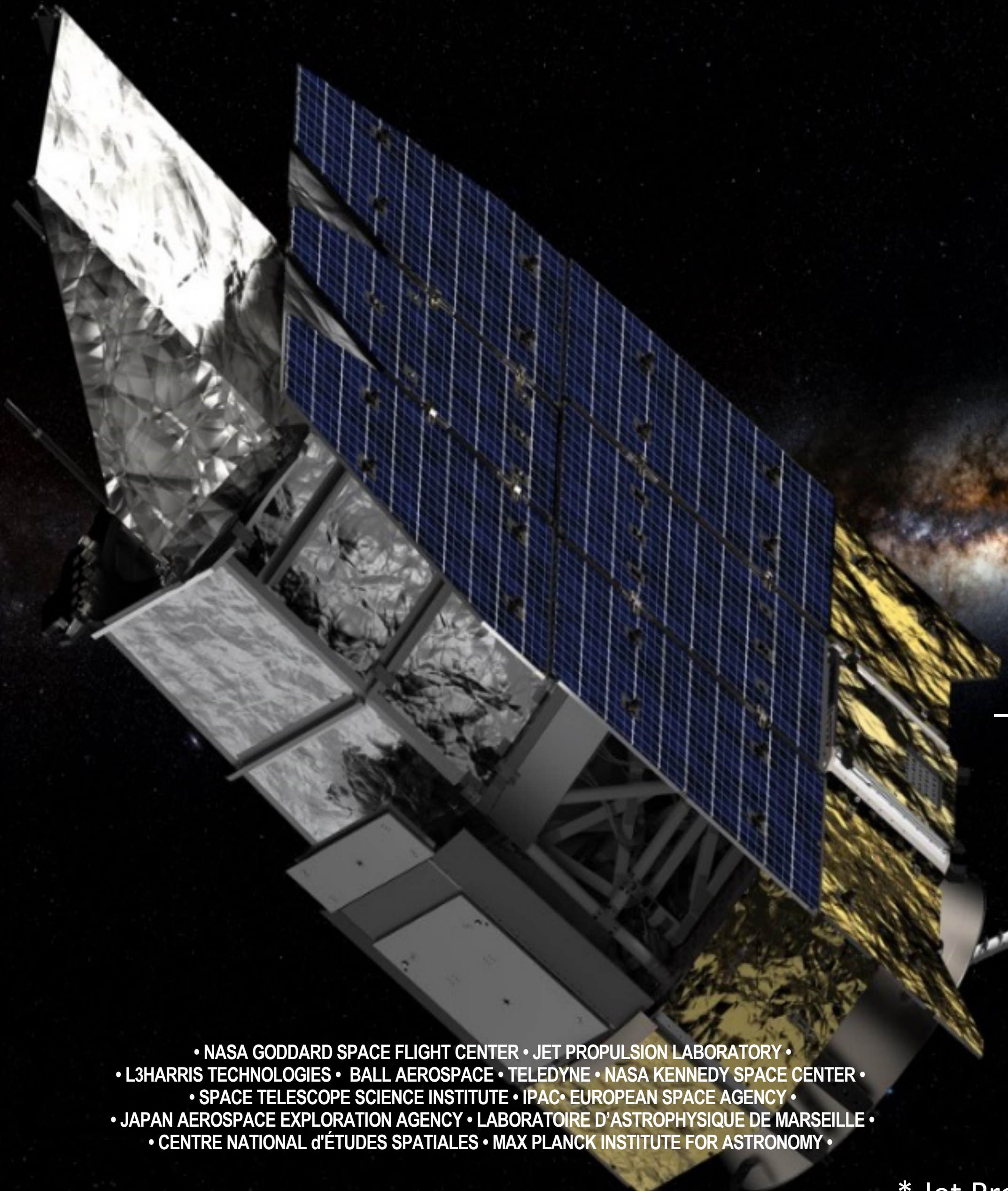
This document has been reviewed and determined not to contain export controlled data.



Coronagraph Instrument DRM

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Level 1
Technology Demonstration Requirement

From all the baseline and threshold science requirements provided in the *Level 1 Program-Level Requirements* for the Nancy Grace Roman Space Telescope (RST) Project (RST-MGMT-REQ-0044), the one that applies to the Coronagraph Instrument is the Technology Threshold Requirement 5 (TTR5).

TTR5: ***Roman* shall be able to measure brightness of an astrophysical point source w/ SNR≥5 located 6 – 9 λ/D from an adjacent star with V_{AB} ≤ 5, flux ratio ≥ 10^{-7}; bandpass shall have a central wavelength ≤ 600 nm and a bandwidth ≥ 10%.**

- **TTR5 is the *sole pass/fail criterion* for the Coronagraph Instrument technology demonstration**

- **TTR5** says `be able to measure' and may be demonstrated *directly* on an astrophysical companion that is consistent with **TTR5**, in case the companion exceeds the requirements, or, in its absence, *by analysis*.

- Meeting **TTR5** also requires the collection of calibration data that is consistent with the required precision and accuracy in **TTR5**. These include absolute photometry, flat fielding, detector's gain and noise properties, optical core throughput, and astrometry and are gathered prior and/or after **TTR5** observations. CGI calibration plans passed a JPL EPR in April 2021

TTR5 children: MRD-426, CGIRD-505, CGI-511

Level 2: MRD-436:

Roman shall be able to measure using CGI the brightness of an astrophysical point source to an SNR of 5 or greater within 10 hours of integration time on the target in CGI Filter Band 1 for an object with a source-to-star flux ratio as faint as 1×10^{-7} at separations from 6-9 λ/D.

Level 3: CGIRD-505:

CGI shall be able to measure in Band 1 the flux ration of a 1×10^{-7} contrast point source located 6-9 λ/D from a V=5 star with a Flux Ratio Noise (FRN) of 2×10^{-8} within 10 hours of integration time.

Level 3: CGIRD-511:

CGI shall be able to perform in-orbit commissioning (IOC) of each coronagraphic mask configuration in <150 hours of dedicated time when CGI controls observatory pointing.

Roman Ground System Requirements

A sample of some particular requirements of interest

Req#	Identifier	Category	Req Title	Object Text	Rationale	Parent (DOORS Out-links)
GSRD-46	ESA-05.010	Telemetry	Ka-band Contact Time	ESA shall provide a minimum of 4 hours of Ka-band contact time to support Roman Space Telescope science downlink operations on a daily basis, with a service availability of 95%.	4 hours is the minimum to support the daily mission science data volume. Assumes ESA 35 meter NNO-3 ground station.	MRD-331 Daily Data Volume Accommodation
GSRD-124	MOC-04.016	Commanding	Science Data Downlink	The MOC shall assure science data stored on-board is commanded for downlink within 24 hours.	Stored science data must be downlinked within 24 hours to meet mission science data latency requirements.	MRD-24 On Board Storage Latency
GSRD-128	MOC-05.010	Telemetry	Housekeeping Telemetry Receipt	The MOC shall receive and process Housekeeping Telemetry in real-time consistent with the Roman Space Telescope telemetry downlink rate.	The Roman Space Telescope S-band downlink rate is configurable between 1 and 683 kbps.	MRD-274 S-Band Downlink Rate Range
GSRD-129	MOC-05.015	Telemetry	SOC Housekeeping Telemetry Latency	The MOC shall deliver Housekeeping Telemetry to the SOC within 24 hours of receipt in the MOC.	SOC requires various information contained within the housekeeping telemetry stream in order to perform science and WFI operations. H/K telemetry delivery is expected to be a subset of EU converted mnemonics, or unprocessed WFI Relative Calibration System (RCS) Files from the housekeeping recorder.	MRD-25 Downlink, Transmission, and WFI Level 1 Processing and Release
GSRD-134	MOC-05.035	Telemetry	Lost Ka-band Contact Recovery	The MOC shall recover lost science data due to a missed Ka-band contact within 7 days of the missed contact.	Provides flexibility to allow recovery without necessarily having to add additional Ka-band downlink time.	MRD-254 Stored Science Data Recovery
GSRD-264	SOC-04.010	Commanding	Observation Plan Duration	The SOC shall generate Observation Plan Data that enables autonomous Observatory science operations for at least 10 days without ground intervention.	SOC role in sustaining autonomous science operations for an adequate period of time.	MRD-53 Autonomous Operations
GSRD-279	SOC-08.030	Planning & Scheduling	Observation Content Modification	The SOC shall permit observers to modify observation content between program approval and the uplink of observing plan files, subject to applicable policies.		MRD-341 General Observer/Guest Investigator Support
GSRD-292	SOC-08.095	Planning & Scheduling	Timeline Modification	The SOC shall be able to modify the observation timeline to enable a Target of Opportunity (ToO) observation to execute within 2 weeks of the decision to proceed.	A TOO request is defined by submission of a revised observation through SOC observation definition software.	MRD-334 Target of Opportunity
GSRD-298	SOC-09.020	Archive	Level 0 Science Telemetry Archive	The SOC shall archive Level 0 science data products within 2 hours of receipt, 95% of the time.	Level 0 data refers to "raw" science files received from short-term archive at DAPHNE.	MRD-25 Downlink, Transmission, and WFI Level 1 Processing and Release MRD-423 Downlink, Transmission, and CGI Level 1 Processing and Release

ESA: European Space Agency. MOC: Mission Operations Center, GFSC. SOC: Science Operations Center, Space Telescope Science Institute

Roman Ground System Requirements

Req#	Identifier	Category	Req Title	Object Text	Rationale	Parent (DOORS Out-links)
GSRD-357	SSC-05.015	Telemetry	CGI Technology Demonstration Support	The SSC shall support the CGI technology demonstration program and any follow-on CGI science programs.		MRD-340 Core Survey Support
GSRD-358	SSC-05.020	Telemetry	CGI Level 1 Science Data Product Generation	The SSC shall perform Level 1 CGI science data processing.		MRD-423 Downlink, Transmission, and CGI Level 1 Processing and Release
GSRD-474	SSC-05.056	Telemetry	HOWFSC/GITL Processing	The SSC shall perform the HOWFSC GITL processing to calculate camera and deformable mirror settings for CGI to "dig the dark hole" on a reference star for each set of CGI observations.	Required to support Ground In The Loop (GITL) processing for CGI High Order Wave front Sensing and Control (HOWFSC) operations. Originally was managed by CGI FSW, but is now a ground function.	MRD-327 Science and Mission Operations
GSRD-475	SSC-05.057	Telemetry	HOWFSC/GITL Processing Latency	The SSC shall complete each set of HOWFSC GITL processing in no greater than 15 minutes from the beginning of data transfer from MOC to SSC to the end of the transfer of the completed products from the SSC back to the MOC.	Required to support GITL processing for CGI HOWFSC operations. Originally was managed by CGI FSW, but is now a ground function.	MRD-327 Science and Mission Operations
GSRD-452	SSC-07.005	Health & Safety	CGI Monitoring	The SSC shall support monitoring of the CGI performance during I&T, commissioning, Technology Demonstration, and thru the Community Participation Program (CPP).	CGI monitoring is required to verify correct operation and diagnose potential problems throughout the mission.	MRD-388 Observatory Health and Safety
GSRD-359	SSC-08.005	Planning & Scheduling	CGI Science Observation Planning	The SSC shall provide tools for CGI observation planning.	This requirement is for planning the observations to validate the Technology Demonstration goals.	MRD-327 Science and Mission Operations
GSRD-360	SSC-08.010	Planning & Scheduling	CGI Engineering Observation Planning	The SSC shall provide tools for preparing engineering and calibration observations with the CGI.	This requirement is for planning/packaging any instrument engineering commanding or ancillary calibration observations which need to be put in a nominal sequence.	MRD-327 Science and Mission Operations
GSRD-363	SSC-09.005	Archive	CGI Level 1 Science Data Product Archive Timing	The SSC shall deliver Level 1 CGI science data products to the SOC Archive within 21 hours of receipt of the last input data needed for Level-1 processing, 90% of the time.	2 hours allocated for SOC archiving of Level 0 products (SOC-09.020) and one hour for SOC ingest of Level 1 products (SOC-09.026).	MRD-423 Downlink, Transmission, and CGI Level 1 Processing and Release

SSC: Science Support Center, IPAC, Caltech

Notice that L1 data are just raw **FITS**. It’s the CGI team’s responsibility to turn that into L2-L4 data products and do our performance assessment. There is not established a timeline for that yet.

GITL uses a different path (S band) for sending the image data needed for GITL to CTC quickly, to do the GITL computations, but it’s not science data.

If the **pointing** drifts or needs to be corrected, LOWFS has a fast tip/tilt control loop; offloads will be sent to the telescope as needed.

GSRD-124 MOC-04.016 Commanding Science Data Downlink The MOC shall assure science data stored on-board is commanded for downlink within 24 hours. Stored science data must be downlinked within 24 hours to meet mission science data latency requirements. MRD-24 On Board Storage Latency

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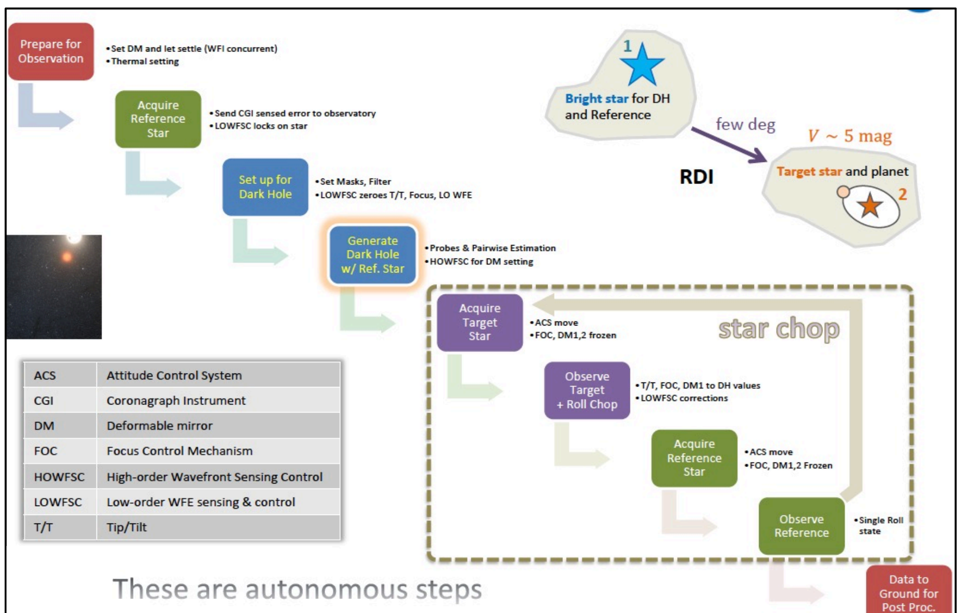
Roman Ground System Requirements

Req#	Identifier	Category	Req Title	Object Text	Rationale	Parent (DOORS Out-links)
GSRD-39	DSN-14.005	General	DSN Mission Support	The DSN shall support Roman Space Telescope pre-launch I&T activities, launch, early orbit, a 90-day commissioning phase, an operations phase of at least 5 years, and EOM activities.	DSN S-band support as per Service Level Agreement, nominally 24 hrs/day during first 3 days of the mission, 12 hrs/day during commissioning, and 6 hrs/day during Phase-E.	MRD-11 Operational Phase Lifetime MRD-13 Commissioning Phase Duration MRD-113 Limitation of Orbital Debris MRD-326 Mission Support
GSRD-124	MOC-04.016	Commanding	Science Data Downlink	The MOC shall assure science data stored on-board is commanded for downlink within 24 hours.	Stored science data must be downlinked within 24 hours to meet mission science data latency requirements.	MRD-24 On Board Storage Latency
GSRD-374	SSC-14.015	General	Nominal Operations Staffing at SSC	The SSC shall be capable of Roman Space Telescope operations with a nominal staffing of 8 hours per day, 5 days per week.	Subject to requirements for targets of opportunity, anomaly investigations, or other critical or high priority operations.	MRD-328 8 by 5 Operations
GSRD-153	MOC-14.015	General	MOC Staffing	The MOC shall be capable of sustaining autonomous real-time operations for a minimum of 96 hours to support a nominal 8 by 5 staffing profile.	Capability to perform automated real-time operations for a minimum of 96 hours supports M-F evening hours and extended holiday weekends.	MRD-53 Autonomous Operations MRD-328 8 by 5 Operations
GSRD-311	SOC-14.015	General	Normal Operations Staffing	The SOC shall be capable of Roman Space Telescope operations with a nominal staffing of 8 hours per day, 5 days per week.	Subject to requirements for targets of opportunity, anomaly investigations, or other critical or high priority operations.	MRD-328 8 by 5 Operations

Coronagraph Instrument: Observing Campaigns

- The Coronagraph Instrument is allocated a total of 90 *notional* days within the first 18-months of the 5-year mission to execute Observing Campaigns
- Each campaign consists of a similar slew-exposure sequence:
  - Acquire a **Reference Star** and perform High-Order Wavefront Sensing and Control (HOWFSC) with Ground in the Loop (GITL). This setup time occurs before the observation begins
  - Perform sequences of **Observing Scenario** 11 (**OS-11)**, an Observation Cycle Concept, with exposures from Reference and Target Star pairs
  - Collect **calibration data** before and/or after an **OS-11** cycle

Note: The algorithm used to do EXCAM (CGI Camera) acquisition assumes that there are no sources with a V_{mag} less than V_{source} + 3 within 30", or it will not be able to identify which star to drive to a target pixel.



ACS	Attitude Control System
CGI	Coronagraph Instrument
DM	Deformable mirror
FOC	Focus Control Mechanism
HOWFSC	High-order Wavefront Sensing Control
LOWFSC	Low-order WFE sensing & control
T/T	Tip/Tilt

Action Item: Tentative list of reference stars. Related topic: CGI target list and properties

Action Item: “Single Reference Differential Imaging reference star risk.” There’s no hard disk or file system on board. So far, memory is allocated for a single reference star associated with a target star. See final slide with AIs for more details

HOWFSC-GITL Operational Concept

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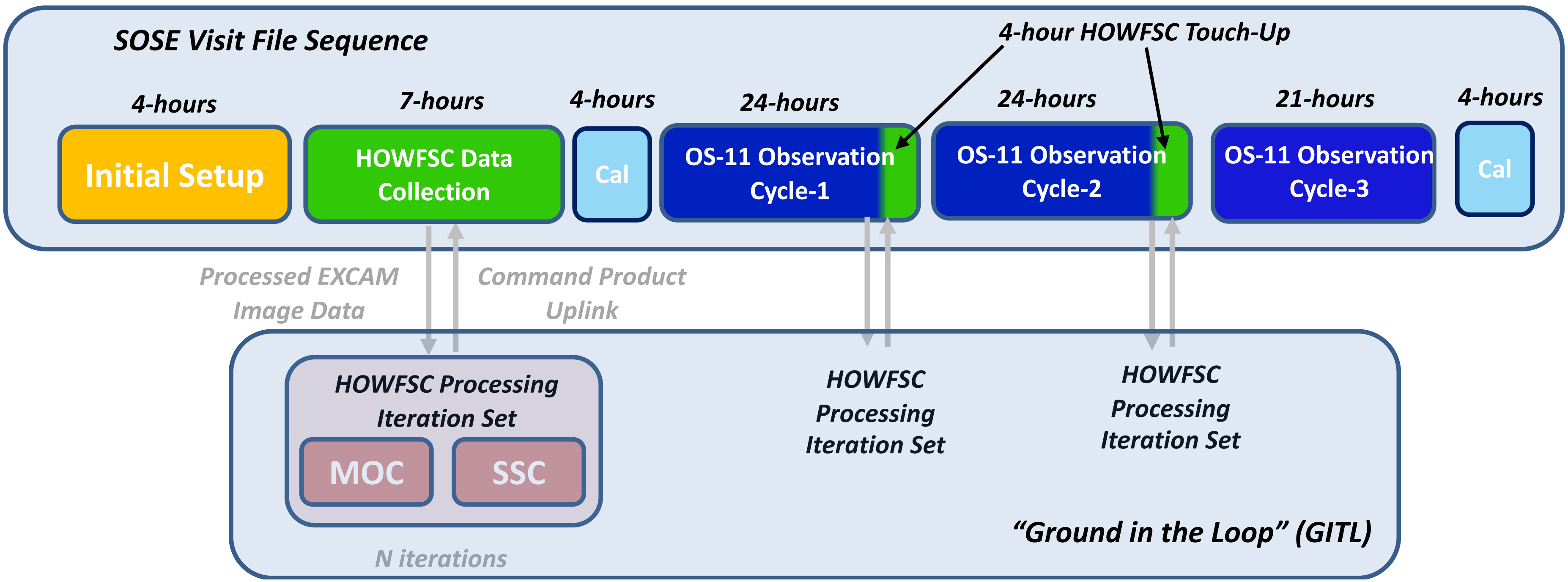
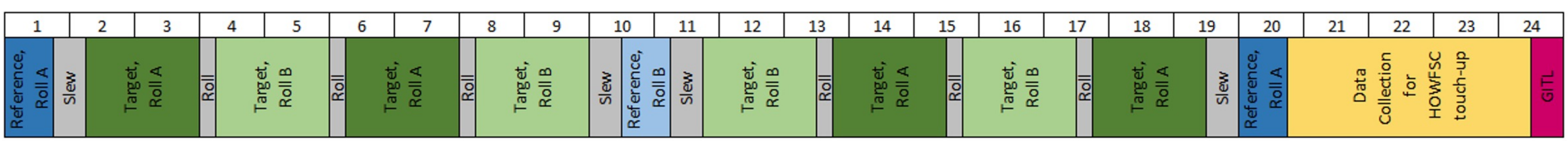
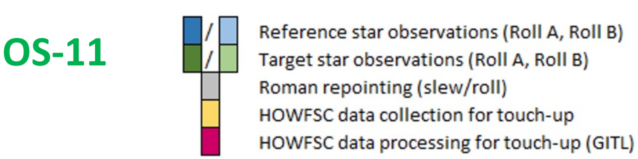
NASA

HOWFSC – High Order Wavefront Sensing Control, GITL – Ground In The Loop
SOSE – Science Observation Sequence Engine
MOC – Mission Operations Center, SSC – Software Support Center



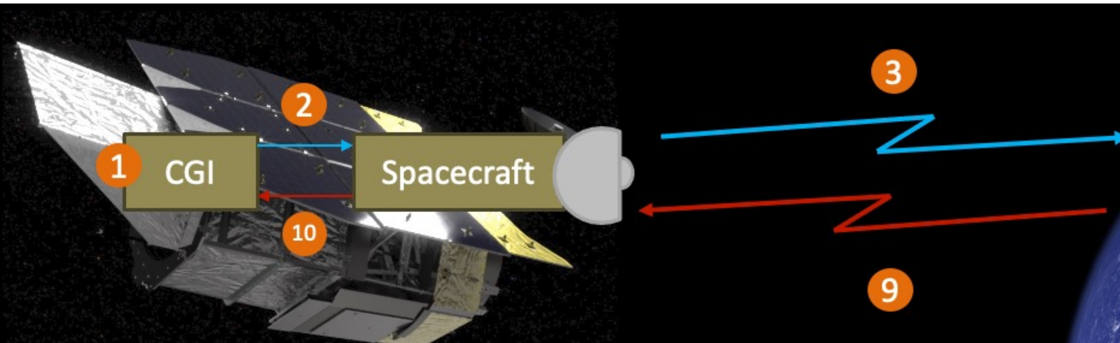


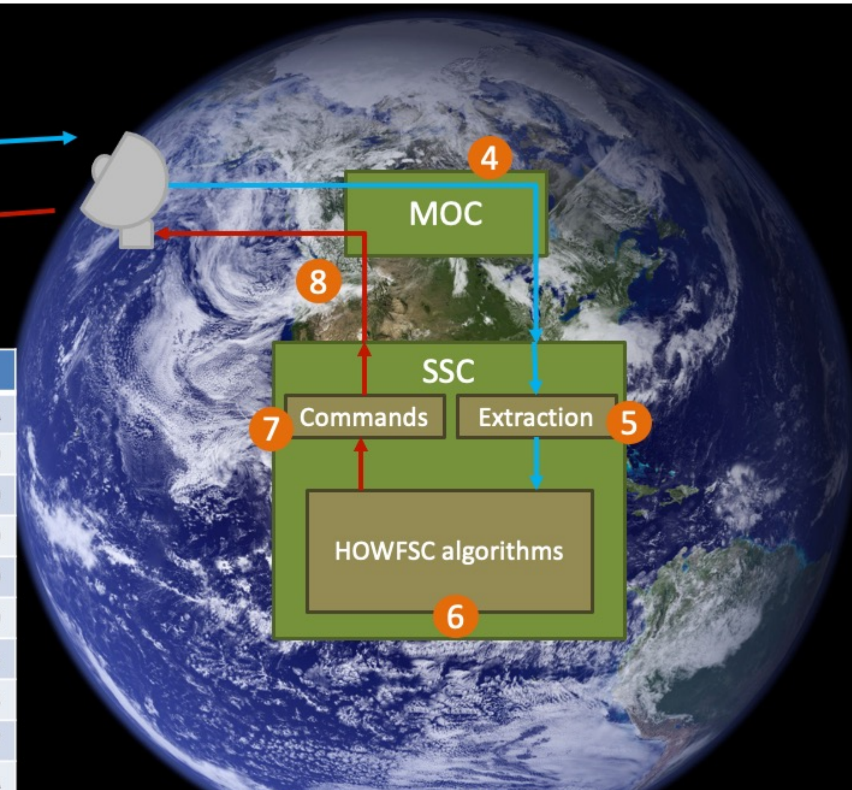


Action Item: check duty cycle and reliability of thruster heaters. How long should they be on? CGI has more frequent momentum dumps: WFI's happen every 4 days (during 5 years), CGI's every 6-22 hours (during its 90 allocated days). Oscar Hsu suggests to perform momentum unloading during slews and rolls. There is a Request For Action on catbed heater reliability due to either leaving on for extended period of time and/or cycling every 6-22 hours to be provided by September 2021. See 07/29/21 meeting notes for details.

HOWFSC-GITL Operational Concept

HOWFSC/GITL: Timing





Step	HOWFSC/GITL Activity	Duration (sec)
1	CGI takes images and processes them in response to sequenced commands.	N/A
2	HOWFSC/GITL frame data is sent in packets to Housekeeping Recorder.	540
3	Packets radiated via S-band to ground station.	150
4	Ground station forwards to MOC, which forwards to SSC.	270
5	SSC extracts frames from raw packets and provides them as HOWFSC inputs.	10
6	HOWFSC software computes instrument settings for next iteration.	10
7	SSC prepares uploads for next iteration.	5
8	Commands/data/variables are passed via MOC to ground station.	8
9	HOWFSC uploads uplinked via S-band (includes staging and telemetry checks).	337
10	Data and parameters updated in CGI, to that the next iteration uses new settings.	N/A
	TOTAL	1330 (22 min)

Durations are CBEs assuming highest possible data volumes and slowest possible transfer speeds.

HOWFSC-GITL Operational Concept

From **Chris Connor and Oscar Hsu**:

Roman is using the standard data and engineering support services as per 820-100 (see below). In this document, we have requested 24-hours coverage for the 1st 3 days of the mission, 12 hours per day between Mission Day 4 and Mission Day 90 (end of commissioning phase), and 6 hours per day for the remainder of the mission.

From **Chris Silve** (MOC SE lead) :

"The DSN will have to run an updated User Loading Profile (ULP) process for Roman that reflects the 6 hours of contact time between Canberra and Madrid. I believe the process of signing the SLA includes a commitment to providing the 6 hours each day. From discussions with the DSM MIM, they don't seem to be concerned with what we are asking. I think the likelihood of being bumped is low, barring a mission spacecraft emergency."

Reference documents:

- https://deepspace.jpl.nasa.gov/about/commitments-office/mission-documents/
- https://deepspace.jpl.nasa.gov/files/820-100-G1.pdf

TTR5-focused DRM

- At the time of writing this review, there is **no identified** target star that has a known astrophysical companion satisfying the TTR5 conditions

- There is an on-going effort to identify stars with a high probability of having an **astrophysical companion** satisfying TTR5 conditions. Additionally, as mentioned before, TTR5 can also be verified **by analysis** or **by exceeding** its requirements

  Action Item: see next slide

- During the campaigns, there will also be some time devoted to **engineering activities**, at an expected rate of 0.5 days per 2-3 months. For instance:
  - Check data used to build HOWFSC models
  - Check detailed positioning of coronagraph masks
  - Recalibrate camera's response

- It is also necessary to collect **calibration data** in support of TTR5 verification:
  - Absolute photometric calibration
  - Core-throughput calibration
  - Camera's gain and non-linearity
  - Flat fielding
  - Astrometric calibration
  - On the other hand, camera's noise characteristics (darks, Clock Induced Charge, Charge Transfer Inefficiency, …) will be obtained while WFI is observing

Potential topic for a future meting: review of calibration collection, setup and HOWFSC times

- Finally, we want to test the **stability** of the instrument performance over time (time scales of hours)

TTR5-focused DRM

Action Item from previous slide: study the likelihood of having a TTR5 target. Ideas (from Vanessa Bailey, John Debes, Stephen Kane, Dmitry Savranski, Bruce Macintosh, and Kerri Cahoy). Notice that these predictions depend to some extend on models, not only direct observations at CGI band 1 (575 nm $\pm$ 10%)

i/ **Background star as astrophysical companion**

ii/ **Cold white dwarf companion** (hard). John's comment sent by email: "A Teff=3000 K white dwarf is 11 Gyr old and has an absolute magnitude of 17.1 and are rare. In order to have the right contrast ratio it would need to be in orbit around a star with absolute magnitude ~ -0.4, which according to Eric Mamajeck's tables suggests either a B7V or a subgiant/giant star. Presumably B7V's are out due to the advanced WD age, so you are then left with the same issue as with looking at post-main sequence stars with V<=5. I think white dwarfs are out…"

iii/ **Giant stars with faint companions**

iv/ **Likelihood of background star from Gaia DR2 proper motions**

v/ **By analysis with exozodi disk, translating extended object sensitivity to point-like equivalent**: John is working on the case of epsilon Eridani. Sergi derived some *preliminary* integration times and it is a good diffuse CGI target. We have to review both the surface brightness and the conversion factor for the core throughput between a disk and a point-like source.

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TTR5-focused DRM

- We have derived instrumental setup times, calibration times, and **exposure times** on target taking into account the latest laboratory and instrumental model data. These are Current Best Estimates, **CBE,** following standard Model Uncertainty Factors, **MUF,** policies

- A **TTR5** campaign will last at least **2 to 3 days**, and probably more, in order to gather enough data to ensure meeting **TTR5** in the least number of campaigns **See next slide**

- **Cadence**: at the beginning of the mission and then every ~ 1 month, respecting WFI scheduling. The goal is to fulfill **TTR5** as soon as possible to achieve mission success and use the time margin to partially fulfill the mission **PLRA** objectives (not all Objectives can be satisfied with only **TTR5** observations)

- For instance, let's define **TTR5.1** as a campaign with a target that has a known companion that meets or exceeds TTR5 requirements. And **TTR5.2** one that does not have it. A **sequence of TTR5**-like observations could be:
  - 1 campaign with **TTR5.1**. For example, with target of low galactic latitude: verification by *background object*
  - 1 campaign with **TTR5.2.** For example, 47 UMa (V=5.03): verification by *analysis*
  - Repeat both campaigns to test *stability*, jitter and drift stability, data set for vibrational model, …
  - If the instrumental performance is good enough, verify TTR5 by *exceeding* its requirements with known targets
  - Perform two consecutive campaigns with the same target star but *different reference stars*

If the observatory and instrument perform as expected, it is likely that TTR5 will be verified in ~5-10 campaigns
(≤ 25 days, margin over notional 90 days ≥72%)

TTR5 is the top priority and other tests will be postponed or descoped to accommodate additional TTR5 observations if TTR5 is not met in the period notionally allocated

TTR5 Observations in Some Detail

TTR5 observations:

- As of 06/08/21, CGI Perf estimates that TTR5 may be achieved in 0.06 hours (6-9 l/D). P.S. The critical SNR for a 1e-7 target around a V=5 star is 54-57, for 6-9 l/D. SNR=8 is achieved in 0.13 hours
- Exposure time only is with margin ~ 30 min
- Reference star and OS11 operational factor (x 24/14) ~ **1 hour for one TTR5 observation**
- OS11 cycle: we want to test full OS11 cycles including touch-up and GITL
- Stability tests. We want to probe:
  - Scales of OS11 cycle: repeat the acquisition a few times during the same observing sequence
  - Scales of weeks: revisit
- Calibration (conservative b/c it is performed at each campaign): **12.5** hours total (bands 3, 4 and polarization *not* included in TTR5)
- One TTR5 sequence may take, including calibrations and OS11 operations about **13.5** hours
- Setup time for imaging: **11** hours
- 23.5 hours for setup plus calibrations
- Any campaign may be defined with a complete OS11 cycle or a partial OS11 cycle with some engineering time (<=0.5 days)
- **TTR5.1**: it has a known companion object that meets or exceeds TTR5 requirements. For instance, a star close to the galactic plane. I choose HD189577 (V=5.3) only as a proxy for a TBC low galactic latitude target
- **TTR5.2**: it does not have a known companion.
- Total of **2 days per TTR5** campaign: 1 day for setup + calibrations and 1 OS11 cycle with or without engineering time (<=0.5 days)

TTR5-focused DRM:

- TTR5 campaigns until TTR5 is met. For instance, a sequence of 5 TTR5-like observations would be:
  - 2 with 47 UMa (verification by analysis). Repeatability
  - 2 with target of low galactic latitude (verification by background object). Repeatability
  - 1 with two reference stars
  - And so on
- Cadence: at the beginning of the mission and then every ~ 1 month, respecting WFI scheduling. The goal is to fulfill TTR5 as soon as possible to achieve mission success and use the time margin to fulfill the mission objectives
- Likely, **5 campaigns** is a reasonable proxy to meet TTR5 and some other objectives, partly. Equivalent to 10 days
- Margin over 90 days would be **89%**

Coronagraph Instrument Technology Objectives

Mostly in-space

No objective is a pass/fail criterion for the coronagraph instrument

PLRA 2.2.1: Coronagraph with Active Wavefront Control: The CGI will demonstrate **coronagraphy in space** with an obscured aperture and active wavefront control. *Roman* would fulfill this objective by detecting a companion object next to a star, **on at least two stars**, at a contrast level and separation that requires a functional coronagraph and wavefront control capability.

PLRA 2.2.2: Coronagraph Elements: The CGI will advance the **engineering and technical readiness** of key coronagraph elements **needed for future missions** capable of detecting and characterizing Earth-size planets. These elements include coronagraph masks, low-order wavefront sensors, high actuator count deformable mirrors, and low noise detectors. Roman would fulfill this objective by demonstrating **in-space operation** of the elements listed.

PLRA 2.2.3: Advanced Coronagraph Algorithms: The CGI will support development and in-flight demonstration of coronagraph software that could enhance the capability or simplify the architecture of future missions. *Roman* would fulfill this objective by demonstrating the **ability to modify the wavefront sensing and control algorithms during the prime science mission**.

PLRA 2.2.4: High Contrast Performance Characterization: *Roman* will perform measurements that characterize the integrated performance of the coronagraph and observatory as a function of **time, wavelength, and polarization**. *Roman* would fulfill this objective by gathering data on a target star that enables in-flight performance characterization of the coronagraph, including a **revisit** of the target and a repointing maneuver.

PLRA 2.2.5: High-Contrast Data Processing: The CGI will demonstrate advanced data processing and analysis techniques required to identify, spectrally characterize and distinguish astronomical sources in the presence of instrumental and astrophysical background noise at high contrast. *Roman* would fulfill this objective by **producing photometric, astrometric, and spectrographic measurements of astrophysical object(s),** including at least one point source **and at least one extended source**.

TTR5-focused DRM
Partially Fulfills PLRA Objectives

No objective is a pass/fail criterion for the coronagraph instrument

- There is an opportunity to fulfill some of the mission objectives with the **TTR5** observations:
  - **PLRA 2.2.1** may be fulfilled contingent on whether two targets with 1E-7 companions at 575nm can be identified
  - **PLRA 2.2.2 would be fulfilled if TTR5 is met**
  - **PLRA 2.2.3 would be fulfilled with a revisit of any successful TTR5 campaign** (minimalist interpretation: same algorithm, different weighting coefficients between two subsequent visits)
  - **PLRA 2.2.4** only partly with a revisit of a successful **TTR5** campaign. It's necessary to include other observing bands and polarization.
  - **PLRA 2.2.5** only partly with **TTR5**. It is necessary to include spectroscopy, extended objects, and a point source

TTR5 is the top priority and other tests will be postponed or descoped to accommodate additional TTR5 observations if TTR5 is not met in the period notionally allocated

History

From "**PLRA Update & Flowdown to L4 & L5 Requirements**" presented by Derek Barnes, Michael Evans (**7/22/2020**)

- Prior to PDR, CGI descoped IFS and replaced it with slit-prism spectroscopy. That was the design presented at PDR.
- This change was reflected at PDR and was accepted by NASA HQ per memo, but did not make it officially into L1 PLRA, L2 MRD and L3 CGIRD.
- At KDP-C, updated PLRA descoped CGI performance requirements other than threshold TTR5. CGI was instructed to retain its PDR design, but could descope from that to threshold performance at CGI manager's discretion.
- This change was propagated by Roman project per CCR-0209.
- This CGI ECR responds to Roman CCR-0209 by cleaning up affected L4 and L5 requirements.
- Previously this ECR was brought forth with just spectroscopy flowdown.
- Is being expanded to include the entire contents of CCR-0209.
- No design changes are being requested by this ECR, just a cleanup /flowdown of requirements to the design we are building.
  - Goal is to save time and make these changes now to requirements in one big ECR rather than several ECRs down the road.
  - Can help to inform minimum set of required tests at instrument level.

ECR: Environmental Compliance and Restoration. **CCR**:

Deprecated Requirements (now "Shoulds")

No "should" is a pass/fail criterion for the coronagraph instrument

- NASA instructed to maintain the design of the Coronagraph Instrument at the time of the Preliminary Design Review (PDR). Besides PLRAs objectives, CGI-TECH level 2 requirements and children are unofficially kept as deprecated requirements (now "***shoulds")*** that may be verified on a best-effort basis once TTR5 is verified (see next slide for full wording):
  - CGI-TECH-1: **High Contrast Direct Imaging**
  - CGI-TECH-2: **High Contrast imaging spectroscopy**
  - CGI-TECH-3: **Wavefront Control for Large Annular FoV**
  - CGI-TECH-4: **Polarization of Disks**
  - CGI-TECH-5: **Exoplanet Astrometric Accuracy**
  - CGI-TECH-6: **WFS Telemetry**
  - CGI-TECH-7: **Telescope Polarization**
  - CGI-TECH-8: **Measure Pointing Jitter**
  - CGI-TECH-9: **Measure Slow Wavefront Aberrations**

Potential topic for a future meting: review potential CGI target list and properties

Note: Stephen Kane and Zhexing Li have provided updated orbital parameters for CGI Reflected Light exoplanets (07/21)

- We have identified some **known targets** that would fulfill these objectives and show the in-flight performance limit of the coronagraph instrument
- All these targets **exceed** TTR5 requirements or are of a different kind: different wavelength, extended, polarization, bright enough for spectroscopy
- We have derived instrumental setup times, calibration times, and **exposure times** on target taking into account the latest laboratory and instrumental model data. These are CBE following standard MUF policies

Potential topic for a future meting: review of tools that estimate CGI's integration times

- The Nominal DRM addresses these deprecated requirements on a **best effort basis,** but are **not pass/fail criteria**

TTR5 is the top priority and other tests will be postponed or descoped to accommodate additional TTR5 observations if TTR5 is not met in the period notionally allocated

CGI-TECH Objectives: full text

CGI-TECH deprecated level 2 requirements that are now should once TTTR5 is met

CGI-TECH-1: High Contrast Direct Imaging
WFIRST CGI should be able to measure the brightness of an astrophysical point source to an **SNR of 10 or greater within 10 hours** of integration time on the target in CGI Filter **Band 1** for an object with a source-to-star flux ratio as faint as 1e-7 at separations from 0.16 arcsec to 0.21 arcsec, **5e-8 *[dmag=18.25]*** at separations from 0.21 arcsec to 0.4 arcsec, and 1e-7 at separations from 0.4 arcsec to 0.45 arcsec.

CGI-TECH-2: High Contrast imaging spectroscopy
WFIRST CGI should be able to measure spectra of an astrophysical point source with R = 50 or greater spectral resolution with a wavelength accuracy of 2 nm or smaller to an **SNR of 10** within **100 hours** of integration time on the target in CGI Filter **Band 3** for an object with a source-to-star flux ratio as faint as 1e-7 at separations from 0.21 arcsec to 0.27 arscec, **5e-8 *[dmag=18.25]*** at separations from 0.27 arcsec to 0.53 arcsec, and 1e-7 at separations from 0.53 arcsec to 0.60 arcsec.

CGI-TECH-3: Wavefront Control for Large Annular FoV
WFIRST CGI should be able to measure the brightness around a star as faint as V = 5 mag with an **SNR of 10** or greater within **24 hours** of integration time on the target in CGI Filter **Band 4** for an **extended source** with an integrated surface brightness per resolution element equivalent to a source-to-star flux ratio as faint as 1e-7 at separations from 0.47 arcsec to 0.54 arcsec, **5e-8 *[dmag=18.25]*** at separations from 0.54 arcsec to 1.36 arcsec, and 1e-7 at separations from 1.36 arcsec to 1.44 arcsec.

CGI-TECH-4: Polarization of Disks
WFIRST CGI should be able to map the linear polarization of a circumstellar debris disk that has a **polarization fraction greater or equal to 0.3** with an **uncertainty of less than 0.03** in CGI Filter **Band 1** and CGI Filter **Band 4**, assuming an **SNR of 100** per resolution element.

CGI-TECH Objectives: full text

CGI-TECH deprecated level 2 requirements that are now should once TTTR5 is met

CGI-TECH-5: Exoplanet Astrometric Accuracy
WFIRST CGI should be able to measure the relative astrometry between an astrophysical point source and its host star, in photometric images, for separations from **0.21 arcsec to 1.36 arcsec**, with an accuracy of **5 milli-arcsec** or less, assuming an **SNR of 10** or greater, including systematic errors.

CGI-TECH-6: WFS Telemetry
WFIRST CGI should be able to capture wavefront control system telemetry concurrently with science data, including raw wavefront sensor measurements and commanded deformable mirror actuator values

CGI-TECH-7: Telescope Polarization
WFIRST CGI should be able to measure the complex electric fields of incident light in two orthogonal polarization states

CGI-TECH-8: Measure Pointing Jitter
WFIRST CGI should be able to measure observatory tip/tilt disturbances at the CGI occulter at frequencies from 0.1 Hz to 100 Hz with accuracy better than 0.5 mas rms on sky per axis for a V=2 mag or brighter star.

CGI-TECH-9: Measure Slow Wavefront Aberrations
WFIRST CGI should be able to estimate the average rate of change over 1 hour period at the CGI occulter for each of focus, astigmatism, coma, trefoil, and 3rd-order spherical aberrations, with accuracy better than 0.1 nm/hour, when pointed at a V=2 mag or brighter star

Building a Campaign. Example: Imaging with NF

- NF Imager:
  - HR 4796 (DD), beta Pic (DD), HD 219134 h (RV), HD206893 B (SL), and a Faint Disk (EZ)
  - Integration times to achieve SNR=5 (or 8) (latest performance and EB mode):
    - **HR 4796**: 0.02 (0.05) hours
    - **Beta Pic**: 0.06 (0.15) hours
    - **HD 219134 h**: 5.1 (13.2) hours (V=5.6, FR=3e-9)
    - **HD 206893 B**: 11.1 (17.3) hours (V=6.7, FR=8e-9). P.S. absent in IMDB. Used GCI Perf directly, instead of EXOSIMS
    - **Faint disk with FR=5e-8 and V<=5.6 (TBC)**: 0.19 hours P.S. HD 139664, V=4.6, FR=2.5e-8, DRM mode=0.2 hours in EXOSIMS)
  - Increase exposure time for HR 4796, beta Pic and the Faint Disk to achieve greater SNR, SNR=20, x16
    - **HR 4796**: 0.3 hours
    - **Beta Pic**: 1.0 hours
    - **Faint disk with FR=5e-8 and V<=5.6 (TBC)**: 3.0 hours
  - Reference star and OS11 operational factor (x 24/14)
    - **HR 4796**: 0.5 hours
    - **Beta Pic**: 1.7 hours
    - **HD 219134 h**: 8.7 hours
    - **HD 206893 B**: 29.0 hours
    - **Faint disk with FR=5e-8 and V<=5.6 (TBC)**: 5.2 hours
  - Accessibility:
    - HR 4796: 46% (38% while outside the micro-lensing survey)
    - Beta Pic: 100%
    - HD 219134 h: 83% (59% while outside the micro-lensing survey**) Block January 4th 2027. It could be joined with WFOV observations**
    - HD 206893 B: 38% (33% while outside the micro-lensing survey)
    - Faint disk with FR=5e-8 and V<=5.6 (TBC): assumed to be accessible without major constraints
  - Setup time: **11 hours**
  - Calibration (conservative): **12.5** hours total (band 3 and polarization *not* included)
  - Include engineering time or longer exposure time to **complete 2 OS11** cycles
    - **B1.1**: HR 4796, 1.0 days setup + calibration, 1.0 days observing + engineering time (<=0.5 days)
    - **B1.2**: Beta Pic, 1.0 days setup + calibration, 1.0 days observing + engineering time (<=0.5 days)
    - **B1.3**: HD 219134 h, 1.0 days setup + calibration, 1.0 days observing + engineering time (<=0.5 days)
    - **B1.4**: HD 206893 B, 1.0 days setup + calibration, 1.2 days observing (conservative: 3 days)
    - **B1.5:** Faint disk, 1.0 days setup + calibration, 1.0 days observing + engineering time (<=0.4 days)
- **NF-only DRM**:
  - Total of **5** with a duration of **2 days each**
  - **Total of 10 days**
  - Each campaign may have a complete OS11 cycle
  - **Any of these targets can substitute a TTR5 campaign**
- Additional challenging target to test performance limits: HD 984 B (SL, V=7.3, FR=2.7e-5, SNR=5, 0.02 hours, 38% accessibility, no overlap with microlensing survey)

Calibrations (conservative)

- **Absolute calibration**
  - Cadence: **1-6 months** (TBR)
  - Duration: **2.0-3.0 hours**. 2-4 stars * 10-30 min (with ND 4.75 filter in place; without it, it's just ~10 seconds for each target) + repointing time (15 min each)
- **Flat fielding (including K gain and nonlinearity)**
  - Cadence: either at the beginning or at the end of **each observation** (to avoid moving any of the PAMs, DMs between observations and calibration)
  - Duration: **3 hours** (0.5-1 hour Uranus/Neptune + 1 hour for pointing, worst case of 180º and 1 hour for K gain and non-linearity). Baseline observations may require longer calibration times, ~2 hours in Uranus/Neptune, total of ~4 hours (10/06/21)
- **Core throughput**
  - Cadence: : at the beginning or end of **each observation**. If the solution is stable, it may be taken only every few months
  - Duration: **4.0-6.0 hours** average. TTR5: 10 mas sampling, 3.2 hours. Including 20 mas sampling: 4 hours. Baseline: 4-9l/D compared to 6-9 l/D, factor of 1.44, pattern and details TBC: 4 * 1.44 = 5.76~6 hours.
- **Astrometry**
  - Cadence: at the beginning or end of **each observation**. If the solution is stable, it may be taken only every few months
  - Duration: **1.5 hours**. 1 hour of exposure time for 100 dithers plus 30 min od re-pointing
- **Spectroscopy**
  - Cadence: at the beginning of **each observation**
  - Duration: TBC
- **Polarimetry**
  - Cadence: at the beginning of the **2** observing campaigns with polarization
  - Duration: **7 hours total (including 2 hours to calibrate an ND filter)**

TOTAL broad band imaging: 10.5 – 17.5 hours. Polarimetry: plus 7 hours. Spectroscopy: TBC

Notice that other calibrations will be conducted while the coronagraph instrument is not observing, and WFI is observing. These calibrations do not count towards the allocated observing time for the coronagraph instrument. For instance:

- **CTI**
  - Cadence: every 3 months
  - Duration: 1 hour
- **Detector Noise Background (Darks & CIC)**
  - Cadence: prior to each observing block
  - Duration: 45 min

Nominal DRM
Fulfills All Requirements and Objectives

This is an example of a minimum Nominal DRM Scheduling with ~44 days (50% margin over a notional allocation of 90 days) that would altogether verify TTR5, PLRA objectives and CGI-TECH deprecated requirements:

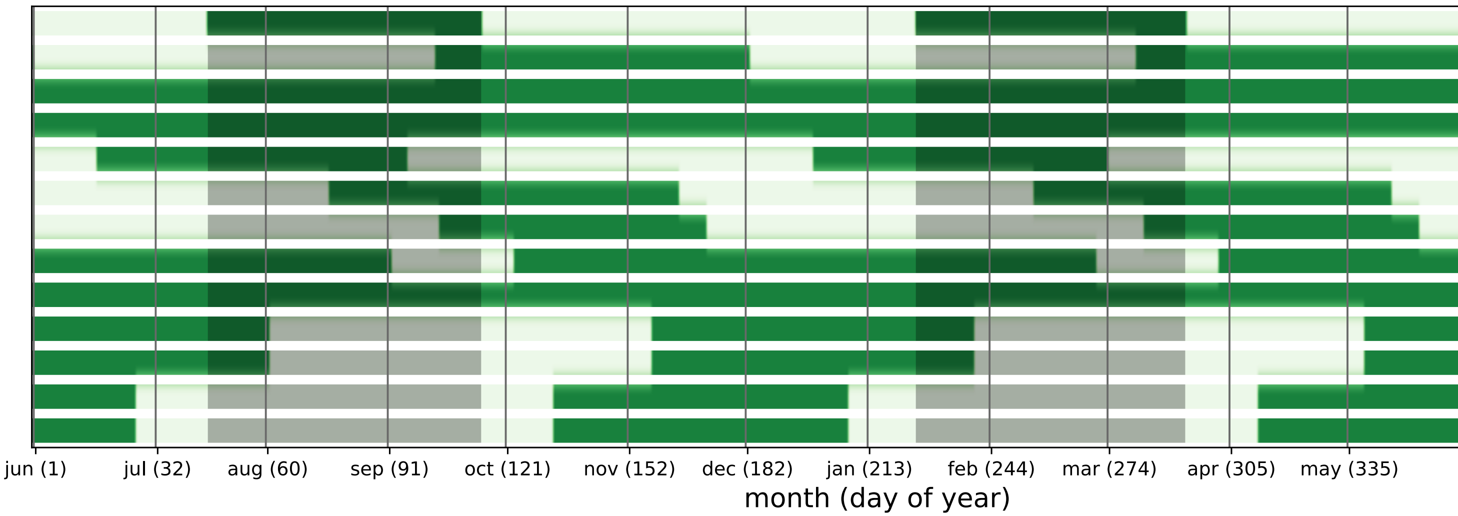
Campaign	Duration (days)	Requirement and/or Objectives
TTR5.1	3+3	**TTR5**, **PLRA** 2.2.1, 2.2.2, 2.2.3 (revisit), 2.2.4 (partly), 2.2.5 (partly), **CGI-TECH** 1 (partly)
TTR5.2	3	**TTR5** (by analysis), **PLRA** 2.2.2, 2.2.3, 2.2.4 (partly)
B1.2	2	**PLRA** 2.2.2, 2.2.3, 2.2.5 (partly)
B1.3	2	**TTR5** (by excess), **PLRA** 2.2.1, 2.2.2, 2.2.3, 2.2.4 (partly), 2.2.5 (partly), **CGI-TECH** 1, 5
B1.4	2	**TTR5** (by excess), **PLRA** 2.2.1, 2.2.2, 2.2.3, 2.2.4 (partly), 2.2.5 (partly), **CGI-TECH** 1, 5
B1.5	2	**PLRA** 2.2.2, 2.2.3, 2.2.5 (partly)
B3.1	5	**PLRA** 2.2.1, 2.2.2, 2.2.3, 2.2.4 (partly), 2.2.5 (partly), **CGI-TECH** 2, 5
B4.2	2	**PLRA** 2.2.5 (partly), **CGI-TECH** 3
B4.3	2	**PLRA** 2.2.1, 2.2.2, 2.2.3, 2.2.4 (partly), 2.2.5 (partly), **CGI-TECH** 5
B4.4	2	**PLRA** 2.2.1, 2.2.2, 2.2.3, 2.2.4 (partly), 2.2.5 (partly), **CGI-TECH** 5
B4.5	2	**PLRA** 2.2.2, 2.2.3, 2.2.5 (partly), **CGI-TECH** 3
B1.1+BP1.1	6	**PLRA** 2.2.2, 2.2.3, 2.2.4 (partly), 2.2.5 (partly), **CGI-TECH** 4
B4.1+BP4.1	6	**PLRA** 2.2.2, 2.2.3, 2.2.4 (partly), 2.2.5 (partly), **CGI-TECH** 3, 4
Additional Engineering	2	**PLRA** 2.2.2, 2.2.3, 2.2.4 (partly), **CGI-TECH-6, 7, 8, and 9**

- All campaigns include setup, calibration time and some margin for either longer exposure times or engineering time
- **B#.target** refers to a campaign observing a **target** in Band **#**. Notice that TTR5 requires **Band 1** only.
- PLRA 2.2.3 (Advanced Coronagraph Algorithms) may benefit from an extended observation on a successful target or revisit

Nominal DRM
Fulfills All Requirements and Objectives

One example of a minimum Nominal DRM Scheduling with ~44 days that would altogether verify TTR5, PLRA objectives and CGI-TECH deprecated requirements: 50% margin over a notional allocation of 90 days

- The graphic below shows the observing windows when the selected targets are accessible by *Roman*
- We include the WFI Galactic Bulge Time Domain Survey (GBTDS), which is ascribed to **WFI** observing time
- Notice that TTR5.1 (a target with a companion as defined in TTR5) is merely *notional as of today*



Target	Accessibility	Campaign
* GBTDS:	38%	WFI
47UMa:	45%	TTR5.2 2d
Beta Pic:	100%	B1.2 2d
Beta Pic:	100%	B4.2 2d
HD139664:	42%	B1.5 2d
HD189577:	49%	TTR5.1 2d
HD206893:	38%	B1.4 2d
HD219134:	83%	B1.3 2d
HR2562:	100%	B4.3 2d
HR4796:	46%	B1.1+BP1.1 6d
HR4796:	46%	B4.1+BP4.1 6d
HR8799:	42%	B4.4 2d
HR8799:	42%	B3.1 5d

Potential topic for a future meting: review CGI targets (TTR5, Self Luminous, Reflected Light, Debris Disks, Exozodiacal Light and Polarization

The additional margin time if TTR5 is met will be used to cover observation retries, perform engineering tests that verify mission PLRA CGI Objectives and deprecated CGI L2s, or conduct challenging observations that will show the limiting performance of the Coronagraph Instrument. For instance, a deep dive in spectroscopic mode for 47 UMa, exoplanetary systems with V>5 host stars, exozodiacal light, or additional faint debris disks and polarization

TTR5 is the top priority and other tests will be postponed or descoped to accommodate additional TTR5 observations if TTR5 is not met in the period notionally allocated

Nominal DRM in more depth

- **Example of a nominal DRM with some time margin to meet mission objectives (44+ days)**:
  - **14** campaigns (plus at least 1 revisit)
  - **3 TTR5-only** campaigns: **TTR5.1** and **TTR5.2**. Total of **9** days. 3 days each, including either 1 OS11 complete cycle with longer integration time or engineering time (<=0.5 days). 1 revisit with a second HOWFSC implementation (eg: using different relative weights, or a different algorithm)
  - **4 Band 1** baseline campaigns: **B1.2**, **B1.3**, **B1.4, and B1.5**. Total of **8** days. 2 days each, including either 1 OS11 complete cycle with longer integration time or engineering time (<=0.5 days). Block some time near the end of Dec 2028 for B1.3 (no overlap with GBTD survey)
  - **4 Band 4** baseline campaigns: **B4.2, B4.3**, **B4.4**, and **B4.5**. Total of **8** days. 2 days each, including longer integration time or some engineering time (<=0.5 days). No complete OS11 cycle, unless an additional day is added
  - **1 Band 1** campaign with and without polarization: **B1.1** + **BP1.1**. 4 OS11 cycles, including calibration. Total of **6** days, with longer integration time or engineering time (<=0.5 days)
  - **1 Band 4** campaign with and without polarization: **B4.1** + **BP4.1**. 4 OS11 cycles each, including calibration. Total of **6** days, with longer integration time or engineering time (<=0.5 days).
  - **1 Band 3** campaign: **B3.1**. Total of **5** days (TBC) with 2-3 OS11 complete cycles or some engineering time (<=0.5 days)
  - Additional engineering time to help fulfill mission objectives: **2** days.
  - Total of **41 days**: 35.8 days observing + calibrations, and 5.2 days of engineering time. Margin of **49** days out of 90 (54%)
  - Additional time margin in case of successful campaigns would be used for:
    - Revisits
    - Challenging targets in Band 1 (e.g., HD 984 B) and Band 4 (e.g., HD 95086 b)
    - Challenging targets in band 3. For instance, deep dive in 47 UMa, especially in band 3 spectroscopy
    - Additional engineering time to help meet mission objectives (PLRA and L2/CGI-TECH)

Summary & Forward Plan

- **TTR5** is the ***sole pass/fail criterion*** for the Coronagraph Instrument technology demonstration
- A **TTR5-focused DRM** partially fulfills PLRA Objectives
- If the instrument and observatory behave as expected, **TTR5** might be accomplished within the first 25 days of a notional 90 days allocation for the Coronagraph Instrument. This provides a notional margin of $\geq$72%
- **TTR5** is the **top priority** and other tests will be postponed or descoped to accommodate additional **TTR5** observations if **TTR5** is not met in the period notionally allocated
- A **Nominal DRM** is comprised of both TTR5 and non-TTR5 observing modes
- A **Nominal DRM** fulfills all requirements and objectives
- If the instrument and observatory behave as expected, a **Nominal DRM** might be accomplished within the first 44 days of a notional 90 days allocation for the Coronagraph Instrument. This provides a notional margin of $\geq$ 50%

- The **forward plan** includes:
  - Refreshing the **target catalog** for TTR5 and other potential targets
  - Keeping the latest **instrumental performance folded** into the expected exposure time calculations
  - Introducing **scheduling algorithms** into the DRM planning
  - Reviewing **calibration data** collection methods and duration

Any other suggestions?

Action Items to Follow up on

AI.1: Study the likelihood of having a TTR5 target. Ideas (from Vanessa Bailey, John Debes, Bruce Macintosh):

- Background star as astrophysical companion: galactic plane likelihood (center and anti-center). Remember that the Galactic Bulge Time Domain Survey (galactic center) has scheduling priority over CGI observations. **POC**: Macintosh SIT?
- Cold white dwarf companion: if it is bright enough, and it is cool enough it might be a good candidate for TTR5: 1e-7 at ~0.5 micron. **POC**: ?
- Giant stars with faint companions: faint companions detected as transients and/or with RV. Beware that the apparent angular size should be not greater than 2 milli-arcsec (to generate an optimal dark hole) and V~5. **POC**: ?
- By analysis with exozodi disk, translating extended object sensitivity to point-like equivalent. Potential case: epsilon Eridani. **POC**: John Debes?

AI.2: List of potential reference stars. Related topic: potential CGI target list and properties. **POC**: Brian Kern.

AI.3: What can be learned from precursor observations to avoid unsuitable cases? For instance, reference stars with potential dust, faint companions, … **POC**: Vanessa Bailey, Maggie Turnbull?

AI.4: Catalog search for binaries/multiples in target & reference stars w/ WDS & Gaia. **POC**: Lea Hirsh

AI.5: Literature search of reference star properties (unassigned)

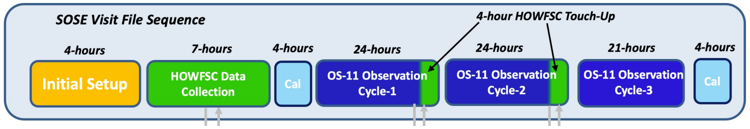
AI.6: Single reference star risk: There's no hard disk or filesystem onboard, so each sequence parameter has an assigned memory location. Memory is allocated for only a single reference star. However, there are a couple spare memory slots for each sequence, as redundancy, and potentially future work could update flight software to use those to allow for additional reference stars. OR (probably easier) one could design multiple sequences with different reference stars and request that they are executed back to back, with all but the 1st sequence skipping the initial dark hole digging. Again, that would have to be future software work. **POC**: Vanessa Bailey.

AI.7: check duty cycle and reliability of thruster heaters. How long should they be on? CGI has more frequent momentum dumps: WFI's happen every 4 days (about 45 minutes to unload) (during 5 years), CGI's every 6-22 hours and based on the attitude and size of rolls (during its 90 allocated days). The hardest part is maintaining wheel speeds below 5 Hz. Oscar Hsu suggested to perform momentum unloading during slews and rolls. There is a Request For Action on catbed heater reliability due to either leaving on for extended period of time and/or cycling every 6-22 hours to be provided by September 2021. **POC**: Oscar Hsu.

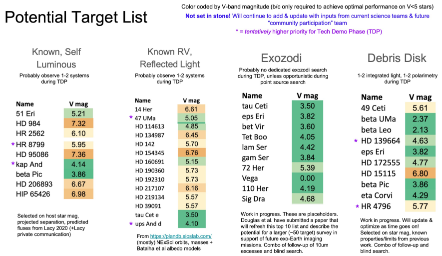
Other Action Items are found in outerspace

Topics for future Meetings

T1: Review of calibration collection, setup and HOWFSC times



T2: Review CGI targets (TTR5, Self Luminous, Reflected Light, Debris Disks, Exozodiacal Light and Polarization, reference stars and properties (precursor/binaries/dust)


Potential Target List

Color coded by V-band magnitude (b/c only required to achieve optimal performance on V<5 stars)

Not set in stone! Will continue to add & update with inputs from current science teams & future "community participation" team

* = *tentatively* higher priority for Tech Demo Phase (TDP)

Known, Self Luminous

Probably observe 1-2 systems during TDP

Name	V mag
51 Eri	5.21
HD 984	7.32
HR 2562	6.10
* HR 8799	5.95
HD 95086	7.36
* kap And	4.14
beta Pic	3.86
HD 206893	6.67
HIP 65426	6.98

Selected on host star mag, projected separation, predicted fluxes from Lacy 2020 (+Lacy private communication)

Known RV, Reflected Light

Probably observe 1-2 systems during TDP

Name	V mag
14 Her	6.61
* 47 UMa	5.05
HD 114613	4.85
HD 134987	6.45
HD 142	5.70
HD 154345	6.76
HD 160691	5.15
HD 190360	5.73
HD 192310	5.73
HD 217107	6.16
HD 219134	5.57
HD 39091	5.57
tau Cet e	3.50
* ups And d	4.10

From https://plandb.sioslab.com/ (mostly) NExScI orbits, masses + Batalha et al albedo models

Exozodi

Probably no dedicated exozodi search during TDP, unless opportunistic during point source search

Name	V mag
tau Ceti	3.50
eps Eri	3.82
bet Vir	3.60
Tet Boo	4.05
lam Ser	4.42
gam Ser	3.84
72 Her	5.39
Vega	0.00
110 Her	4.19
Sig Dra	4.68

Work in progress. These are placeholders. Douglas et al. have submitted a paper that will refresh this top 10 list and describe the potential for a larger (~50 target) survey in support of future exo-Earth imaging missions. Combo of follow-up of 10um excesses and blind search.

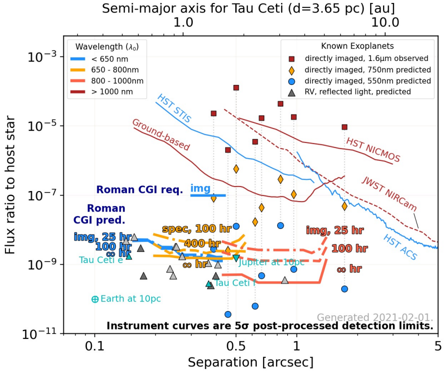
Debris Disk

1-2 integrated light, 1-2 polarimetry during TDP

Name	V mag
49 Ceti	5.61
beta UMa	2.37
beta Leo	2.13
* HD 139664	4.63
eps Eri	3.82
HD 172555	4.77
HD 15115	6.80
beta Pic	3.86
eta Corvi	4.29
* HR 4796	5.77

Work in progress. Will update & optimize as time goes on! Selected on star mag, known properties/limits from previous work. Combo of follow-up and blind search.

T3: Review of tools that estimate CGI's integration times (includes orbital ephemeris, debris disks, exozodiacal targets and polarization)



Any other suggestions?

Let's choose! [Link to anonymous google poll]

Updates

14 Her as a DRM target?

The 14 Herculis planetary system[4][12]

Companion (in order from star)	Mass	Semimajor axis (AU)	Orbital period (days)	Eccentricity	Inclination	Radius
b	$\geq 4.64 \pm 0.19\ M_J$	2.77 ± 0.05	1773.4 ± 2.5	0.369 ± 0.005	—	—
c	$\geq 5.8^{+1.4}_{-1.0}\ M_J$	$16.4^{+9.3}_{-4.3}$	68^{+64}_{-25} years	$0.45^{+0.17}_{-0.15}$	—	—

Wikipedia. See also, Imaging Mission Data Base. NASA Exoplanet Archive. Exoplanet.edu

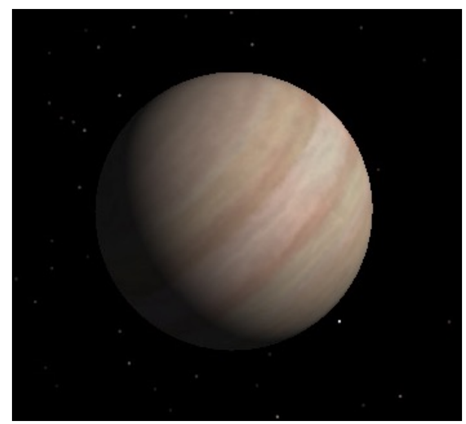
14 Her (star)
V=6.62
d=17.9 pc, 58.5 ly
K0 V, **L** = 0.6 L_Sun
HD 145675
HIP 79248

(4) Wittenmyer, Robert A.; et al. (January 2007). "Long-Period Objects in the Extrasolar Planetary Systems 47 Ursae Majoris and 14 Herculis". *The Astrophysical Journal*. **654** (1): 625–632. arXiv:astro-ph/0609117. Bibcode:2007ApJ...654..625W. doi:10.1086/509110. S2CID 14707902.

Confirmed and improved constraints for 14 Her c from:

(12) Rosenthal, Lee J.; Fulton, Benjamin J.; Hirsch, Lea A.; Isaacson, Howard T.; Howard, Andrew W.; Dedrick, Cayla M.; Sherstyuk, Ilya A.; Blunt, Sarah C.; Petigura, Erik A.; Knutson, Heather A.; Behmard, Aida; Chontos, Ashley; Crepp, Justin R.; Crossfield, Ian J. M.; Dalba, Paul A.; Fischer, Debra A.; Henry, Gregory W.; Kane, Stephen R.; Kosiarek, Molly; Marcy, Geoffrey W.; Rubenzahl, Ryan A.; Weiss, Lauren M.; Wright, Jason T. (2021), *The California Legacy Survey I. A Catalog of 177 Planets from Precision Radial Velocity Monitoring of 719 Nearby Stars over Three Decades*, arXiv:2105.11583. Accepted in ApJS

Both are gas giants
Detected with Radial velocity
No direct imaging



14 Her b as a DRM target?

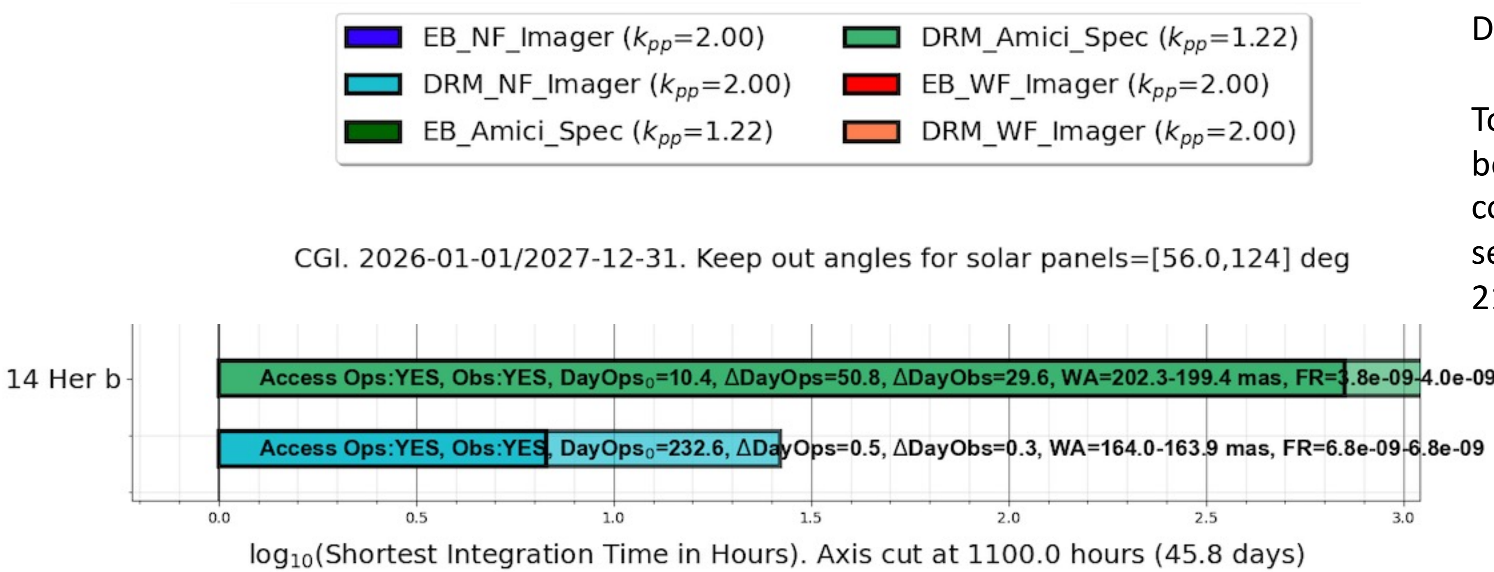
14 Her b:

- **Band 1** (Narrow Field Imager): within FOV, but too faint. Flux ratio c∼7x10^{-9}. When it is closer to the host star, and bright enough for band 1, it is inside the coronagraph dark hole. P.S. when all model uncertainty factors are set to 1, this target may be detected with SNR≳10

- **Band 3** (Spectroscopy): within FOV, but too faint. Close to the instrumental limit. Flux ratio ∼ 4x10^{-9}. Similarly, as with band 1. P.S. Similar note, but with SNR ≳ 5

- **Band 4** (Wide Field Imager): Inside the inner working angle. Not visible.

Conclusion for 14 Her b: not a good DRM target for the Roman coronagraph



Disclaimer: MUFS=1

Tool to be shared before the coronagraph info session in October 21

14 Her c as a DRM target?

14 Her c (estimates will be reviewed after the updated orbital parameters in SIOS Imaging Mission Database become available (*):

Semi-major axis range corresponds to 676 mas - 1436 mas angular separation from the host star (parallax=55.8 mas)

- **Band 1** (Narrow Field Imager): likely outside the FOV: 156-436 mas, and it would be too faint
- **Band 3** (Spectroscopy): likely outside the FOV: 198-567 mas, and it would be too faint
- **Band 4** (Wide Field Imager): likely within the FOV. How bright can it be?
  - Reflected Light:
    - Assuming an albedo like Jupiter in these wavelengths (average of 0.45), a planetary phase in quadrature (there's no constraint on is inclination), Lambertian phase function, an actual planet-star distance within the 1-σ range of the semi-major axis (to be reviewed once the ephemeris update is available), and an estimated planet radius of 1.0 $R_{jupiter}$ because there's no precise estimates, we can estimate the flux ratio to be about:

$$FR = \frac{0.45}{\pi}\left(\frac{1.0\times 71492\ km}{(12.1 - 25.7)\times 149597871\ km}\right)^2 \in (5\times10^{-11}, 2.2\times10^{-10})$$

  - CGI Performance ETC: CBE predict that for band 4, an infinite time integration could reach SNR=3 on a target with 3×10^{-10}.
  - 14 Her c is thus likely too faint to becoming a member of the DRM target list due to its reflected light... What about self emission. How warm may it be?

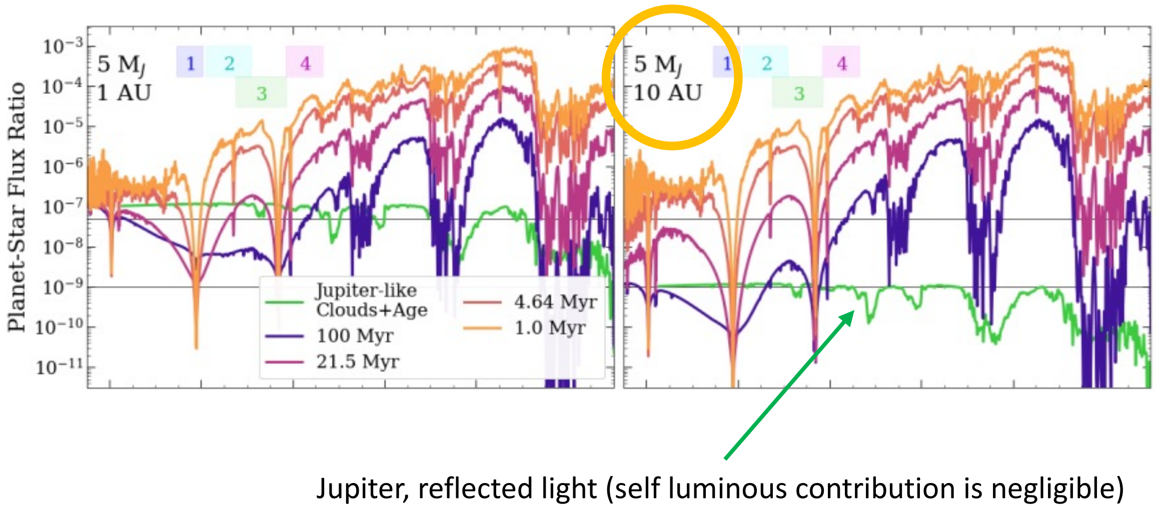
(*) CGI members involved: Stephen Kane (UC Riverside), Zhexing Li (UC Riverside), Corey Spohn (Cornell), Dmitry Savranski (Cornell)

14 Her c as a DRM target?

Brianna Lacy's quick analysis 09/08/21*

- Assuming that the age of 5.1 gigayears and mass of 5.8 Jupiter masses are correct, according to A. Burrows, M. Marley, W.B. Hubbard et al. (1997) ApJ. 491, 2, 856, the effective temperature is only around **250 K** (Jupiter is T_{eq}=165 K).

- From B. Lacy, and A. Burrows. "Prospects for Directly Imaging Young Giant Planets at Optical Wavelengths". ApJ. Volume 892, Issue 2, id.151, 20 pp. (2020), figure 10:



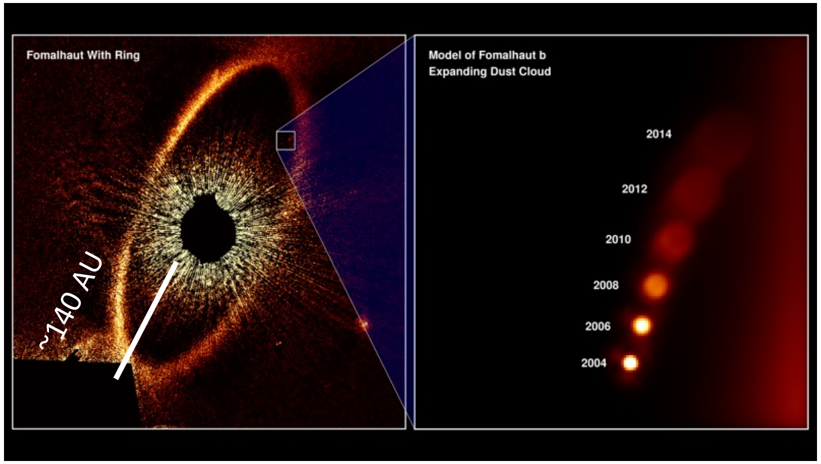
Color lines for an exoplanet at T_{eq}=568 K, except for Jupiter. Also 14 Her c is likely farther away than 10 AU and much older. There's no model for this exoplanet at hand yet, but it might have some contribution in band 4 to increase the flux ratio so that 14 Her c could become a new DRM target (near the bottom of the list, but we do not have many!)

We'll review the final case once Corey's update is public!
Detective work!

*Brianna Lacy's email: blacy@astro.princeton.edu and brianna.i.lacy@gmail.com

Formalhaut and eps Eridani as exozodiacal DRM targets

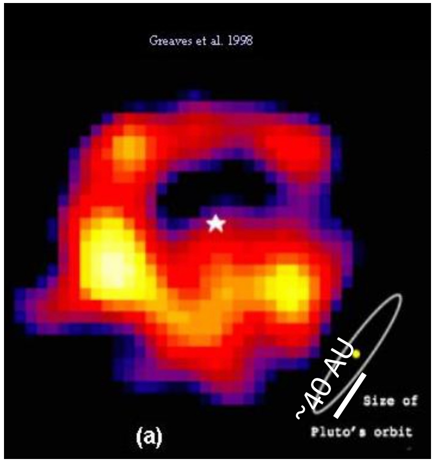
Formalhaut (aka Eye of Sauron)



A. Gáspár and G.H. Rieke, PNAS May 5, 2020 117 (18) 9712-9722; https://doi.org/10.1073/pnas.1912506117

Although originally thought to be a massive exoplanet, the faintness of Fomalhaut b in the infrared and its failure to perturb Fomalhaut's debris ring indicate a low mass. We use all available data to reveal that it has faded in brightness and grown in extent, with motion consistent with an escaping orbit. This behavior confirms suggestions that the source is a dispersing cloud of dust, produced by a massive collision between two planetesimals. The visible signature appears to be very fine dust escaping under the influence of radiation pressure.

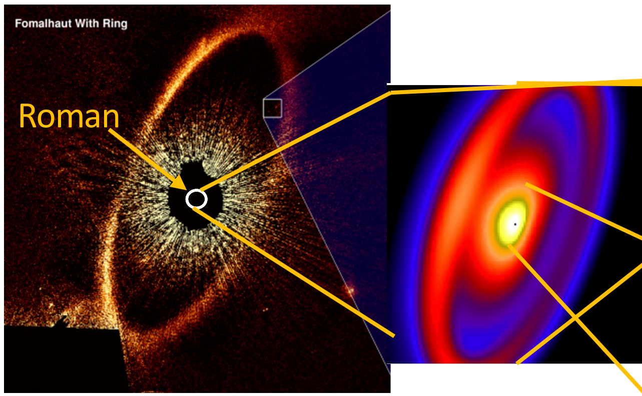
ε Eridani



Greaves, J. S., Holland, W.S., Moriarty-Schieven, et al. 1998, "A dust ring around epsilon Eri: Analog to the young solar system", Ap.J.lett, vol. 506, L133-L137

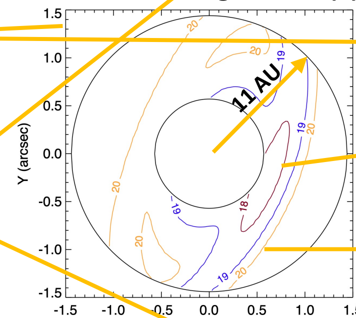
Formalhaut as an exozodiacal DRM target

Based on John Debes's predictions: Formalhaut_EpsEri.pdf (09/03/21, debes@stsci.edu)



Formalhaut:
V mag: 1.16
Distance: 7.70 pc, 25.1 ly. **Parallax**: 129.8 mas.
FOV Band 1 (Narrow Field Imager): 1.2 – 3.4 AU
FOV Band 3 (Slit Prism): 1.5 – 4.4 AU
FOV Band 4 (Wide Field Imager): 3.6 – 11 AU

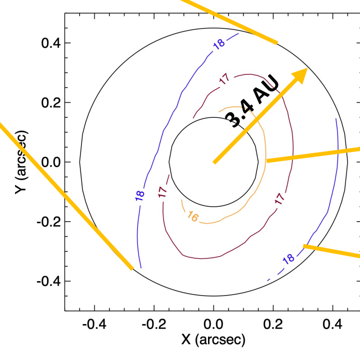
Surface brightness in absolute V mag/arcsec² (*)



Band 4. Shaped Pupil Mask

ΔV=18-1.16 mag/arcsec^2. 1 resel = 1 FWHM = 71.7 mas.
Brightness per resel = $10^{-\Delta V/2.5}$x(FWHM/1000)^2 = 9.4x10^{-10}
Effective point source brightness (optimistic x10)=**9.4x10^{-9}**
CBE (SNR=5, 10, 20) = 0.09, 0.37, 1.50 hours

ΔV= 20-1.16 mag/arcsec^2
Effective point source brightness=**1.5x10^{-9}**
CBE (SNR=5, 10, 20) = 0.83, 3.53, 19.0 hours



Band 1. Hybrid Lyot Mask

ΔV=16-1.16 mag/arcsec^2. 1 resel = 1 FWHM = 50.0 mas.
Brightness per resel = $10^{-\Delta V/2.5}$x(FWHM/1000)^2 = 2.9x10^{-9}
Effective point source brightness (optimistic)=**2.9x10^{-8}**
CBE (SNR=5, 10, 20) = 0.07, 0.34 hours, it can't reach 20

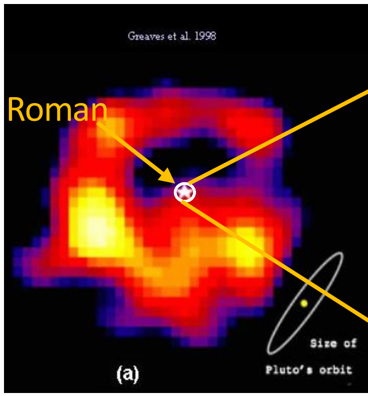
ΔV= 18-1.16 mag/arcsec^2
Effective point source brightness=**4.6x10^{-9}**
CBE: 2.6, can't reach SNR=10

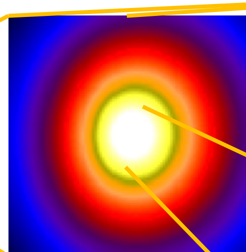
Caveat: we don't know for sure how to scale from these IR observations. The disks could potentially be brighter if they are made of a different composition or grain size distribution than the Solar System zodiacal light

(*) Contour images are flipped in both x/y axis! for easy use of arrows

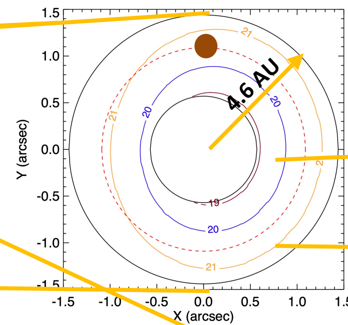
ε Eri as an exozodiacal DRM target

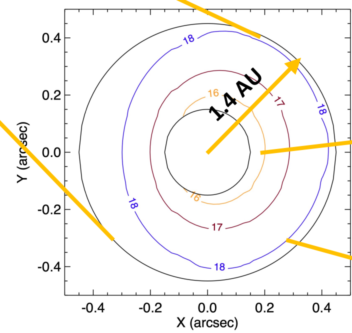
Based on John Debes's predictions: Formalhaut_EpsEri.pdf (09/03/21, debes@stsci.edu)





Surface brightness in absolute V mag/arcsec^2





ε Eri:
V mag: 3.74
Distance: 3.2 pc, 10.48 ly. **Parallax**: 311.4 mas.
FOV Band 1 (Narrow Field Imager): 0.5 – 1.4 AU
FOV Band 3 (Slit Prism): 0.6 – 1.8 AU
FOV Band 4 (Wide Field Imager): 1.5 – 4.6 AU

● Possible planet location of ε Eri b. Likely planet creates a gap or other structures in the disk

Band 4. Shaped Pupil Mask

ΔV=19.5-3.74 mag/arcsec^2. 1 resel = 1 FWHM = 71.7 mas.
Brightness per resel = $10^{-\Delta V/2.5}$x(FWHM/1000)^2 = 2.5×10^{-9}
Effective point source brightness (optimistic x 10)=**2.5×10^{-8}**
CBE (SNR=5, 10, 20) = 0.03, 0.11, 0.43 hours

ΔV= 21-3.74 mag/arcsec^2
Effective point source brightness=**6.4×10^{-9}**
CBE (SNR=5, 10, 20) = 0.12, 0.50, 2.0 hours

Band 1. Hybrid Lyot Mask

ΔV=16-3.74 mag/arcsec^2. 1 resel = 1 FWHM = 50.0 mas.
Brightness per resel = $10^{-\Delta V/2.5}$x(FWHM/1000)^2 = 3.1×10^{-8}
Effective point source brightness (optimistic)=**3.1×10^{-7}**
Good case for TTR5
CBE (SNR=5, 10, 20) = 0.02, 0.08, 0.40 hours

ΔV= 18-3.74 mag/arcsec^2
Effective point source brightness=**4.9×10^{-8}**
CBE(SNR=5)=0.04. It can't reach SNR=10

Caveat: we don't know for sure how to scale from these IR observations. The disks could potentially be brighter if they are made of a different composition or grain size distribution than the Solar System zodiacal light

Coronagraph Instrument Performance in Context

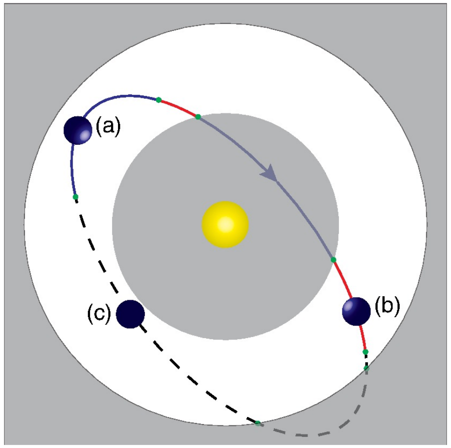
- Knowing the **actual performance** of the Roman Coronagraph helps understand its yield beyond simpler methods that idealize the instrument (most of the times because of a lack of public information outside the Coronagraph team).

- **DI-Plot-Flux-Ratio** (next) is one step towards a better communication of Roman Coronagraph capabilities

- **EXOSIMS + CGI Perf**(ormance) is another step in the same direction that will be released in a month from now.

- Current best estimates of the detectability power of any instrument **matters** for completeness studies. For instance:

Integration time adjusted completeness.
Dean Keithly, Dmitry Savransky, Corey Spohn,
J. of Astronomical Telescopes, Instruments, and Systems, 7(3), 037002 (2021).



Coronagraph Instrument Performance in Context

Roman CGI Performance in Context

https://github.com/nasavbailey/DI-flux-ratio-plot (*)

Performance predictions :

Description: Model-predicted 5σ final detection limits for a V=5 G0V star in the three official observing modes. Model uncertainty factors (MUFs) for observatory and CGI set to unity. No performance margins. Incorporate results from OS9, with further updates to CGPERF tables, bench warping and DM temperature stability, and coating reflectivity. (Oct 1, 2020 spreadsheet version)

Bandpass:

narrow FOV imaging : 575nm / 10% BW, Hybrid Lyot coronagraph.

spectroscopy : R=50 spectroscopy, 730nm / 15% BW, Shaped Pupil bowtie coronagraph.

wide FOV imaging : 825nm / 10% BW, Shaped Pupil wide field of view coronagraph.

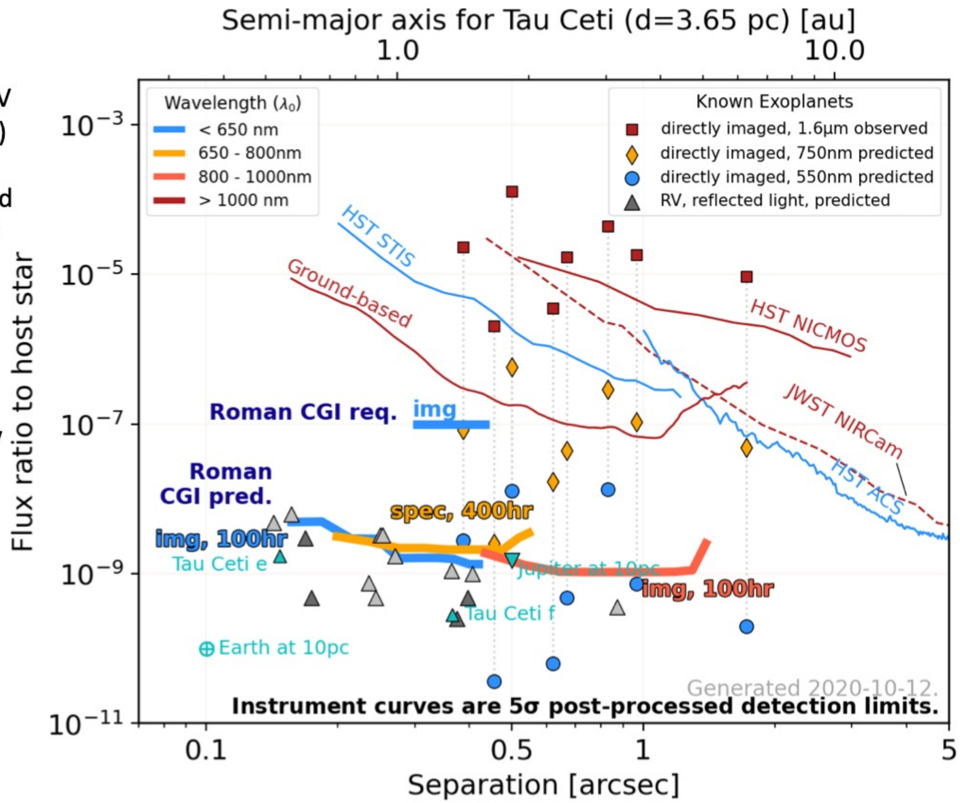
Integration time:

imaging : 100hr

spectroscopy : 400hr.

Post-processing: Reference PSF subtraction, with an assumed additional factor of 2 improvement over the basic-RDI residual speckle component, from the application of more sophisticated post-processing techniques.

Reference: B. Kern & B. Nemati spreadsheet, personal communication.



(*) Vanessa Bailey's repo

Stellar types from A0V to M5V have some impact. This is for G0. See next for a comparison with different types

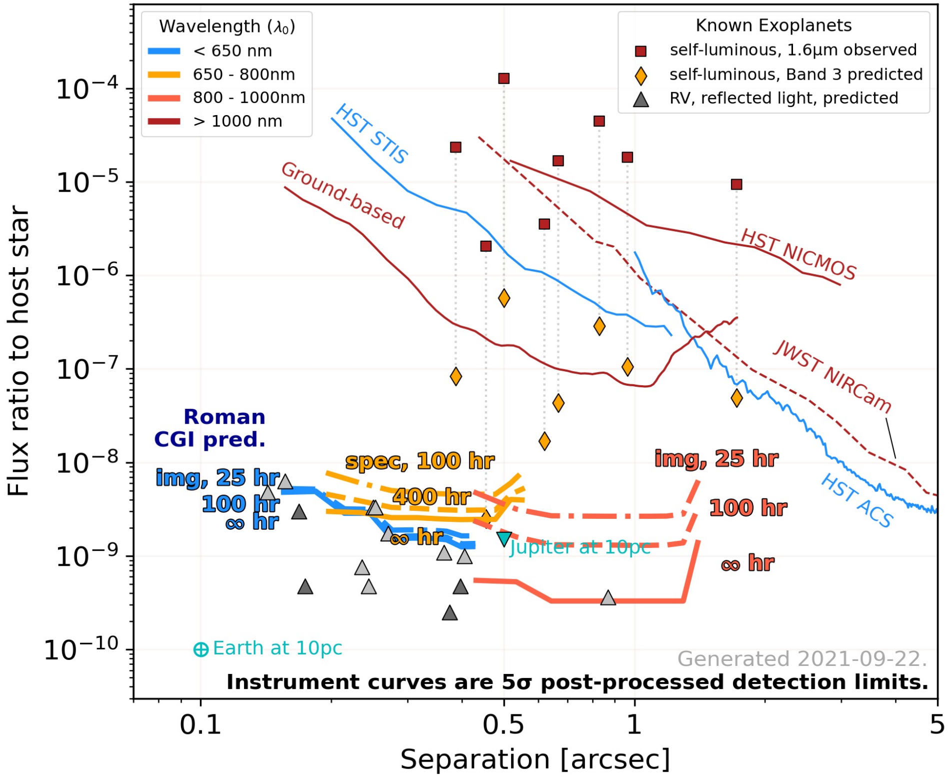
Roman CGI Performance in Context

https://github.com/nasavbailey/DI-flux-ratio-plot (*)

Performance predictions :
Description: Model-predicted 5σ final detection limits for a V=5 G0V star in the three official observing modes. Model uncertainty factors (MUFs) for observatory and CGI set to unity. No performance margins. Incorporate results from OS9, with further updates to CGPERF tables, bench warping and DM temperature stability, and coating reflectivity. (**Feb 1, 2021** spreadsheet version)
Bandpass:
- narrow FOV imaging : 575nm / 10% BW, Hybrid Lyot coronagraph.
- spectroscopy : R=50 spectroscopy, 730nm / 15% BW, Shaped Pupil bowtie coronagraph.
- wide FOV imaging : 825nm / 10% BW, Shaped Pupil wide field of view coronagraph.

Integration time:
- imaging : **25, 100, 10000hr ('infinite time')**
- spectroscopy : **100, 400, 10000hr**

Post-processing: Reference PSF subtraction, with an assumed additional factor of 2 improvement over the basic-RDI residual speckle component, from the application of more sophisticated post-processing techniques.
Reference: B. Kern & B. Nemati spreadsheet, personal communication.

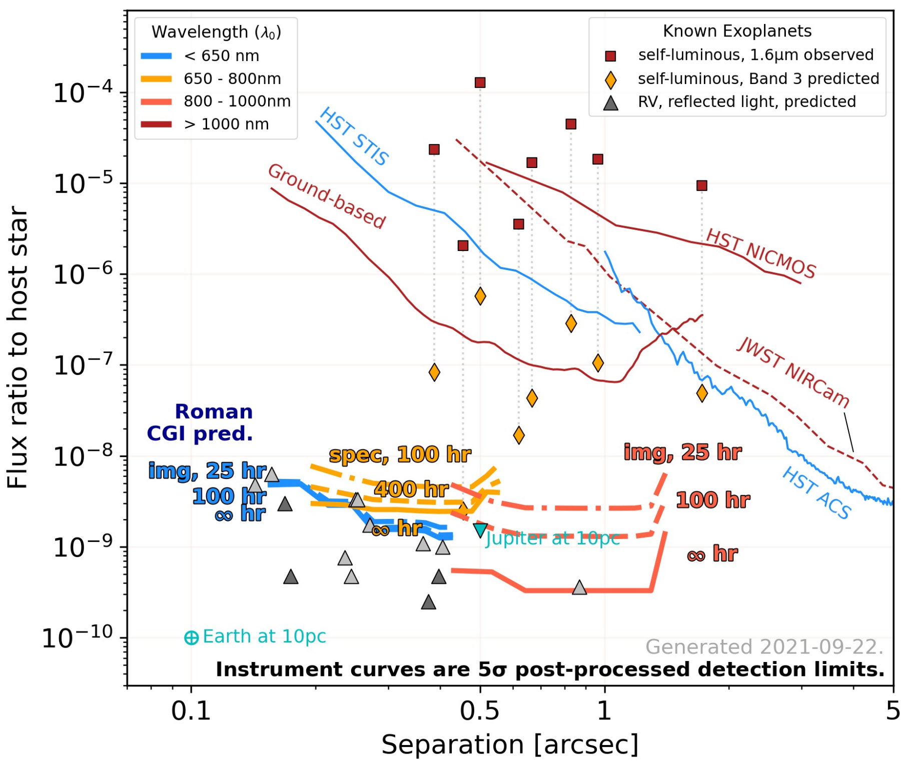


(*) Vanessa Bailey's repo

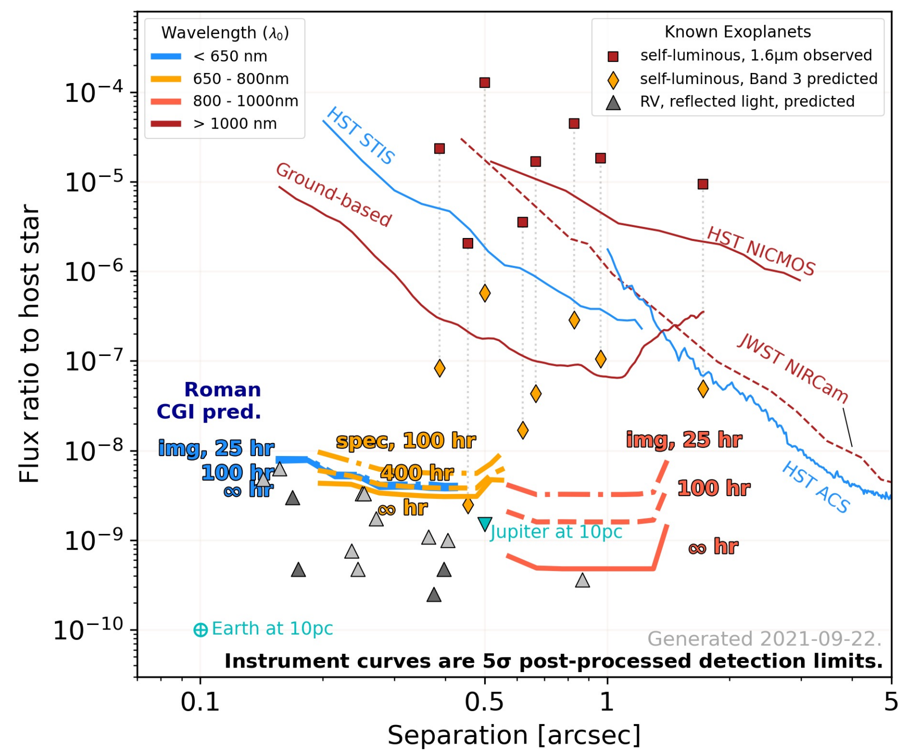
Stellar types from A0V to M5V have some impact. This is for G0. See next for a comparison with different types

Coronagraph Instrument Performance in Context

Model uncertainty factors set to unity



Model uncertainty factors set to CBE (Sep 22)



It's all committed to GitHub 🙌

Stellar types from A0V to M5V have some impact. This is for G0. See next for a comparison with different types

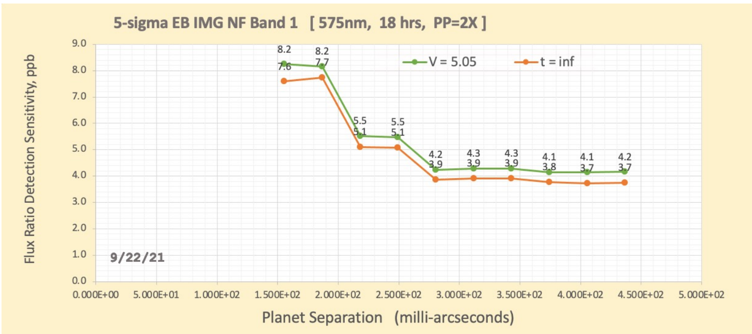
Coronagraph Instrument Performance in Context
Effect of Stellar Type for same V mag

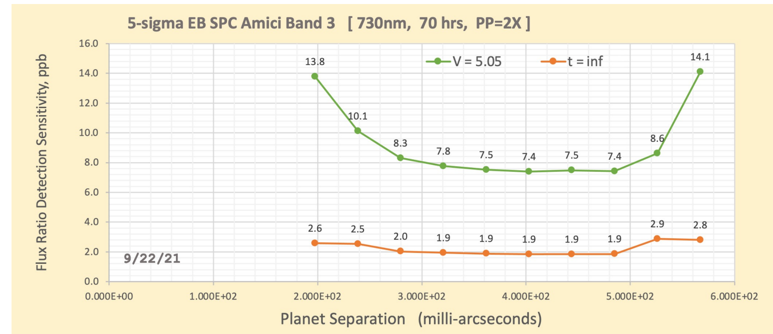
Results obtained with CGI Perf

NF Imager: Band 1 (MUFs in). Hardly any effect

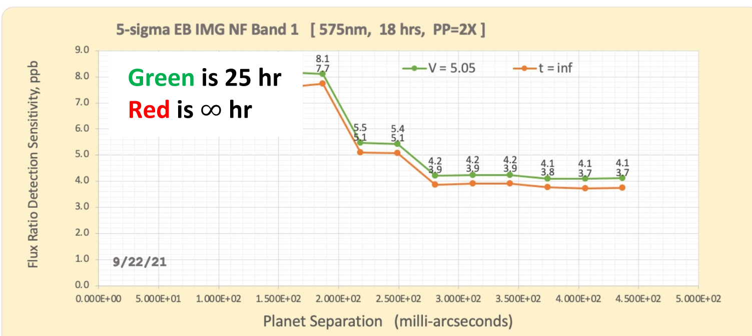
SPC Amici: Band 3 (MUFs in). Some effect

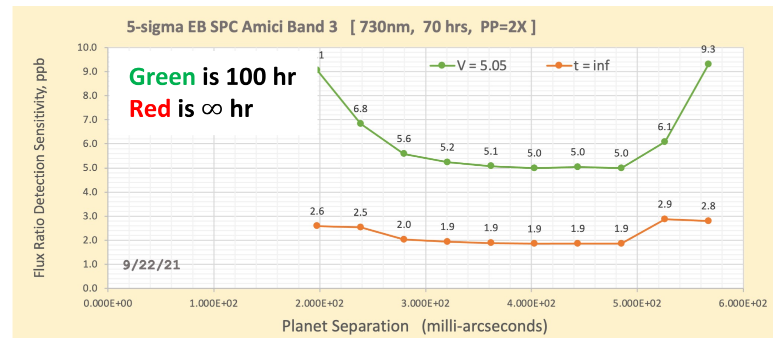
A0V



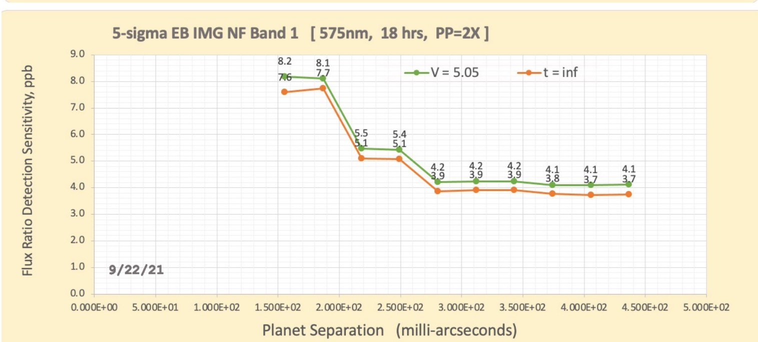


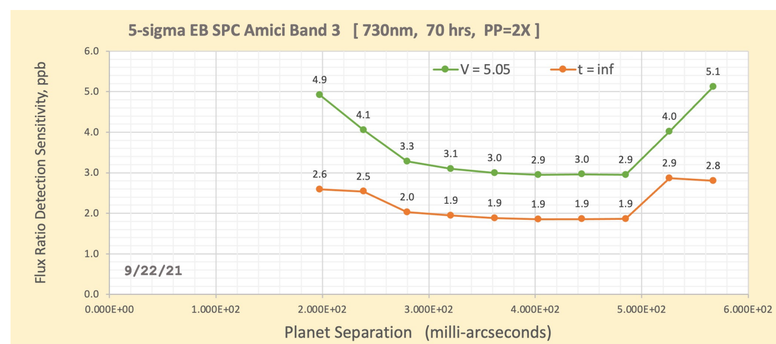
G0V





M5V





P.S. Notice that the red lines do not change: ∞ photons

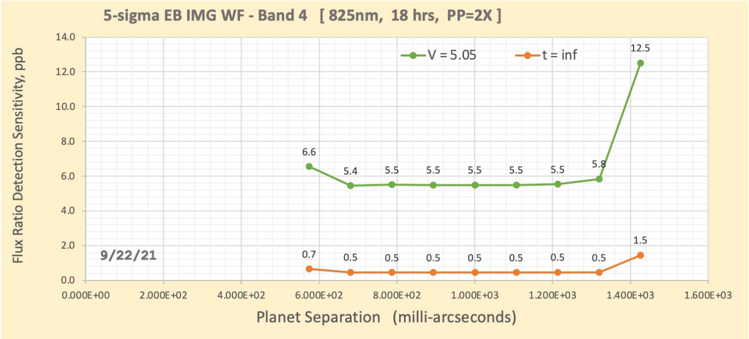
Beware y axis may change!

Coronagraph Instrument Performance in Context
Effect of Stellar Type for same V mag

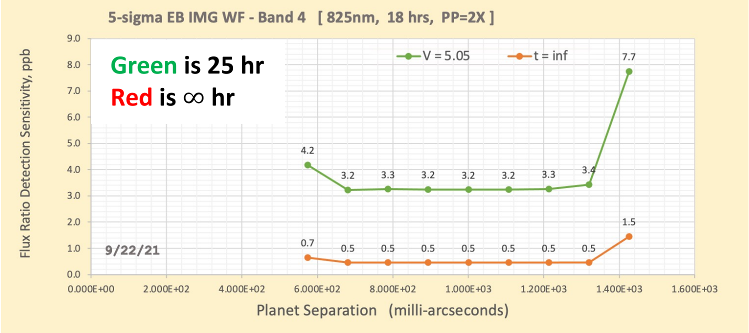
Results obtained with CGI Perf

WF Imager: Band 4 (MUFs in). Some effect

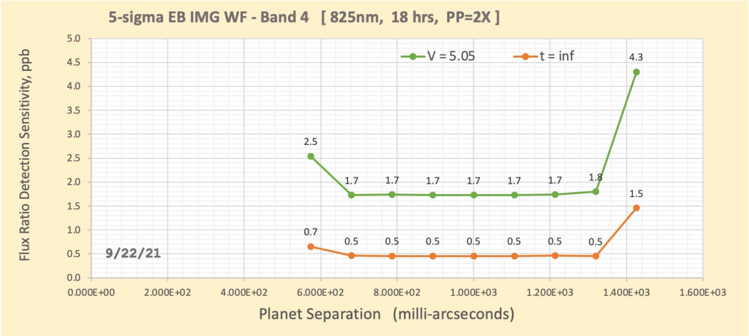
A0V



G0V



M5V



P.S. Notice that the red lines do not change: ∞ photons

Beware y axis may change!

Updates

- October 26 (all acknowledged):

Observation Applications *Note: notional target list, emphasizing that it's not definitive; observing scenario if not already covered*	Sergi Hildebrandt Rafels	15	10:40 am	1:40 pm

- October 28:

Exposure Time Calculator for the Roman Coronagraph Instrument	Corey Spohn & Sergi Hildebrandt Rafels	10	11:50 am	2:50 pm

  - Dedicated pre-release session in the next few days

- Plandb (Planet Data Base at SIOS Lab):

  - Choices for the public release of completeness: star spectral type, Optimistic (MUFless)/Conservative (CBE MUFs), Long/intermediate/Short exposure times

  - Orbital ephemeris (once available for all, Sergi will re-run the ETC and share the results with all of us)

Full version available in outerspace

Roman Coronagraph Instrument target selection

For SAG22 3/8/21 meeting

Vanessa Bailey, Sergi Hildebrandt Rafels, & Dean Keithly
With input from Bruce Macintosh, Mark Marley, and Dmitry Savransky

Observing modes

CGI Filter	λ_{center} (nm)	FWHM (approx)	Mask Type	Working Angle	Starlight Suppression Region (azimuthal extent)
1	**575**	**10%**	**HLC**	**3-9 λ/D**	**360°**
2	660	17%	SPC bowtie	3-9 λ/D	2 x 65°
2	656	1%	SPC bowtie	3-9 λ/D	2 x 65°
3	**730**	**17%**	**SPC bowtie**	**3-9 λ/D**	**130°**
4	**825**	**11%**	**SPC wide FOV**	**6.5-20 λ/D**	**360°**

Only the white highlighted rows modes are officially supported. Other modes (eg: gray rows) will be installed but not fully testbed before flight, and those will not be officially supported during the technology demonstration phase. For a complete list of installed filters please see https://roman.ipac.caltech.edu/sims/Param_db.html

Types of targets

Tech demo phase (TDP)

- **Known self-luminous young planets**: observe at new wavelengths
- **Known RV planets:** image for the first time (reflected visible light)
- **Known debris disks**: imaging and polarimetry at new wavelengths and/or higher spatial resolution
- **Exozodi**: opportunistically during deep imaging of RV systems
- **Calibrators**: single stars for PSF reference; phot / spec / pol / astrometry standards

Post TDP

- All of the above, plus
  - potential for observing protoplanetary disks
  - **blind search** for new reflected light planets
  - Blind search new exozodi (future mission exo-Earth search targets prioritized)

Target list philosophy

- Include more targets that we could observe in the time allocated
- Include some "stretch goal" targets that are beyond current performance predictions

Coronagraph Instrument hardware-driven requirements

- V<5 (requirement); V<7 (aspiration)
  - Probably possible to observe V>7 with substantially degraded performance (likely unsuitable for reflected light planet imaging)
- stellar angular diameter <2 mas
  - Driven by coronagraph mask limitations
  - Spectroscopic binaries cause similar effect as larger angular diameter
- single stars
  - no equal mag binaries within 1-2'
  - delta mag constraints get tighter at closer separations
  - Nothing with deltamag<~20 inside the CGI FOV (1.5”).

Potential Target List

Color coded by V-band magnitude (b/c only required to achieve optimal performance on V<5 stars)

Not set in stone! Will continue to add & update with inputs from current science teams & future "community participation" team

* = *tentatively* higher priority for Tech Demo Phase (TDP)

Known, Self Luminous

Probably observe 1-2 systems during TDP

	Name	V mag
	51 Eri	5.21
	HD 984	7.32
	HR 2562	6.10
*	HR 8799	5.95
	HD 95086	7.36
*	kap And	4.14
	beta Pic	3.86
	HD 206893	6.67
	HIP 65426	6.98

Selected on host star mag, projected separation, predicted fluxes from Lacy 2020 (+Lacy private communication)

Known RV, Reflected Light

Probably observe 1-2 systems during TDP

	Name	V mag
	14 Her	6.61
*	47 UMa	5.05
	HD 114613	4.85
	HD 134987	6.45
	HD 142	5.70
	HD 154345	6.76
	HD 160691	5.15
	HD 190360	5.73
	HD 192310	5.73
	HD 217107	6.16
*	HD 219134	5.57
	HD 39091	5.57
	tau Cet e	3.50
*	ups And d	4.10

From https://plandb.sioslab.com/ (mostly) NExScI orbits, masses + Batalha et al albedo models

Exozodi

Probably no dedicated exozodi search during TDP, unless opportunistic during point source search

	Name	V mag
	tau Ceti	3.50
*	eps Eri	3.82
	bet Vir	3.60
	Tet Boo	4.05
	lam Ser	4.42
	gam Ser	3.84
	72 Her	5.39
	Vega	0.00
	110 Her	4.19
	Sig Dra	4.68
*	Formalhaut	1.16

Work in progress. These are placeholders. Douglas et al. have submitted a paper that will refresh this top 10 list and describe the potential for a larger (~50 target) survey in support of future exo-Earth imaging missions. Combo of follow-up of 10um excesses and blind search.

Debris Disk

1-2 integrated light, 1-2 polarimetry during TDP

	Name	V mag
	49 Ceti	5.61
	beta UMa	2.37
	beta Leo	2.13
*	HD 139664	4.63
	eps Eri	3.82
	HD 172555	4.77
	HD 15115	6.80
	beta Pic	3.86
	eta Corvi	4.29
*	HR 4796	5.77

Work in progress. Will update & optimize as time goes on! Selected on star mag, known properties/limits from previous work. Combo of follow-up and blind search.