Critical Technology Demonstrations

The Roman Coronagraph is an advanced technology demonstrator for future missions that will directly image Earth-like exoplanets.

Ultra-Precise Wavefront Sensing & Control

Large-format Deformable Mirrors

High-contrast Coronagraph Masks

Ultra-low noise photon counting EMCCD Detectors

Data Post-Processing

The Roman Coronagraph will premiere in space the technologies needed by future missions to image and characterize rocky planets in the habitable zones of nearby stars.

By demonstrating these tools in a system with end-to-end, scientific observing operations, NASA will reduce the cost and risk of a future flagship mission.

Bertrand Mennesson (JPL)
Instrument performance requirements and current-best-estimated performance are based on laboratory demonstrations and model predictions, as of January 4, 2023. Laboratory demonstrations and model refinements are ongoing.

Coronagraph Community Participation Program

• Team that will use Roman’s Coronagraph Instrument to meet its objectives associated with an in-space technology demonstration of a high-contrast coronagraph.

• Opportunity for proposers to work with the coronagraph instrument team to plan and execute its technology demonstration observations.

• Proposals accepted only from small groups. PI of each selected investigation, plus coronagraph project & international partner representatives, form the Community Participation Program Team.

• Certain focus areas will be identified in the solicitation (things like target/observation prep work; simulations; operation preparation; data analysis tools). Proposers can choose from the list, and can include other areas.

c/o Dominic Benford
(https://roman.ipac.caltech.edu/docs/CGI_info_talks/day_oct26/Benford.pdf)
Potential Technology Demonstration Phase Observations

• Self luminous planet image and spectra
• Reflected light planet image and spectrum
• Bright debris disk polarimetry
• Faint debris disk detection
Coronagraph Architecture

- Three observation modes implemented with three different sets of masks/filters
- Share the same optical beam train, with two wavefront control loops to achieve high contrast (better than 1E-8)
• In the Roman Payload, the Coronagraph Instrument mounts onto the Instrument Carrier (IC) shared with the Wide Field Instrument. The Tertiary Collimator Assembly (TCA; not shown) is the optical interface between the telescope and CGI, and relays an exit pupil onto the Fast Steering Mirror (FSM).
• Phase C design as of November 2020.

• The first deformable mirror, DM 1, is positioned at a relay pupil following the FSM. DM 2 is positioned 1 meter away to enable correction of amplitude errors and phase errors originating from out-of-pupil surfaces.
• Both coronagraph mask types, the Hybrid Lyot and Shaped Pupil Coronagraphs (HLC and SPC), are implemented on the same optical beam train and selected by changing masks at the planes labeled SPAM, FPAM, LSAM, and FSAM.
• Observing mode is selected by mechanisms after the Lyot stop.
Coronagraph Elements

**Magnified for illustration. Each FPAM substrate can carry multiple coronagraphic elements.**

Blue-indicated contributed optics that are not part of requirements

\[ \lambda_1 = 575 \text{ nm}, \ 9.8\% \]
\[ \lambda_2 = 660 \text{ nm}, \ 16.8\% \]
\[ \lambda_3 = 730 \text{ nm}, \ 16.8\% \]
\[ \lambda_4 = 825 \text{ nm}, \ 11.7\% \]
## Observing Modes

<table>
<thead>
<tr>
<th>Band</th>
<th>$\lambda_{\text{center}}$</th>
<th>FWHM</th>
<th>BW</th>
<th>Mode</th>
<th>FOV radius</th>
<th>FOV Coverage</th>
<th>Pol.</th>
<th>Coronagraph Mask Type</th>
<th>Support Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>573.8 nm</td>
<td>56.5 nm</td>
<td>9.8%</td>
<td>Narrow FOV Imaging</td>
<td>0.14” – 0.45”</td>
<td>360°</td>
<td>Y</td>
<td>Hybrid Lyot</td>
<td>Required (TTR5)</td>
</tr>
<tr>
<td>2</td>
<td>659.4 nm*</td>
<td>110.9 nm</td>
<td>16.8%</td>
<td>Slit + R~50 Prism Spectroscopy</td>
<td>0.17” – 0.52”</td>
<td>2 x 65°</td>
<td>-</td>
<td>Shaped Pupil</td>
<td>Unsupported</td>
</tr>
<tr>
<td>3</td>
<td>729.3 nm</td>
<td>122.3 nm</td>
<td>16.8%</td>
<td>Slit + R~50 Prism Spectroscopy</td>
<td>0.18” – 0.55”</td>
<td>2 x 65°</td>
<td>-</td>
<td>Shaped Pupil</td>
<td>Best effort</td>
</tr>
<tr>
<td>4</td>
<td>825.5 nm</td>
<td>96.8 nm</td>
<td>11.7%</td>
<td>“Wide” FOV Imaging</td>
<td>0.45” – 1.4”</td>
<td>360°</td>
<td>Y</td>
<td>Shaped Pupil</td>
<td>Best effort</td>
</tr>
</tbody>
</table>

* 660 nm spectroscopy is the lowest priority for fabrication, implementation, and on-sky testing. If resources are limited, this mode may not be exercised during the Technology Demonstration Phase.

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"Best effort" (Bands 2, 3, 4) modes will not be end-to-end performance tested prior to launch. They will be tested at component and assembly level (eg: are masks aligned in their mounting plates?). Prioritize hardware and fixed firmware over software that could be completed after CGI delivery. Most key hardware for the ‘best effort’ modes is in hand already. Software development is prioritizing Band 1 + HLC. It is possible that there will not be time to complete all software for one or more of the “best effort” modes prior to CGI delivery to payload integration and test, though nothing other than resources would preclude completing later.
```
# Filters

<table>
<thead>
<tr>
<th>name</th>
<th>( \lambda_0 ) [nm]</th>
<th>FWHM [nm]</th>
<th>Primary Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>1F (1) *</td>
<td>573.8</td>
<td>56.5</td>
<td>Obs</td>
</tr>
<tr>
<td>2F (2)</td>
<td>659.4</td>
<td>110.9</td>
<td>Obs</td>
</tr>
<tr>
<td>3F (3)</td>
<td>729.3</td>
<td>122.3</td>
<td>Obs</td>
</tr>
<tr>
<td>4F (4)</td>
<td>825.5</td>
<td>96.8</td>
<td>Obs</td>
</tr>
<tr>
<td>1A</td>
<td>554.8</td>
<td>18</td>
<td>WFS **</td>
</tr>
<tr>
<td>1B</td>
<td>574.5</td>
<td>18</td>
<td>WFS</td>
</tr>
<tr>
<td>1C</td>
<td>594.7</td>
<td>19</td>
<td>WFS</td>
</tr>
<tr>
<td>2A</td>
<td>614.2</td>
<td>21.6</td>
<td>WFS</td>
</tr>
<tr>
<td>2B</td>
<td>639.4</td>
<td>15.1</td>
<td>WFS</td>
</tr>
<tr>
<td>2C</td>
<td>656</td>
<td>6.2</td>
<td>Wavecal ***</td>
</tr>
<tr>
<td>3A</td>
<td>680.6</td>
<td>24.9</td>
<td>WFS</td>
</tr>
<tr>
<td>3B</td>
<td>702.3</td>
<td>23</td>
<td>WFS</td>
</tr>
<tr>
<td>3C</td>
<td>725.9</td>
<td>20</td>
<td>WFS</td>
</tr>
<tr>
<td>3D</td>
<td>752.5</td>
<td>24.1</td>
<td>WFS</td>
</tr>
<tr>
<td>3E</td>
<td>753.3</td>
<td>7.2</td>
<td>Wavecal</td>
</tr>
<tr>
<td>3G</td>
<td>777.1</td>
<td>27.1</td>
<td>WFS</td>
</tr>
<tr>
<td>3H</td>
<td>753.3</td>
<td>7.2</td>
<td>Wavecal</td>
</tr>
<tr>
<td>3I</td>
<td>777.1</td>
<td>27.1</td>
<td>WFS</td>
</tr>
<tr>
<td>3J</td>
<td>753.3</td>
<td>7.2</td>
<td>Wavecal</td>
</tr>
<tr>
<td>4A</td>
<td>791.7</td>
<td>29.8</td>
<td>WFS</td>
</tr>
<tr>
<td>4B</td>
<td>823.9</td>
<td>28</td>
<td>WFS</td>
</tr>
<tr>
<td>4C</td>
<td>856.5</td>
<td>30.2</td>
<td>WFS</td>
</tr>
</tbody>
</table>

* Bands 1, 2, 3, 4 are shorthand for Bands 1F, 2F, 3F, 4F

** WFS = High-order wavefront sensing

*** Wavecal = spectroscopy wavelength calibration

https://roman.ipac.caltech.edu/sims/Param_db.html
Roman Coronagraph Passbands

Band 1
- Imaging & Polarimetry
- R~50 Spectroscopy

Band 2
- Imaging & Polarimetry
- R~50 Spectroscopy

Band 3
- Imaging & Polarimetry
- R~50 Spectroscopy

Band 4
- Imaging & Polarimetry

Broadband filters

Narrowband Engineering Filters

% Transmission

Wavelength (nm)

1A  2A  3A  4A  1B  2B  3B  4B  3C  4C
Not all mask+filter combinations are valid

• High-Contrast masks are designed to operate at a specific wavelength (Band 1, 2, 3, or 4).
  • In principle, can be used with sub-bands of primary band (e.g., SPC bowtie for Band 2 would also work for Band 2A, 2B, 2C, 3A, 3B, because they are all subsets of Band 2).

• Combinations other than the supported ones (slides 8-9) may not be commissioned during the Tech Demo Phase
Unsupported observing modes

- Band 2 slit spectroscopy is now an unsupported observing mode
- Additional masks contributed by NASA’s Exoplanet Exploration Program to fill empty slots in mechanisms.
  - Bands 2 and 3 spectroscopy with 60° rotated slit
  - Bands 1 and 4 Wide FOV with grid dot mask for multi-star WFC
  - Bands 2, 3, 4 HLC
  - “low contrast” classical Lyot stops with large inner working angles for “outside the dark hole” observations
  - Transmissive Zernike WFS dimples for focal plane WFS demo
- Caveat: No funding for on-sky commissioning identified at this time. Analogous to HST/STIS Bar5.
- For more info: see Riggs+ SPIE O&P 2021
Target constraints for coronagraphic observations

Reference Star
- V < 3
- <= 1 mas angular diameter
- Hot O/B
- WFSC & PSF reference

Target Star
- V < 5 (maybe V<7; TBD)
- < 2 mas strongly preferred

All stars must be single:
Nothing equally bright within ~45";
increasingly stringent at smaller separations

Target vs Reference should have small delta (spacecraft) pitch for better thermal stability

See also these presentations:
- “Working with Simulated Datasets” (Ygouf)
- “Overview of Observing Scenarios and Their Simulated Datasets” (Krist)
- “Target vetting” (Bailey)

Adapted from J. Krist
Residual tip/tilt jitter impacts contrast, sets V<5 host star requirement

Tip/tilt control on

Tip/tilt control off

Probably graceful degradation at V>5, but TBD. Project is using V~7 cutoff for coronagraphic target lists. See backup slide about faint star and non-coronagraphic pointing/jitter performance

Shi, F., et al., SPIE, Vol 10698, p 106982O-5 2018 ; flight-like jitter tests on V=5 "star"
Note: feed-forward will NOT be implemented in flight (ie: tip/tilt control will be feedback only)
Pointing constraints: ±34° pitch, ±13° roll vs. sun, 22° Earth avoidance; 11° Moon avoidance

Telescope slew rate for long slews is ~0.05dgr/sec

See Hildebrand Rafels Talk
Hybrid Lyot Coronagraph

- The HLC provides a full 360° high contrast field of view.
- Focal plane occulting mask is a circular, \( r = 2.8 \frac{\lambda}{D} \) partially-transmissive nickel disc overlaid with a PMGI dielectric layer with a radially and azimuthally varying thickness profile.
- The HLC design incorporates a numerically optimized, static actuator pattern applied to both deformable mirrors.
- Lyot stop is an annular mask that blocks the telescope pupil edges and struts.

References

Shaped Pupil Coronagraph

- The shaped pupil apodizer is a reflective mask on a silicon substrate with aluminum regions for reflection and black silicon regions for absorption.
- The hard-edged occulting mask has either a bowtie-shaped opening for characterization (spectroscopy) mode or an annular aperture for debris disk imaging.
- The SPC Spectroscopy designed in 2017 produces a 2 x 65° bowtie dark zone from 3.0 – 9.1 $\lambda_c/D$ over a 15% bandpass.
- The SPC Wide Field of View design produces a 360° dark zone from 5.9 – 20.1 $\lambda_c/D$ in a 10% bandpass.

References

- N. T. Zimmerman, et al., JATIS Vol 2 id. 011012 (2016) - http://dx.doi.org/10.1117/1.JATIS.2.1.011012
- K. Balasubramanian, et al., JATIS Vol2 id. 011005 (2015) - https://doi.org/10.1117/1.JATIS.2.1.011005

Spectroscopy SPC (2017 design) simulations at $\lambda_c = 660$ and 770 nm including system aberrations, pointing jitter, and wavefront control operations. The circles correspond to $r = 3$ and 9 $\lambda_c/D$.

Flight mask designs for the spectroscopy shaped pupil coronagraph. Design by A.J. E. Riggs (JPL).
Wavefront Control

- The baseline Roman Coronagraph design includes four active optics to control the wavefront: a **fast steering mirror** (FSM), a flat **focusing mirror** (FCM), and two **deformable mirrors** (DM 1 and DM 2) with 48x48 actuators each.

- High-order wavefront control is implemented by the Electric Field Conjugation (EFC) method. The EFC loop operates on science focal plane data by measuring the interaction of aberrated on-axis starlight with a sequence of DM actuator probes.

- Pointing, focus, and low-order wavefront drifts are sensed by the **Low-Order Wavefront Sensing and Control** (LOWFS/C) subsystem using the Zernike phase-contrast technique on starlight rejected from the occulting mask. Corrections to Zernike modes Z5—Z11 are applied to DM 1.

- The FSM control loop corrects line-of-sight pointing jitter to below 0.95 milliarcsec.

References


Conceptual diagram of the Zernike phase contrast wavefront sensor (F. Shi, et al., 2016).

Optimized DM surfaces applied in HLC data simulations.
Wollaston Prism Polarimetry (Band 1 or 4 imaging)

Linear polarized fraction (LPF) goal:
RMSE < 3% per resel

LPF = \sqrt{\frac{(I_0 - I_{90})^2 + (I_{45} - I_{135})^2}{I_{tot}}}

1 pair at a time
Pairs separated by 7.5” on chip
Slit is deployed to planet position

Prism disperses the Shaped Pupil PSF

Spectrum is extracted from image after post-processing (Reference Star Subtraction)

Variable resolution. R=50 at bandpass center, ±10
EMCCD Detectors

- Electron Multiplying CCD (EMCCD) technology is advantageous for a coronagraph application.
  - Programmable gain provides wide dynamic range suitable for bright scenes expected during acquisition and coronagraph configuration, while photon counting capability can be used for faint light observations with zero read noise.

- EMCCD detectors are baselined for direct imaging, spectroscopy and wavefront sensing applications in CGI.
  - Subarray readout suitable for a wavefront sensor application enables 1000 frame-sec\(^{-1}\) operation to accommodate tip-tilt sensing.

- Work at JPL is focused on low flux characterization with radiation damaged sensors.
  - JPL has invested in modifications to the commercial version of the EMCCD that are expected to improve margins against radiation damage in a flight environment.

- JPL’s EMCCD test lab has measured a low flux threshold of 0.002 c-psf\(^{-1}\)-sec\(^{-1}\), equivalent to a 32.4 magnitude star through a 2.4m telescope at 500 nm with 10% bandwidth.
  - Devices irradiated to 5 years equivalent life at L2 meet coronagraph technology requirements.
Data Post-processing

- Investigations on algorithms for CGI data post-processing have encompassed both end-to-end data simulations and analysis of laboratory testbed data.
- Reference differential imaging (RDI) trials have probed a range of wavefront stability and noise scenarios. Simulations with spacecraft rolls have also enabled tests of Angular differential imaging (ADI).

1. Post-Processing of OS9 Simulated HLC-Band 1

*From raw to photon-counted data*  

**Classical PSF subtraction**

2. Laboratory SPC bow-tie frame recorded at HCIT in a static environment (essentially noiseless other than speckles) with injected fake planet at $10^{-8}$ flux ratio

Example application of RDI to SPC data from HCIT, demonstrating the matched-filtered recovery of a fake point source inserted into one image (circled in red)

_Ygouf et al., 2020_

**Left:** Post-processing contrast gain plotted against reference library correlation for five datasets. Above a certain correlation coefficient, the post-processing gain is comparable to the gain from classical PSF subtraction.

References

Ground System Architecture

HOWFS = high-order wavefront sensing
GITL = Ground In The Loop

Data Downlink:
Ka-Band (observation data)
S-Band (commands, housekeeping and HOWFS data)

Raw observation image files ("L1 data products") will be in STScI Archive < 72hr after observation.

CGI scheduling done weeks or months in advance to ensure ground station contact during critical HOWFS GITL periods. CGI does not support ‘joysticking’ or mid-observation changes!

Purple area of the Observation Data Analysis Environment = “sandbox” area available to CPP and CTC to develop and test data processing algorithms.
Dynamic contrast demonstration with a Low Order Wavefront Sensing and Control (LOWFS/C) system integrated on the Occulting Mask Coronagraph testbed. When line-of-sight disturbances and low order wavefront drift (slow varying focus) are introduced on the testbed, the LOWFS senses the pointing error and wavefront drift and corrects them by commanding a fast steering mirror and one of the DMs. Demonstrations with both the SPC and HLC masks surpassed their 10⁻⁸ contrast goal (F. Shi, et al., Proc SPIE Vol 10400, 2017).
<table>
<thead>
<tr>
<th>Name</th>
<th>Author</th>
<th>Description</th>
<th>Format</th>
<th>URL</th>
<th>References</th>
</tr>
</thead>
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## Simulations Resources

<table>
<thead>
<tr>
<th>Name</th>
<th>Author</th>
<th>Description</th>
<th>Format</th>
<th>URL</th>
</tr>
</thead>
</table>
| Fast Linearized Coronagraph Optimizer (FALCO) | AJ Riggs (JPL) | wavefront correction simulator, DM-integrated coronagraph design, testbed operation. CGI simulations | MATLAB and Python3 source codes with Wiki | https://github.com/ajeldora do/falco-matlab  
https://github.com/ajeldora do/falco-python  
https://github.com/ajeldora do/falco-matlab/wiki |
| FALCO + WFIRST CGI PROPER model       | AJ Riggs (JPL) | Run end-to-end HOWFSC with the official Phase B model of the WFIRST CGI; Produces: CGI dark hole images and performance tables | MATLAB         | https://github.com/ajeldora do/falco-matlab/wiki/01b%29-Examples-using-the-WFIRST-CGI-PROPER-model |
### Reference Documents

**Caveat:** performance predictions have degraded over time; you should sanity check older papers’ conclusions against the latest contrast curves!

<table>
<thead>
<tr>
<th>Reference</th>
<th>URL</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Community White Papers submitted to the NAS Exoplanet Science Strategy Committee, co-chairs D. Charbonneau &amp; S. Gaudi. Among the CGI-related papers are: Kasdin et al., Bailey et al., Mennesson et al., Marley et al., B. Crill et al., and others.</strong></td>
<td><a href="http://sites.nationalacademies.org/SSB/CurrentProjects/SSB_180659">http://sites.nationalacademies.org/SSB/CurrentProjects/SSB_180659</a></td>
<td>2018</td>
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<tr>
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<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight designs and pupil error mitigation for the bowtie shaped pupil coronagraph on the Nancy Grace Roman Space Telescope</td>
<td><a href="https://ui.adsabs.harvard.edu/abs/2022JATIS...8b5003G/abstract">https://ui.adsabs.harvard.edu/abs/2022JATIS...8b5003G/abstract</a></td>
<td>2022</td>
</tr>
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Web Resources

• JPL Roman Coronagraph Website
  • https://www.jpl.nasa.gov/missions/the-nancy-grace-roman-space-telescope/
  • Coronagraph Overview and Capability

• Goddard Roman Website
  • https://roman.gsfc.nasa.gov
  • Mission Overview
  • Science Overview
  • Resources (images and multimedia, documents, newsroom, and press releases)

• Roman at IPAC
  • https://roman.ipac.caltech.edu
  • Science Overview
  • Documentation
  • Simulations (both WFI and the Coronagraph)
  • Community Engagement (including Workshops, Meetings and Talks and Preparatory Science)
    • Roman Virtual Lecture Series https://roman.ipac.caltech.edu/Lectures.html
  • Publications