State of the Art of Coronagraph Technology

Brendan Crill, Pin Chen, Nick Siegler

NASA Exoplanet Exploration Program
Jet Propulsion Laboratory / California Institute of Technology

Jan 7, 2024
Requirements

We are here

Coronagraph lab demos are here

Roman gets us here

Dynamic lab demo’s for HWO need to be here
Best Broadband Contrast Lab Demonstrations to Date

- Best obscured segmented pupil demonstration
- Best static segmented pupil demonstrations
- Best vortex coronagraph demonstration (classical Lyot)
- Best coronagraph demonstration (classical Lyot)
- Best starlight suppression demonstration (starshade)

Diagram:
- Best dynamic segmented pupil demonstrations (in-air)
- HWO goal
- Contrast goal ≤ 10^{-10}

Graph parameters:
- Angle [mas] on a 6m telescope at 640 nm
- Normalized intensity

Legend:
- HCIT clear pupil Lyot
- HCIT clear pupil VVC4
- HCIT clear pupil VVC5
- Princeton testbed 25mm starshade
- 681nm (55 MS1b) 10% band
- HCIT clear pupil VVC4
- 635nm (Ruane et al. 2022) 10% band
- HCIT obstructed-s-segmented pupil PIAACMC
- 650nm (Belikov et al. 2022) 10% band
- HCIT segmented pupil VVC4
- 650nm (Riggs et al. 2022) 10% band
- HCIT clear pupil PIAA
- 800nm (Guyon et al. 2014) 10% band
- HCIT clear pupil SLEEC
- 550nm (Trauger et al in prep) 10% band
- HiCAT (in air) segmented pupil PAPLC
- 660nm (Por et al 2023 in prep) 10% band
- HCIT Roman pupil HLC
- 550nm (CGI Milestone 9 (2017)) 10% band

Version 2023.12.14
State of the Art Lab Demonstrations  
(Segmented Apertures)

**Soummer et al (2022):** Phase-apodized Lyot Coronagraph

*Segmented mirror simulating a segmented off-axis mirror in air*

*2x10^-8 average contrast*

*2-13 \(\lambda/D\)*

*0% bandwidth*

*unpolarized light*

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**Belikov et al (2022):** PIAACMC

*Segmented mask simulating a static segmented on-axis mirror in vacuum*

*1.8x10^-8 average contrast*

*3.5-8 \(\lambda/D\)*

*10% bandwidth*

*polarized light*

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**Riggs et al (2022):** Vortex Coronagraph

*Segmented mask simulating a static segmented off-axis mirror in vacuum*

*4.7x10^-9 average contrast*

*3-10 \(\lambda/D\)*

*10% bandwidth*

*polarized light*
Habitable Worlds Observatory requirements
(CBE, ref. Astro2020 Table E.1)

- **IWA**: ~60 mas:
  - VVC (LUVOIR-B) design meets requirement for $\lambda < 0.62$ $\mu$m (6-meter aperture), whereas the required spectral coverage might be as wide as 0.3 – 1.8 $\mu$m
- **OWA for Spectroscopy**: ~500 mas
  - VVC (LUVOIR-B) design meets requirement for $\lambda > 0.52$ $\mu$m, whereas the required spectral coverage might be as wide as 0.3 – 1.8 $\mu$m
- **OWA for Imaging Only**: ~1”
  - VVC (LUVOIR-B) design meets requirement for $\lambda > 1.0$ $\mu$m
- **Contrast**: ~1E-10
  - APLC and HLC (LUVOIR-A) designs surpass the requirement (even for an on-axis aperture) for *average* contrast (over the stated dark zone) and *point-source* stars
  - At 3 $\lambda/D$, only the HLC (LUVOIR-A) design produces 1E-10
  - Stellar diameter (or pointing jitter) has a large impact on contrast at 3 $\lambda/D$, but much smaller impact on average contrast
  - WFE due to random segment-piston jitter is generally disastrous at 100 pm RMS but tolerable at ~10 pm RMS
- **Bandwidth**: ~20% or greater
- Meeting all requirements will likely require a combination of coronagraphs
Seo et al (2019): classic Lyot coronagraph, 550 nm 10% band: $3.82 \times 10^{-10}$ contrast

Vortex coronagraph baselined for LUVOIR-B and HabEx

Lyot coronagraph NOT baselined for HabEx or LUVOIR

Contrast at Inner Working Angle always worse than average
**Recent Coronagraph Lab Demonstrations**

<table>
<thead>
<tr>
<th>Coronagraph Type</th>
<th>HWO goal</th>
<th>Classical Lyot</th>
<th>Vector Vortex charge 4</th>
<th>Phase Apodized Pupil Lyot Coronagraph</th>
<th>Phase Induced Amplitude Apodization Coronagraph</th>
<th>Vector Vortex charge 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture Type</td>
<td></td>
<td>Circular unobscured (off-axis monolith)</td>
<td>Off-axis segmented mirror</td>
<td>Circular on-axis static segmented mask</td>
<td>Circular off-axis static segmented mask</td>
<td></td>
</tr>
<tr>
<td>Deformable Mirrors</td>
<td>2x 96 x 96</td>
<td>2 AOX (each 48 x 48 act)</td>
<td>2 AOX (each 48 x 48 act)</td>
<td>2 BMC MEMs (each 1k act)</td>
<td>1 BMC MEMs (1k act)</td>
<td>1 BMC MEMs (2k act)</td>
</tr>
<tr>
<td>Separation Range</td>
<td>3-45 λ/D</td>
<td>5-13.5 λ/D (vs 3-10 λ/D)</td>
<td>3-8 λ/D</td>
<td>2 – 13 λ/D</td>
<td>3.5 – 8 λ/D</td>
<td>3-10 λ/D</td>
</tr>
<tr>
<td>Dark Hole Azimuthal Extent (deg)</td>
<td>360</td>
<td>180 (vs 360)</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>Mean Raw Contrast over Sep. Range</td>
<td>1 x 10^{-10}</td>
<td>4 x 10^{-10} (idem)</td>
<td>5.9 x 10^{-9} (1.6 x 10^{-9})</td>
<td>2 x 10^{-8}</td>
<td>1.8 x 10^{-8}</td>
<td>4.7 x 10^{-9}</td>
</tr>
<tr>
<td>Central wavelength (nm)</td>
<td>300-1300</td>
<td>550</td>
<td>635</td>
<td>638</td>
<td>650</td>
<td>635</td>
</tr>
<tr>
<td>Spectral bandwidth</td>
<td>20%</td>
<td>20% (10%)</td>
<td>20% (10%)</td>
<td>Monochromatic</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Number of polarizations</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
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</tr>
<tr>
<td>Off-axis Throughput</td>
<td>high</td>
<td>medium</td>
<td>high</td>
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<td>high</td>
</tr>
<tr>
<td>Sensitivity to low order aberrations</td>
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<td>low</td>
<td>medium</td>
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<tr>
<td>Facility and Testbed</td>
<td>JPL HCIT-2 DST</td>
<td>JPL HCIT-2 DST</td>
<td>STScI HiCAT</td>
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<td>JPL HCIT-2 DST</td>
<td></td>
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<tr>
<td>Vacuum Operation</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
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*Currently demonstrated static contrast performance degrades when moving toward coronagraphs with higher throughput and lower sensitivity to aberrations, moving from monolithic to segmented apertures, and from off-axis to on-axis*
## Recent Starlight Suppression Demos

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## Simulated Coronagraph Performances

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<tr>
<th>Coronagraph Type</th>
<th>Aperture Type</th>
<th>Aperture [m]</th>
<th>( \lambda_c ) [nm]</th>
<th>BW</th>
<th>IWA [( \lambda/D )]</th>
<th>OWA [( \lambda/D )]</th>
<th>Core Throughput</th>
<th>Average Contrast</th>
<th>Contrast @ 3( \lambda/D ), point star</th>
<th>Contrast @ 3( \lambda/D ), 1 mas star</th>
<th>( \Delta )Contrast @ 3( \lambda/D ) due to 100 pm rms piston jitter</th>
</tr>
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<tbody>
<tr>
<td>VVC</td>
<td>LUVOIR-B</td>
<td>8</td>
<td>575</td>
<td>10%</td>
<td>2.8</td>
<td>28</td>
<td>30%</td>
<td>5.E-10</td>
<td>3.E-10</td>
<td>1.E-09</td>
<td>6.E-09</td>
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<td>APLC</td>
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<td>3.8</td>
<td>12</td>
<td>15%</td>
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- The table includes only coronagraphs recently analyzed by SCDA*
- The designs used deformable mirrors with 64 actuators across the diameter
- Manufacturability of the designs will be assessed (as part of the ExEP Coronagraph Technology Roadmap work)
- The table does not include all important aberrations. For example, all three coronagraphs are extremely sensitive to misalignment of the telescope’s exit pupil with respect to the coronagraph’s entrance pupil.
- The listed APLC and HLC are for LUVOIR-A. The LUVOIR-B aperture can enable substantially better performance (contrast/throughput/IWA). An HLC-LUVOIR-B design will be completed in FY23

*Segmented Coronagraph Design & Analysis study led by the ExEP