Roman Space Telescope

Coronagraph Instrument (CGI) Status

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August 12, 2020

CL#20-3533
Outline

- Recap of key coronagraph technologies
- Major events (changes) since PDR (9/2019)
- CGI baseline design and con-ops updates
- CGI technologies for future missions
- Path to CGI CDR
- Summary
## Coronagraph on Key NASA Flagship Missions

<table>
<thead>
<tr>
<th>Instrument name</th>
<th>Hubble</th>
<th>Webb</th>
<th>Roman</th>
</tr>
</thead>
<tbody>
<tr>
<td>NICMOS</td>
<td>NICCam</td>
<td>MIRI</td>
<td>CGI</td>
</tr>
<tr>
<td>STIS</td>
<td>NIRCam</td>
<td>NIRISS</td>
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<tr>
<td>ACS</td>
<td></td>
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<tr>
<td>Coronagraph type</td>
<td>Lyot</td>
<td>Lyot</td>
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<td>Lyot</td>
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<td>Lyot</td>
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<tr>
<td>Lyot, with</td>
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<tr>
<td>Gaussian</td>
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<td></td>
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<tr>
<td>phase mask;</td>
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<td></td>
</tr>
<tr>
<td>1) Quadrant</td>
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<tr>
<td>Lyot, Gaussian</td>
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<td>apodization</td>
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<tr>
<td>Aperture</td>
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<td>Masking</td>
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<td>Interferometry</td>
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<tr>
<td>1) Hybrid</td>
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<tr>
<td>Lyot</td>
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<tr>
<td>2) Shaped pupil</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contrast (raw)</td>
<td>1E-5</td>
<td>1E-5</td>
<td>1E-4</td>
</tr>
<tr>
<td></td>
<td>1E-5</td>
<td>1E-5</td>
<td>8E-9</td>
</tr>
<tr>
<td>Contrast (proc)</td>
<td>1E-6</td>
<td>1E-6</td>
<td>8E-7</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>8E-10</td>
</tr>
<tr>
<td>Active wavefront</td>
<td>No</td>
<td>No</td>
<td>Yes on</td>
</tr>
<tr>
<td>sensing and</td>
<td>No</td>
<td>No</td>
<td>telescope</td>
</tr>
<tr>
<td>control</td>
<td></td>
<td></td>
<td>No on</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Coronagraph</td>
</tr>
<tr>
<td>IWA (arcsec)</td>
<td>0.5</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td></td>
<td>1.7</td>
</tr>
<tr>
<td>Key Exo-planet</td>
<td>HR 8799</td>
<td>HD 141569</td>
<td>Fomalhaut b,</td>
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<tr>
<td>science example</td>
<td>(1998)</td>
<td>disk (Konishi</td>
<td>(Kalas et al.</td>
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<tr>
<td></td>
<td>(Lafreniere</td>
<td>et al. 2016)</td>
<td>2008)</td>
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<td></td>
<td>et al. 2009)</td>
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</table>

Roman CGI continues **space** coronagraphy, with addition of active wavefront sensing and control.
Three observation modes implemented with three different sets of masks/filters, in respond to L1 requirements (TTR5) and objectives.

Share the same optical beam train, with two wavefront control loops to achieve high contrast (better than $1E^{-8}$).
Early Investment Reduced CGI New Technology

Risks to Roman Mission

Coronagraph is added to WFIRST mission. (2013)

HLC/SPC/LOWFS demonstrated separately (2015)

WFIRST CGI Testbed built (2016)

Broadband (10%) contrast demonstrated in dynamic environment (2017, TRL-5)

Testbed Achieved 1.6e-9 raw contrast
550 nm, 10% BW
3 – 9 lambda/D

Hybrid Lyot Coronagraph

CGI Ground & In-Orbit commissioning operations demonstrated in testbed environment (2019)

CGI has achieved required technology maturity levels for a flight project
CGI in Roman Payload

- Roman Space Telescope Payload
  Includes
  - Imaging Optics Assy (IOA)
  - Tertiary Collimator Assy (TCA)
  - Instrument Carrier (IC)
  - Wide Field Instrument (WFI)
  - Coronagraph Instrument (CGI)
CGI at a Glance (baseline post PDR)

- Dimension: 1.687X1.092X1.760 (m³)
- Mass: 304Kg (CBE)
- Power: 349W Operations (CBE)
- Temperature: ~20°C optical bench

- Wavelength: 460-980nm
- Field-of-view: 20X20 arcsec max
- Pointing jitter: 0.5mas
- Prism spectrometer: R~50
- Wollaston polarizers: 0°+90°, 45°+135°
- Pupil imaging
- Phase retrieval optics

- EMCCD Camera #1: 1K X 1K pixels – Exoplanet
- EMCCD Camera #2: 50 X 50 pixels used – LOWFS
- Camera temperature: -105°C

- WPC Processor: command and data handling
- LOWFS Board (2X RTG4 FPGA): Pointing control

- Data rate: 4.6 Mbps (CBE)
- Data volume: 0.4 Tbits/day (CBE)
Major Events since PDR (9/2019)

After CGI PDR (9/2019) and WFIRST PDR (11/2019), CGI has been working with JPL and NASA to address CGI programmatic risks. There have been a number of positive steps:

• **12/2019.** Per NASA Tiger Team recommendation:
  – CGI re-baselined high-order wave-front sensing and control (HOWFS/C) from “in-orbit” to “ground-in-the-loop”. This results in descope of two key electronics hardware (1) processor; (2) solid-state recorder. In addition, this change greatly simplifies the flight software.

• **2/28/2020.** KDP-C, NASA agreed to:
  – Relax CGI requirement by removing CGI L1 Baseline rqmts, leaving only 1 Threshold rqmt in PLRA (TTR5 – direct imaging).
  – Reduce CGI mission life-time requirement from 5.25 years to ~1.75 years (18 months tech demo plus 3 months in-orbit check-out).
  – Remove starshade accommodation requirement for WFIRST, and put on hold starshade accommodation designs (both S/C and CGI). WFIRST will pick up the starshade accommodation design after Astro2020 decadal recommendations.
  – Re-classify CGI from risk class C to risk class D per NPR 8705.4.
  – Manage CGI directly (programmatic), CGI has its own cost cap ($334M through IOC) without HQ-UFEs
  – Maintain PDR design as allowed by CGI resources (mass, power, budget, schedule, etc.)

• **5/1/2020.** CGI received additional ~40 JPL DP/FPP waivers from DTAB (Class D Technology Advisory Board)
  – More streamlined mission assurance approach is being finalized under QARTA – Quality Assurance Requirements Tailoring Agreement.
Re-cap Technical Requirements: 2-1

- Healthy margin ~90%
- CGI project intends to maximize the margin for the given constraints (programmatic and interfaces)

CGI TTR5 remains in PLRA (one mode)

CGI CBE performance (three modes)


Courtesy of V. Bailey
Technical resources such as mass and power often drive flight projects to simplify (de-scope) capabilities. Example: IFS descope;
Progress highlights: Major interfaces with payload and S/C stabilized

- CGI to OTA interface: pupil finalized
- CGI to IC interface: 1st mode 35Hz agreed, load-path agreed
- CGI to S/C interface: data, timing, electrical power agreed
Progress highlights:

Optical Bench MICD frozen

- Enables optical bench contractor (ATK) to progress on schedule
- Optical bench CDR ~10/2020
- Optical bench delivery ~10/2021

MICD: mechanical interface control document
Progress highlights: Interface between electronics chassis and thermal pallet frozen

• Thermal radiator contract definitized recently (with Space Dynamics Lab)
mK thermal control is crucial to speckle noise stability thus post-processing gain
- Multi-layer insulator (MLI) to help maintain thermal stability
- Dedicated mk CTCE – Coronagraph Thermal Control Electronics
- 10 thermal control zones on the optical bench, and 2 on DMs
Progress high-light:
- Completed opto-mechanical peer review recently, one design accommodates all three different types of inter-connect (Fuzz button, micro-coil spring, nail pin)
Fast Steering Mirror (FSM) and Focus Control Mirror (FCM)

Progress highlight:
- FSM CDR passed recently; flight PZT screening completed; FSM flight model fabrication underway.
- FCM engineering development unit (EDU) fabrication underway.
Camera Assembly
(EX Cam, LOW Cam) and Proximity Electronics

Progress high-light:
• Camera housing: Tungsten housing to maximize CGI performance over mission life (Roman 5 years)
• EMCCD (ESA contribution): Wafer batch 1 is reported 100% complete at e2v
• ABB/Nuvu making good progress on proximity electronics, EDU delivery ~10/2020
Roman Space Telescope

SPAM: Shaped Pupil Alignment Mechanism
FPAM: Focal Plane Alignment Mechanism

Dummy masks to be replaced by ExEP contributed SPC and MSWC masks

Dummy masks to be replaced by ExEP contributed HLC and ZWFS masks

Pink box = ExEP contributed
LSAM: Lyot Stop Alignment Mechanism
FSAM: Field Stop Alignment Mechanism

 Lanka masks to be replaced by ExEP contributed Lyot stop

(CAD Drawing to be updated for 4 masks)

Pink box = ExEP contributed
CFAM: Color Filter Alignment Mechanism

DPAM: Dispersion Polarizing Alignment Mechanism

- **CFAM**
  - λ₁, λ₂, λ₃
  - Filters: λ₁a, λ₁b, λ₁c, λ₂a, λ₂b, λ₂c
  - λ₃a, λ₃b, λ₃c, λ₃d, λ₃e
  - SS x4
  - CLEAR

- **DPAM**
  - Imaging Lenses
  - Pol Lenses
  - Pupil Lens
  - Phase Retrieval x4
  - Spectro 1, Spectro 2
The Exoplanet Exploration Program is currently funding contributed hardware as well as corresponding technology maturation efforts as needed.

- Algorithms development
- Testbed demonstrations

CGI has no additional performance requirements for these contributions.

=> No additional programmatic risk to CGI.
L1 Requirements Demonstration – Operations Optimization

Need both active wavefront control and optimized in-orbit operations to meet L1 requirements.
CGI Operations (dark-hole digging)

Configuration:
- CGI +
- CGI Verification Source (CVS):
  - Simulated pupil
  - Simulated wavefront error
  - Pin-hole + broadband laser to simulate star

Configuration:
- Roman with CGI
  - During orbit insertion to L2
  - Bright reference stars

Configuration:
- Roman with CGI
  - At L2
  - Bright reference stars
  - Target stars (with planets, disks)
  - Differential imaging

2022 2023 2024 2025 2026 2027 2028 2029 2030

Review

Commissioning

CGI I&T

Launch 9/2025

Orbit Insertion

Roman Baseline 5-Year Operations

Possible Extension of CGI Participating Scientist Program

CGI Del 8/2023

CGI L3/L4 Perf Verification

2022

2023

2024

2025

2026

2027

2028

2029

2030

2022

2023

2024

2025

2026

2027

2028

2029

2030
Roman CGI as the Exo-Earth Imaging Coronagraph Tech Demo

• In many areas, meeting the requirements for CGI puts us in the regime of performance for the next generation, Earth detecting coronagraphs.
# Top Level Mission Parameters Compared

<table>
<thead>
<tr>
<th>Top Level Characteristics</th>
<th>Roman CGI (CBEs)</th>
<th>HabEx Required (VVC6)</th>
<th>LUVOIR Required</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>A: APLC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B: VVC6</td>
</tr>
<tr>
<td>IWA (in lambda/D)</td>
<td>3 (HLC at 575 nm 5PC at 730 nm)</td>
<td>3.1 (at 500 nm)</td>
<td>A: 4.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B: 3.5 (both at 500 nm)</td>
</tr>
<tr>
<td>Flux Ratio Detection Limit at IWA</td>
<td>10^-8 (10σ)</td>
<td>10^-10 (10σ)</td>
<td>10^-10 (10σ)</td>
</tr>
<tr>
<td>Spectral Bandwidth</td>
<td>10% (HLC)</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>15% (5PC)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>50 (5PC)</td>
<td>70</td>
<td>140 (VIS IFS); 70 (NIR IFS); 200 (NIR Single Point Source)</td>
</tr>
<tr>
<td>Multiplanet Spectroscopy Capability</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Polarimetric Capability</td>
<td>Yes, 4 linear states, 2 at a time</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

### Value as a Technology Demonstrator

Roman CGI compared to future missions:

- CGI more stringent than future missions
- CGI in family with future missions
- CGI easier than future missions

**Courtesy of B. Mennesson, et al.**
## Deformable Mirrors

<table>
<thead>
<tr>
<th>Deformable Mirrors (DM)</th>
<th>Roman CGI (CBEs)</th>
<th>HabEx Required (VVC6)</th>
<th>LUVOIR Required</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>A: APLC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B: VVC6</td>
</tr>
<tr>
<td>Number of actuators</td>
<td>48 x 48</td>
<td>64 x 64</td>
<td>A: 128 x 128</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B: 64 x 64</td>
</tr>
<tr>
<td>Number of DMs per coronagraph channel</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>DM stroke range (µm)</td>
<td>&gt; 0.5</td>
<td>&gt; 0.5</td>
<td>&gt; 0.5</td>
</tr>
<tr>
<td>DM stroke resolution (pm)</td>
<td>7.5</td>
<td>2.5</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Value as a Technology Demonstrator

Roman CGI compared to future missions:

- **Green**: CGI more stringent than future missions
- **Blue**: CGI in family with future missions
- **Red**: CGI easier than future missions

Courtesy of B. Mennesson, et al.
## Low Flux Detection

<table>
<thead>
<tr>
<th>Low Flux Detection</th>
<th>Roman CGI (CBEs)</th>
<th>HabEx Required (VVC6)</th>
<th>LUVOIR Required A: APLC B: VVC6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon counting</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Point source flux / PSF core broad-band imaging, (e-/s)</td>
<td>0.14 (HLC around 575 nm)</td>
<td>0.01</td>
<td>0.06 (A)</td>
</tr>
<tr>
<td>Point source flux / PSF core per spectral bin, (e-/s)</td>
<td>0.027 (SPC around 730 nm)</td>
<td>0.0004</td>
<td>0.0008 (A)</td>
</tr>
<tr>
<td>Detector Format</td>
<td>1024 x 1024 (imaging and spectroscopy)</td>
<td>1024 x 1024 (imaging) 2048 x 2048 (IFS)</td>
<td>1024 x 1024 (imaging) 4096 x 4096 (IFS)</td>
</tr>
<tr>
<td>dQE at 550nm</td>
<td>0.5</td>
<td>&gt; 0.56</td>
<td>0.72 (CBE)</td>
</tr>
<tr>
<td>Effective Read Noise, e- (after EM gain)</td>
<td>0.015</td>
<td>&lt; 0.1 (CBE: 0)</td>
<td>0 (CBE)</td>
</tr>
<tr>
<td>Dark Current (e-/pix/s)</td>
<td>1.3x 10^-4</td>
<td>&lt; 4 x 10^-4 (CBE: 3 x 10^-5)</td>
<td>3 x 10^-5 (CBE)</td>
</tr>
<tr>
<td>Clock-induced Charge (e-/pix/read)</td>
<td>0.005</td>
<td>&lt; 6 x 10^-2 (CBE: 1.3 x 10^-3)</td>
<td>1.3 x 10^-3 (CBE)</td>
</tr>
<tr>
<td>Lifetime at specified detector parameters</td>
<td>5 years</td>
<td>&gt; 5 years</td>
<td>&gt; 5 years</td>
</tr>
</tbody>
</table>

### Value as a Technology Demonstrator

Roman CGI compared to future missions:

- **CGI more stringent than future missions**
- **CGI in family with future missions**
- **CGI easier than future missions**

**Courtesy of B. Mennesson, et al.**
### Wavefront Sensing and Control

<table>
<thead>
<tr>
<th>Wavefront Sensing and Control</th>
<th>Roman CGI (CBEs)</th>
<th>HabEx Required (VVC6)</th>
<th>LUVOIR Required A: APLC B: VVC6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Order Wavefront Sensing and Control</td>
<td>Yes (up to Z11)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Pointing jitter after correction (mas rms per axis)</td>
<td>0.35 for V = 5 0.20 for V &lt; 3</td>
<td>&lt; 0.3</td>
<td>&lt; 0.3</td>
</tr>
<tr>
<td>Residual Defocus (pm) drift after correction</td>
<td>3 (OS9 temporal rms)</td>
<td>&lt; 1315</td>
<td>A: &lt; 33, B: &lt; 7</td>
</tr>
<tr>
<td>Residual Astigmatism (pm) drift after correction</td>
<td>3 (OS9 temporal rms)</td>
<td>&lt; 157</td>
<td>A: &lt; 50, B: &lt; 14</td>
</tr>
<tr>
<td>Residual Coma (pm) drift after correction</td>
<td>2 (OS9 temporal rms)</td>
<td>&lt; 94</td>
<td>A: &lt; 1, B: &lt; 8</td>
</tr>
<tr>
<td>Residual Spherical (pm) drift after correction</td>
<td>2 (OS9 temporal rms)</td>
<td>&lt; 76</td>
<td>A: &lt; 2, B: &lt; 4</td>
</tr>
<tr>
<td>High order wavefront drift in pm after any correction</td>
<td>5 (OS9 temporal rms)</td>
<td>&lt; 5</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Laser Metrology</td>
<td>No (M1-M2-M3)</td>
<td>Yes (6 per M1 segment-M2-M3)</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**Value as a Technology Demonstrator**

- **Roman CGI vs. HabEx and easier of LUVIOR A/B**
  - CGI more stringent than future missions
  - CGI in family with future missions
  - CGI easier than future missions

**Courtesy of B. Mennesson, et al.**
PSP – Participating Scientist Program

- PSP = Participating Scientist Program (to be changed to Community Participation Program)
- Kick-off ~May 2021, continuing through Phase E
- ~10 external scientists from partner countries and US institutions.
  - US team members to be competed via open call in late 2020
- Work with Coronagraph Technology Center (CTC) at JPL in tech demo preparation and operations. Add value by complementing the technologist/engineering experience of JPL staff on CTC:
  - Lead by CGI Technologist (CTC)
  - Assist analysis of image data from I&T
  - Maintain target database, advise observation planning
  - Simulate, process, and interpret astrophysics observations
  - Simulated datasets for performance analysis and community engagement
  - Flux- and wavelength-calibrated spectra
  - High-precision astrometry
  - Polarimetry calibration and interpretation
  - Research alternative wavefront sensing and control algorithms
  - Engage broader astronomy community
  - Publish science and technology results from tech demo phase
Four international partners with contributions:

- **EMCCD from e2v/ESA**
  - No major changes since PDR, COVID impact is minimum:
    - Wafer batch #1 completed on schedule
    - Wafer batch #2 ~46% complete

- **Precision Alignment Mechanisms (PAMs) from MPIA**:
  - Changes since PDR: DLR co-funding lost due to budget re-prioritization at DLR; NASA agreed to replace the lost DLR funding, MPIA on contract with JPL since 12/2019. Progress continues without impact due to DLR funding situation

- **Off-axis parabolas (OAPs) from LAM/CNES**:
  - Changes since PDR: found four of the eight OAPs not suited for LAM’s approach (stress polishing). NASA agreed to fund US vendor (II-VI Optical Systems) to polish these four (#1, #2, #3, #8) using traditional approach to mitigate schedule and technical risks.

- **Polarization Optics from JAXA**:
  - No major changes since PDR, some COVID schedule impacts:
    - Polarization prisms and lenses experience COVID schedule impact. Working to buy from US vendor (non-rad-hard) optics for EDU development. Flight units schedule being worked.
    - Mask substrates (Si for SPC, and Fused Silica for HLC) batch #1 delivered to JPL on 7/31/2020, just in time for flight mask fab. Batch #2 schedule for late 10/2020 as backups.
CGI continues making progress during COVID-19

- CGI staff working from home since 3/17/2020
- JPL has approved ~25 CGI critical tasks, with ~88 CGI “Mission Essential” personnel to return to lab since 4/2020
  - (1) DM TRL-6 development; (2) electronics; (3) camera; (4) mask fab and testing; (4) mechanisms; (5) Performance testbed; (6) parts qualifications.
- All services such as mechanical fab, e-fab, environmental test labs, analytical labs, etc. are open to support CGI for limited capacities
Due to COVID impact, CGI CDR has been rescheduled from 2/2021 to 4/2021.
  - Different degrees of supply chain COVID impacts across the board

Maintain 8/2023 CGI delivery, by taking 2 months out of I&T schedule (dropping two months of testing for two modes)

DM TRL-6 interconnect demonstration ~ 11/2020
  - Currently carry three different methods for risk reduction (1) 2nd generation fuzz button, (2) micro coil springs, (3) nail pins
  - Down select to one approach ~ end of 8/2020 after risk mitigation studies
  - Focus on one type for 11/2020 demonstration

Prior to CGI CDR, we expect to complete all element/assembly-level CDRs (9/2020 – 2/2021)

FY21 budget risk and COVID impact
Summary

• CGI is making solid progress toward CDR (4/2021)
  – DM interconnect TRL-6 technology maturation ~ 11/2020
  – External interfaces stabilized: CGI to OTA, IC, and S/C
  – Internal interfaces frozen: Optical bench, electronics thermal pallet, etc.
  – Next steps: complete all the detailed designs, release ALL drawings by CDR

• Maintain an acceptable risk posture
  – KDP-C requirement relaxations to CGI, off-ramps to protect CGI schedule and budget, Tiger Team recommendations for simplifications
  – ExEP contribution of additional masks without increasing CGI programmatic risks

• CGI continues coronagraphy in space on NASA flagship missions, demonstrating key technologies for future earth 2.0 imaging missions
Back-up charts
### Acronyms

- **CAD** Computer Aided Design
- **Cam** Camera
- **CF** Color Filter
- **CFAM** Color Filter Alignment Mechanism
- **CFWM** Color Filter Wheel Mechanism (aka Color Filter Alignment Mechanism)
- **CGI** Coronagraph Instrument
- **CSAM** Camera Selector Alignment Mechanism
- **CTCE** Coronagraph Thermal Control Electronics
- **DI** Direct Image
- **DICam** Direct Imaging Camera
- **DM** Deformable Mirror (by Xinetics)
- **DME** Deformable Mirror Electronics
- **DPAM** Dispersion Polarizing Alignment Mechanism
- **EXCam** Exoplanetary systems Camera
- **FM** Folding Mirror
- **FCM** Focus Control Mirror
- **FPA** Focal Plane Array
- **FPAM** Focal Plane Alignment Mechanism
- **FPM** Focal Plane Mask
- **FS** Field Stop
- **FSAM** Field Stop Alignment Mechanism
- **FSM** Fast Steering Mirror
- **IC** Instrument Carrier
- **ICE** Instrument Control Electronics

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<th>Acronym</th>
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<tr>
<td>IFS</td>
<td>Integral Field Spectrometer (PISCES at GFSC)</td>
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<tr>
<td>IFSCam</td>
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<tr>
<td>ISE</td>
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<td>LOBE</td>
<td>LOWFS Optical Barrel Element</td>
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<td>LOCam</td>
<td>Low Order [Wave Front Sensing] Camera</td>
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<td>MLI</td>
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<td>WFIRST</td>
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<td>OBSA</td>
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<td>Spherical Mounted Reflector</td>
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