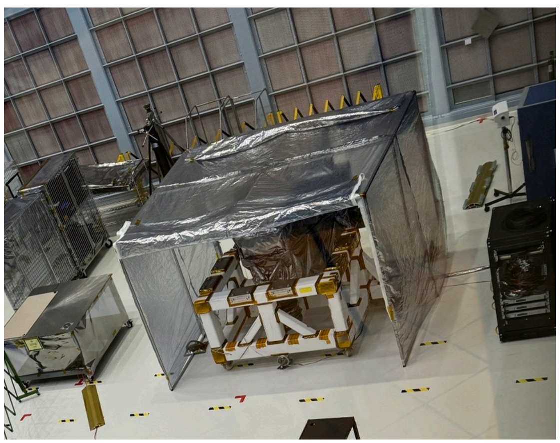


Delivery to NASA Goddard – May 2024

NASA JPL, Pasadena, California



NASA Goddard, Greenbelt, Maryland



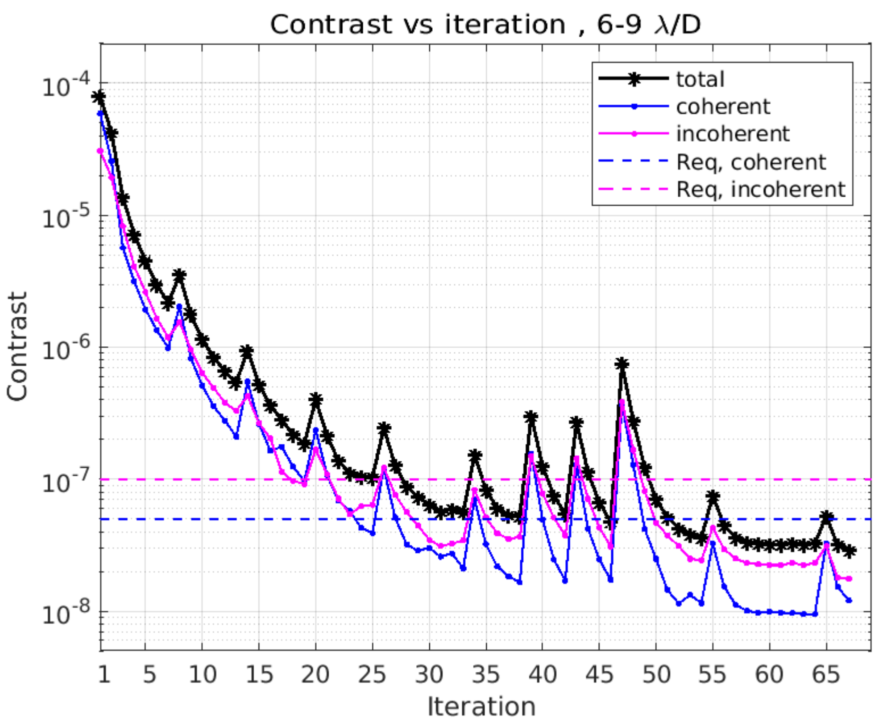
Coronagraph Instrument arrived at GSFC on May 19, 2024

Conclusions

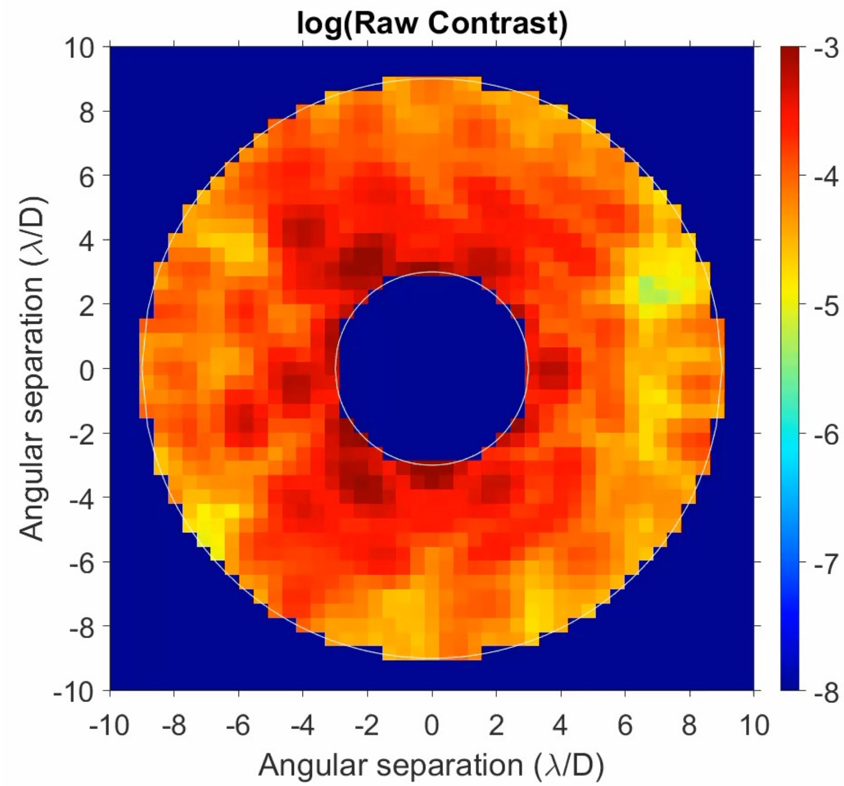
- **Roman Coronagraph Instrument successfully completed its I&T program and delivered to GSFC on May 19, 2024**
- Coronagraph will be a part of Roman Observatory I&T through 2026, but no further coronagraphic tests are planned or feasible until launch
- Coronagraph tech demo is planned for 90 days spread over the first 18 months of RST operations
- Coronagraph team at JPL continues to work with the Roman Project at GSFC, Coronagraph Ops at IPAC and Coronagraph Community Participation Program (CPP) to support Roman I&T and prepare for instrument commissioning and tech demo
- Coronagraph includes significant capability beyond that tested during I&T; can be commissioned in orbit if time and resources allow
- We gratefully acknowledge the contributions of numerous engineers and technologists to the results presented today

BACKUP

Narrow Field-of-View (Hybrid Lyot) Dark Hole Convergence

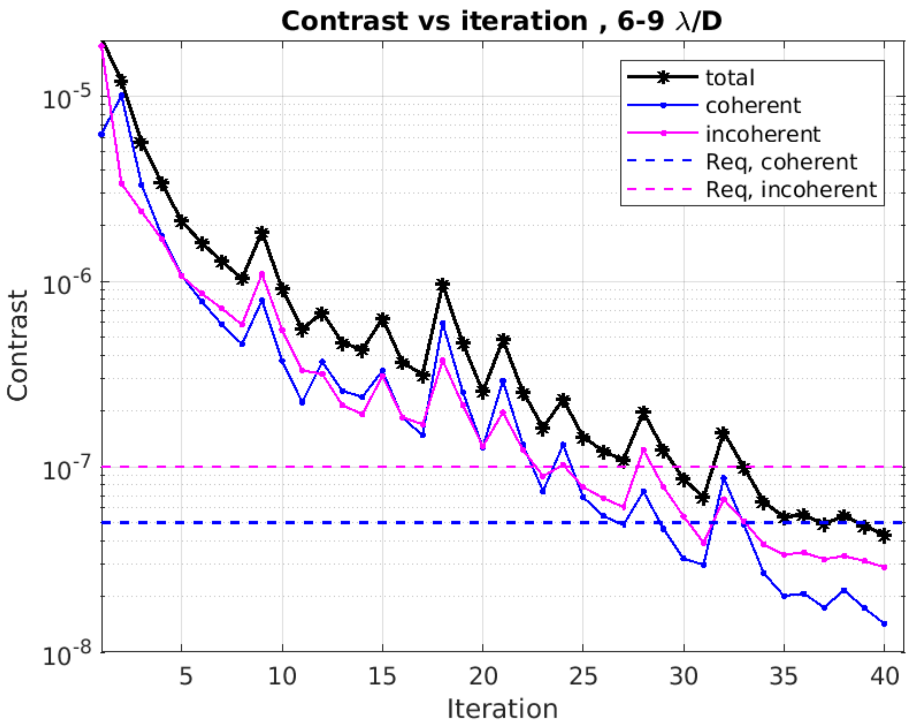


"Beta bumps" represent purposeful changes in control regularization

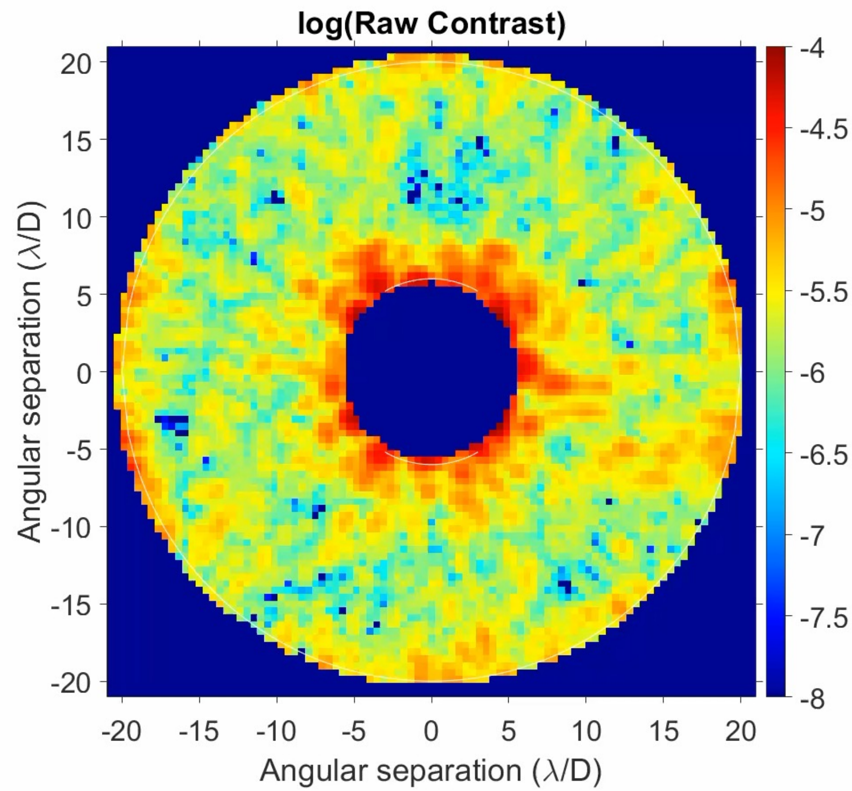


Number of iterations and time to dig the dark hole consistent with modeling and IOC/Tech Demo plans

Wide Field-of-View (Shaped Pupil) Dark Hole Convergence



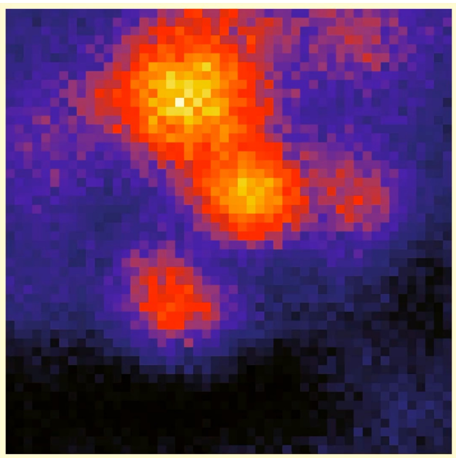
"Beta bumps" represent purposeful changes in control regularization



Number of iterations and time to dig the dark hole consistent with modeling and IOC/Tech Demo plans

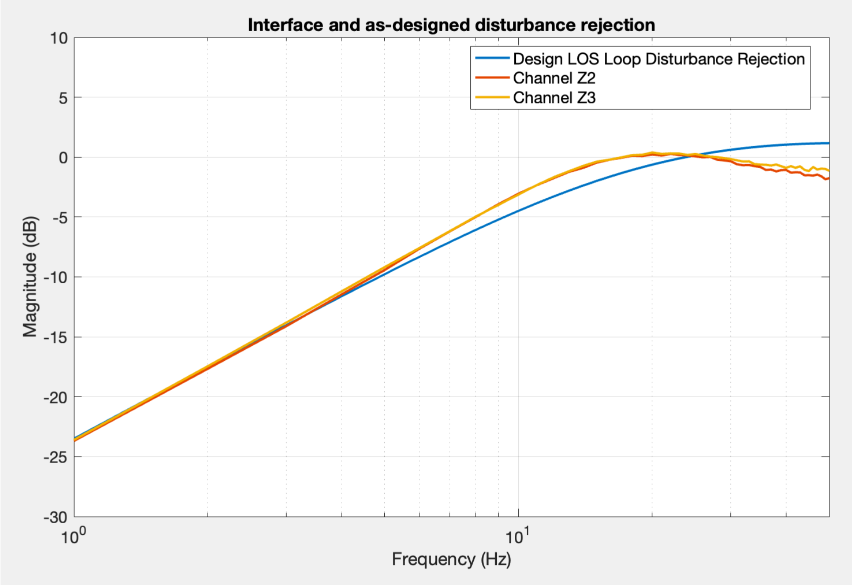
Line of Sight Control w/ Fast Steering Mirror

Requirement: Residual Pointing Error on the Focal Plane Mask, rms, on-sky, per axis	CBE based on TVAC		Margin (%)
	Tip (Z2)	Tilt (Z3)	
1.0 mas	0.45 mas	0.31 mas	>55



Sample disturbance rejection movie of LOCAM images (loop closed at 1.6 second mark)

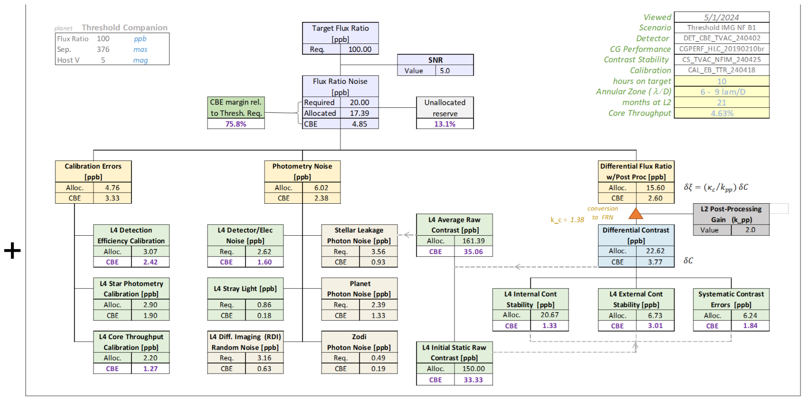
Disturbance rejection shows excellent match with design



Line-of-Sight Control and two types of Star Acquisition (EXCAM and Raster) demonstrated excellent performance

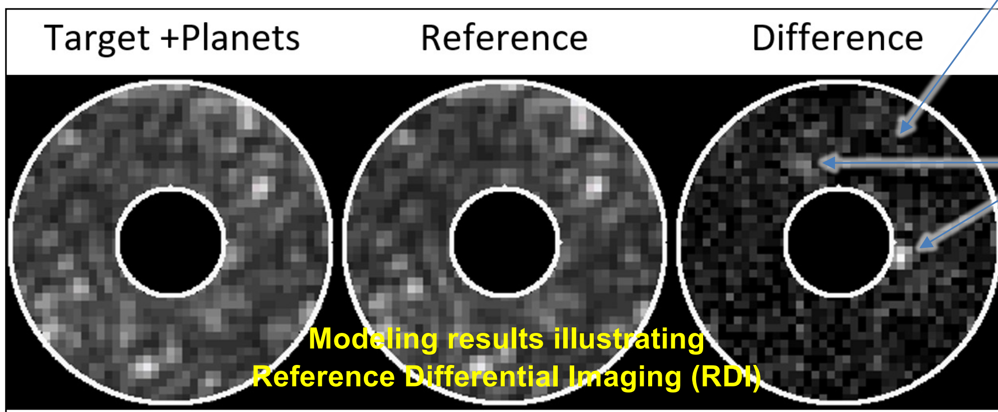
Top-level Performance against Requirement

- Flux Ratio Noise (FRN) is the top performance metric that verifies the threshold performance requirement (TTR5): *make SNR=5 measurement of 10^{-7} flux ratio planet around V=5 target star, in 10 hrs:*
  - **Requirement: Coronagraph flux ratio noise FRN < 2×10^{-8}**



- With **measured** raw contrast, camera noise, tip/tilt rejection, core throughput + stability analysis predictions passed through the FRN budget:

  Flux Ratio Noise = 4.85×10^{-9} => margin of 75.8% vs. requirement
  - All model-derived parameters include MUFs
  - Observatory interface jitter and drift CBEs << requirements
  - Will continue to work with RST to update "mission-level" CBEs

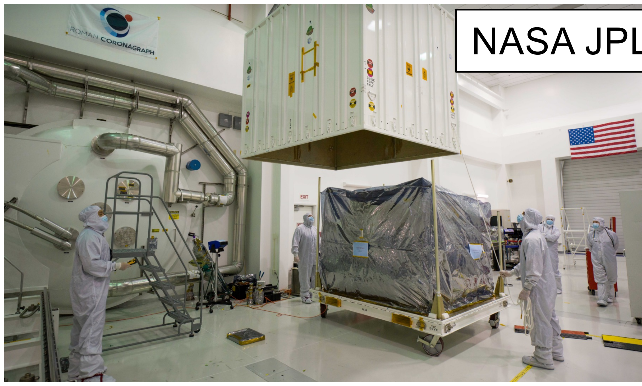


- More on error budgets in Nemati et al., JATIS, 2023, *9*(3), p.034007.
- More on modeling in Krist et al., JATIS, 2023 *9*(4), p.045002.

>75% margin against the top level performance (Flux Ratio Noise) requirement

Delivery to NASA Goddard – May 2024

NASA JPL, Pasadena, California



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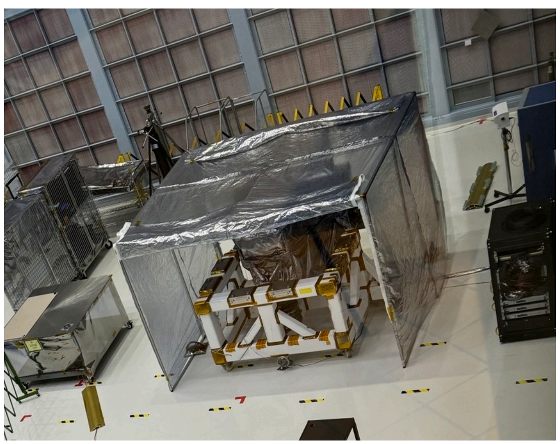
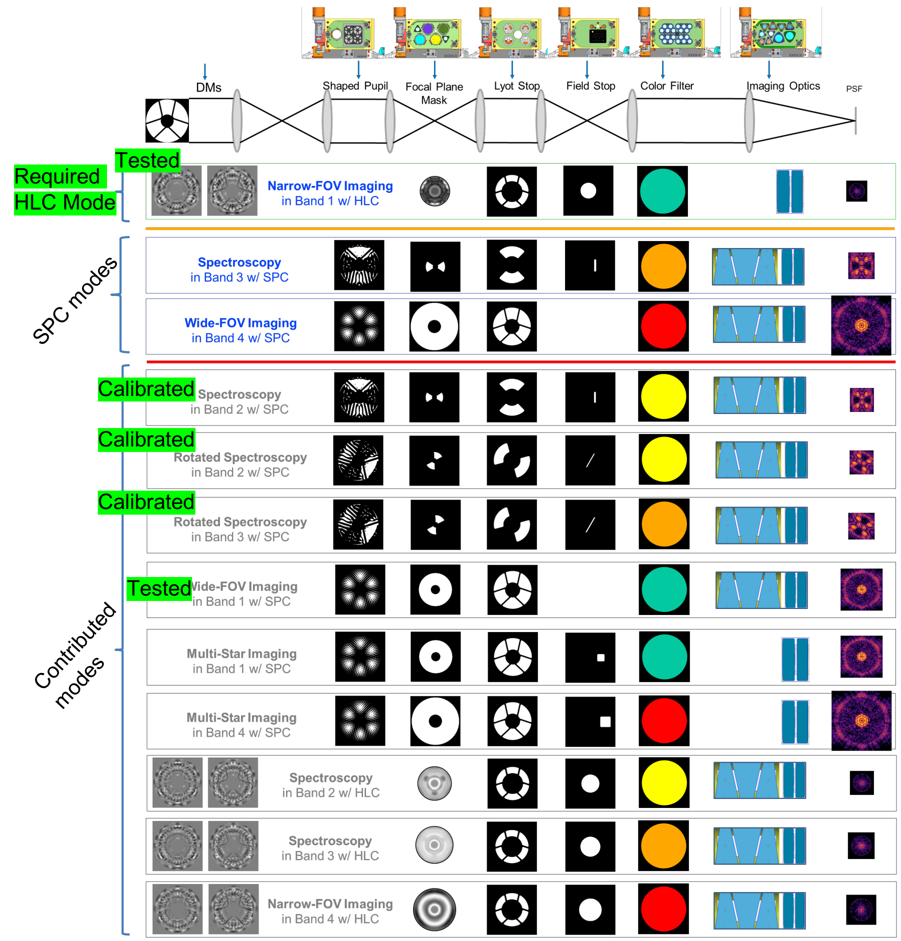


Coronagraph Instrument arrived at GSFC on May 19, 2024

Coronagraph Mask Configurations: Tested vs. Launched

- Coronagraph includes significant capability beyond what was tested during I&T to verify requirements

- These modes can be commissioned in orbit if time and resources allow



Riggs et al, 2021, Vol. 11823, pp. 611-633 SPIE

Raw Contrast for Narrow FoV (Hybrid Lyot) and Wide FoV (Shaped Pupil) Modes [2/2]

L4 Raw Contrast Requirements derived from CGIRD-505 (TTR5) Flux Ratio Noise (FRN) Requirement*	Requirement	NFoV/HLC 6-9 λ/D Meas.**	WFoV/SPC 6-9 λ/D Meas.**
Imaging with Narrow FoV Initial Static Coherent Raw Contrast, 6-9 λ/D, narrow FoV mode, filter band 1	$\leq 5x10^{-8}$	$0.98x10^{-8}$	$1.42x10^{-8}$
Imaging with Narrow FoV Initial Static Incoherent Raw Contrast, 6-9 λ/D, narrow FoV mode, filter band 1	$\leq 1x10^{-7}$	$2.35x10^{-8}$	$2.85x10^{-8}$

*Raw contrast and Flux Ratio Noise (FRN) are different performance metrics despite a similar exponential form; they cannot be used interchangeably. While raw contrast is the most useful and common optical performance metric, FRN folds in noise terms associated with the observatory and instrument instability in the context of the observing scenario, camera noise, calibration errors, and all other known noise contributions to the measurement of the planet-star flux ratio.

** Experimental photometric calibration with +/-10% uncertainty. While quantifying uncertainty on the coherent/incoherent split estimation is challenging, the fact that the total (coherent+incoherent) contrast meets the the tighter coherent contrast requirement proves that both requirements are met under the most conservative assumptions.

TTR5-derived raw contrast requirements successfully demonstrated in 2 different mask configurations

Acronyms

Cam	Camera
CBE	Current Best Estimate
CFAM	Color Filter Alignment Mechanism
CGI	Coronagraph Instrument
CTCE	Coronagraph Thermal Control Electronics
CVS	Coronagraph Verification Stimulus (GSE)
DI	Direct Image
DM	Deformable Mirror
DME	Deformable Mirror Electronics
DPAM	Dispersion Polarization Alignment Mechanism
EMCCD	Electron-Multiplying Charge-Coupled Device
EXCam	Exoplanetary systems Camera
FM	Fold Mirror
FCM	Focusing Mirror assembly
FPA	Focal Plane Array
FPAM	Focal Plane Alignment Mechanism
FPM	Focal Plane Mask
FRN	Flux Ratio Noise
FS	Field Stop
FSAM	Field Stop Alignment Mechanism
FSM	Fast Steering Mirror
GSE	Ground Support Equipment
GSFC	(NASA) Goddard Space Flight Center
HOWFSC	High Order Wavefront Sensing and Control
IC	Instrument Carrier
ICE	Instrument Control Electronics
ISE	Instrument System Engineering
ISE	Instrument Support Electronics
JPL	(NASA) Jet Propulsion Laboratory
HLC	Hybrid Lyot Coronagraph
LOBE	LOWFS Optical Barrel Element
LOCam	Low Order [Wave Front Sensing] Camera
LOWFS	Low Order Wave Front Sensing
LS	Lyot Stop
LSAM	Lyot Stop Alignment Mechanism
MLI	Multi-Layer Insulation
MUF	Model Uncertainty Factor
NFoV	Narrow Field of View
NTE	Not To Exceed
OTA	Optical Telescope Assembly
PAM	Precision Alignment Mechanism
PAME	Precision Alignment Mechanism Electronics
PMN	Lead Magnesium Niobate
PRT	Platinum Resistance Thermometer
RDI	Reference Differential Imaging
RST	Roman Space Telescope
SPAM	Shaped Pupil Alignment Mechanism
SPC	Shaped Pupil Coronagraph
TCA	Tertiary Collimator Assembly
WFI	Wide Field Instrument
WFIRST	Wide Field Infrared Survey Telescope
WFoV	Wide Field of View
OBSA	Optical Bench Structure Assembly