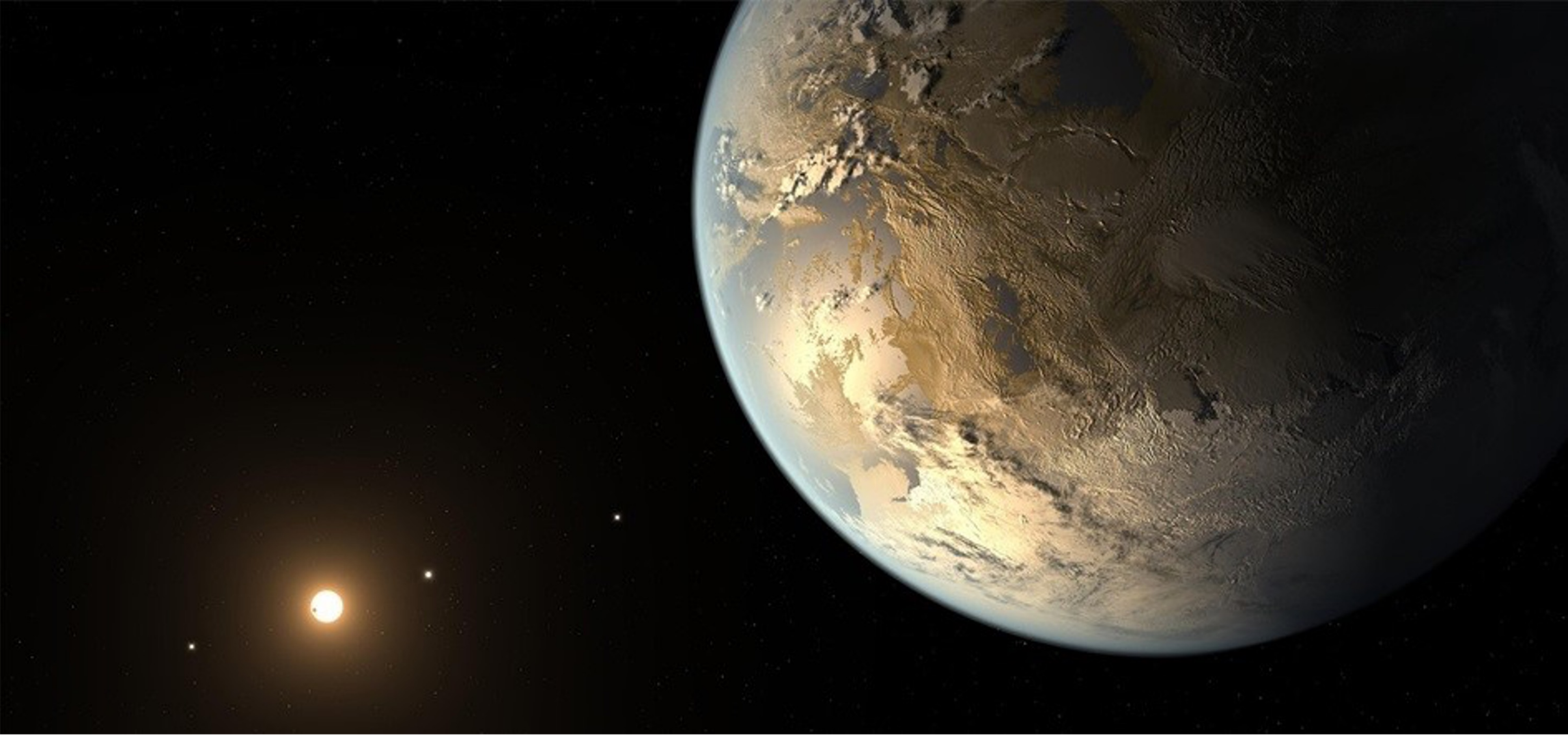

NASA Exoplanet Exploration Program

The Coronagraph Technology Roadmap Working Group

Final Report

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Please see full list of participants in this report

- This document has been reviewed and determined not to contain export controlled technical data.
- The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

Table of Contents

1. Participants
2. Executive Summary of Findings
3. Deliverables, Scope, & Assumptions
4. Provisional Key Driving Requirements
   A. Wavefront-Stability Environment
   B. Starlight-Suppression Key Performance Parameters
   C. Coronagraph Adaptive Optics
   D. Detectors
   E. Post Processing
5. State of the Art and Technology Gaps
6. Gap Details
7. Learning from Roman Space Telescope's Coronagraph Instrument
8. Technology Maturation Plan and Required V&V Facilities
9. Glossary of Abbreviations
10. Appendix

1. Participants

Participants

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- Vis Design-Point Lead: Vanessa Bailey (JPL)
- NIR Design-Point Lead: Olivier Guyon (NAOJ)
- UV Target List: Eric Mamajek (ExEP), Karl Stapelfeldt (ExEP), Dmitry Savransky (Cornell)
- EBS Validation & UI Lead: Sarah Steiger (STScI)
- Detector & Dichroic-Beamsplitter Fact Finding: John Trauger (JPL)
- Hybrid Lyot Coronagraph Design & Segment Edge Roll-off Simulation Software Lead: Dwight Moody (JPL)
- Coating Uniformity Sensitivity Analysis: John Krist (JPL)

Special thanks to Ms. Angel Zhu (formerly JPL, now Harvard) for graphic design of the roadmap chart on p. 13

2. Executive Summary of Findings

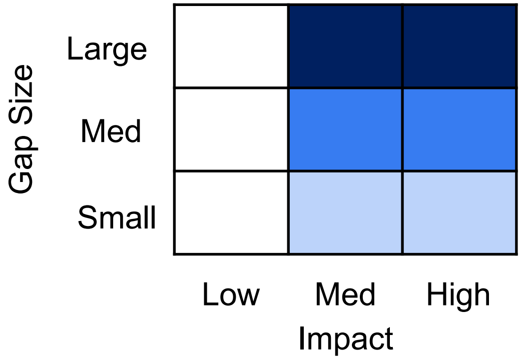
Executive Summary

- We summarize our findings in terms of coronagraph technology gaps to achieving TRL 5 for the Habitable Worlds Observatory
- The impact of each gap is quantified using the Provisional Key Driving Requirements (Section 3). Their derivation utilized the open-source Error Budget Software (EBS) developed under CTR, with comparisons to relevant literature.
- The gaps sizes are based on current State of the Art (Section 4).
- This report is a roadmap to reducing these gaps (by advancing SotA)

Impact:
Low: insignificant to small reduction in projected mission return
Medium: moderate reduction in projected mission return
High: significant reduction in projected mission return

Gap size:
Small: Requirement < 2 x SotA performance
Medium: Requirement < 10 x SotA performance
Large**:** Requirement > 10 x SotA perfromance

Priority for technology road maps:
Dark blue: Invest immediately in multiple technology options, including emergent technologies where appropriate. Balance portfolio in consideration of impact.
Medium Blue: Invest timely in SotA technologies. Balance portfolio in consideration of impact
Light Blue: Advance existing technologies with appropriate timeline



Executive Summary

- After summarizing the top gaps, this report substantiates the gap evaluations in terms of assumed/provisional requirements and technological SotA (Section 5).
- The rest of the report presents a maturation plan that builds upon what we learn from the Roman Space Telescope Coronagraph Instrument (Roman Coronagraph or "CGI") (Section 6). We first present Required V&V test facilities (Section 7) and then the actual maturation plan (Section 8).
- We developed EBS and used it to derive many key provisional requirements. Full documentation of the computation settings and outputs will be available on the code repository by the end of August 2024: https://github.com/chen-pin/ebs

- **This report focuses on identifying technology gaps and maturation schedule. For potential technological solutions, we reference the following recent reports and publications:**
  - ExEP Coronagraph Design Survey Working Group (Co-Leads: R. Belikov, C. Stark), 2024, "The Coronagraph Design Survey Final Report" (will be posted at https://exoplanets.nasa.gov/exep/)
  - ExEP Deformable Mirror Technology Roadmap Working Group (Co-Leads: E. Bendek, T. Groff, & D. Liu), 2024, "The Deformable Mirror Technology Roadmap Working Group" (will be posted at https://exoplanets.nasa.gov/exep/)
  - ExEP Coronagraph Technology Roadmap UV Design Point Team, 2024, "A near-ultraviolet coronagraph instrument study for the Habitable Worlds Observatory"
  - N. Jovanovic, et al., 2023, "2023 Astrophotonics Roadmap: pathways to realizing multi-functional integrated astrophotonic instruments," J. Phys. Photonics, 5, 042501, DOI 10.1088/2515-7647/ace869

Executive Summary

- **All gaps are based on SotA performance (not projected future performance)**
- **WFE-Stability Environment Gap.** The coronagraph instrument is not able to achieve required contrast noise floor for planet detection in relevant environment of observatory and DMs WFE instabilities. **Large gap, High impact.**
- **Starlight-Suppression-Optics Subsystem Gap**. Starlight-suppression optics do not meet static performance (throughput, IWA/FoV, raw contrast, wavelength, and bandwidth) requirements to enable mission exoplanet yield. NUV and NIR testbed capabilities need to be developed. Development of a standalone UV instrument might be necessary. NIR coronagraphy/spectroscopy might require emergent technologies. **Medium gap for Vis, Large gap for UV & IR, High impact.**
- **Mission efficiency Gap.** HWO design concepts utilize dichroic beam splitters for multi-channel observations. Such optics have never been tested. **Large gap, Medium impact.**
- **Detectors Gap :** Detectors do not meet noise, dynamic range, and lifetime requirements. **Small gap for imaging, Large gap for spectroscopy, Medium impact (imaging) High impact (spectroscopy).**

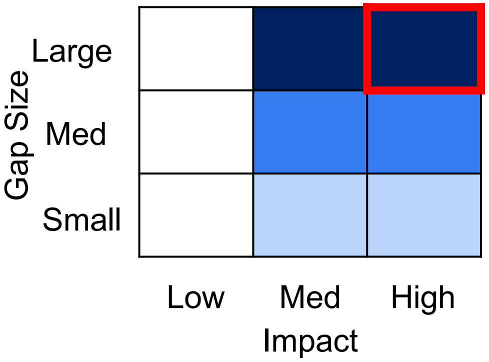
Executive Summary

- **Deformable Mirrors Gap.** DM subsystem not meeting actuator count, stability, surface, mass/volume, and/or schedule requirements. **Large gap for actuator count, Medium gap for everything else, High impact**.

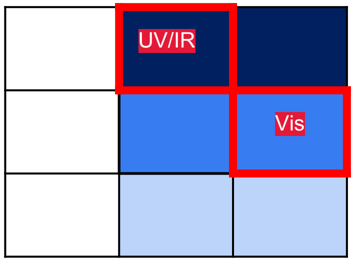
- **Algorithms Gap.** Starlight-Suppression and post processing. Dark-hole-digging algorithms not able to compute solutions. Post processing enhancement insufficient for required planet detection/characterization. **Medium gap, Medium impact.**

- **Modelling Gap**. Model does not capture all contributions to instrument noise floor. Knowledge gap. **Large gap before CGI flight, Medium gap after Roman Coronagraph flight, High impact.**

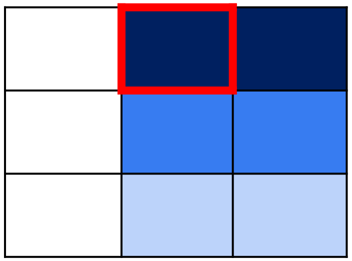
Executive Summary



WFE-Stability

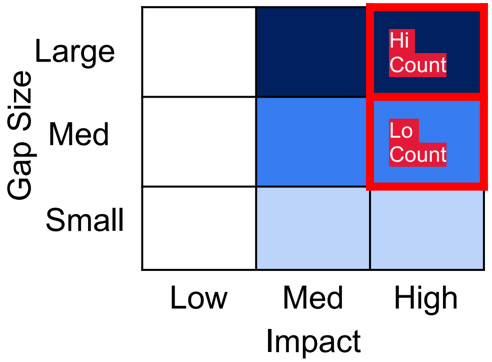


Static performance

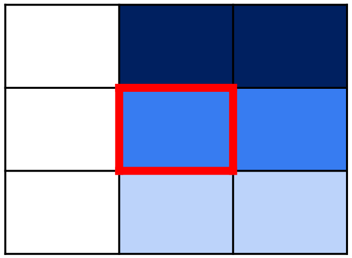


Mission efficiency

Detectors



DMs



Algorithms

Modelling

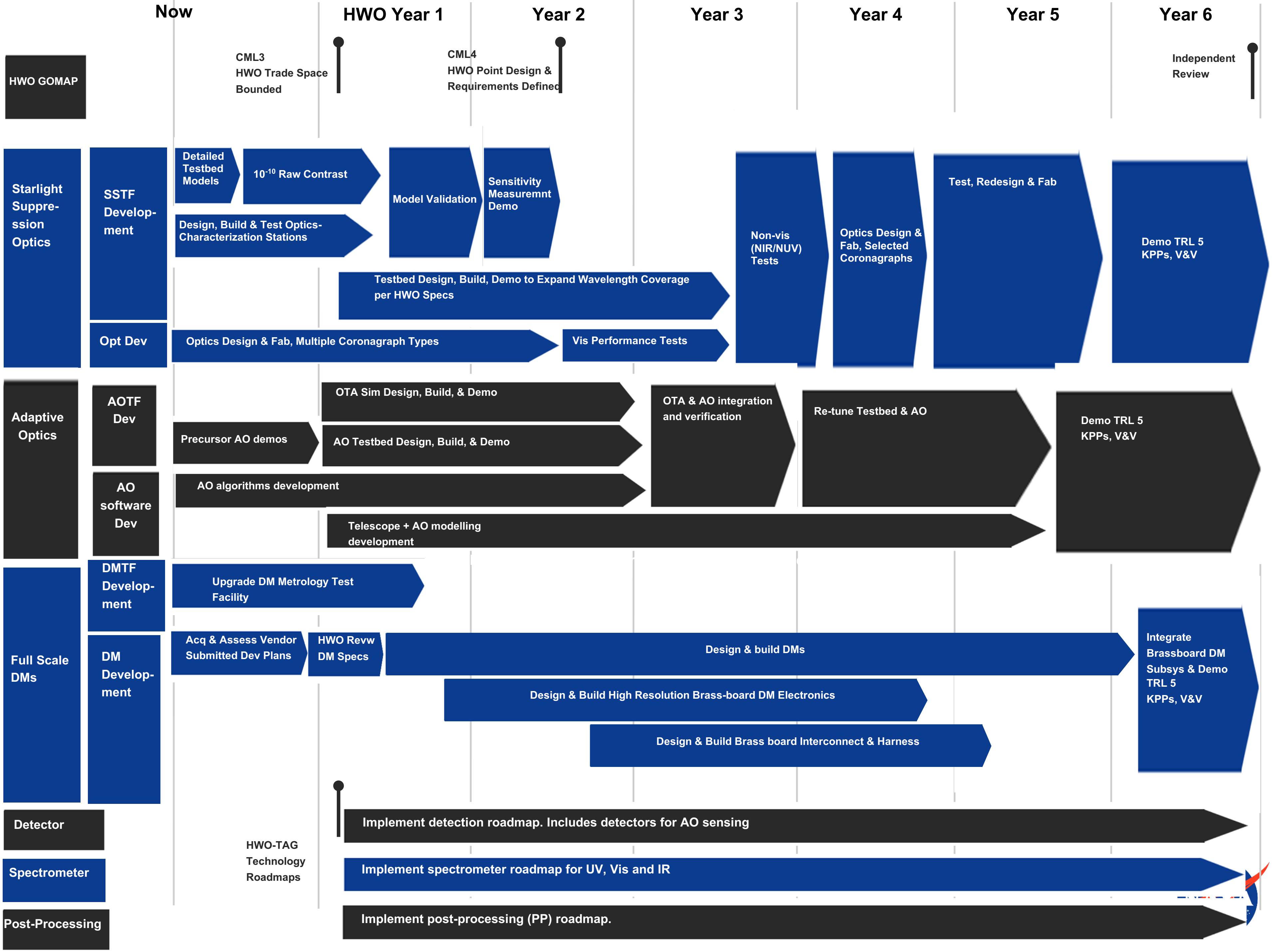
This report discusses how to advance technologies to close gaps

Timeline Assumptions

- Astro2020 recommended that crucial technologies reach TRL 5-6 before the Independent Review. Astro2020 envisioned that HWO technology development to take 6 years, requiring $800M (FY2020) total technology-maturation investment. Therefore, we assume a timeline of six years starting from initiation of funding flow approximating at least ~ $100M/year (in 2020 dollar) to reach TRL 5. For example, if this level of investment starts in October 2025, the envisioned TRL-5 completion can occur by September 2031.
- Based on the current HWO plan, HWO can reach CML 4 by mid 2026, which will provide key definitions for technology development:
    - Draft STM produced and **driving requirements documented**
    - Initial high level scenarios, timelines and **operational modes documented**
    - **System architecture & instrument designs described by mechanical configuration drawings**
    - **Instrument performance requirements** traced to level-1 requirements
    - **Technology options characterized and baseline options selected and justified**

Maturation Plan: Notional Baseline

- The next slide shows our roughly estimated maturation schedule to meet the six-year timeline described in Astro2020
- We posit that the different critical technology elements (starlight suppression optics, adaptive optics, full-scale DMs, etc.) can be matured and validated independently for TRL-5, with clearly defined interface requirements between elements
- We derived notional timescales using the following boundary conditions
  - Overall timeline for developing critical HWO technologies is six years, based on Astro2020
  - The six year clock starts when NASA begins investing in HWO technology on the ~ 10^8 $/yr scale
  - The overall timeline show comprises the above-mentioned six years plus a lead-in period (starting now)
  - Within each development tack of critical technology element , we estimated the relative required timescale for each phase and fit the end-to-end timescale into the overall timeline
- As such, this is *not* a grass-roots-estimated schedule
- The end of each arrow-shaped bar represents a milestone (in accomplishing the corresponding task/objective)
- **Whether or not the envisaged schedule can be accomplished depends on invested resources**



Now | HWO Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Year 6

HWO GOMAP

CML3
HWO Trade Space
Bounded

CML4
HWO Point Design &
Requirements Defined

Independent
Review

Starlight Suppression Optics

SSTF Development
- Detailed Testbed Models
- 10^{-10} Raw Contrast
- Design, Build & Test Optics-Characterization Stations
- Model Validation
- Sensitivity Measuremnt Demo
- Testbed Design, Build, Demo to Expand Wavelength Coverage per HWO Specs

Opt Dev
- Optics Design & Fab, Multiple Coronagraph Types
- Vis Performance Tests

- Non-vis (NIR/NUV) Tests
- Optics Design & Fab, Selected Coronagraphs
- Test, Redesign & Fab
- Demo TRL 5 KPPs, V&V

Adaptive Optics

AOTF Dev
- OTA Sim Design, Build, & Demo
- Precursor AO demos
- AO Testbed Design, Build, & Demo

AO software Dev
- AO algorithms development
- Telescope + AO modelling development

- OTA & AO integration and verification
- Re-tune Testbed & AO
- Demo TRL 5 KPPs, V&V

Full Scale DMs

DMTF Development
- Upgrade DM Metrology Test Facility

DM Development
- Acq & Assess Vendor Submitted Dev Plans
- HWO Revw DM Specs
- Design & build DMs
- Design & Build High Resolution Brass-board DM Electronics
- Design & Build Brass board Interconnect & Harness
- Integrate Brassboard DM Subsys & Demo TRL 5 KPPs, V&V

HWO-TAG
Technology
Roadmaps

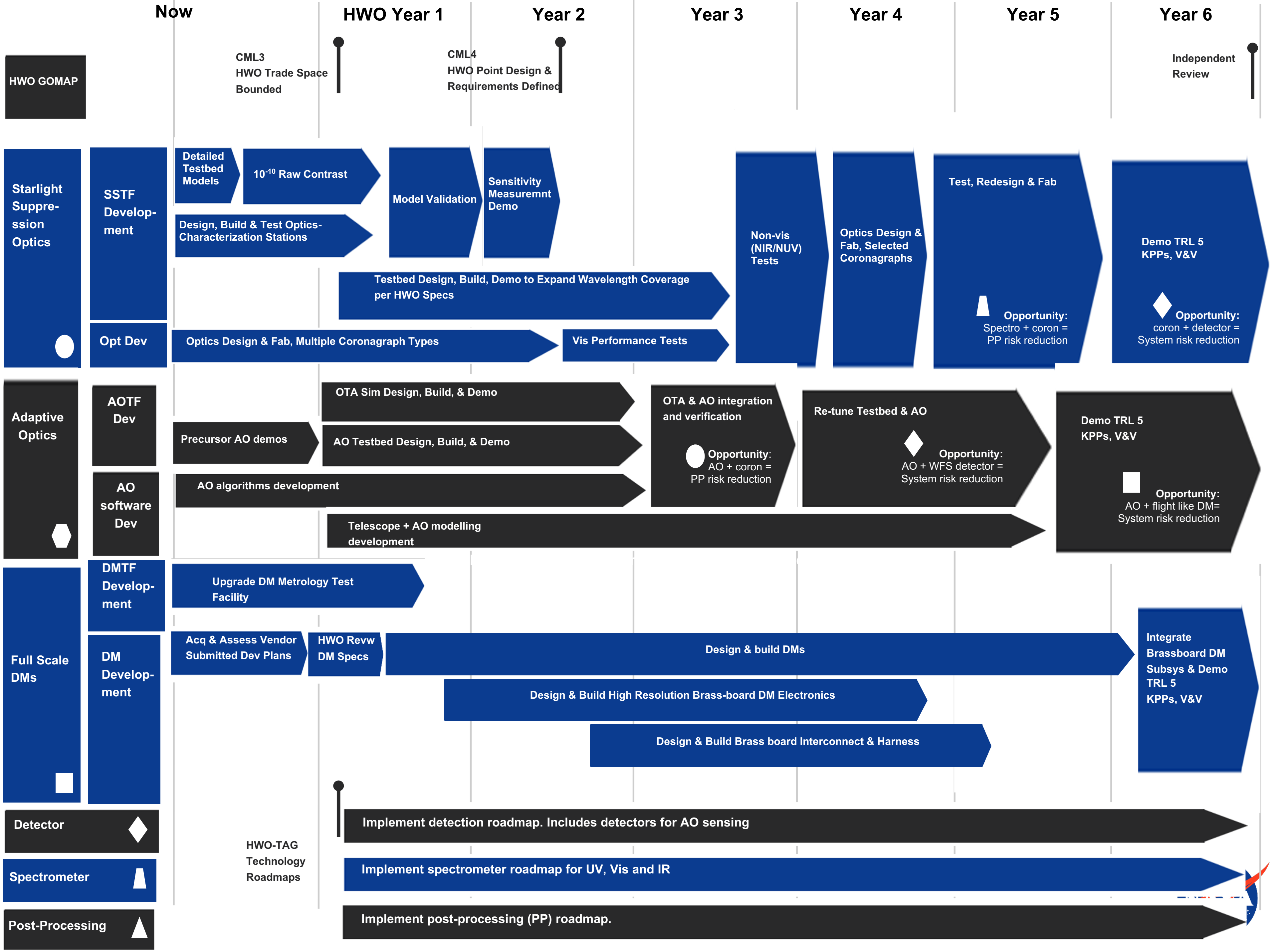
Detector
- Implement detection roadmap. Includes detectors for AO sensing

Spectrometer
- Implement spectrometer roadmap for UV, Vis and IR

Post-Processing
- Implement post-processing (PP) roadmap.

Maturation Plan: Opportunities

- The next slide shows opportunities in risk reduction by integrating different critical technology elements before TRL 5
- Each critical technology element is represented by a different symbol.
- Appearance of a symbol in the track of another critical technology element represents an integration opportunity



HWO GOMAP

Now	HWO Year 1	Year 2	Year 3	Year 4	Year 5	Year 6

CML3
HWO Trade Space Bounded

CML4
HWO Point Design & Requirements Defined

Independent Review

Starlight Suppression Optics ●

- **SSTF Development**
  - Detailed Testbed Models
  - 10^{-10} Raw Contrast
  - Design, Build & Test Optics-Characterization Stations
  - Model Validation
  - Sensitivity Measuremnt Demo
  - Testbed Design, Build, Demo to Expand Wavelength Coverage per HWO Specs
- **Opt Dev**
  - Optics Design & Fab, Multiple Coronagraph Types
  - Vis Performance Tests
- Non-vis (NIR/NUV) Tests
- Optics Design & Fab, Selected Coronagraphs
- Test, Redesign & Fab
  - Opportunity: Spectro + coron = PP risk reduction
- Demo TRL 5 KPPs, V&V
  - Opportunity: coron + detector = System risk reduction

Adaptive Optics ⬢

- **AOTF Dev**
  - OTA Sim Design, Build, & Demo
  - Precursor AO demos
  - AO Testbed Design, Build, & Demo
- **AO software Dev**
  - AO algorithms development
  - Telescope + AO modelling development
- OTA & AO integration and verification
  - Opportunity: AO + coron = PP risk reduction
- Re-tune Testbed & AO
  - Opportunity: AO + WFS detector = System risk reduction
- Demo TRL 5 KPPs, V&V
  - Opportunity: AO + flight like DM= System risk reduction

Full Scale DMs ■

- **DMTF Development**
  - Upgrade DM Metrology Test Facility
- **DM Development**
  - Acq & Assess Vendor Submitted Dev Plans
  - HWO Revw DM Specs
  - Design & build DMs
  - Design & Build High Resolution Brass-board DM Electronics
  - Design & Build Brass board Interconnect & Harness
- Integrate Brassboard DM Subsys & Demo TRL 5 KPPs, V&V

HWO-TAG Technology Roadmaps

- **Detector** ◆ — Implement detection roadmap. Includes detectors for AO sensing
- **Spectrometer** ▲ — Implement spectrometer roadmap for UV, Vis and IR
- **Post-Processing** ▲ — Implement post-processing (PP) roadmap.

Executive Summary

Key findings:

- Multiple vacuum testbeds are necessary. At least one per bandpass (UV/VIS/IR) and one dedicated to wavefront stability (AO).
- DM development needs to start as early as possible.
- System level risk will be carried by model. Significant testbed ressources need to be invested for model validation.
- Multiple opportunities for system-level risk reduction exist after year 2.
- See recommendations in Sec. 5 “Gap Details”

3. Deliverables, Scope, & Assumptions

CTR Deliverables

1. Presented and served as panelist at the “Starlight Suppression Technologies for the IR/O/UV Flagship” splinter session, AAS Meeting, Seattle (Jan 2023)
2. Submitted CTR task plan for ExoTAC review (May 2023)
3. Delivered DM Spatial-Temporal Stability Requirements to DMTR (Jun 2023)
4. Delivered requirement on inter-segment reflectance uniformity to USORT (Jun 2023)
5. Produced a provisional HWO UV Target List (Jul 2023)
6. Presented at the “Science with the Habitable Worlds Observatory and Beyond worksop,” Baltimore, (Jul 2023)
7. Presented at the “Towards Starlight Suppression for the Habitable Worlds Observatory Workshop,” Pasadena (Aug 2023)
8. Developed open-source Error Budget Software (EBS) (Sep 2023)
9. Co-authored the “UV Technology to Prepare for the Habitable Worlds Observatory” white paper (Sep 2023)
10. Briefed HWO TAG on CTR work (Dec 2023)
11. Briefed HWO TAG on Coronagraph Technology Focus Areas (Dec 2023)
12. Supported development of HWO’s Coronagraph Exploratory Cases (Feb 2024)

CTR Deliverables (cont'd)

13. Briefed HWO Integrated Modeling Working Group on end-to-end modeling for investigating exo-Earth yield sensitivity to dynamic wavefront error (WFE) with coronagraph AO (Mar 2024)
14. Participated in HWO Exoplanet Science Yield Working Group's Exposure-Time Calibration task (Mar 2024 - present)
15. Produced the “UV Coronagraph Point Design” white paper (May 2024)
16. Delivered the Coronagraph Technology Roadmap Final Report (May 2024)
17. Will present ExEP Technology Colloquium Series Talk: The Coronagraph Technology Roadmap (June 2024)
18. Presented at SPIE conference, “A standalone UV coronagraph instrument for the Habitable Worlds Observatory,” Juanola-Parramon et al. Yokohama, (Jun 2024)
19. Presented at SPIE conference, “Simulated performance of microwave kinetic inductance detectors towards exoplanet imaging with the Habitable Worlds Observatory,” Steiger et al., Yokohama, (Jun 2024)
20. Presented at SPIE conference, “A Coronagraph Technology Roadmap for Future Space Observatories to Directly Image Earth-like Exoplanets,” Chen et al., Yokohama, (Jun 2024)

Scope

Driving Question: **Where and when does NASA need to invest in coronagraph technology to enable the Habitable Worlds Observatory?**

Objectives

1. Create a roadmap for coronagraph technologies to reach **TRL 5** for the Habitable Worlds Observatory and describe the path to TRL 6
   - Identify viable coronagraph technology candidates while incorporating insights from CGI and basing on LUVOIR and HabEx studies wherever relevant
2. Formulate tasks that ExEP/HCIT should conduct to achieve critical objectives—e.g. **10^{10} contrast demonstration**

Scope

1. We treat the coronagraph as a system that includes adaptive optics (aka WFS&C or LOWFS), starlight-suppression optics, detector, and postprocessing
2. We treat the observatory as a critical part of the relevant *environment* in which the coronagraph must perform

Operating Assumptions: Mission Architecture

1. Any mission architecture we study must be feasible for launch in the first half of the 2040s
2. The observatory is the most significant part of the *relevant environment* in which the coronagraph must perform
3. We assume a segmented telescope with a coronagraph as the reference architecture.
4. Telescope diameter is 6 meters, with characteristics compatible w/ USORT
5. The telescope will have IR, vis, and UV capabilities (but not necessarily the coronagraph instrument)
6. The telescope primary aperture will be at least 6-m in inscribed diameter
7. In-space robotic servicing will be available (e.g. to refurbish the telescope, refuel, update instruments)
8. The telescope will be starshade compatible
9. The telescope will be off-axis with the primary-mirror geometry shown below (8 mm gaps between segment edges)
10. Based on the LUVOIR and HabEx reports, we assume the primary molecular targets are H_2O, O_2, and CO_2, while O_3 and CH_4 are highly desirable.
11. UV and IR are used only for follow-on characterization, with known location of the planetary target to relax coronagraphic FoV (i.e. dark-hole area) requirements.
12. We assume an observing scenario similar to that of the Roman Coronagraph

Operating Assumptions: Fiducial Stars

- Purpose: To formulate provisional requirements, we select fiducial targets to drive exposure time calculations & error budgeting
- Approach
  - Include F, G, and K spectral types
  - Fiducials stars should drive coronagraph performance for ~100 effective HZs: minimal zodi, small HZ separation
- Selection strategy
  - Start with the HWO ExEP Precursor Science Stars list: https://exoplanetarchive.ipac.caltech.edu/cgi-bin/TblView/nph-tblView?app=ExoTbls&config=DI_STARS_EXEP
  - Consider only Tiers A and B stars (99 total), which have minimal zodiacal interference
  - Pick at least one representative star from each of F, G, and K spectral types with the minimal Earth-equivalent-insolation angular separation (EEIAS)
  - Added a "Solar-twin" star (Datson et al. 2014 *MNRAS*): 18 Scorpii

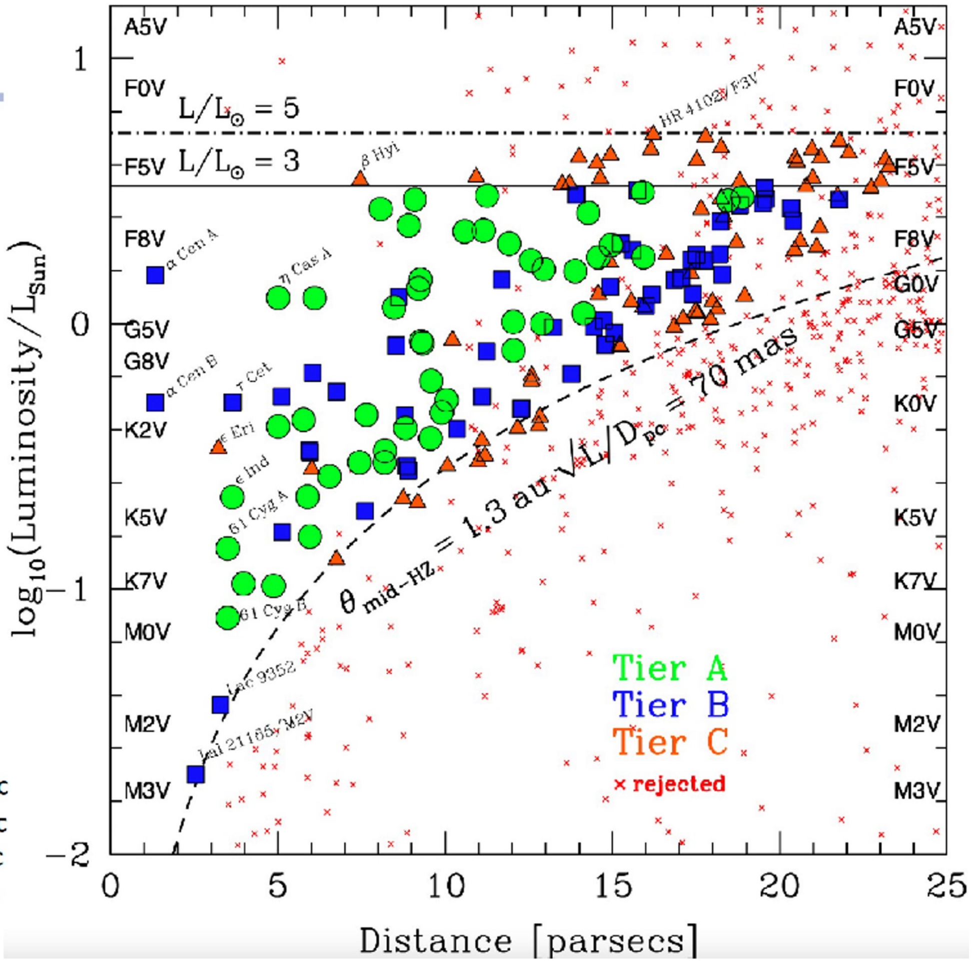
ExEP Target List for HWO

Parameter	Tier A	Tier B	Tier C
IWA constraint	83 mas	72 mas	65 mas
Exoplanet brightness limit (Rc)	30.5 mag	31.0 mag	31.0 mag
Exoplanet-star Brightness ratio limit	4e-11	4e-11	2.5e-11
Disk criterion	No known dust disks of any kind	No disk, or KB disks OK if Ldisk/L* <= 10^{-4}	All disks OK, even if Ldisk/L* >= 10^{-4} or detected HZ warm dust disk
Treatment of binaries	Single or binary companion > 10" sep	Single or binary companion > 5" sep	Single or binary companion > 3" sep
Number of Stars	47	51	66

Sample	F	G	K	M
Tier A	14	15	17	1
Tier B	15	23	11	2
Tier C	37	17	12	0
Total (A+B+C)	66	55	40	3

Approx. magnitude & distance limits:

F*s: V < 6.0, d < 23.3 pc
G*s: V < 6.4, d < 20.5 pc
K*s: V < 7.0, d < 12.8 pc
M*s: V < 7.5, d < 4.0 pc



Fiducial Stars

ID	Dist [pc]	M_V	Spec Type	T_{eff} [K]	Met [dex]	Dia. [mas]	Earth-Equivalent-Insolation Ang Sep [mas]	Earth-Twin Flux Ratio	Earth-Twin RV Ampl [cm/s]
HIP 32439 HD 46588	18.2	5.4	F8V	6204	-0.1	.598	74.2	6.3E-11	7.1
HIP 77052 HD 140538 A (Psi Serpentis A	14.8	5.9	G5V	5682	0.05	.592	61.7	1.4E-10	9.7
HIP 79672 HD 146233 (18 Scorpii)	14.1	5.5	G2Va	5785	0.03	.685	74.0	1.1E-10	8.7
HIP 26779 HD 37394 (V538 Aurigae)	12.3	6.2	K1V	5226	0.1	.639	56.3	2.4E-10	11.5
HIP 113283 HD 216803 (Fomalhaut B)	7.6	6.4	K4Ve	4601	0.04	0.853	58.3	5.9E-10	15.9

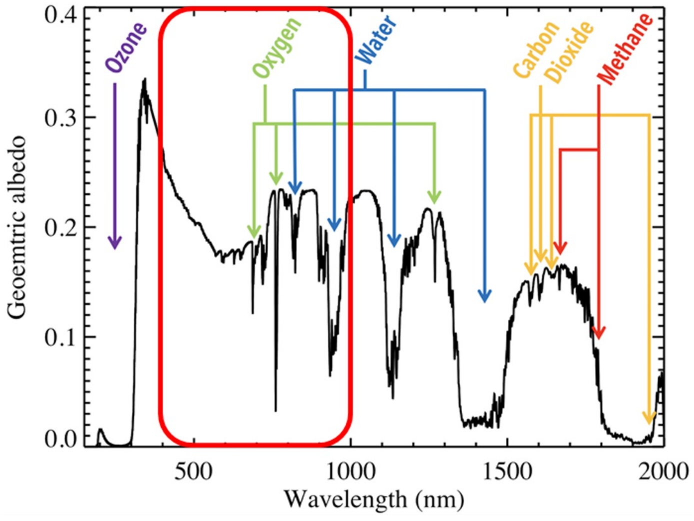
In this report, the impact of a given gap is assessed by the associated performance parameters’ impact on required integration time (to achieve required SNR) for these five fiducial stars

4A. Provisional Key Driving Requirements:

Starlight-Suppression Key Performance Parameters (KPPs)

Visible

- **Spectral coverage and resolution** [LUVOIR Final Report]
    - H_2O: **0.94 µm**, **20% BW**, **SNR=8.5** photometry
    - O_2: **0.76 µm**, **20% BW**, **SNR=10**, **R = 140** spectroscopy
- **Core throughput 0.3**
- **IWA 60 mas**
- **Raw Contrast 3 x 10^{-10}**

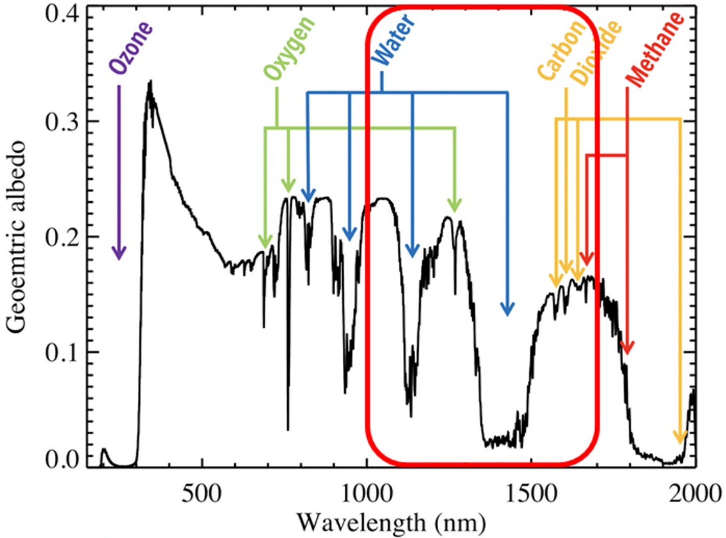


C. Stark

Future HWO Trade: UV, vis, IR spectral coverage, science return, technology risks

- ○ Exozodi brightness (at 3 zodis) is equivalent to 6 x 10^{-10} ~ 1 x 10^{-9} flux-ratio levels for our fiducial stars, buffering the impact of raw contrast
- ○ However, stellar speckles are coherent. They can amplify the effects of WFE instability via the cross term, whereas zodiacal light is incoherent. Our error-budget analyses indicate that **raw contrast has a significant effect (on required integration time) only when it is ≳ 3 x 10^{-10}**

Infrared



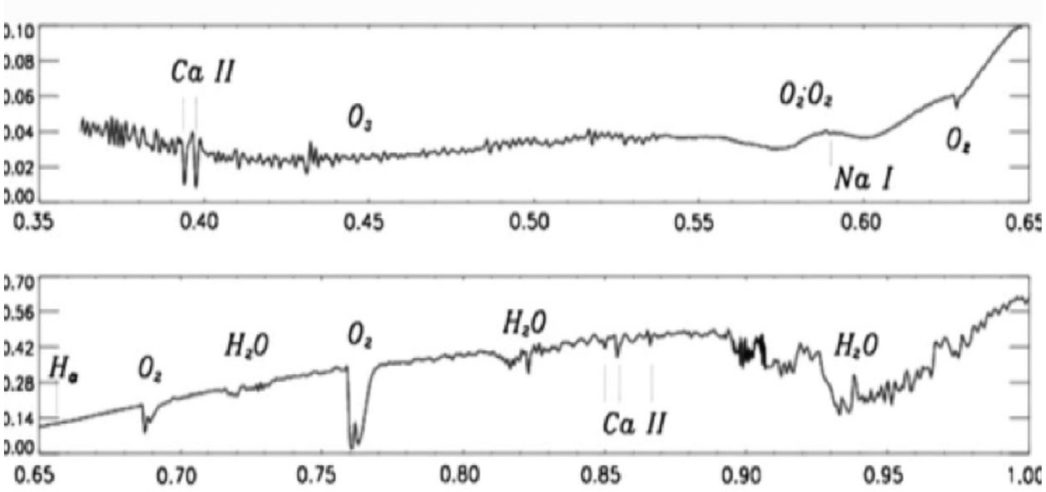
- **Spectral coverage and resolutions**

[Damiano & Hu 2022]

  - H_2O: 1.1 µm, 20% BW, SNR=20, R = 40 spectroscopy
  - CO_2: **1.6 µm, 20% BW, SNR = 20, R = 40** spectroscopy

- **Core throughput 0.3**
- **IWA: 60 mas**
- **Raw contrast: $\sim 3 \times 10^{-10}$**

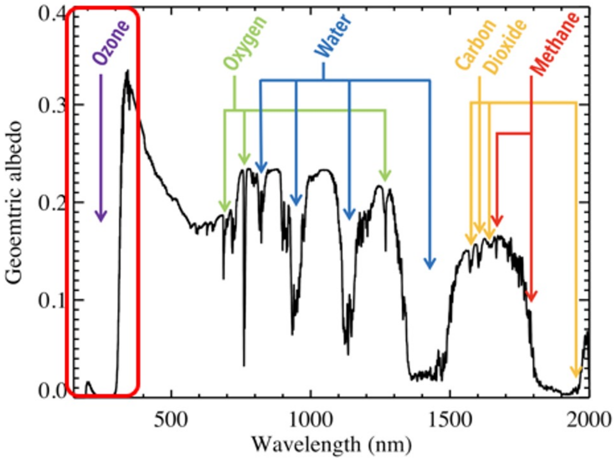
Future HWO Trade: NIR yield vs. IWA vs technology options



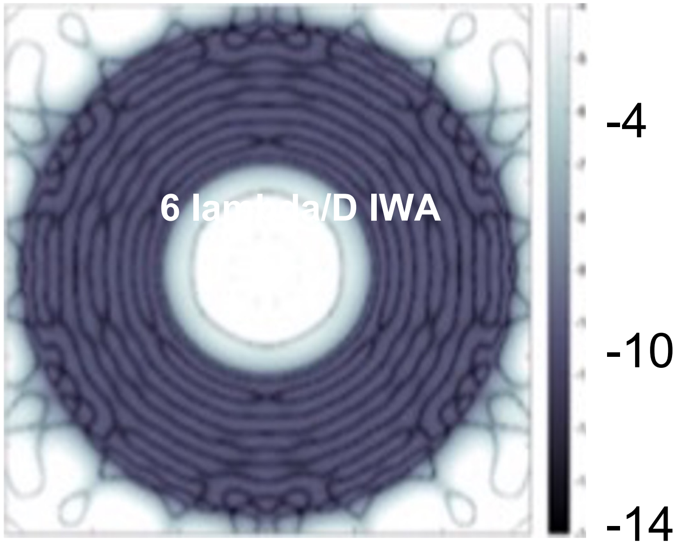
- IR features key spectroscopic diagnostics essential to contextualize Vis spectrum.
- Max resolution in IR is very dependent on available detector technology
- **60 mas IWA = 1.1 λ/D** for λ=1.6 µm & D=6 m. **Major NIR challenge**

Ultraviolet

- **Spectral coverage and resolutions**
  - O$_3$: **250 - 300 nm**, **20% BW**, **SNR = 20**, **R = 7** photometry
- **Core throughput 0.2**
- **IWA 60 mas**
- **Raw contrast** ~ 1 × 10^{-10}



UV coronagraph can tolerate larger IWA (in λ/D) but needs higher throughput than Vis coronagraph.



4B. Provisional Key Driving Requirements:

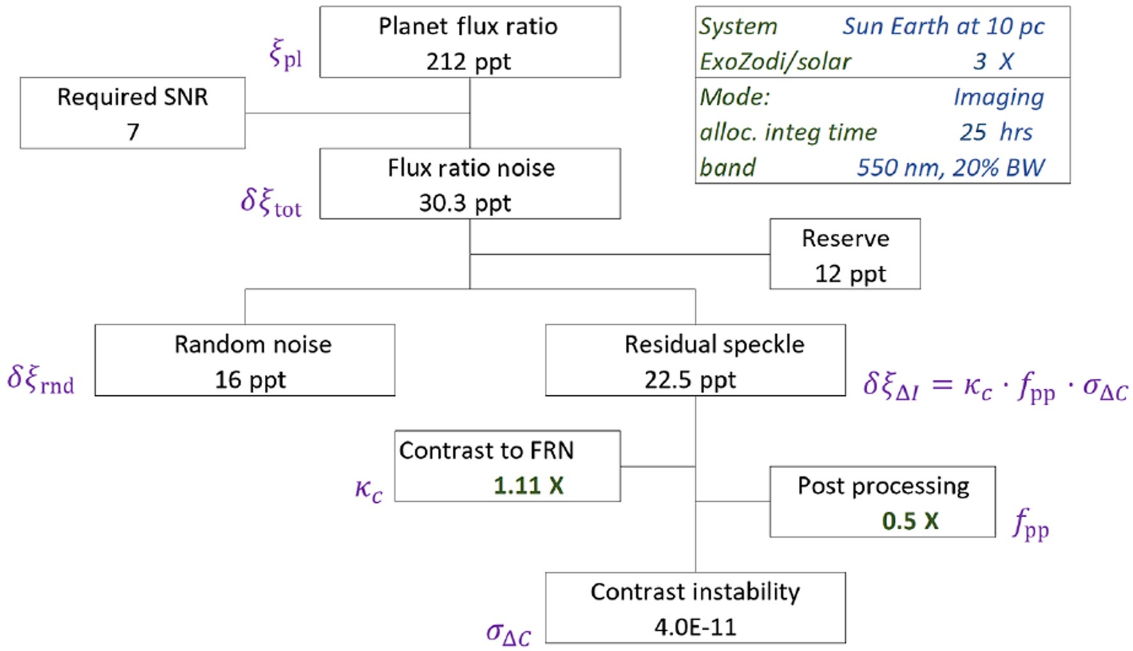
Wavefront-Stability Environment

Flux-Ratio Error Budget

- The planet-star flux ratio, the target SNR, and the integration time required to reach the SNR drive the error budget
- Note that required integration time becomes infinity when the residual-noise-equivalent photon rate ($r_{\Delta I}$) is equal to the planet rate divided by the target SNR
  - $t = \infty$ if $r_{\Delta I} = r_{pl}/\text{SNR}$
- Hence, **there is a break point in $r_{\Delta I}$, over which planet detection is not possible**, regardless of integration time

Notional Example of an Error Budget for Earth-Twin Detection

Nemati et al. 2020 *JATIS*



System	*Sun Earth at 10 pc*
ExoZodi/solar	*3 X*
Mode:	*Imaging*
alloc. integ time	*25 hrs*
band	*550 nm, 20% BW*

ξ_{pl} Planet flux ratio 212 ppt

Required SNR 7

$\delta\xi_{\text{tot}}$ Flux ratio noise 30.3 ppt

Reserve 12 ppt

$\delta\xi_{\text{rnd}}$ Random noise 16 ppt

Residual speckle 22.5 ppt $\delta\xi_{\Delta I} = \kappa_c \cdot f_{\text{pp}} \cdot \sigma_{\Delta C}$

κ_c Contrast to FRN 1.11 X

Post processing 0.5 X f_{pp}

$\sigma_{\Delta C}$ Contrast instability 4.0E-11

Integration-Time Equation

$$t = \frac{\text{SNR}^2 r_n}{r_{\text{pl}}^2 - \text{SNR}^2 r_{\Delta I}^2}$$

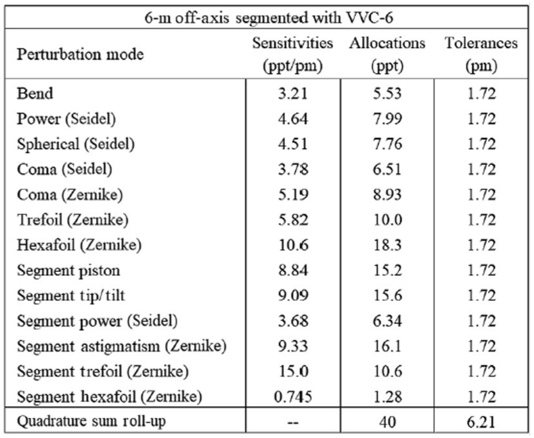
Glossary

- ppt: part per trillion
- r_n: random-noise equiv. photon rate
- r_{pl}: planet photon rate
- $r_{\Delta I}$: residual noise equiv. photon rate (after post-processing)

Requirements on the WFE Environment

Future HWO Trade: observatory stability vs. coronagraph robustness

- The crucial parameter $r_{\Delta I}$ (see previous slide) is a product of **WFE instability at the coronagraph's focal-plane mask (FPM)**, the **contrast sensitivity** to the WFE, and **postprocessing factor** (in mitigation of effective WFE)
- Our error-budget study for detection of the 5 fiducial stars indicate the following key-driving requirements
    - Assumptions
        - Contrast sensitivities w.r.t. "Low" (Z1 - Z11) and "Mid" (4 - 16 cyc/D) spatial-frequency modes: 3 - 10 ppt/pm
        - Raw contrast: ~ 3×10^{-10}
    - **Allowable WFE** in Low & Mid spatial-frequency bins: **2 pm RMS (at the FPM, after observatory stabilization and coronagrah AO, assuming no post-processing gain)**



6-m off-axis segmented with VVC-6			
Perturbation mode	Sensitivities (ppt/pm)	Allocations (ppt)	Tolerances (pm)
Bend	3.21	5.53	1.72
Power (Seidel)	4.64	7.99	1.72
Spherical (Seidel)	4.51	7.76	1.72
Coma (Seidel)	3.78	6.51	1.72
Coma (Zernike)	5.19	8.93	1.72
Trefoil (Zernike)	5.82	10.0	1.72
Hexafoil (Zernike)	10.6	18.3	1.72
Segment piston	8.84	15.2	1.72
Segment tip/tilt	9.09	15.6	1.72
Segment power (Seidel)	3.68	6.34	1.72
Segment astigmatism (Zernike)	9.33	16.1	1.72
Segment trefoil (Zernike)	15.0	10.6	1.72
Segment hexafoil (Zernike)	0.745	1.28	1.72
Quadrature sum roll-up	--	40	6.21

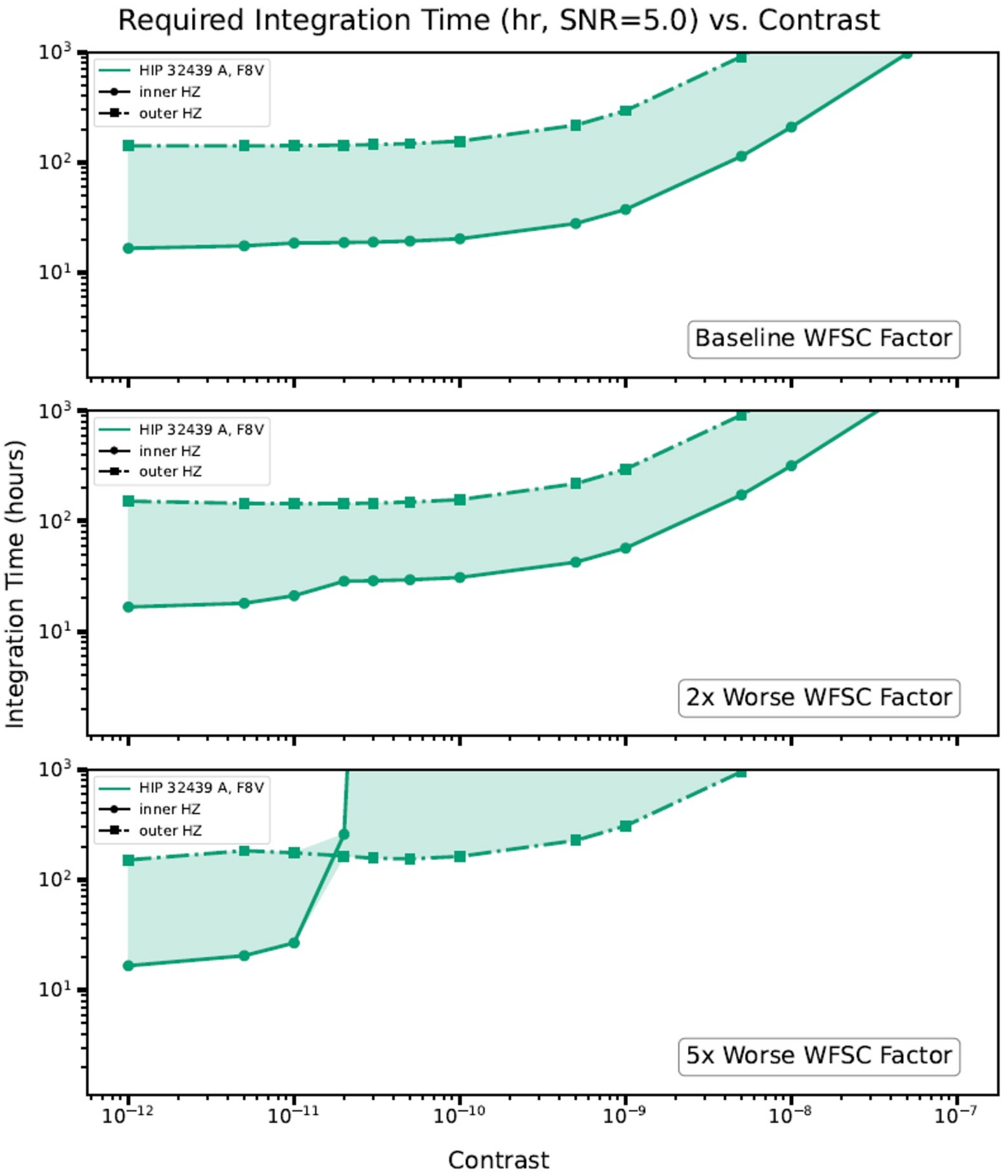
Fig. 26
Nemati et al. 2020 JATIS

A critical requirement for HWO coronagraphy!

Comments re. WFE Environment Requirements

- The 2 pm RMS provisional requirement is in agreement with that in Nemati et al. 2020 (6 pm RMS) considering the following:
  - Nemati et al. assumes a post-processing gain = 2, whereas we do not assume any post-processing enhancement (i.e. gain=1)
  - Our F fiducial star drives contrast-stability requirements, whereas Nemati et al. analyzed a Sun-Earth-twin scenario.
- The following factors can *relax requirements on the observatory WFE stability*:
  - AO in the coronagraph instrument
  - Improvements in contrast sensitivities to WFEs (aka coronagraph robustness)
  - Post-processing advancements (the above-stated provisional requirement assumes no post-processing gain)

Comments re. WFE Environment Requirements



- Degradation w.r.t. static raw contrast is gradual with a knee at ~ 3 x 10^{-10}
- Degrading WFS&C factor by 2x has only slight impact
- Degrading WFS&C factor by 5x poses a clear breakpoint, where required integration time blows up (for the inner HZ). This corresponds to 2 pm at FPM. Note: *t* does not blow up for the outer HZ because of the smaller assumed HIGH spatial frequency WFEs from the telescope (see p. 37) compared to LOW & MID.
- See the same behavior for all (FGK) fiducial stars.

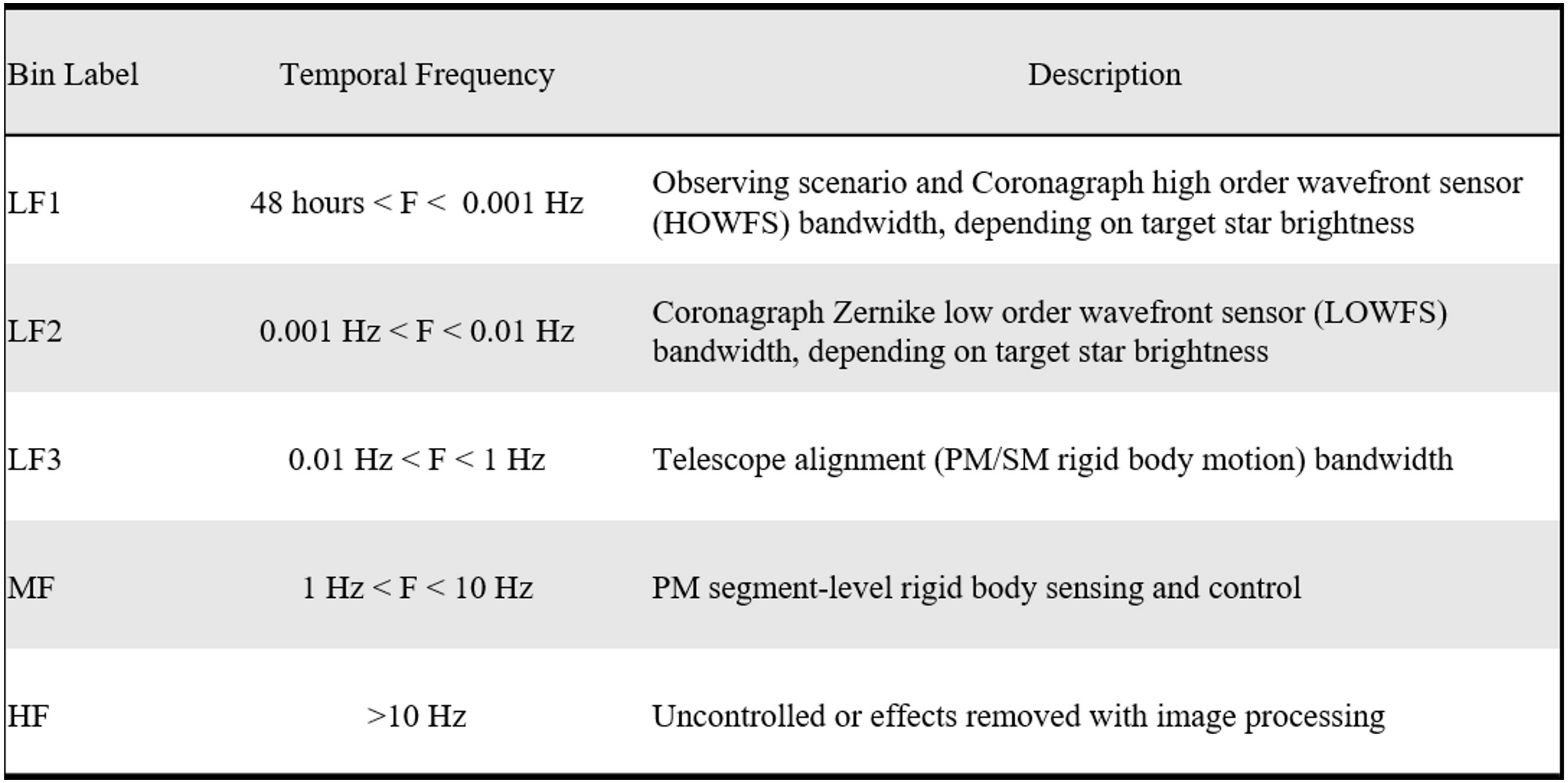
4C. Provisional Requirements:

Coronagraph AO

Provisional Requirements: AO

Adopted USORT's spatio-temporal binning approach based on Coyle et al. (2019, SPIE), with the addition of a static "temporal-frequency" bin

Temporal Frequency Bins

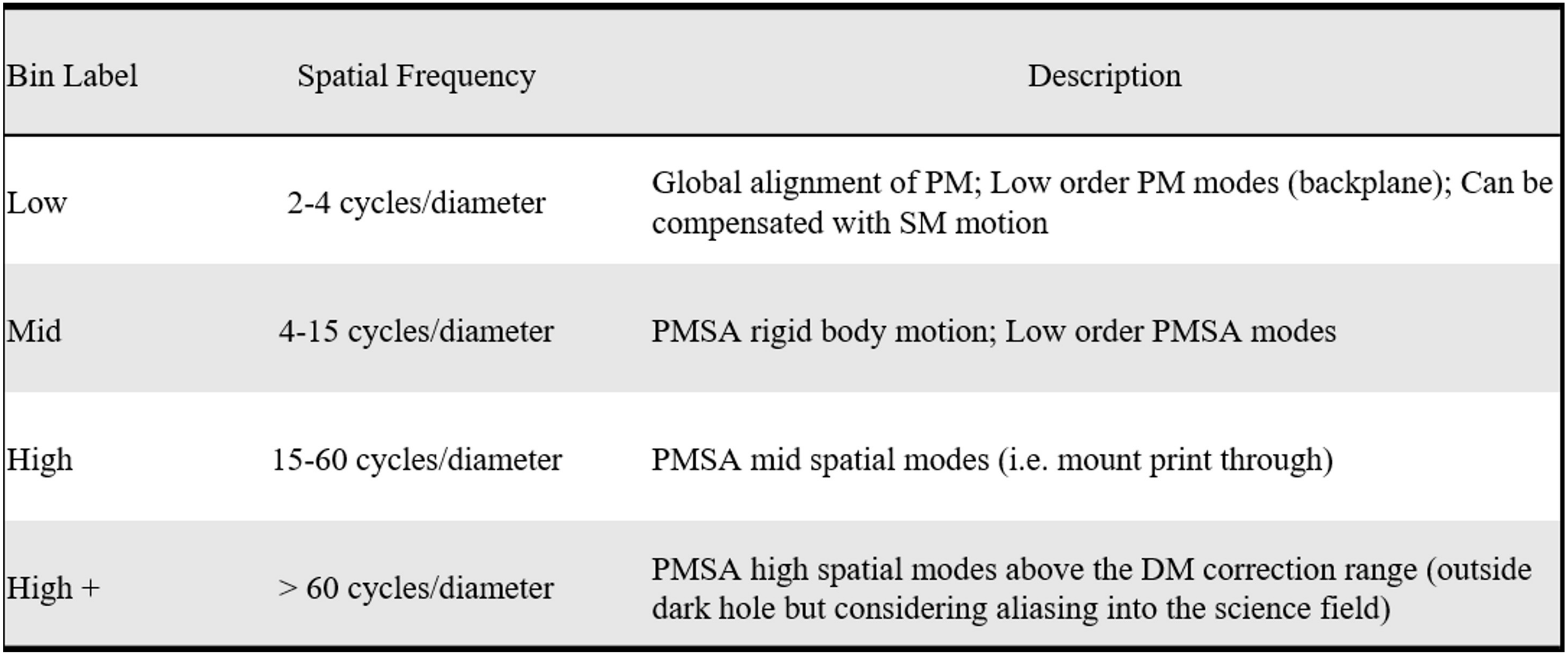


Bin Label	Temporal Frequency	Description
LF1	48 hours < F < 0.001 Hz	Observing scenario and Coronagraph high order wavefront sensor (HOWFS) bandwidth, depending on target star brightness
LF2	0.001 Hz < F < 0.01 Hz	Coronagraph Zernike low order wavefront sensor (LOWFS) bandwidth, depending on target star brightness
LF3	0.01 Hz < F < 1 Hz	Telescope alignment (PM/SM rigid body motion) bandwidth
MF	1 Hz < F < 10 Hz	PM segment-level rigid body sensing and control
HF	>10 Hz	Uncontrolled or effects removed with image processing

Provisional Requirements: AO

Adopted USORT’s spatio-temporal binning approach based on Coyle et al. (2019, SPIE), with the addition of a static “temporal-frequency” bin

Spatial Frequency Bins



Bin Label	Spatial Frequency	Description
Low	2-4 cycles/diameter	Global alignment of PM; Low order PM modes (backplane); Can be compensated with SM motion
Mid	4-15 cycles/diameter	PMSA rigid body motion; Low order PMSA modes
High	15-60 cycles/diameter	PMSA mid spatial modes (i.e. mount print through)
High +	> 60 cycles/diameter	PMSA high spatial modes above the DM correction range (outside dark hole but considering aliasing into the science field)

Provisional Requirements: AO

Assumed open-loop RMS wavefront changes between target and reference star observations (based on values from USORT, B. Sitarski)

Spatial frequency

Temporal frequency

WFE	[pm]			
	LOW	MID	HIGH	HIGH+
STATIC	20000	15000.00	5000.00	5000.00
LF1	87.30	26.20	40.00	0.00
LF2	87.30	26.20	40.00	0.00
LF3	87.30	5.20	3.50	0.00
MF	17.50	5.20	3.50	0.00
HF	17.50	5.20	3.50	0.00

Required drift-mitigation factors (assuming AO subsystem using DMs to compensate WFE changes)

Spatial frequency

Temporal frequency

	LOW	MID	HIGH	HIGH+
STATIC	0.0E+00	0.0E+00	0.0E+00	0.0E+00
LF1	**1.0E-02**	**1.8E-02**	1.0E+00	1.0E+00
LF2	**1.0E-02**	**1.9E-02**	1.0E+00	1.0E+00
LF3	**9.9E-03**	**8.4E-02**	1.0E+00	1.0E+00
MF	**4.7E-02**	**8.7E-02**	1.0E+00	1.0E+00
HF	**4.8E-02**	**9.0E-02**	1.0E+00	1.0E+00

These values are representative results of an **EBS Monte Carlo run** that yield reasonable exposure times (~ 1 - 5 days for planet detection)

Provisional Requirements: AO

Final, post-AO wavefront "at the FPM"

Spatial frequency

Temporal frequency

POST-AO WFE				
	LOW	MID	HIGH	HIGH+
STATIC	0.0E+00	0.0E+00	0.0E+00	0.0E+00
LF1	8.8E-01	4.7E-01	4.0E+01	0.0E+00
LF2	8.9E-01	5.0E-01	4.0E+01	0.0E+00
LF3	8.7E-01	4.3E-01	1.0E+00	0.0E+00
MF	8.2E-01	4.5E-01	1.0E+00	0.0E+00
HF	8.4E-01	4.7E-01	1.0E+00	0.0E+00
SUMSQ	3.7E+00	1.1E+00	3.2E+03	0.0E+00

Final Contrast floor (coronagraph sensitivities based on Nemati et al. 2020 *JATIS*)

Separation

Delta C			
[ARCSEC]	LOW	MID	
4.4E-02	1.2E+01	1.0E+01	**1.6E+01**
6.1E-02	1.2E+01	5.2E+00	**1.3E+01**
7.9E-02	0.0E+00	3.1E+00	**3.1E+00**
9.6E-02	0.0E+00	3.1E+00	**3.1E+00**
1.1E-01	0.0E+00	1.6E+00	**1.6E+00**
1.3E-01	0.0E+00	1.6E+00	**1.6E+00**

These values are representative results of an **EBS Monte Carlo run** that yield reasonable exposure times.

Provisional Requirements: DM

- See the DMTR Final Report for a comprehensive set of DM performance goals
- Actuator count: ≥ 96 actuators across the pupil diameter
- Rationale
  - Nyquist frequency (48 λ/D, λ = 0.6 µm, D = 6 m) corresponds to 1" in the image plane, this supports imaging outer HZ of nearby stars and outer giant planets. It is also between LUVOIR and HabEx baseline values
    - LUVOIR: 128 actuators/D, D = 8 or 15 m
    - HabEx: 64 actuators/D, D = 4 m
    - 96 actuator
  - 96 actuators/D is approximately the limit of feasibility using incumbent manufacturing methodologies for PMN-electrostrictive and MEMS-electrostatic DMs

Future HWO Trade: Science return, DM actuator format & stroke, wavefront control architecture, telescope architecture

Provisional Requirements: DM

Stroke

Frequencies to constrain electronics: e.g. 20-bit dithering on 16-bit electronics means we can't drive fast.

Static	1 actuator (High SF)	10 actuators (Mid SF)	Global modes (Low SF)
instrument driven	250 nm	10 nm	10 nm
Telescope driven	10 nm	30 nm	10 nm

Time Varying	1 actuator (High SF)	10 actuators (Mid SF)	Global modes (Low SF)
instrument driven	25 nm	1 nm	1 nm
Telescope driven	100 pm	100 pm	300 pm

*Stroke values do not assume a DM apodization command or gravity offloading during ground testing

Stability

Frequency	1 actuator (High SF)	10 actuators (Mid SF)	Global modes (Low SF)
0 Hz ("stability")	<1 nm	<stroke/10*	<stroke/10*
50 Hz	0.5 pm	5 pm	50 pm
1 Hz	0.5 pm	5 pm	50 pm
0.1 Hz	1 pm	10 pm	100 pm
0.001 Hz	1 pm	10 pm	100 pm

*Soft requirement, can be larger but requires large move at "power on"

DM settling time of ~1 month at "power on", ~0.5 days during science operations in follow up mode.

Required stroke (after flattening), including budget for telescope WFE + drift, coronagraph apodization, EFC, & AO/LOWFS: > 500 nm PV (possible relaxation pending woofer-tweeter architecture, coronagraph design, and telescope stability)

4D. Provisional Requirements:

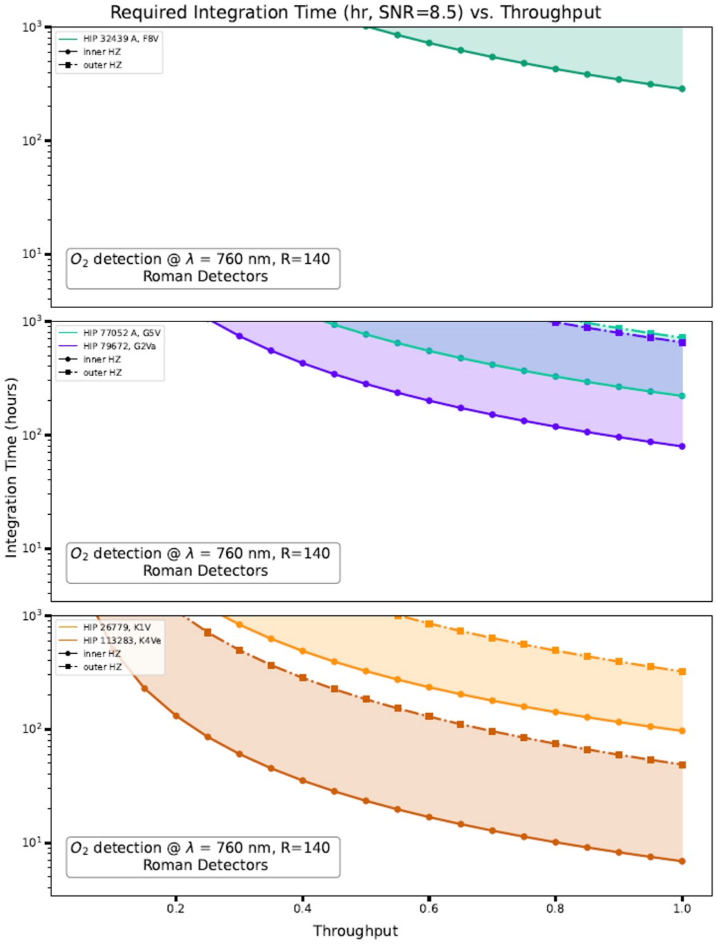
Detectors

Provisional Requirements: Detectors

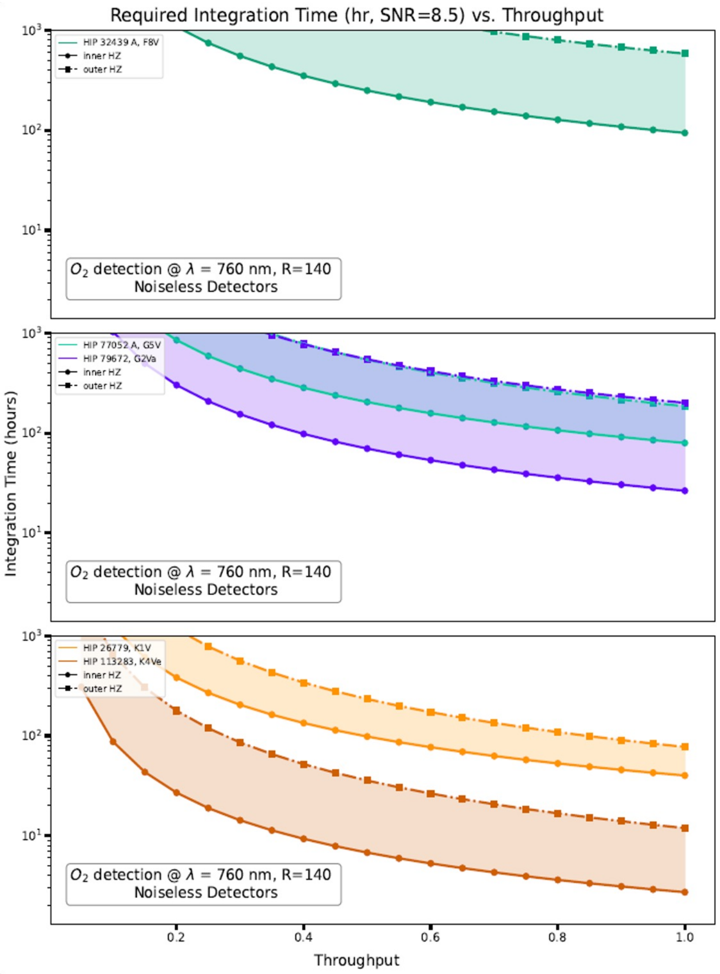
- Spectroscopy drives detector noise requirement
- Exo-zodiacal light is frequently the dominant random-noise source. Therefore, we require detector noise << exo-zodi noise
- For R = 140 in the vis, 3 zodi exo-zodiacal brightness level, exo-zodiacal count rate is on the order of 0.01 count/s ⇒ exo-zodiacal shot noise ~ 0.1 $\mathrm{Hz}^{-1/2}$
- We set a **requirement of < 0.01 $\mathrm{Hz}^{-1/2}$ detector noise** (5x below exo-zodi)

*Computation of exo-zodi wavelength dependence is currently under investigation

Provisional Requirements: Detectors (cont’d)



Assuming Roman-CGI EMCCD Noise Levels



Noiseless Detector

Detector noise requirement is a strong function of throughput. High throughput is required even with a noiseless detector

4E. Provisional Requirements:

Post-processing

Provisional Requirements: Post Processing

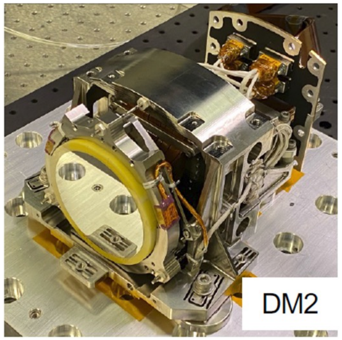
- We define post-processing as a numerical procedure that enhances the effective contrast stability (i.e. effectively reduces $\boldsymbol{\sigma}_{\Delta C}$ in Nemati et al. 2020 JATIS). This is a generalization of the Roman Coronagraph and Nemati et al. (2020) definition.
- Roman CGI simulations using a PCA post-processing algorithm estimated gain ~ 2 for CGI. Per Roman Coronagraph's definition, the 2x gain is the factor obtainable beyond single-roll classical RDI.
- We do not set a specific provisional requirement for post-processing gain
- The above-stated provisional AO, contrast sensitivity, and WFE stability requirements were derived assuming no post-processing gain (i.e. gain = 1)
- **Advancing post-processing methodologies to relax the formidable requirements on WFE stability is very important**

5. State of the Art (SotA) and Technology Gaps

Deformable Mirrors

- ExEP completed a DM Technology Survey in 2021 and identified 3 top manufacturers, each using a fundamentally different technology: Northrop Grumman’s AOA Xinetics (AOX), Boston Micromachines Corp. (BMC), ALPAO
- **See the DMTR Final Report for the DM technology maturation roadmap**
- We briefly summarize distinguishing characteristics of each technology

Deformable Mirrors: Electrostrictive Actuation



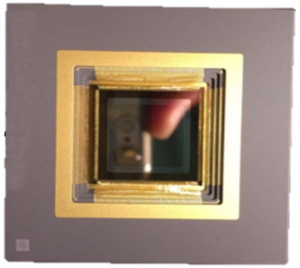
CGI DM, v. Bailey

- Main vendor: AOX
- Actuation mechanism: electrostriction using PMN

(lead magnesium niobate) actuators

- Pros
- Delivered flight DMs for Roman Coronagraph Instrument (CGI)
- The only DMs that currently enable raw contrast substantially better than 10^{-9} contrast
- Cons
- PMN has intrinsic settling time of ~ 1 week to reach 1 pm/hr stability
- Connectorization methods thus far involve imposing stress on the PMN, which in turn can significantly change the mirror shape.
- Ultimate array-size limit with established manufacturing processes: 96x96

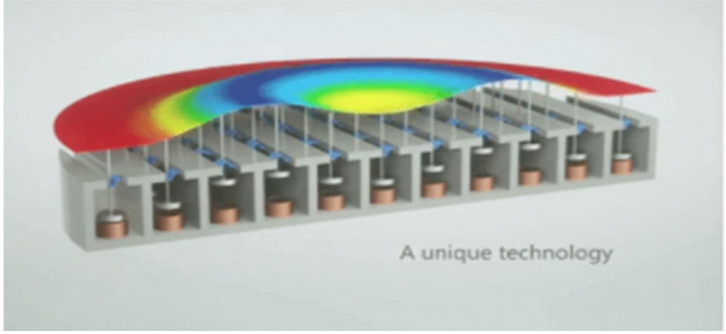
Deformable Mirrors: Electrostatic Actuation



- Main vendor: Boston Micromachines Corp. (BMC)
- Actuation mechanism: electrostatic force using MEMS actuators
- Pros
    - No observable drift observed thus far at ~ 10^{-9} raw contrast level
    - Wire-bonded connectorization avoid stress on the mirror surface
- Cons
    - Surface print-through pattern, with repeating fine structure at every actuator, produce harmonic satellite speckles leaking into the coronagraphic dark zone. Currently limiting contrast to ~ $1x10^{-9}$ in the High Contrast Imaging Testbed
- Ultimate array-size limit with established manufacturing processes: ~ 96x96

Deformable Mirrors: Electromagnetic Actuation

- Main vendor: ALPAO (France)
- Actuation mechanism: electromagnetic force using voice-coil-like structure
- Pros
  - High achievable actuator count
- Cons
  - Large actuator pitch
  - Heat dissipation at each actuator, which can cause mirror deformations
  - Picometer stability/resolution not demonstrated



DM State-of-the-Art Performance Summary

PARAMETER	HWO PERFORMANCE GOAL	AOX	BMC	ALPAO
1. Actuator count	96 x 96	64 x 64 (3 devices delivered to JPL, one placed into HCIT)	64 x 64 For GPI, ref: PNAS | September 2, 2014 | vol. 111 | no. 35 | 12661–12666	64 x 64
2. Actuator Stability and Drift	≤ 5 pm/hr rms	~5 pm/hr rms	~1 pm/hr rms	6 nm/hr rms
3. Actuator Resolution	≤ 2 pm	~ 8 pm (100 V/16 bit)	0.65 pm (125 V/20 bit)	140 pm
4. Actuator Stroke	≥ 500 nm PV	~ 200 nm	1500 nm	10000 nm
5. Actuator Pitch	≤ 1 mm	~1 mm	0.4 mm, 2k DM	1.5 mm
6. Residual WFE	≤ 1 nm rms	~3 nm rms	~4 nm rms (print through)	4 nm rms
9. Demonstrated Contrast Ratio	$\leq 1 \times 10^{-10}$ 2 DMs, 20%BW, unobscured segmented pupil	3.82×10^{-10} 2DM2, 10%, 550nm, Unobscured ExEP Milestone	6.12×10^{-9} 08/11/2023, two 2k DMs, Pupil Unobscured, Full image, 10% BW, Center Waveoength 550nm Pressure100Torr, Test bed DST1	No data

Credit: DMTR Final Report

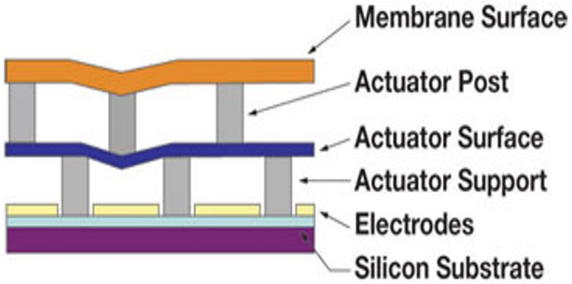
Deformable Mirrors: General Conclusions

- **See the Deformable Mirror Technology Roadmap (DMTR) for a comprehensive report**
- Overall Status:
  - No technology meets all requirements
  - Two technologies are clearly the most mature: PMN/electrostrictive and MEMS/electrostatic
  - Array Size Limit: Using current fabrication technologies for either approach, exceeding ~ 96 x 96 array size will be difficult
- **Major Technology Gaps**:
  - Both technologies: **production yield** of DMs with all actuators meeting requirements
  - Current **test facilities** are not adequate to verify milestone demonstrations (e.g. pm stability at short timescales) of DMs, esp. as we develop them to full 96x96 format
  - Compact drive electronics with path to flight

Deformable Mirrors: General Conclusions (cont'd)

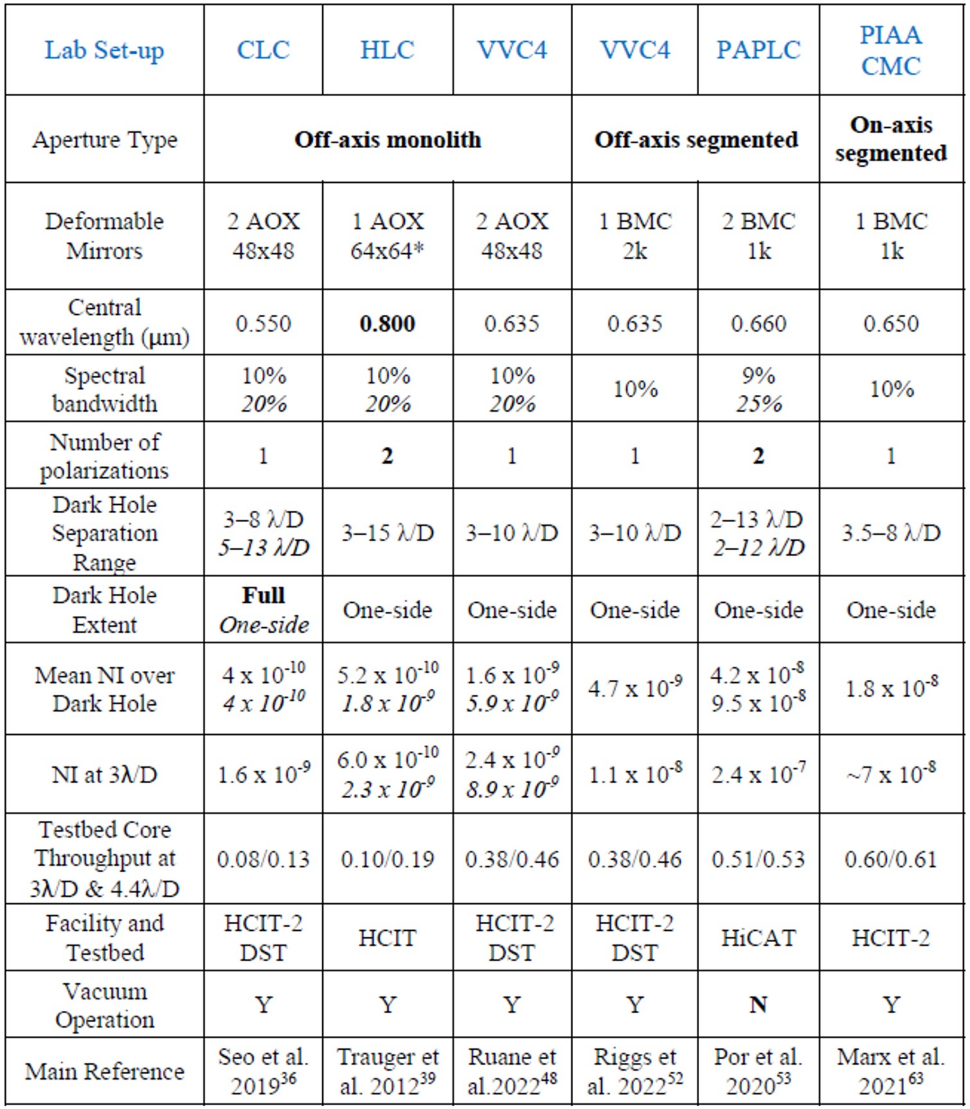
- **Major Technology Gaps**:
  - PMN Technology,
    - DM **connectorization** is a technology gap deserving major attention; attaching ~ 10^4 pins to the back of a mirror while maintaining picometer surface stability is really hard!
    - PMN has intrinsic **drift** that settles over time. The can become a high impact gap if this prevents achieving adequate contrast in time frames compatible with HWO's observing scenario.
  - MEMS Technology
    - **Print-through surface error** diffract light into the image dark zone, currently limiting contrast to 10^{-9} level.

A 48x48 PMN DM, with (non-flight) pins on the back side connecting to flex-print cables



Starlight-Suppression Optics: Lab Demonstrations

CLC: classic Lyot coronagraph
HLC: hybrid Lyot coronagraph
VVC4: vector vortex charge 4 coronagraph
PAPLC: phase-apodized pupil Lyot coronagraph
PIAA-CMC: phase-induced amplitude apodization complex mask coronagraph
NI: normalized intensity (similar to raw contrast, ref. Nemati et al. 2020)

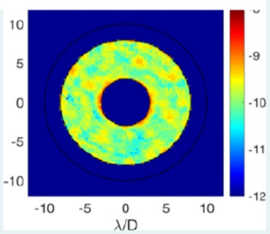
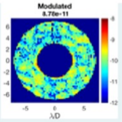
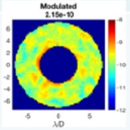
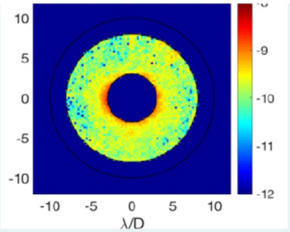
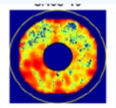
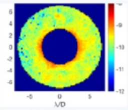
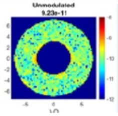


Lab Set-up	CLC	HLC	VVC4	VVC4	PAPLC	PIAA CMC
Aperture Type	**Off-axis monolith**			**Off-axis segmented**		**On-axis segmented**
Deformable Mirrors	2 AOX 48x48	1 AOX 64x64*	2 AOX 48x48	1 BMC 2k	2 BMC 1k	1 BMC 1k
Central wavelength (µm)	0.550	**0.800**	0.635	0.635	0.660	0.650
Spectral bandwidth	10% *20%*	10% *20%*	10% *20%*	10%	9% *25%*	10%
Number of polarizations	1	**2**	1	1	**2**	1
Dark Hole Separation Range	3–8 λ/D *5–13 λ/D*	3–15 λ/D	3–10 λ/D	3–10 λ/D	2–13 λ/D *2–12 λ/D*	3.5–8 λ/D
Dark Hole Extent	**Full** *One-side*	One-side	One-side	One-side	One-side	One-side
Mean NI over Dark Hole	4 x 10^{-10} *4 x 10^{-10}*	5.2 x 10^{-10} *1.8 x 10^{-9}*	1.6 x 10^{-9} *5.9 x 10^{-9}*	4.7 x 10^{-9}	4.2 x 10^{-8} 9.5 x 10^{-8}	1.8 x 10^{-8}
NI at 3λ/D	1.6 x 10^{-9}	6.0 x 10^{-10} *2.3 x 10^{-9}*	2.4 x 10^{-9} *8.9 x 10^{-9}*	1.1 x 10^{-8}	2.4 x 10^{-7}	~7 x 10^{-8}
Testbed Core Throughput at 3λ/D & 4.4λ/D	0.08/0.13	0.10/0.19	0.38/0.46	0.38/0.46	0.51/0.53	0.60/0.61
Facility and Testbed	HCIT-2 DST	HCIT	HCIT-2 DST	HCIT-2 DST	HiCAT	HCIT-2
Vacuum Operation	Y	Y	Y	Y	**N**	Y
Main Reference	Seo et al. 2019[36]	Trauger et al. 2012[39]	Ruane et al.2022[48]	Riggs et al. 2022[52]	Por et al. 2020[53]	Marx et al. 2021[63]

Credit: Mennesson et al. 2024, submitted to JATIS [https://arxiv.org/abs/2404.18036]

Starlight-Suppression Optics: Lab Demonstrations

- JPL's High Contrast Imaging Testbed (HCIT) facility's Decadal Survey Testbed (DST) currently has a baseline contrast of 4x10^{-10} mean contrast, 3 - 8 λ/D full annular dark zone, 10% bandwidth
- Analysis by Seo et al. (2019) identified the following terms of residual light

Contrast, 3.82E-10 Total		Measured	Model/Indirect Expectation	Morphology	
Modulated 1.81E-10 	**LSB effect of DM actuators**	8.78E-11	~1E-10	Specklish	
	Chromatic Control Residual	9.32E-11	~4E-11	Specklish	
Unmodulated 2.01E-10 	**Occulter Ghost** (+Chromatic Residual)	1.01E-10	~1E-10	Patterned March with wavelength	
	Testbed LoS Jitter impact	4.19E-11	< 1E-11	Centered	
	Unknown	5.04E-11	N/A	Diffused	

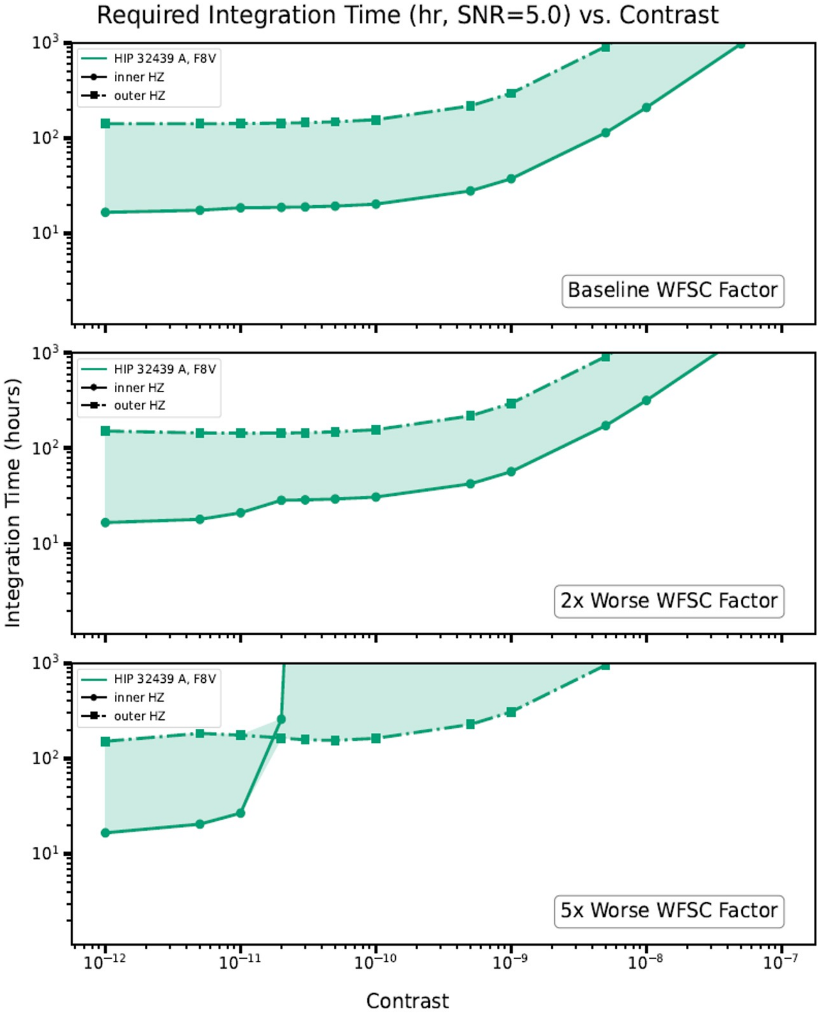
- Recent demonstration of 20-bit electronics and ghost-reflection analysis provide a path to 2x10^{-10}

Starlight-Suppression Optics: Lab Demonstrations

- General Status
    - See Mennesson et al., “Current laboratory performance of starlight suppression systems, and potential pathways to desired Habitable Worlds Observatory exoplanet science capabilities,” 2024 (submitted to *JATIS*) for a comprehensive review
    - No single type of coronagraph has simultaneously achieved all (contrast, throughput, FoV, IWA, spectral bandwidth, spectral coverage) requirements
    - CLC & HLC lead in contrast, PIAA-CMC in throughput, PAPLC in IWA, while VVC offers a good balance of characteristics
    - Plugging demonstrated combinations of characteristics (raw contrast, core throughput, bandwidth, etc.) into an exposure time calculation for an Earth twin at 12 pc predicts:
        - Detection requires > 10 hr integration time for SNR = 7, Earth-twin @ 12 pc
        - **Spectroscopy requires > 1 month integration time at R=70, λ = 0.75 μm, SNR = 10 (noiseless detector)**

Starlight-Suppression Optics: Lab Demonstrations

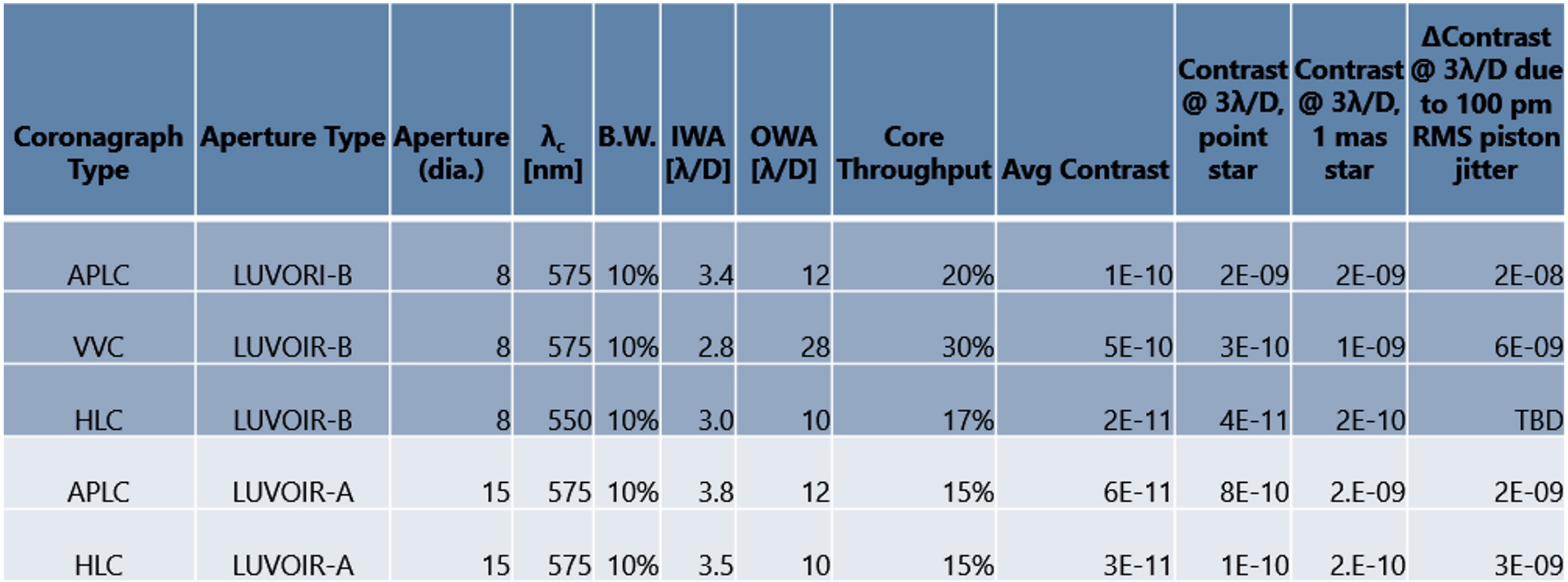
- **Major Performance Gap**
  - Simultaneous achievement of 3×10^{-10} raw contrast and 0.3 core throughput with 20% bandwidth, while maintaining SoTA contrast sensitivity.
    - In general, SotA coronagraphs demonstrate only one of these three KPP at a time



Starlight-Suppression Optics: Lab Demonstrations

- **Major Ground Test Facility Gaps**
    - Existing coronagraphic testbeds have not demonstrated the capability to make the following key types of measurements
        - Raw broadband contrast $< 4 \times 10^{-10}$
        - Contrast sensitivity to WFEs
        - Measurements outside the 0.55 - 0.8 μm range (i.e. lacking near-UV and near-IR testbeds)
        - Measurements with sources simulating natural stars (thermal source with finite angular diameter). Broadband measurements thus far utilize supercontinuum, spatially unresolved sources

Starlight Suppression Optics: Simulated Performance



Coronagraph Type	Aperture Type	Aperture (dia.)	λ_c [nm]	B.W.	IWA [λ/D]	OWA [λ/D]	Core Throughput	Avg Contrast	Contrast @ 3λ/D, point star	Contrast @ 3λ/D, 1 mas star	ΔContrast @ 3λ/D due to 100 pm RMS piston jitter
APLC	LUVORI-B	8	575	10%	3.4	12	20%	1E-10	2E-09	2E-09	2E-08
VVC	LUVOIR-B	8	575	10%	2.8	28	30%	5E-10	3E-10	1E-09	6E-09
HLC	LUVOIR-B	8	550	10%	3.0	10	17%	2E-11	4E-11	2E-10	TBD
APLC	LUVOIR-A	15	575	10%	3.8	12	15%	6E-11	8E-10	2.E-09	2E-09
HLC	LUVOIR-A	15	575	10%	3.5	10	15%	3E-11	1E-10	2.E-10	3E-09

- Full-annulus dark zones
- The table includes only coronagraphs recently analyzed by ExEP Segmented Coronagraph Design & Analysis (SCDA) study program
- The designs used DMs with 64 actuators across the diameter
- Manufacturability of the designs will be assessed (as part of the Coronagraph Technology Roadmap work)
- All 3 coronagraphs are extremely sensitive to shear between telescope’s exit pupil and the coronagraph’s entrance pupil, not shown in this table. The tolerance is ~ 10^{-5} x pupil diameter
- **See the ExEP CDS Final Report for a comprehensive survey**

Starlight Suppression Optics: Simulated Performance

- <u>General Status</u>
  - The table above is indicative of SotA modeled performance for full annular dark zones vis-a-vis segmented pupils. LUVOIR-A is on axis and LUVOIR-B is off-axis with 6.7 m inscribed diameter, a close analog to Astro2020’s HWO description.
  - Coronagraphs with best contrast performance (e.g. HLC, APLC) tend to have relatively poor core throughput

- **<u>Major Technology Gaps</u>**
  - Simultaneous achievement of core throughput ($\gtrsim 0.3$), raw Contrast ($\lesssim$ 1E-10), and low contrast sensitivity to WFEs
  - IWA ($\lesssim$60 mas) at wavelengths longer than ~ 0.6 μm
  - NIR coronagraph designs
  - UV coronagraph designs

Starlight Suppression Modeling, Roman Coronagraph

- **Status**

  Roman CGI HOWFSC model successfully validated multiple times: on testbed during CGI Tech Dev phase; before CGI PDR (for HLC/narrow-FOV); and again with Roman CGI during CGI thermal-vacuum test (TVAC):
  - **Consistent good agreements** on *raw coherent contrast floor, convergence speed, and key sensitivities* (pred err <35% mostly)
  - Validated model **a critical tool** throughout CGI project phases from flight design, fabrication, component issue risk assessment, CGI TVAC HOWFSC execution guidance and PFRs resolutions, etc.
- **Gaps**
  - Incoherent contrast of the as-built systems still significantly higher than in model
  - Validity itself not automatically extends to new coronagraph types (of HWO), while some lessons applicable

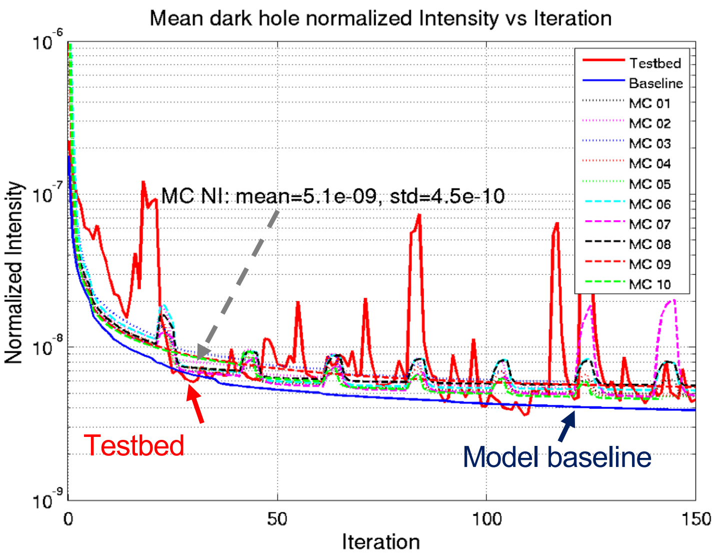
Zhou et al. Proc. SPIE, 10407(2017); Proc. SPIE, 11443(2020);
Zhou et al. JATIS (2025, in preparation)

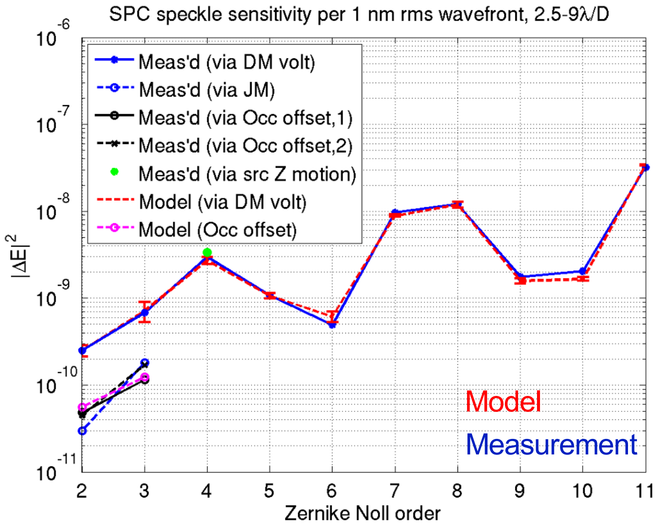
Starlight Suppression Modeling, Roman Coronagraph

HOWFSC Model Validation – Pre-PhaseA, Tech. Dev.

Excellent agreement between model predictions and testbed results (% errors)

- ***Contrast floor*** (coherent)***:*** mean ~30%; chromaticity ~34% avg
- ***Contrast convergence speed***: comparable (envelope)
- ***Contrast sensitivity*** (open Loop):
  - Low order Zernike Z2~11 WFE: max < 25%; avg ~ 9%, @ 1nm rms
  - Occulter mask lateral shear: <20%, at 1e-10 ΔC
  - Shaped pupil mask lateral shear: ~33%, at 1e-8 ΔC





SPC/Spect mode

Zhou, H., et al., Proc. SPIE, 10400 (2017)

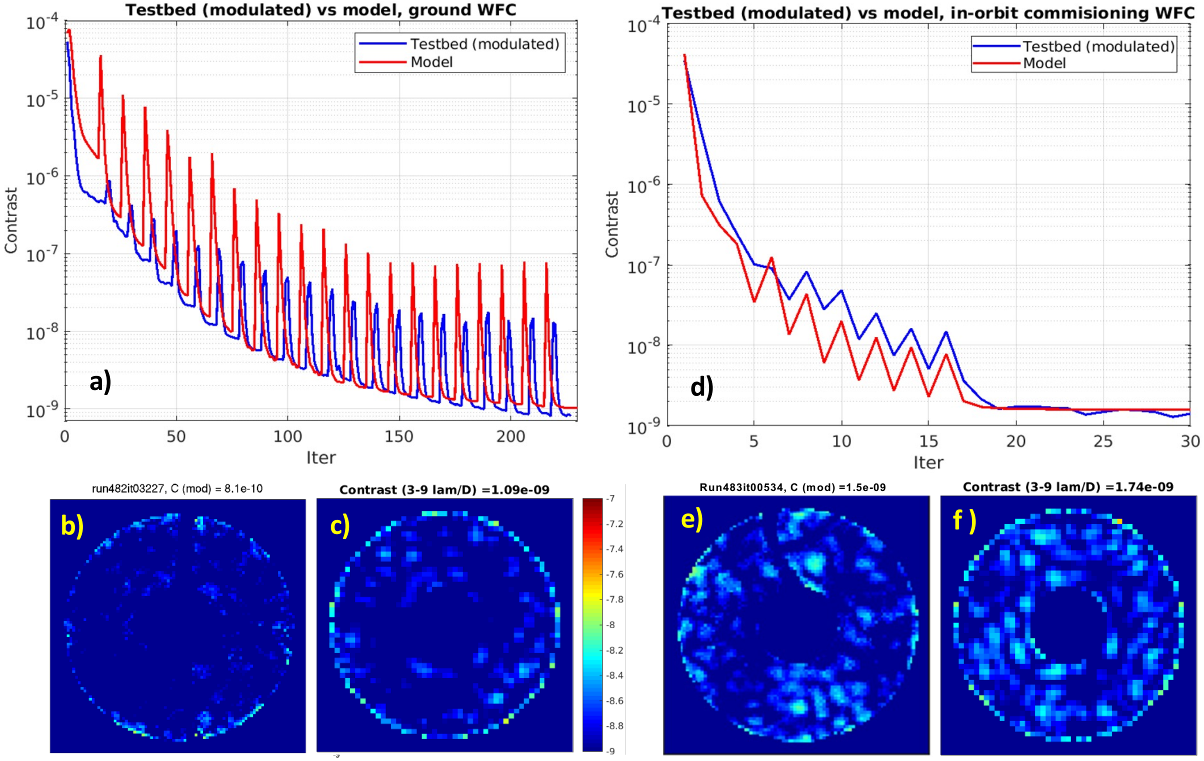
Starlight Suppression Modeling, Roman Coronagraph

HOWFSC Model Validation – PhaseB

Excellent agreements on both raw **coherent *contrast floor & its convergence speed:*** <u>prediction error</u> (ground and IOC): ~< 35% of TB

***Step 1*. Ground DM Solution WFSC**

***Step 2*. (IOC) WFSC**



Testbed (coherent) Model Testbed (coherent) Model

HLC/nFOV mode

Good agreement on key contrast sensitivities:

Tip/tilt (Z2/Z3):	~40%
Pupil mask lateral shear:	~18%
Pupil mask clocking:	~70%
Beam walk:	~40%

Zhou, H., et al., Proc. SPIE, 11443 (2020)

Starlight Suppression Optics: Roman Space Telescope Coronagraph (RST-CGI)

- CGI will be the first coronagraph in space with active wavefront control (dark-hole digging using DMs)
- Pupil obscurations by secondary-mirror-support structure presented a new challenge in coronagraph design, culminating in a new era of coronagraphy for obscured/segmented pupils
- Utilizes a baseline combination of 3 coronagraphs: hybrid-Lyot with narrow FoV (HLC-nFOV), shaped pupil for spectroscopy (SPC-spec), and shaped pupil with wide FoV (SPC-wFOV)
- Threshold requirements:
  - Capability to measure, with SNR ≥ 5, an astrophysical point source located between 6 - 9 λ/D from a star of $M_V \leq 5$, with a flux ratio $\geq 10^{-7}$
  - Bandwidth: 10% @ λ < 0.6 μm
- Surpassed performance requirements in recent thermal-vacuum testing.
- Delivery to RST in May 2024.
- Launch Date: May 2027

Starlight Suppression Optics: Roman Space Telescope Coronagraph (RST-CGI), cont'd

- Current best estimate of in-orbit performance using high fidelity models
  - Contrast: 6 x 10^{-9}
  - Core throughput: 4%

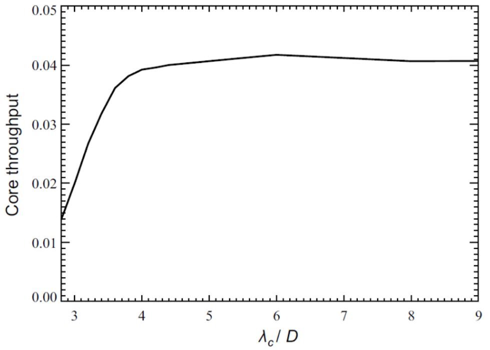
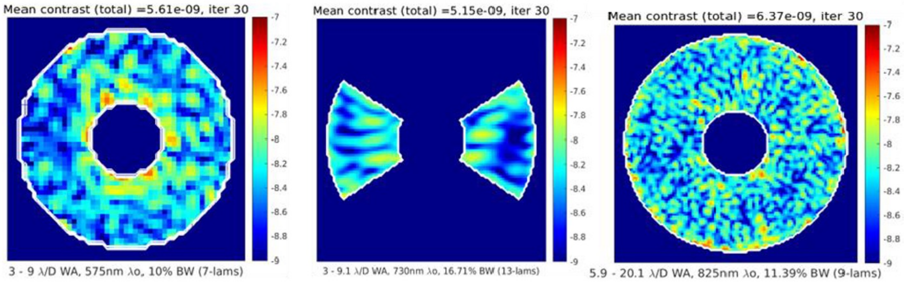


Fig. 11 HLC band 1 field PSF core throughput fraction versus field position.



Mean contrast (total) =5.61e-09, iter 30

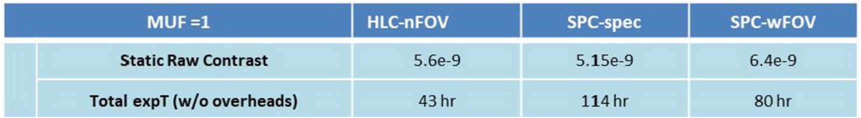
Mean contrast (total) =5.15e-09, iter 30

Mean contrast (total) =6.37e-09, iter 30

3 - 9 λ/D WA, 575nm λo, 10% BW (7-lams)

3 - 9.1 λ/D WA, 730nm λo, 16.71% BW (13-lams)

5.9 - 20.1 λ/D WA, 825nm λo, 11.39% BW (9-lams)



MUF =1	HLC-nFOV	SPC-spec	SPC-wFOV
Static Raw Contrast	5.6e-9	5.15e-9	6.4e-9
Total expT (w/o overheads)	43 hr	114 hr	80 hr

Zhou et al. 2023 Proc. SPIE

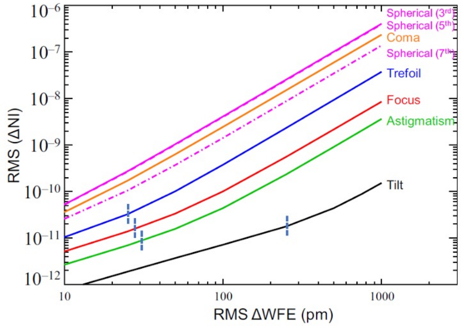


Fig. 6 HLC (band 1) contrast changes relative to low-order aberration measured over a $r = 3$ to 5 λ_c / D annulus. The default image was obtained after running WFC on the aberrated system model and includes polarization but no jitter and has a dark hole mean NI of 9×10^{-10} over 3 to 5 λ_c / D. Vertical dashed lines indicate the approximate aberration sensitivity transitions from linear (leftward) to quadratic (rightward). The spherical and coma transitions occur < 10 pm RMS.

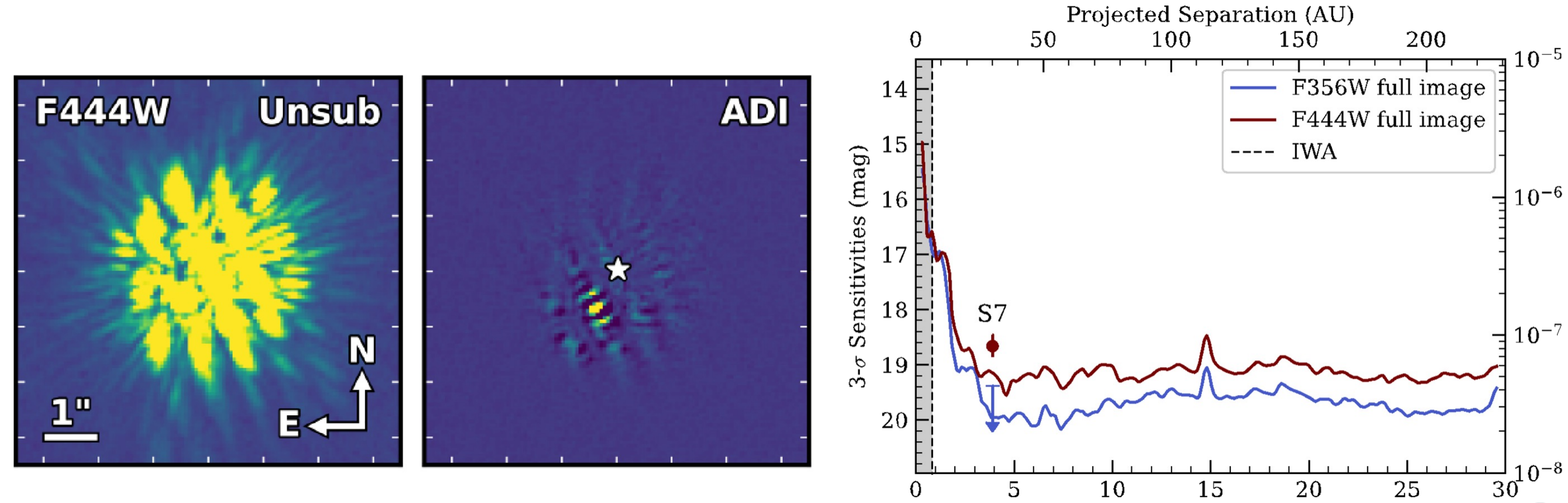
Krist et al. 2023 JATIS

Starlight Suppression Optics: Roman Space Telescope Coronagraph (RST-CGI), cont'd

- Extremely informative, recent papers on CGI
  - Krist et al. (2023), "End-to-end numerical modeling of the Roman Space Telescope coronagraph," *JATIS*, doi: 10.1117/1.JATIS.9.4.045002
  - Nemati et al. (2023), "Analytical performance model and error budget for the Roman coronagraph instrument," *JATIS*, doi: 10.1117/1.JATIS.9.3.034007
  - Zhou et al. (2023), "Roman Coronagraph HOWFSC Modeling: Case Study and Raw Contrast Performance Prediction," *Proc. SPIE*, doi: 10.1117/12.2681773

Starlight Suppression Optics: Near Infrared

- State of the Art: Near-IR coronagraphs observe exoplanets from the ground and in space, but not at HWO performance levels
    - JWST NIRCam operates routinely at 1x10^{-4} raw contrast, 1x10^{-5} post processed, and 4x10^{-7} on a bright star [e.g. Ygouf et al. 2024 *ApJ*]. NIRCam does not have DMs.
    - Ground based coronagraphs operates routinely at 1x10^{-5} raw contrast, 1x10^{-6} post processed, 5x10^{-7} on a bright star. Ground based coronagraphs use DMs for atmospheric correction



Ygouf et al. 2024 *ApJ*

Starlight Suppression Optics: Near Infrared (cont’d)

- State of the Art: Lab Demos & Emergent Tecnologies
  - Currently, there is a paucity of coronagraph designs or laboratory demonstrations that **provide adequate IWA to reach habitable zones above 1 µm**
  - Photonic nulling technologies
    - Photonic Lantern Nuller (PLN) nullers and spectrometers can work at small IWA
      - Mode-selective photonic lantern separates incident light into individual fiber-propagation modes, thereby distinguishing off-axis planetary light from on-axis starlight
      - Fundamental limit at λ/(2D)
      - Modal cross-talk and testbed WFEs currently limit achievable contrast to ~ 10^{-2} [refs. in fig. caption below]
      - Significant theoretical and experimental work is necessary to understand fundamental limits

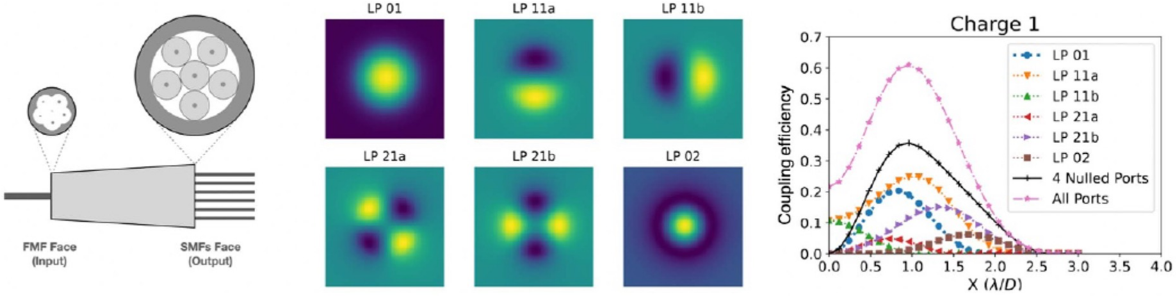


Fig. 39 from Jovanovic et al. (2023) showing how a PLN maps LP modes of input light into single-mode fibers, resulting in selective ports that suppress on-axis light. Also see Xin et al. (2024) *JATIS*.

Starlight Suppression Optics: Near Infrared (cont'd)

- State of the Art: Lab Demos & Emergent Tecnologies
    - Photonic nulling technologies
        - Photonic Nulling Chips (PNCs)
            - Valdez et al. @ Stanford U.: Four Mach Zenhder interferometers (4-MZI) integrated on chip demonstrated 1 x 10^{-7} suppression with 4-MZI PIC (wavelength 1550 ± 10 nm); same architecture reported recently in Jewell et al. 2024 SPIE and Sirbu et al. 2024 SPIE. This is an on-chip nulling demonstration and does not directly map into an IWA/OWA/core throughput paradigm.
            - 8 x 10^{-9} suppression with 6-MZI PIC; also at 1550 nm reported in overview SPIE presentation Sirbu et al 2024 (Valdez et al forthcoming with additional technical details).
            - Free-space coupling demonstration showing coronagraphic nulling on-axis and coronagraphic throughput on-axis; this was a functional demonstration with a small fill-factor on the chip, also at 1550 nm and reported in Sirbu et al. 2024 (Fogarty et al also forthcoming with additional technical details on model vs testbed comparisons)
            - Main performance limitation: manufacturing imperfections and environmental factors causing errors in light-splitting ratios (i.e. imbalances in interferometric nulling)

Starlight Suppression Optics: Near Infrared (cont'd)

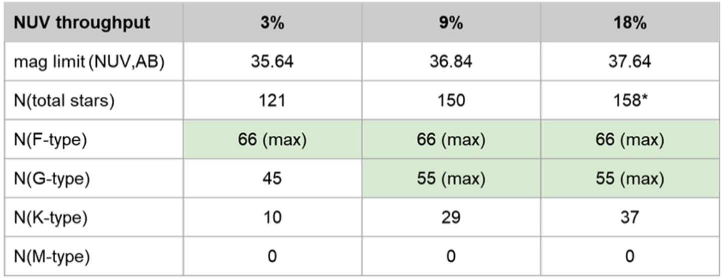
- State of the Art
  - Vortex Fiber Nulling (VFN)
    - An optical vortex in the pupil paired with a single-mode fiber in the focal plane rejects on-axis starlight but transmits light in an annular zone.
    - Insensitive to planet position within the annular (orbital) region
    - Broadband lab-demo [Echeverri et al. 2023, Proc. SPIE]
      - Null depth: 9×10^{-5}
      - Planet coupling efficiency: 7.7%
      - Contrast (null depth/planet coupling efficiency): 1×10^{-3}
      - Bandwidth: 15% @ 0.65 μm
      - IWA: 0.8 λ/D
      - OWA: 1.9 λ/D
    - On-Sky Performance at Keck II Telescope [Echererri et al. 2023, JATIS, 2024 ApJ Lett]
      - Detection of companion at 2×10^{-3} flux ratio with SNR = 3, leveraging high spectral resolution to extract planetary signal from background
    - Currently limited by sensitivity to WFE instability and mask chromaticity

Starlight Suppression Optics: Near-Infrared, cont'd

- **Major Technology Challenges & Gaps**
  - **Achieving IWA (60 mas) is the primary challenge in the near-IR.** 60 mas is merely 1.1 λ/D for λ = 1.6 μm, D = 6 m
    - Achievable IWA is limited by stellar angular size, WFE instability (especially pointing jitter), and design of starlight-suppression optics (coronagraph masks)
  - Nulling technologies can meet the IWA challenge but face substantial gaps
    - Contrast needs many (~ 7) orders of magnitude improvement
    - Device and mask imperfections limit performance
    - Sensitivity to WFE instabilities (especially pointing jitter) place limits on performance, as nulling techniques rely on spatial-mode selection to achieve contrast.
    - The is a knowledge gap regarding fundamental limits of photonic nulling technologies
    - VFN FoV is limited to ~ 1 λ/D annular band per vortex mask

Starlight Suppression Optics: Near-Ultraviolet

- **See the CTR UV Report “A near-ultraviolet coronagraph instrument study for the Habitable Worlds Observatory” led by R. Juanola Parramon**
- **Major Technology Challenges & Gaps**
  - Low detectable photon flux
    - Low throughput due to lower coating reflectance than vis
    - Lower detector QE compared to vis
    - Stars are dimmer, and therefore lower planetary flux as well, compared to vis
    - CTR estimated the UV system throughput/QE (see Appendix slides) and conducted a UV target analysis. We found that this might eliminate **26% of viable (vis) targets** in the ExEP HWO Target List. The loss was mainly in K stars.



NUV throughput	3%	9%	18%
mag limit (NUV,AB)	35.64	36.84	37.64
N(total stars)	121	150	158*
N(F-type)	66 (max)	66 (max)	66 (max)
N(G-type)	45	55 (max)	55 (max)
N(K-type)	10	29	37
N(M-type)	0	0	0

Number of Accessible Targets in the Galex NUV Band for O3 Detection. Preliminary estimates by K. Stapelfeldt, E. Mamajek, D. Savransky. (June 7, 2023)

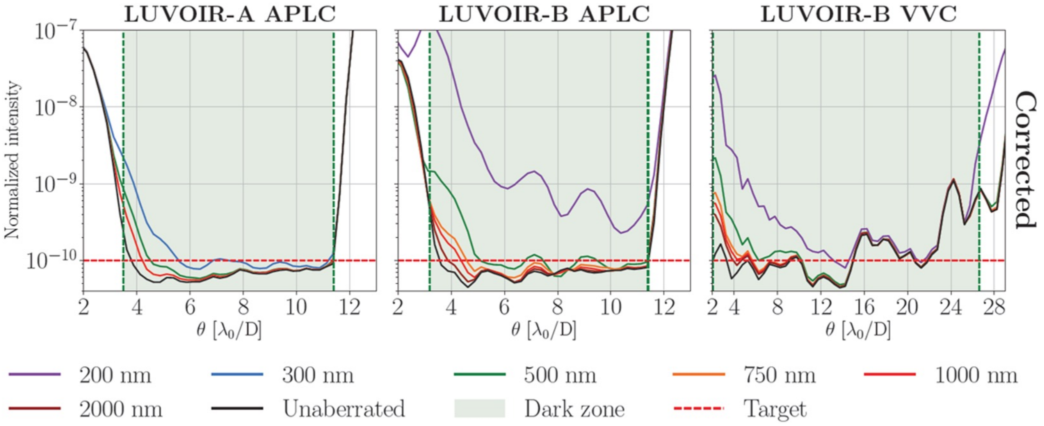
Starlight Suppression Optics: Near-Ultraviolet (cont'd)

- **Major Technology Challenges & Gaps**
  - Tighter wavefront sensing and control requirements
    - The same WFE physical amplitude is double in phase amplitude at 250 nm vs. 500 nm, requiring tighter sensing and control
  - More intense scattered light by optical surfaces and particles
    - Knowledge gap: large uncertainties exist in scattering into small angles, especially by particulate contaminants
  - Higher sensitivity to contamination
    - Absorption and scattering by contaminants are much stronger in the UV
    - Need to evaluate whether this is an (contamination control) engineering or technology problem

Starlight Suppression Optics: Near-Ultraviolet (cont'd)

- **Major Technology Challenges & Gaps**
  - Larger polarization aberrations
    - Contrast degradation due to polarization aberrations is especially pronounced at short wavelengths.
    - The effect projects mainly into tip-tilt and astigmatism. Thus, degradation occurs at small working angles.
    - Fortunately, most UV targets are at large working angles in terms of λ/D.
      - 100 mas ⇒ 12 λ/D @ λ = 250 nm, D = 6 m
    - Coronagraphs can be designed to mitigate effects of polarization aberration, by enhancing low-order-WFE tolerance

Future HWO Trade: UV throughput, IWA, polarization-aberration tolerance



Will & Fienup 2019 Proc. SPIE

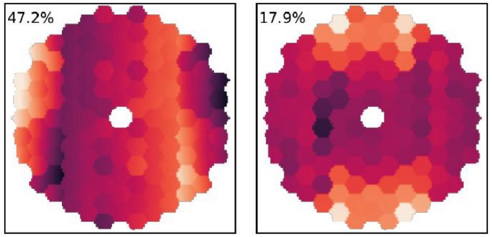
Coronagraph AO: Simulations

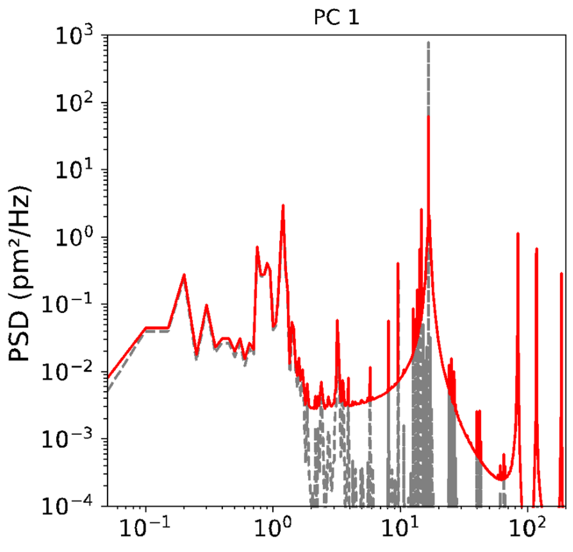
Future HWO Trade: Artificial vs. natural reference source for AO

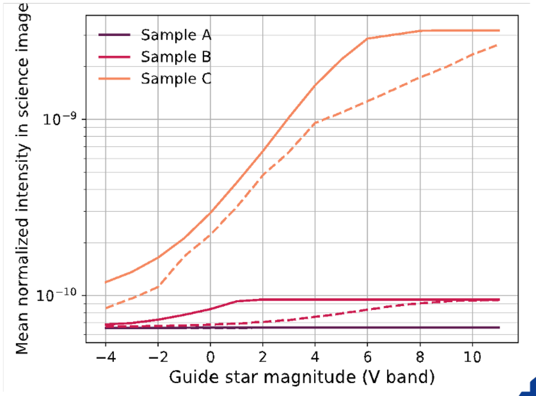
- Potier et al. (2022), numerical study on coronagraph AO main general conclusions
  - Sensor SNR fundamentally limits control performance. Therefore, photon rate fundamentally limits control gain and bandwidth using an optical wavefront sensor
    - **In the photon-noise-limited regime**, WFS&C provides useful contrast stabilization **only when the fiducial light source is sufficiently bright and the wavefront perturbations are sufficiently large**
  - Predictive control can significantly increase control performance, effectively extending useful source brightness, but has fundamental limitations
    - Per **Bode's theorem (aka the "waterbed effect")**, if sensitivity to disturbance is suppressed at some frequency range, it is necessarily increased at some other range.
  - Results highly dependent on spatial modal content, e.g. segment to segment correlations.
  - Therefore **from a coronagraph AO PoV, it is better to have wavefront variance concentrated in a smaller number of vibrational modes. Telescope structures w/ fewer DoF, higher symmetry, and higher stiffness are desirable.**

Coronagraph AO: Simulations

- Pueyo et al. (2022) and Sahoo et al. (2022) used semi-analytical models to quantify fundamental limits associated with stellar brightness in the worse case scenario of random/uncorrelated movements of segments w.r.t. to neighbors. Theoretical gains of factors of 10 - 100. The more robust the coronaraph the greater the gain.
  - Results consistent with Potier et al. For drift timescales longer than ~1 mins (thermal) enough photons for AO correction at $3x10^{-11}$
- Dube et al. (2022) JOSA “Exascale integrated modeling of low-order wavefront sensing and control for the roman Coronagraph Instrument”: Demonstrated techniques for λ/10000-precision modeling of wavefront sensing and control with large improvements in computational speed.

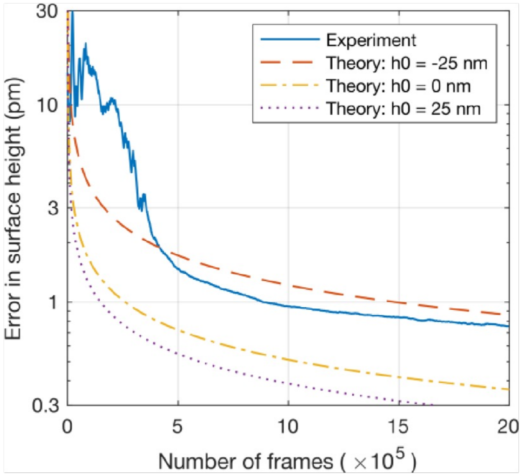




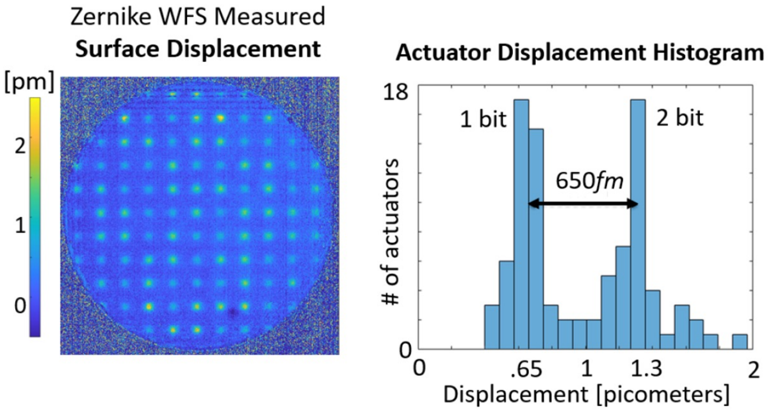


Coronagraph AO: Laboratory Demonstration

- **Picometer (or better) sensing and actuation have been demonstrated in the lab**
  - Ruane et al. (2020, *JATIS*) demonstrated 0.75 pm sensitivity with 1.2 h integration using a Zernike wavefront sensor
  - Noyes et al. (2023, *Proc. SPIE*) demonstrated 1-pm DM wavefront control



0.75 pm WFE Sensing Demo: Blue solid trace shows empirical measurement error vs. number of exposure frames integrated (10 ms/frame). [Ruane et al. 2020]



0.65 pm DM Surface Actuation Demo:
Left panel: DM surface height extracted from 10,000 wavefront-sensor images
Right panet: Histogram of DM actuation displacements showing 0.65 pm resolution [Noyes et al. 2023]

Coronagraph AO: Laboratory Demonstration (cont'd)

- **CGI Demonstrations**
  - Shi et al. (2019, *SPIE*)
    - Demonstrated sub-mas sensing and control of vibration induced line of sight using Roman CGI LOWFS architecture
    - Demonstrated contrast maintenance below 1e-8 (controlling Z1-Z3) using Roman CGI LOWFS architecture
  - Dube et al. (AAS 2020) demonstrated contrast maintenance below 1e-8 (controlling Z1-Z7) using Roman CGI LOWFS architecture and low photon flux.

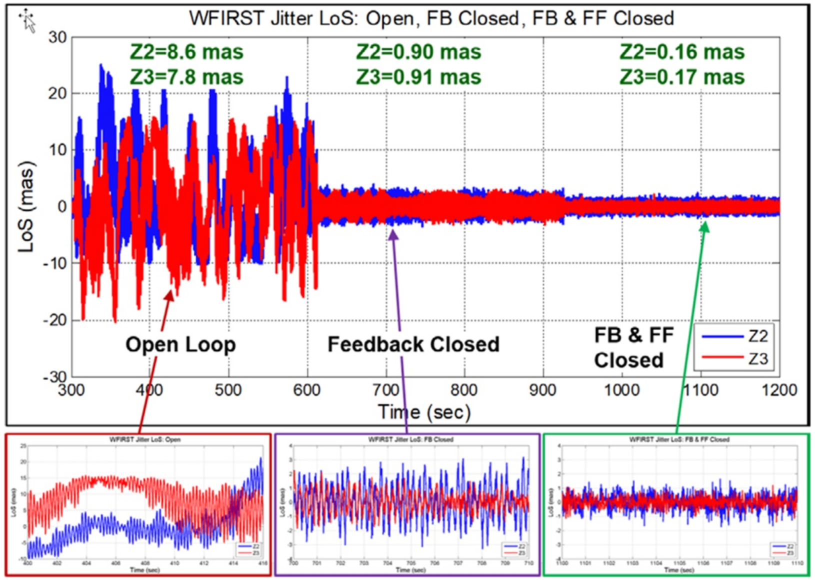


Figure 5. LoS performance with multiple RWA disturbances injected by the JM. The figure shows the time traces of LOWFS sensed LoS tip-tilt errors labeled as Z2 (blue) and Z3 (red). The LOWFS sensor measurements (nm RMS) have been converted to the on-sky LoS angle in unit of milli-arcsecond (mas). The main panel on top shows the time traces of the measured LoS with FSM loops open (left segment), closed loop with feedback (FB) control only (middle segment), and closed loop with both feedback (FB) and feed forward (FF) controls (right segment). The RMS LoS error of Z2 and Z3 of each segments are listed on top of corresponding segments. At the bottom, three panels show the zoom-in view of the time traces under different control conditions. Please noted the open loop plot (lower left panel) has a much larger Y-axis scale.

Shi et al. (2019)

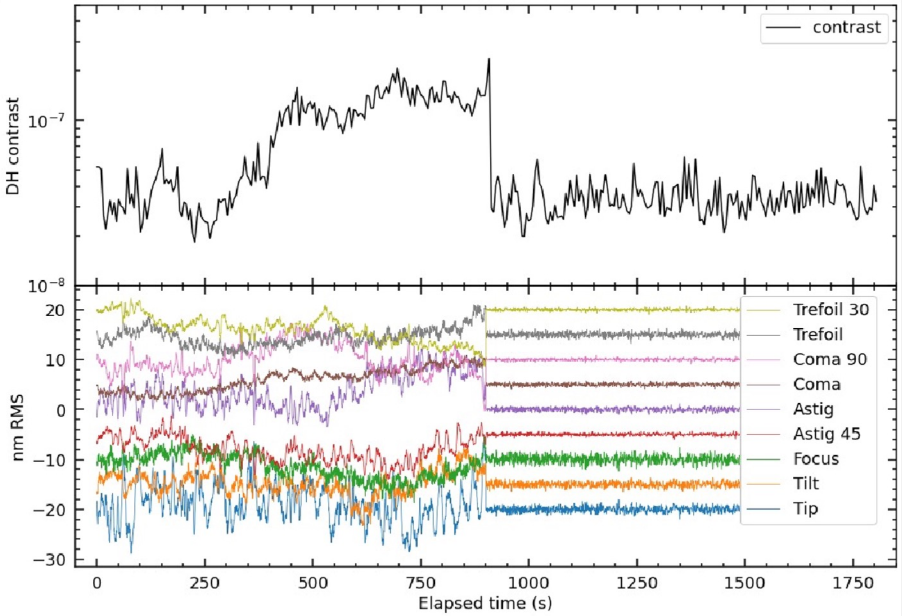
Coronagraph AO: Laboratory Demonstration (cont'd)

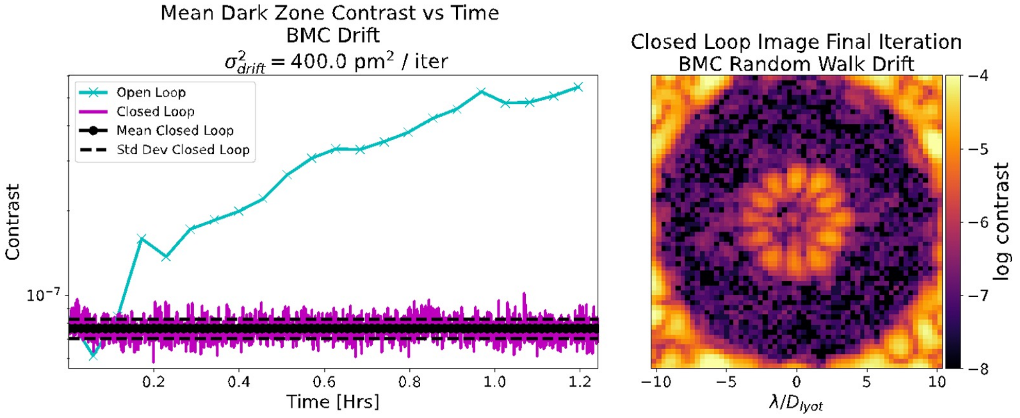
- Pourcelot et al. (2022, A&A) and Soummer et al. (2022, SPIE) demonstrated contrast maintenance at ~5x10^{-8} (controlling Z1-Z11) using APLC+LOWFS architecture

- Redmond et al. (2022, SPIE) demonstrated contrast maintenance at ~5x10^{-8} using science camera images in the Dark Hole.

- Poon et al. (2023, SPIE), demonstrated contrast maintenance at ~5x10^{-8} using science camera images outside of the Dark Hole (LDFC)

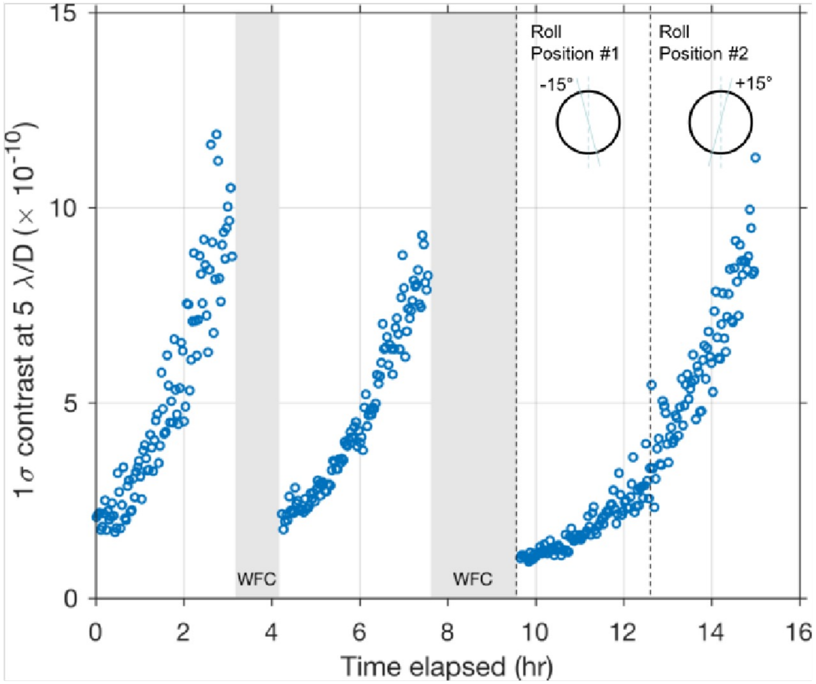
Multiple sensing and control architectures being demonstrated in testbed. CGI will provide TRL 9 demonstration of LOWFS in space





Coronagraph AO: Ground Test Facility

- **SotA**
  - Stability of existing vacuum testbeds ~1e-10 per hour drift (Seo et al. 2019). Hypothesized root cause, DM drift.
  - Experimental environment need to be sufficiently quiet:
    - to inject disturbances commensurate with HWO thermal and dynamical environment at sufficient SNR.
    - measure noise rejections levels that validate models of closed loop operations.



Coronagraph AO: Laboratory Demonstration (cont’d)

- **Major Performance Gaps**
  - Operations around a 3 x 10^{-10} raw contrast, or around a wavefront commensurate with 3 x 10^{-10} raw contrast (if no coronagraph in AOTF)
  - Contrast stability at the 3 x 10^{-11} level, or wavefront stabilization at levels commensurate with 3 x 10^{-11} contrast stability (if no coronagraph in testbed).
- Contrast stabilization in the presence of the disturbances commensurate with HWO thermal and dynamical environment (note that both control gain and capture range are important).
- **Major Simulations Gaps**
  - Predicted/simulated wavefront noise rejection levels need to be validated with experimental data.

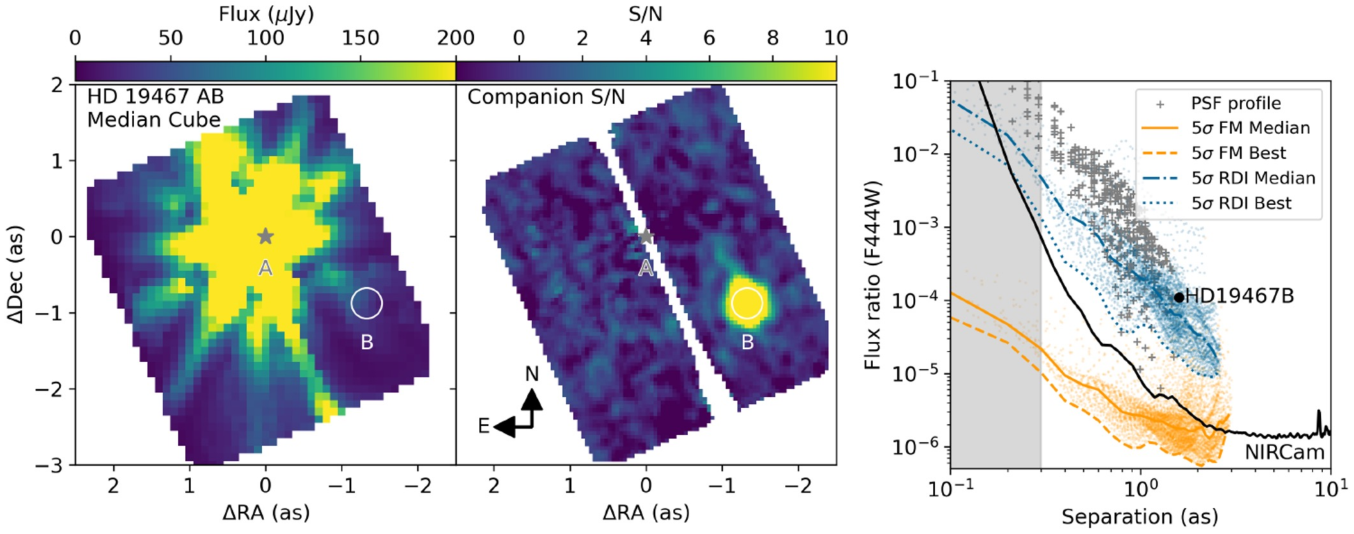
Detectors: State of the Art

__Future HWO Trade__: Detector noise, spectral resolution, cryogenic requirements

- Survey of the state of the art was not carried out in the context of CTR (TAG to conduct it).
- Detector technologies for science instrument can be developed in parallel of starlight suppression technologies. Data obtained using a bright source can be made noisier after the fact to validate algorithms in the low photon count regime (Redmond et al., 2022).
- Detector technologies for wavefront sensing need to be integrated into starlight suppression technologies. WFS biases can be a limiting factor for raw contrast.
- SotA detector noise is a major factor in error budget for spectroscopy
- CTR's detector fact-finding spreadsheet is included in the appendix

Spectroscopy: State of the Art

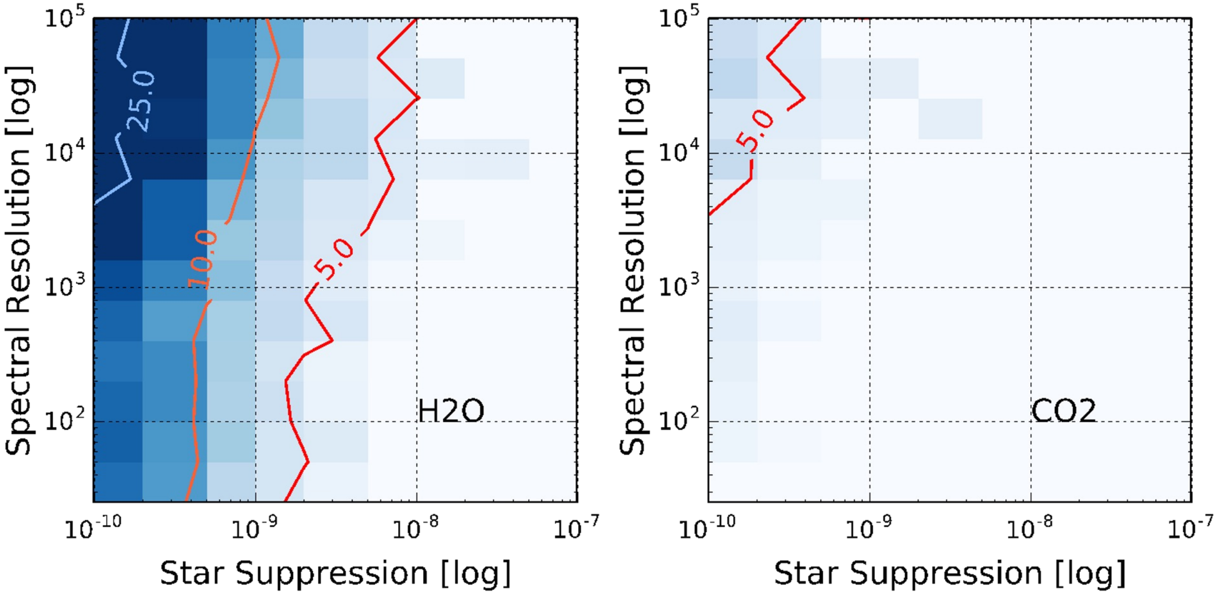
- R~20-70 routinely used for self-luminous exoplanet detection using ground based instruments at ~1x10^{-5} contrasts.
- R~2000 will be routinely used for self-luminous exoplanet characterization with JWST at ~1x10^{-5} contrasts. (Ruffio et al., 2023).
- R~30000 routinely for self-luminous exoplanet characterization using ground based instruments at ~1x10^{-5} contrasts. (Xuan et al., 2022).



Ruffio 2023, arxiv, submitted to ApJ

Spectroscopy: Gaps

- **Major Knowledge gaps:**
  - How does contrast gain scale with spectral resolution in the reflected light regime?
  - How does chromaticity of speckle (at ~3x10^{-10} level) impact the measurement of the planet's continuum.
- **Major experimental gap:**
  - Lack of vacuum tests coupling coronagraphs and spectrograph at ~3x10^{-10} levels



6. Gap Details

Gap: WFE-Stability Environment

Description

A coronagraph instrument built on SotA technology is not able to achieve required contrast noise floor for planet detection in relevant environment of observatory WFE instabilities

- Key issues
  - WFE stability has a critical impact on planet detectability. Beyond a threshold WFE instability, the coronagraph cannot detect the target planet regardless of integration time and raw contrast level.
  - AO in the coronagraph system can relax observatory requirements, but SotA control bandwidth and gain are limited by the fiducial light-source's photon flux, contrast sensitivity, coronagraph AO, post processing.
  - Improving coronagraph robustness, post-processing, and other methodologies can mitigate the gap as well, but need substantial innovation and development

Gap: WFE-Stability Environment (cont'd)

Impact: High

- Impacts on Level-1 mission requirements

Gap Size: Large

- Current coronagraph sensitivities require ~ 2 pm RMS WFE stability *at the focal-plane mask* (FPM) in low and mid spatial frequencies. This requires substantial developments in technologies including observatory stabilization, coronagraph design, post processing, PSF subtraction, and/or dark-hole maintenance technologies.
- Potential mitigating technologies require investments and/or increase system complexity (and thereby, mission schedule risk)

Gap: WFE-Stability Environment (cont'd)

Recommendations:

Study feasibility and realizable enhancements from the following technologies and invest where appropriate

  - High bandwidth measurement of WFEs (at the coronagraph entrance pupil) from observatory mechatronic sensors (e.g. capacitive edge sensors) to circumvent the photon-flux limit
  - Post processing & PSF subtraction
  - Dark-hole maintenance methodologies

- Conducting these studies ASAP is imperative because the findings can impact mission-level design and observing scenario.
- Invest in developing coronagraph designs with high WFE tolerance
- Conduct early trade of artificial vs. natural wavefront-fiducial source, with evaluations of performance risk and system complexity

Gap: Starlight-Suppression-Optics Subsystem

Description

SotA Starlight-suppression optics do not meet static performance (throughput, IWA/FoV, raw contrast, wavelength, and bandwidth) requirements to enable required mission exoplanet yield

- Key issues
  - Substantial gaps exist between demonstrated and predicted contrast performances, indicating gap between as-manufactured optical characteristics and idealized model representations.
    - Need error-budget, modeling, and V&V of starlight-suppression test beds to *understand* noise contributors at ~ 10^{-11} level
  - NIR requires very small IWA in terms of λ/D
  - UV involves high sensitivity to scattering, contamination, and polarization aberrations

Gap: Starlight-Suppression-Optics Subsystem (cont'd)

Impact: High

- Impacts on Level-1 mission requirements

Gap Size: Medium for Vis (due to CGI heritage), Large for UV and IR

- Meeting starlight suppression + all other performance requirements in the UV, and IR is a major leap compared to SotA.
- DST has mitigated the Vis contrast gap, but all other performance requirements need to be demonstrated.
- Existing demonstrations fall between 0.55 and 0.8 µm. IR demonstrations with DMs do not exist. No demonstration in the UV.
- A possible pathway is to utilize separate UV and vis/IR instruments and different types of coronagraphs to get the job done. However, the increase in mission complexity add mission schedule and cost risk.
- Emergent, possibly disruptive technology concepts exist, but are at low maturity with substantial knowledge gaps

Gap: Starlight-Suppression-Optics Subsystem (cont’d)

Recommendations:

- Invest in error-budget, modeling, and V&V activities of starlight-suppression test beds to fully identify and quantify noise contributors at ~ 3 x 10^{-11} level
- Develop ground-test-facility roadmaps for NUR, NIR, and emergent technologies
- Define HWO NIR coronagraphy requirements ASAP
- Devise on- and off-ramps for NIR emergent technologies
- Leveraging findings in the CDS Final Report, develop and implement a NIR coronagraph technology roadmap.

Gap: Deformable Mirrors

Description

SotA DMs with larger than 64x64 actuator format (e.g. 96x96 actuators) have not demonstrated required stability, the ability to enable required contrast, form factor to support required mass/volume, and/or manufacturing schedule requirements

- Key issues
    - DM interconnects: Need > 7K connections/DM with insignificant stress on the mirror surface
    - Need simultaneous achievement of adequate surface quality and stability
    - Manufacturing schedule is long (~ 3 years per production cycle)
    - SotA flight DM electronics can drive HWO system mass/volume budget
    - DM actuator pitch can drive instrument volume and, in in turn, observatory configuration
    - Supply chain risk (small number of vendors, each with substantial challenges)

Impact: High

- Impacts Level-1 mission requirements

Gap: Deformable Mirrors (cont'd)

Gap Size: Large

- Technology-development paths exist to address major issues, but need to be proven. Existence of multiple issues increases overall likelihood.

Recommendations

- Implement DM technology development according to the ExEP DMTR findings, some key issues to address are highlighted in the previous slide
- Initiating investments ASAP is imperative due to long development and production cycles.
- Conduct a thorough study of wavefront-control architectures (e.g. woofer tweeter, super-Nyquist wavefront-control, sparse DMs) vs. DM maturity, risk, and cost

Gap: Mission efficiency

Description

Current HWO design concepts utilize dichroic beam-splitters to split light from the telescope into multiple beams to achieve simultaneous multi-channel observations, which might be necessary to achieve mission science yield. The requirements to ensure quality of these optics for coronagraphy to the 10^{-10} level have not been defined. Throughput, bandwidth, IWA, etc. impact mission efficiency as well; they are included in the starlight-suppression optics area.

Impact: Medium

- This gap, if not closed, can impact overall mission science return: time devoted to exoplanet science case might be larger than envisioned by LUVOIR/HabEx.

Gap Size: Large

- There is a high likelihood that requisite spatial uniformity will not be demonstrated in testbed at $3x10^{-10}$ contrast. If true, mission efficiency will be factors of many away from what HWO needs.

Gap: Mission efficiency (cont'd)

Recommendations

Conduct early study to assess feasibility of using dichroic beam-splitters

- Thin-film and coronagraph modeling to establish a preliminary set of requirements using assumed manufacturing tolerances and patterns of spatial variations
- Design and procure a custom set of dichroic beamsplitters
- Design and build a broadband Mueller-matrix polarimeter
- Characterize the dichroic beamsplitters. Update/validate the modeled manufacturing tolerances and spatial patterns. Produce updated requirements for HWO.
- Conducting the study ASAP is imperative because this gap, if not closed, can impact observatory-level design and overall mission science return

Gap: Detectors

Description

SotA detectors do not meet noise, dynamic range, and lifetime requirements.

- Key issues
  - SotA, EMCCD, detectors produce excessive noise for HWO spectroscopy, and their in-orbit lifetimes need to be improved (e.g. Nemati's error-budget analysis for O_2 spectroscopy with HWO-like observatory using SotA EMCCD indicate excessive required integration time to achieve SNR). There is a need for low noise detectors for all (NUV, vis, and NIR) bands, especially for NIR spectroscopy
  - SotA NIR photon-counting detectors' operating temperatures challenge observatory thermal design
  - If HWO decides to utilize energy-resolving detectors, which require sub-Kelvin operating temperatures, the starlight-suppression subsystem must be isolated from mechanical disturbances generated by the cryogenic subsystem

Impact: High

- Impacts Level-1 mission requirements

Gap Size: Medium for imaging, Large for spectroscopy (NIR)

Gap: Detectors (cont'd)

Recommendations:

- Conduct early detector trades
- Formulate and implement the technology roadmap that the HWO TAG Detector Technology Subgroup will produce

Gap: Algorithms

Description

SotA dark-hole-digging algorithms are likely not able to compute solutions quickly enough vis-a-vis DM drift and/or mission observing scenario. Post-Processing algorithms might not yield the necessary contrast gain.

- Key Issues
  - SotA algorithm (EFC) can require many hours to achieve required contrast for each science exposure, depending on factors such as image acquisition, computation, and model fidelity.
  - Complexity of EFC (or equivalent algorithms) might require ground-in-the-loop computing architecture, thus placing stringent stability requirements just for dark hole digging.
  - Temporal or chromatic properties of the dark-hole speckle field might not be comparable to post-processing factors obtained with other (e.g ground based) instruments.

Impact: Medium

- Dark-hole-digging timescales mostly impact mission efficiency. Post processing not as essential if AO is used.

Gap Size: Medium

- Existing methods sufficient for CGI, significant improvements is needed for HWO but not an enormous leap.

Gap: Algorithms

Recommendations:

- Mature and dedicate early testbed time to more efficient (faster convergence, less CPU hungry) dark-hole-digging, dark-hole-maintenance, PSF/background removal, and multi-star-wavefront-control algorithms.

- Conduct early trade of on-board vs. ground-in-the-loop computation, develop and implement computation technology roadmap

- Conduct early trade of post-processing methodologies, spectrometers, and detectors (including energy-resolving detectors).

- Conducting this study ASAP is imperative because it can impact mission design

- Conduct studies to investigate the other above-mentioned key issues, develop and implement a post-processing technology roadmap

Gap: Modelling

Description

Models underlying starlight suppression error budget do not sufficiently capture as-built instrument properties in a HWO scenario

- Uncertainties in coronagraph sensitives are large
- Optical properties at millimeter to sub-micron lateral and sub-nanometer to picometer vertical scales have not been characterized with sufficient precision
- Stray light or luminescence interference need to be modeled and assessed in a HWO-relevant manner

Impact: High

- Impacts L1 requirements.

Likelihood: High (before CGI flight), Med (after CGI flight)

- Successful CGI tech demo will mitigate some aspects of this gap.

7. Learning from CGI

Learning from the Roman Space Telescope's Coronagraph Instrument Experience

- ExEP conducted extensive surveys to capture experience from the CGI project that are useful for future reference. Please see the CGI Knowledge Share and the DM Knowledge Share reports, due out later this year.
- See also Feng Zhao's (CGI Deputy Project Manager) "Roman Coronagraph Instrument (CGI) 'Lessons' for the Future" presentation: https://smd-cms.nasa.gov/wp-content/uploads/2023/11/02a-lessons4future-cgi.pdf
- We summarize in the follow slides some high level points relevant to HWO

Learning from CGI: Architecture & Early Trades

- Conduct early trades on allocating functionalities (e.g. dark-hole digging) to on-board vs. ground-in-the-loop computation
- Conduct an early trade on Spectroscopy approach (e.g. IFS, slit spectrograph, energy-resolving detectors)
- Avoid non-common-path errors in wavefront sensing
- Adopt a coronagraph architecture that can accommodate multiple coronagraph mask configurations, and allow later infusion of technology breakthroughs.
- Prioritize software architecture in system design and trade studies
- Invest in early detector technology studies and trades, including associated electronics and firmware/software functions. Define operational requirements to detectors based on science cases.

Learning from CGI: Planning, Management, & System Engineering

- Procure deformable mirrors (DMs) early. Each DM has unique characteristics that can impact design and ConOps
- In conjunction with the above, plan two cycles of flight mask design if possible, with the final design and fab as late as possible to capture any as-build defects from other assemblies, flight DMs in particular.
- Reserve engineering resources and con-ops to accommodate as-built DMs with requirement deviations
- Invest early in high circuit density, high reliability (rad hard) ASICs for DM electronics
- Procure enough flight spares to allow for more a robust implementation plan and build flight-like engineering modules (EMs) to prevent subsystems from using up spares as test units
- Plan out stability model cross-checks and select experiments on key components that have the highest risks of model incompleteness.
- Due to coronagraph complexity, build full instrument engineering model, not only at the sub-element level. Run flight-like software to enforce writing meaningful/portable software early in instrument development.

Learning from CGI: Planning, Management, & System Engineering

- For optical modeling of coronagraphs, adequately staff the team with modelers representing different skills sets, including diffractive/HOWFSC, ray-tracing, and stray light (at a lower level). The modelers need to be have continuous insight into both the optical testbeds and flight design and built (including deformable mirrors and wavefront control software architecture), to make sure the modeling addresses project's concerns in a relevant and timely manner. Modeling team must exercise rigorous configuration control of all models.
- Ensure that the coronagraph team is in the approval loop on the observatory design requirements and changes.
- Team members at partnering centers should be provided as much access as possible to project lines of communication (meeting attendance, data repository, direct contact with all members of the team rather than through single point-of-contact).
- Ensure staffing continuity of key cognizant engineers, QA, and specialized technicians through all stages of hardware development

Learning from CGI: Planning, Management, & System Engineering

- Fund 2 types of DMs in parallel, make flight optical bench to accommodate either type, and select the ones that meet technical/schedule requirements
- Invest in physics-based performance and control models and validation in testbeds. System-level performance models are extremely important in timely assessment of designs, as-built flight components, and assemblies to protect schedule and preserve performance.
- Factor in cost V&V cost early in the project because it is a critical effort that requires developing a test system more stable and accurate than the coronagraph instrument. Invest enough time and resources to understand the minimum acceptable V&V plan and carefully derive its requirements. Avoid low-ball designs of key V&V equipment that prohibit later upgrades. In particular, treat dynamic simulator of light from the observatory (GSE) as instruments of equal complexity as their corresponding coronagraphs.

Learning from CGI: Planning, Management, & System Engineering

- Build in extra (volume, mass, power, etc.) margins beyond current Flight Project Best Practices and Design Principles at MCR and MDR for new technologies to accommodate uncertainties
- Ensure requirements flowdown are communicated and appropriately discussed avoid unnecessarily tight requirements on optical components (including DMs), which can drive schedule, complicate parts procurement, and consume valuable resources.
- Ensure communications between cognizant engineers and designers regarding bases of specifications and parts selection.
- Include all stakeholders in GSE design process, especially the end-users that will actually have to use it.

Learning from CGI: Modeling, Verification & Validation

- Subsystem level testing on flight units reduces risk that issues are found at instrument level test. Or, additional testing on testbed if configuration has flight-like hardware in flight-like configuration/quantities.
- Testbed with high fidelity modeling and preferably an instrument EM are critical for validation of stability models
- As the optical hardware is delivered and aligned, incorporate the measured wavefront and alignment data into as-built ray-trace and diffractive optical models in a timely manner in parallel with the alignment process. Both as-built models are important in addressing questions during alignment and testing.
- Perform material testing early to validate design and analysis based on default material properties. Build an institutional database to capture all the material testing done by other projects.
- Apply engineering tolerances to all coronagraphic mask designs, including fabrication errors, alignment errors, etc. and incorporate into performance budget.

8. Technology Maturation Plan and Required V&V Facilities

Technology Maturation Approach

- We envision a **multipronged approach to TRL-5** by developing and testing the following critical technology subsystems of the coronagraph-instrument system in parallel
    - AO, including detectors
    - Full-scale DM
    - Starlight-suppression, including coronagraph masks and dark-hole digging computations
    - Spectrometer and post processing
    - Science camera
- The approach implies clearly defined interface requirements between components/subsystems and **carrying risks in integrated performance**. However, we posit it is the approach to reach TRL 5 within the requisite HWO-GOMAP timeframe
- **Not demonstrating at integrated-system level might become an unacceptable risk, of which HWO must be watchful**. Our maturation chart indicates opportunities for integrating subsystems to reduce risk.
- Maturation requires models and error budgets validated by test results

Required Facilities: Overview

- We envision the following minimum set of test facilities to support major development activities
  a. Subscale-pupil starlight suppression ground test facility (SSTF)
  b. Representative-scale-pupil AO ground test facility (AOTF)
  c. DM ground test facility (DMTF)
  d. Spectrometer & Post-processing ground test facility (SPTF)
  e. Detector ground test facility (DTF)
- All testbeds need models and error budgets to support (mission and instrument) systems V&V, integrated modeling, and interface-requirement definitions

Required Facilities: Subscale-Pupil Starlight-Suppression Ground Test Facility (SSTF)

- The SSTF must enable the following functionalities
  - Validate raw contrast as a function of angular separation
  - Validate predicted coronagraphic throughput as a function of angular separation
  - Validate predicted planetary PSF footprint
  - Validate predicted starlight-suppression bandwidth
  - Validate contrast sensitivities to WFEs
  - Characterize manufactured performance of key optical components for incorporation into models
  - Validate models of coronagraphic performance to optical imperfections and manufacturing tolerances
  - Characterize performance dependence on detector characteristics
  - Enable validations at required HWO wavelengths

Required Facilities: Subscale-Pupil Starlight-Suppression Ground Test Facility (cont'd)

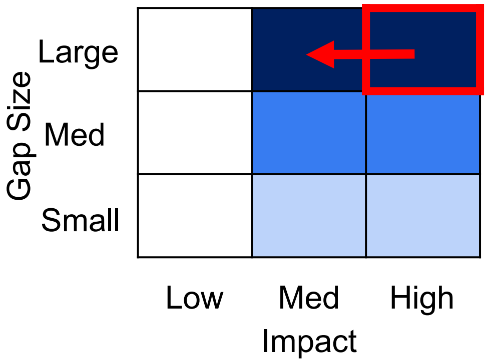
- Comments
    - The SSTF will need different types of testbeds/test-stations
        - coronagraph testbeds
        - optical-component characterization test stations
    - For validation, coronagraph testbed performance must exceed mission requirements to serve at the "ruler." Raw contrast is a key parameter, and it needs to be $< 1 \times 10^{-10}$.
    - Pupil screens ("phase plates") and specialized DMs can be utilized to generate stimuli for contrast-sensitivity measurements
    - Combination of source + detectors in the testbeds should have characteristics scalable to the flight noise level.
    - GOMAP will need a sufficient number of coronagraph testbeds to enable simultaneous testing of multiple coronagraphs. HWO will likely require a combination of coronagraphs, each optimized for distinct objectives, to achieve all of its requirements.

Required Facilities: Subscale-Pupil Starlight-Suppression Ground Test Facility (cont’d)

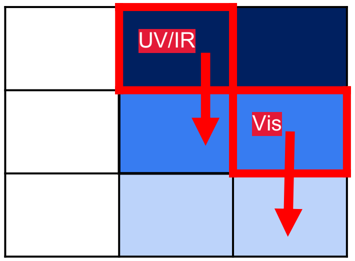
- Comments
  - Initially, the coronagraph testbed does not require full-scale DMs. Current 48x48-actuator DMs should suffice.
  - Proving emergent technologies will require innovations in testbeds
    - Testbed design for photonic technologies require substantial studies. In particular, photonic technologies are inherently sensitive to WFEs, but requirements for characterization are currently unclear.
    - Experience in designing and implementing UV coronagraph testbeds is lacking, which has unique requirements (e.g. contamination control).

Closing gaps with SSTF

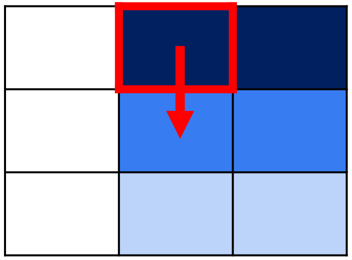
Robust coronagraphs help **WFE-Stability**



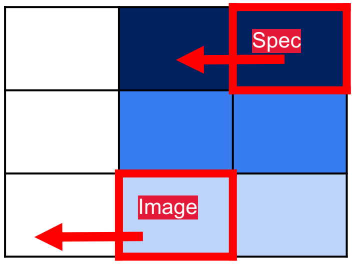
Better contrast, IWA help **Static performance**



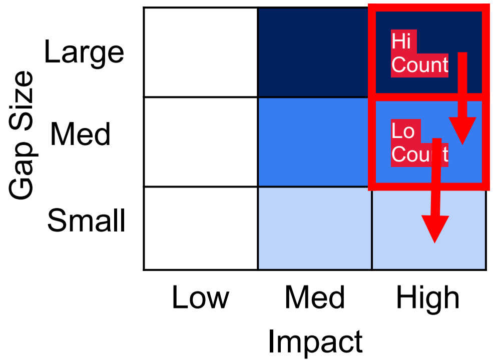
Dichroic validation helps **Mission efficiency**



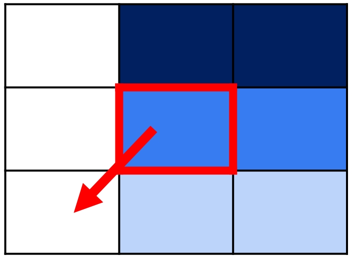
High throughput helps **Detectors**



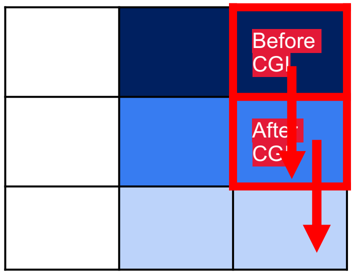
SSTF is **DMs** end to end test facility



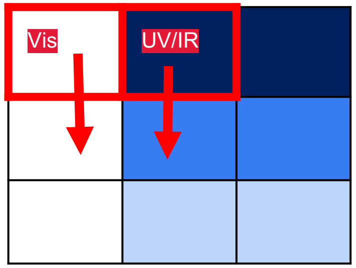
SSTF demonstrates faster DH **Algorithms**



SSTF measures sensitivities used for **Modelling**



A dedicated testbed is needed for **Emerging Tech**



Required Facilities: Representative-Pupil AO Ground Test Facility (AOTF)

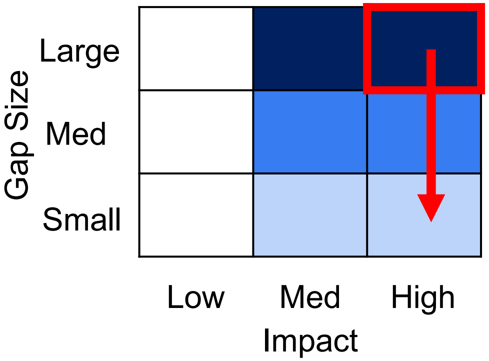
- Functional requirements:
    - Utilize a segmented OTA simulator of an adequate dimensional scale (e.g., scaled telescope stimulus optics with angles of incidence representative of a full-scale optical system)
    - Utilize mission-relevant light sources and detectors
    - Validate coronagraph AO performance
        - Demonstrate dynamic contrast stability in the presence of time varying disturbances representative of the observatory dynamical environment.
        - Demonstrate dynamic contrast stability in the presence of time varying disturbances representative of the observatory thermal environment.
    - Validate predicted scattered-light noise

Required Facilities: Representative-Pupil AO Ground Test Facility (AOTF)

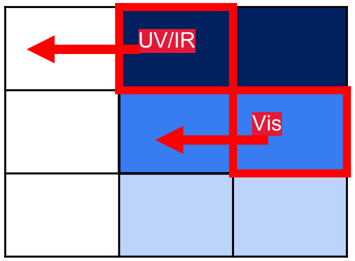
- Key performance requirements:
    - Demonstrate contrast-stability, and scattered-light requirements at IWA and OWA, ~ 10x beyond science requirements (derived by EBS, yield calculations, near-angle scatter models).
    - Extrapolation, with uncertainty quantification, to contrast stability science requirements using high fidelity modeling.
- Comment
    - The AOTF does not necessarily require a starlight-suppression subsystem

Closing gaps with AOTF

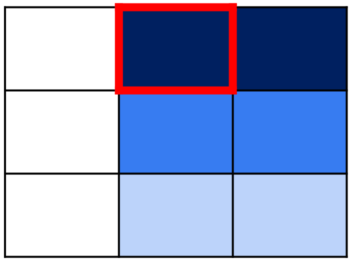
AOTF is will closes
WFE-Stability gap



Stable wavefront
enables degraded
Static performance

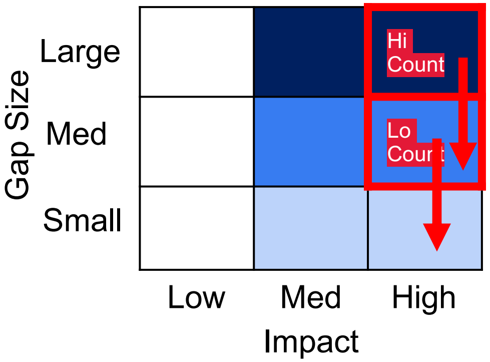


Mission efficiency

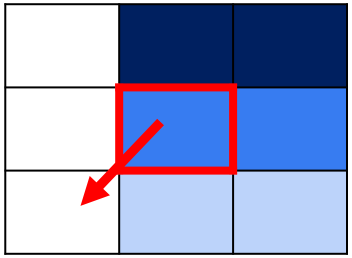


Detectors

AOTF is **DMs** end to
end test facility

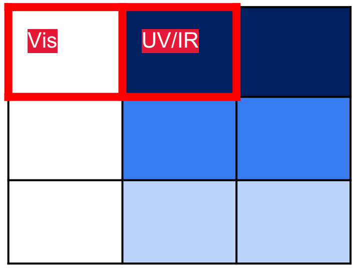


AOTF demonstrates
WFS&C + PP
Algorithms



AOTF measures
noise rejection
predicted by
Modelling

Emerging Tech



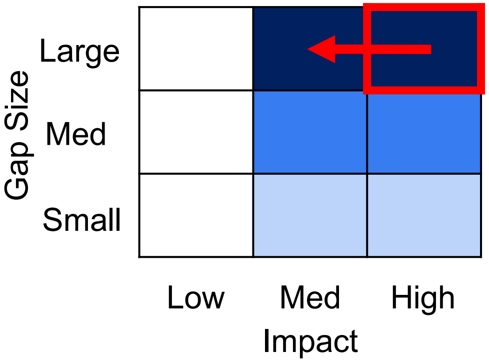
Required Facilities: Spectrometer & Post-processing Ground Test Facility (SPTF)

- Functional requirements
    - Demonstrate integrated throughput of spectrograph architectures
    - Demonstrate post-processing techniques that might relax stability requirements during long spectroscopic exposures.

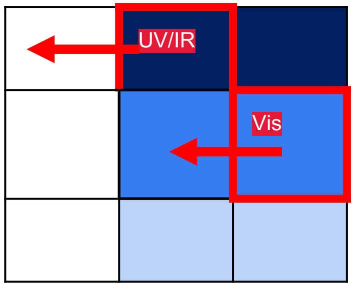
- Key performance requirements
    - Throughput driven by science requirements (EBS, yield calculations).
    - Requirements on post-processing gains TBD.

Closing gaps with SPTF

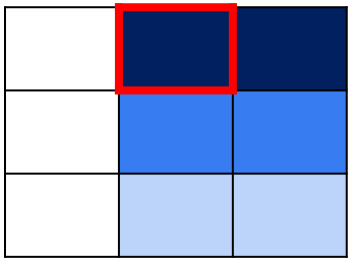
Post processing with SPTF will reduce impact of **WFE-Stability**



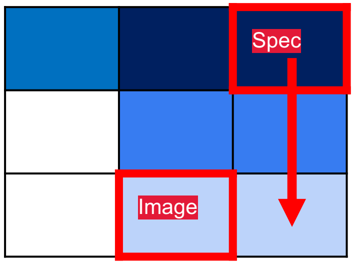
SPTF demonstrate operations with degraded **Static performance**



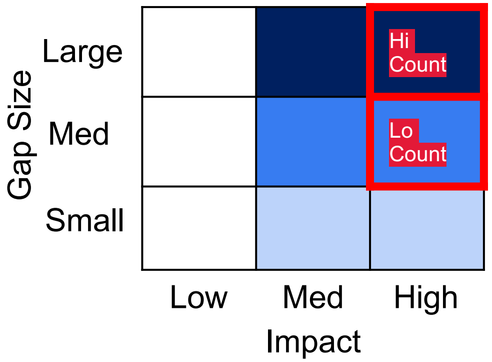
Mission efficiency



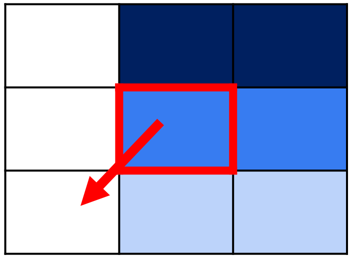
SPTF demonstrates **Detectors** in relevant environment



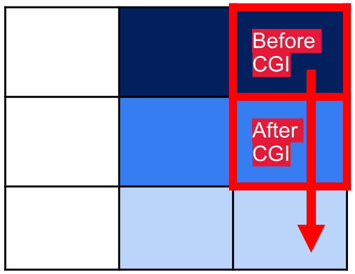
DMs



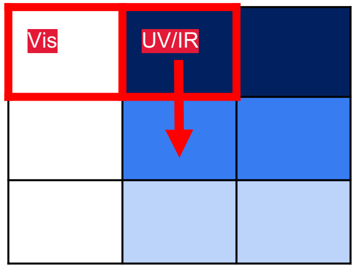
SPTF will demonstrate PP **Algorithms**



SPTF anchors spectrograph **Modelling**



SPTF demonstrates **Emerging Tech** for spectroscopy

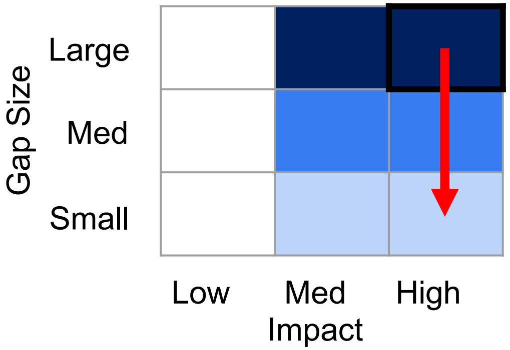


Required Facilities: Detector Ground Test Facility (DTF)

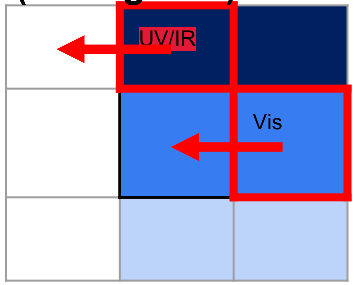
- Functional requirements:
  - Validate detector performances (QE, read noise, dark, flat, CIC) for imaging.
  - Validate detector performances (read noise, dark, flat, CIC) for spectroscopy.
- Key performance requirements
  - Detector performances for imaging and spectroscopy are driven by science requirements (EBS, yield calculations).
  - Detector performances for wavefront sensing are driven by high fidelity model for contrast stability.
- Comment
  - If HWO decides to utilize energy-resolving detectors, DTF and SPTF might become one and the same

Risk reduction with DTF

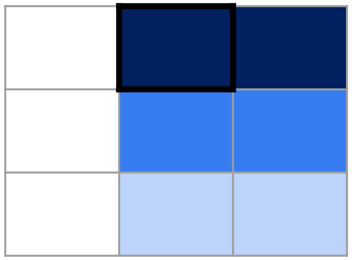
WFE-Stability gap



DTF might enable degraded **Static performance (throughout)**

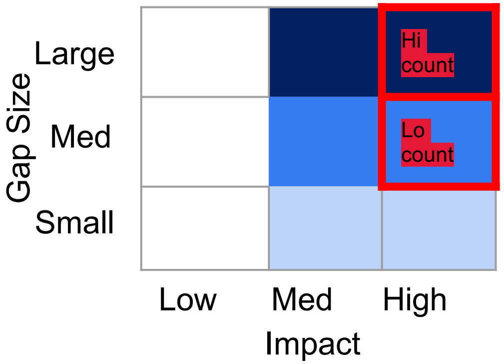


Mission efficiency



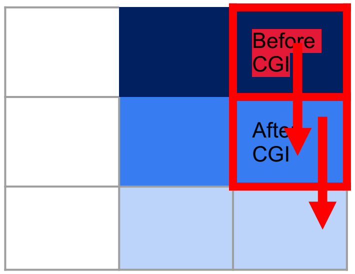
DTF will validate **Detector** technologies

DMs

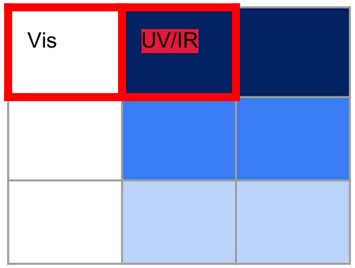


Algorithms

SPTF will anchor detector **Modelling**

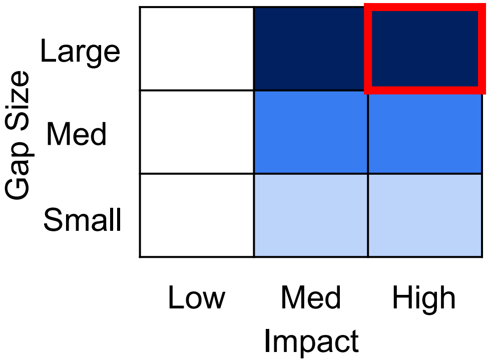


Emerging Tech

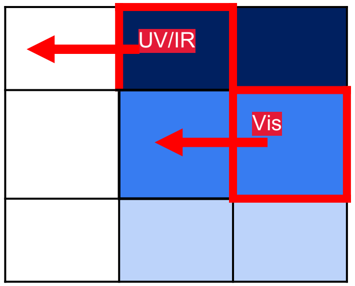


Closing gaps with DTF

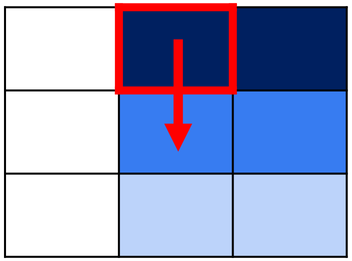
WFE-Stability Gap



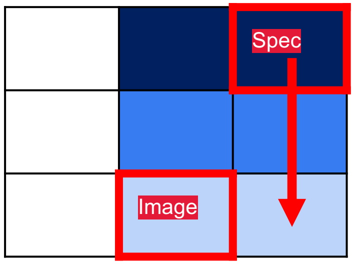
DTF enable degraded **Static performance** (throughput)



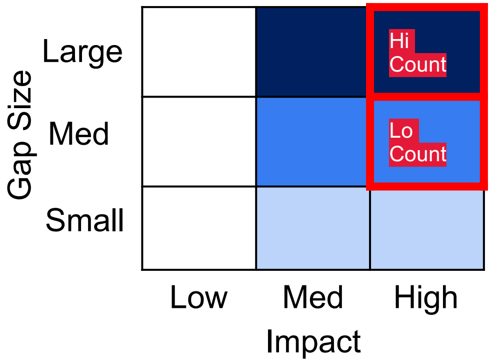
DTF demonstrates higher **Mission efficiency**



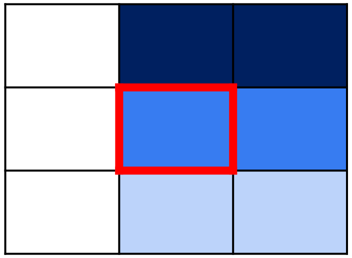
DTF closes **Detectors** Gap



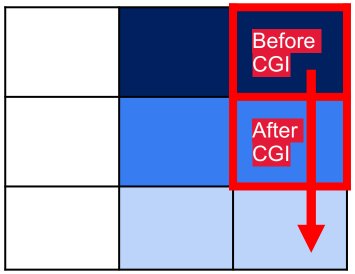
DMs



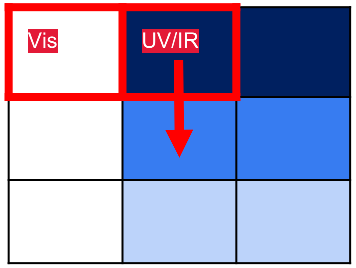
Algorithms



SPTF anchors detector **Modelling**

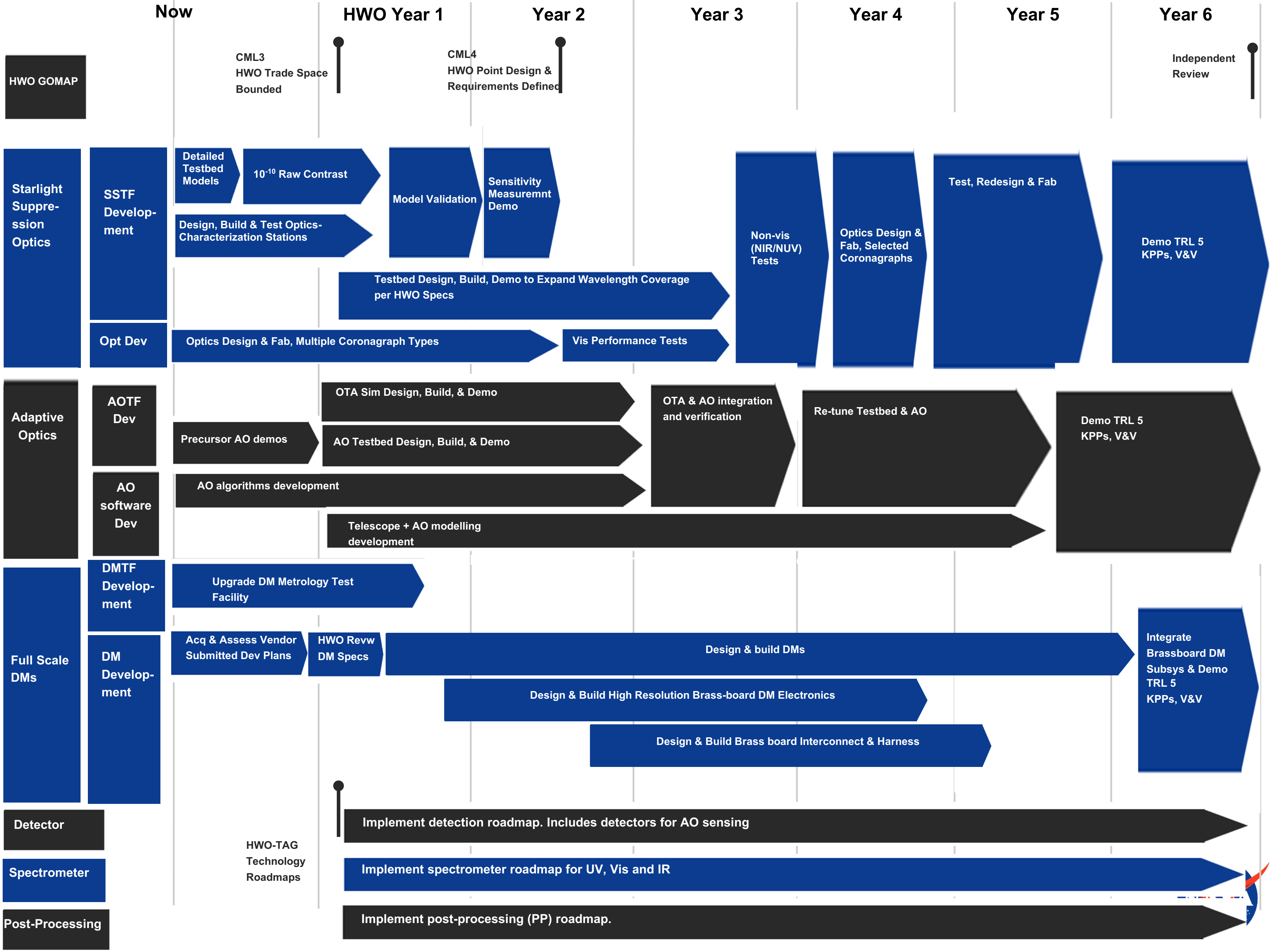


Emerging tech



Maturation Plan: Notional Baseline

- The next slide shows our roughly estimated maturation schedule to meet the six-year timeline described in Astro2020
- We posit that the different critical technology elements (starlight suppression optics, adaptive optics, full-scale DMs, etc.) can be matured and validated independently for TRL-5, with clearly defined interface requirements between elements
- We derived notional timescales using the following boundary conditions
    - Overall timeline for developing critical HWO technologies is six years, based on Astro2020
    - The six year clock starts when NASA begins investing in HWO technology on the ~ 10^8 \$/yr scale
    - The overall timeline show comprises the above-mentioned six years plus a lead-in period (starting now)
    - Within each development tack of critical technology element , we estimated the relative required timescale for each phase and fit the end-to-end timescale into the overall timeline
- As such, this is *not* a grass-roots-estimated schedule
- The end of each arrow-shaped bar represents a milestone (in accomplishing the corresponding task/objective)
- **Whether or not the envisaged schedule can be accomplished depends on invested resources**



Now | HWO Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Year 6

HWO GOMAP

CML3 HWO Trade Space Bounded

CML4 HWO Point Design & Requirements Defined

Independent Review

Starlight Suppre-ssion Optics

SSTF Develop-ment

- Detailed Testbed Models
- 10^{-10} Raw Contrast
- Design, Build & Test Optics-Characterization Stations
- Model Validation
- Sensitivity Measuremnt Demo
- Testbed Design, Build, Demo to Expand Wavelength Coverage per HWO Specs

Opt Dev

- Optics Design & Fab, Multiple Coronagraph Types
- Vis Performance Tests
- Non-vis (NIR/NUV) Tests
- Optics Design & Fab, Selected Coronagraphs
- Test, Redesign & Fab
- Demo TRL 5 KPPs, V&V

Adaptive Optics

AOTF Dev

- OTA Sim Design, Build, & Demo
- Precursor AO demos
- AO Testbed Design, Build, & Demo

AO software Dev

- AO algorithms development
- Telescope + AO modelling development
- OTA & AO integration and verification
- Re-tune Testbed & AO
- Demo TRL 5 KPPs, V&V

Full Scale DMs

DMTF Develop-ment

- Upgrade DM Metrology Test Facility

DM Develop-ment

- Acq & Assess Vendor Submitted Dev Plans
- HWO Revw DM Specs
- Design & build DMs
- Design & Build High Resolution Brass-board DM Electronics
- Design & Build Brass board Interconnect & Harness
- Integrate Brassboard DM Subsys & Demo TRL 5 KPPs, V&V

HWO-TAG Technology Roadmaps

Detector

- Implement detection roadmap. Includes detectors for AO sensing

Spectrometer

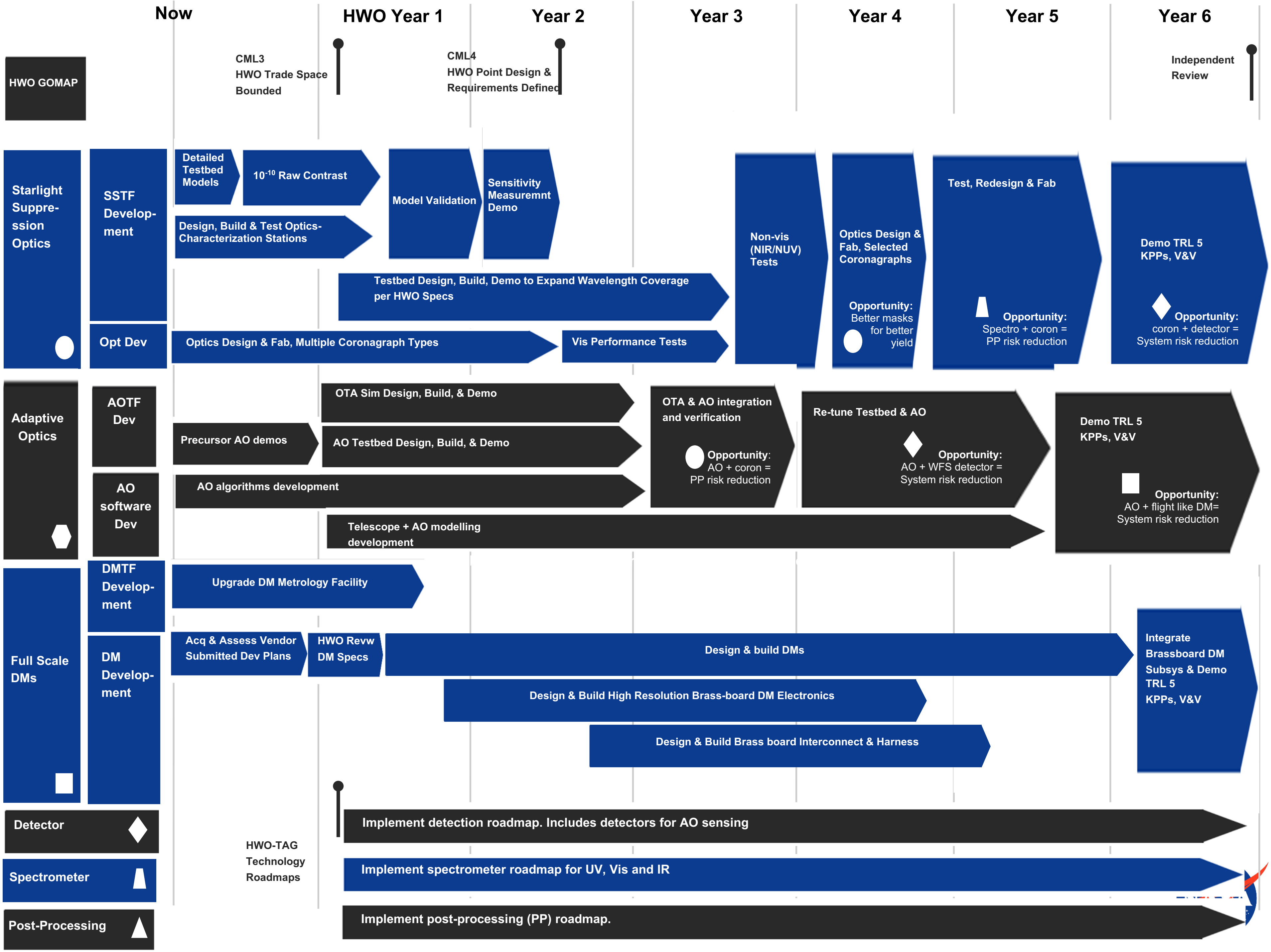
- Implement spectrometer roadmap for UV, Vis and IR

Post-Processing

- Implement post-processing (PP) roadmap.

Maturation Plan: Opportunities

- The next slide shows opportunities in risk reduction by integrating different critical technology elements before TRL 5
- Each critical technology element is represented by a different symbol.
- Appearance of a symbol in the track of another critical technology element represents an integration opportunity



9. Glossary of Abbreviations

Glossary of Abbreviations

Abbreviation	Definition
ADI	angular differential imaging
AO	adaptive optics
AOTF	representative-scale-pupil AO test facility
AOX	Northrop Grumman AOA Xinetics
APLC	apodized-pupil Lyot coronagraph
ASIC	appplication-specific intergrated device
Astro2020	Decadal Survey on Astronomy and Astrophysics 2020 (Astro2020)
BMC	Boston Micromachines Corporation
CDS	Coronagraph Design Survey
CGI	Roman Space Telescope's Coronagraph Instrument
CIC	clock-induced charge
CLC	classic Lyot coronagraph
CML	Concept Maturity Level
CTR	Coronagraph Technology Roadmap
D	diameter
DM	deformable mirror
DMTF	DM test facility
DMTR	Deformable Mirror Technology Roadmap
DST	Decadal Survey Testbed, part of HCIT
DTF	detector test facility
EBS	Error Budget Software
EFC	electric-field-conjugation algorithm
EM	engineering model
EMCCD	electron-multiplying charge-coupled device

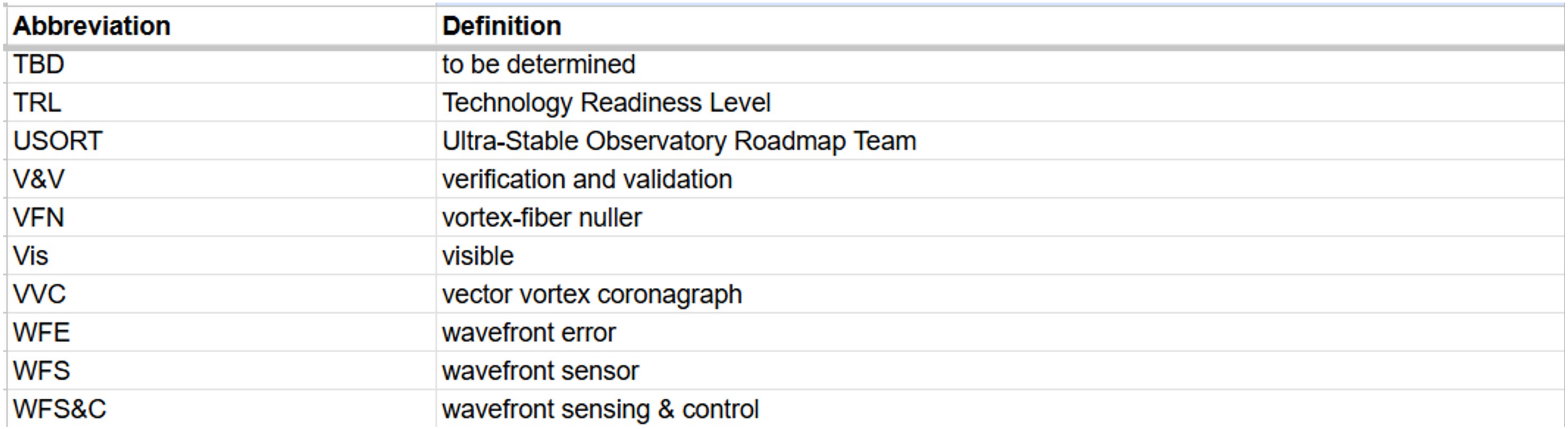
Glossary of Abbreviations (cont’d)

Abbreviation	Definition
ExEP	NASA Exoplanet Exploration Program
ExoTAC	ExEP Technology Assessment Committee
FoV	field of view
FPM	focal-plane mask
GOMAP	Great Observatory Maturation Program
GSE	ground support equipment
HabEx	Habitable Exoplanet Observatory
HCIT	High Contrast Imaging Testbed, an ExEP ground test facility
HLC	hybrid Lyot coronagraph
HOWFS	high order wavefront sensing
HWO	Habitable Worlds Observatory
HZ	habitable zone
IWA	inner working angle
JWST	James Webb Space Telescope
KPP	key performance parameter
LMAPD	linear mode avalanche photodiode
LOWFS	low order wavefront sensing
LP modes	liner polarized modes (spatial modes of propagation in axisymmetric, weakly guided optical fiber)
LUVOIR	Large Ultraviolet Optical Infrared Surveyor
MCR	Mission Concept Review
MDR	Mission Definition Review
MEMS	microelectromechanical systems

Glossary of Abbreviations (cont’d)

Abbreviation	Definition
NIR	near-infrared
NUV	near-ultraviolet
OTA	optical telescope assmebly
OWA	outer working angle
PAPLC	phase-apodized-pupil Lyot coronagraph
PCA	principal component analysis
PIAA-CMC	phase-induced amplitude apotization complex mask coronagraph
PLN	photonic-lantern nuller
PMN	lead magnesium niobate
PoV	point of view
PSF	point-spread function
QA	quality assurance
QE	quantum efficiency
RDI	reference differential imaging
SCDA	Segmented Coronagraph Design and Analysis
SNR	signal-to-noise ratio
SotA	state of the art
SPTF	spectrometer & post-processing ground test facility
SSTF	subscale-pupil starlight-suppression ground test facility
START	Science Technology Architecture Review Team
t	required integration time
TAG	Technical Assessment Group

Glossary of Abbreviations (cont'd)



Abbreviation	Definition
TBD	to be determined
TRL	Technology Readiness Level
USORT	Ultra-Stable Observatory Roadmap Team
V&V	verification and validation
VFN	vortex-fiber nuller
Vis	visible
VVC	vector vortex coronagraph
WFE	wavefront error
WFS	wavefront sensor
WFS&C	wavefront sensing & control

Feedback from Working Group Members

Readme

- A draft of this report was circulate to all members of the CTR Working Group for feedback
- The following slides summarize the 116 feedback comments from 11 members: M. Bottom (U. Hawaii), N. Jovanovic (Caltech), B. Dube (NASA JPL/Caltech), A. Carrier (Lockheed Martin), H. Zhou (NASA JPL/Caltech), C. Stark (NASA GSFC), O. Guyon (U. Arizona), V. Bailey (NASA JPL/Caltech), R. Belikov (NASA ARC), R. Juanola-Parramon (GSFC), N. Siegler (NASA ExEP, JPL/Caltech)
- Rows shaded green indicate that we have implemented suggested changes (or, in a few cases, we removed the content to which the comment pertained). Responses to other comments are yet to be implemented.

REVIEWER	ORIGINAL EMAIL DATE	COMMENT	RESPONSE
Bottom	5/31/2024	Detector noise requirement higher than usual	Revised per follow-on discussions
Jovanovic	5/31/2024	Add photonic testbed to ground test facilities	Included as a gap on p. 9 & 95. Will add call out on photonics development and characterization capabilities as requiring focus if NASA plans to go down that track. Could be part of slide 95 or other.
Dube	5/31/2024	P. 8: Dichroic beamsplitters have been tested, just not in the high contrast context	Will edit accordingly
		P. 8: Add internal stability to detectors	Good point, under consideration
		p. 9: Add size/mass of DM electronics	Good point, under consideration
		p. 9: Add AO modeling (V&V) gap	Good point, under consideration
		p. 13: Making things before CML 3/4 carries risk of expending time and money on things that don't wind up being useful	Good point, under consideration
		p. 13: Is the fabrication meant to be “high potential widgets,” or “systems?”	Need clarification
		p. 33: The slide is difficult to understand	Will edit accordingly
		p. 35: Clarify meaning of mitigation factors and LF	Will edit accordingly
		p. 35: Clarify meaning of mitigation factors and frequency bins	Will edit accordingly
		p. 35: The LF mitigation factors, if they extend down to 1.6 mHz (as for CGI LOWFS), implies an enormous imporvement, even before considering 1/f noise.	Good point, under consideration
		p. 38: There might be no practical way to test 0.5 pm at 50 Hz	Good point, under consideration
		p. 38: Allowing 100 pm at 0.1 Hz seems wild, implying 36 nm/hr	The 100 pm for 0.001 Hz requirement prevents the wild scenario
		p. 41: Say more about EMCCD assumptions? Are you assuming true photon counting always, with associated “dQE”? If not, are you considering the excess noise factor?	Will edit accordingly
		p. 46: I disagree that established manufacturing process makes 96x96 DMs for AOX; they have never done it before. It is “hypothetically” doable by abutting 2x2, 48x48 modules. But for that to make “a DM”, the four modules must be twins. In all of the DMs that have been delivered to JPL, we have never seen two that even look like they are in the same family.	Will edit to clarify
		p. 47: BMC has previously made a 100 x 100 DM on an SBIR, but its yield was awful (conectorization type of problem).	Good point, under consideration

		p. 47: The vias that you mention are periodic with the pitch, (i.e., 96 lambda/D) and extremely far away from a planet near 2 or 3 lambda/D. I think the more significant challenge is the “crinkle” of the thin face sheet under strong actuator effort, which makes the DM have a more nonlinear behavior under large effort than an AOX DM.	Good point, under consideration
		p. 49: Please disenable [disentangle?] drive electronics from the electromechanical device that is the “DM.” Comparing 16 to 20 bits is not like-for-like. I also do not understand 0.65 pm for the BMC DM? BMC gain is ~10nm/volt. 10*(125/2^20)~= 1.2 pm, not 650 fm	Will edit accordingly
		p. 69: Add reference to Dube et al (2022), “exascale integrated modeling of low order wavefront sensing and control for the Roman Coronagraph”	Reference and short description added
		p. 72: Append to final line, “…and low photon flux over a full RDI cycle of ~12 hours”	Will edit accordingly
		p. 75: CGI LOWFS models are highly (again, <<1%) validated to the OMC testbed	Will edit accordingly
		p. 136: Credit Dube	Credit added
Carrier	5/31/2024	p. 8: State that "WFE Stability Environment Gap" is a cross-cutting technology gap	Will edit accordingly
		pp. 11-12: Has team insights into relative technology development budget allocations between Coronagraph and other technology areas such as baffle, etc…or the coronagraph specific budget needs? Would the Astro2020 team have that information based on how it arrived at is $800M technology development estimate?	Answer: We don't know
		pp. 12-13: Maturing component technologies to TRL5 is necessary but likely not sufficient to claim TRL5 as a system. Should not there be a plan for a coronagraph-level test-bed (existing or new?) with component technologies feeding into that test-bed as they mature for system-level demonstration, or else incur an unacceptable risk? Especially in light of the models not capturing all the errors currently. Not currently captured in schedule…but also saw that it is by design…might be questioned.	Good question, will respond.

		p. 22: Should not the team consider the reference stars used for calibration in differential imaging in addition? Or is that a non-constraint?	Good point, under consideration
		What concept of operation is assumed (related to differential imaging in particular)? Need for slews is a major driver on observatory thermal and dynamic stability	Answer: CGI con-ops. Added assumption to the "Operating Assumptions: Mission Architecture" slide
		p. 31: I assume the “Allowable WFE” is post wavefront compensation. May be emphasize one way or the other for clarity.	Edited accordingly
		p. 31: “Allowable WFE”: is that independent of temporal frequency content?	Will edit to clarify
		p. 33: I assume “Integration Time” is total integration time here. Is not there also a dependency on time between wavefront correction updates? The latter is the one most relevant to the wavefront sensing and control system. Has the team insight into what update rate might be achievable for the target stars used in this analysis?	Yes, we refer to the total integration time here. Wavefront control needs to maintain stability over this timescale. The optimal update rate will depend on observatory characteristics and observing scenario, beyond the scope of the CTR study.
		p. 35: Low-Mid-High spatial frequency was defined earlier but missing definition of Low-Mid-High temporal frequency scale (?). Important to others as achieving 10:1 error rejection at 10 Hz is much harder than achieving 10:1 rejection at 1 Hz. Will drive gap interpretation.	Added two slides to define the frequency bins
		p. 36: Would it be better for left table to report RSS instead of SumSquares?	Good question, under consideration
		p. 38: Quantify “we can’t drive fast”…is it really a constraint on HWO given the relatively low temporal frequencies?	Good question, under consideration
		pp. 81-82: Has team early insight into metrology gauge and edge sensor stability requirements given assumed telescope optical prescription? Opening up bandwidth also implies passing more noise from those sensors.	Good question, under consideration
		p. 106: Not demonstrating TRL5 at the system level, it seems, might an unacceptable risk, and become a seriously challenged assumption. May put it up as a critical program discussion topic.	Added bullet point
Zhou	6/1/2024	Add a page or two on state-of-the-art of CGI HOWFSC modeling (and its gaps). Provided slides that we can use.	Inserted the 3 slides

		p. 135: Change Zhou 2023 referencer to 2020 SPIE	Edited accordingly
Stark	5/31/2024 from Chen	We state the NIR IWA challenge and gave an example of 1 lambda/D at 1.6 um for 60 mas. While that is true if we want to characterize all target stars, ultimately we might take what we get. We should add a sentence or two, e.g. stating a trade between NIR target selection and technology options should be conducted (I'm just making this up now per Chris's comment).	Added sticky note recommending trade on "Infrared" slide
Guyon	6/5/2024	p. 15: Unclear what "PP risk reduction" means. Does this refer to PP being a risk reduction opportunity (relaxed requirements on WF stability) ? .. or ... AO+coro integration will allow for testing of PP, which is a rist reduction for PP algorithms ?	Will edit to clarify
		p. 33: need to add note explaining why required exp time is shorter at inner HZ in top 2 plots (planet brighter), but not in bottom plot (WFE mostly affecting near-IWA region ?)	Edited accordingly
		p. 37: Should mention actuator count requirement is especially challenging for UV	Need clarfication
		p. 43: We could define what is meant by post-processing. There are two "flavors": - use science images alone (Roman CGI PCA simulatios) - use WFS/C telemetry + science images	Edited to better define post processing
		p. 63: Chip-integrated photonic device (or photonic nulling chip, PNC) should not be a sub-bullet of PLN. PLN and PNC are two implementations of photonic technologies using waveguides. They could be combined, or not. I suggest making the main bullet "photonic nulling technologies", with PLN and PNC sub-bullets.	Edited accordingly
		p. 65: Replace PLN with "phonic nulling" for generality (refers to both PLN and PNC)	Edited accordingly
		p. 90: Need for low dark current should also be listed (for spectroscopy - especially in NIR)	Edited accordingly

		p. 94: Change "and miniature size" to "in miniature size", as "miniature size" is not a key requirement (small IWA is the key requirement)	Slide removed
Bailey	6/7/2024	Need investment in low internal reflection linear polarizers and quarter wave plates to enable VVCs. Maybe this is part of the “starlight suppression optics subsystem” gap? It could be worth calling out explicitly	Under consideration
		Find and replace CGI with "Roman Coronagraph"	Placed first mention of CGI in quotes to indicate that the abbreviation is just for this report
		p. 43: Clarify that CGI 2x gain is the factor beyond single-roll classical RDI, not vs. raw (see comments on slide)	Edited accordingly
Belikov	6/7/2024	p.6: Priority definitions do not make sense. Why should a low-impact, large gap receive same priority as a high-impact, small gap?	Agree w/ critique. Edited color coding and priority scheme.
		p.6: Impact definitions confusing. Change "mission return" to "risk and/or cost," or "reduction" to benefit	Hopfully, the edits above will make this clearer as well.
		p. 6: For “gap size” definition, I recommend tying it to how challenging it is to close, rather than the size of the gap. I can think of cases where a gap size of 10+ may be trivial to close, and a gap size of < 2 that is very challenging to close. If money had no political undertones, I would classify small / medium / large as needing an investment of o($1M) / o($10M) / o($100M) to close.	Peforming meaningful estimates as suggested is beyond CTR's resources.
		p. 7: Links to CDS reports. Slides: https://exoplanets.nasa.gov/internal_resources/3037/CDS_ExEP_Colloquium_05_20_2024v6.pptx.pdf Recording: https://exoplanets.nasa.gov/internal_resources/3036/ExEP%20Tech%20Colloquium%20Coronagraph%20Design%20Survey%20-%20Rus%20Belikov,%20NASAARC),%20Chris%20Stark%20(NASAGSFC)-20240520%201702-1.mp4 (Written final report coming)	Added link to https://exoplanets.nasa.gov/exep/ for CDS and DMTR
		p. 8, 1st bullet point: I agree with this statement if it talks about current high TRL designs. But, this could be possible with better optimized designs, and we know it is possible with low TRL architectures. I worry that the response to this gap might be to make the telescope even more stable, which will eat everyone else's lunch. I think the way to approach this is to figure out whether it is easier to make the telescope more stable, or the coronagraph more robust. I think rephrasing it the way I suggest would motivate that kind of trade.	Identified telescope stability vs. coronagraph robustness as a future trade for HWO to conduct

		p. 8, 1st bullet point: Replace "The coronagraph instrument is" with "Current high TRL coronagraph designs are"	Will edit accordingly
		p. 8, 2nd bullet point: Replace "Starlight suppression optics" with "Current designs for high TRL starlight suppressions optics"	Will edit accordingly
		p. 8, 3nd bullet point: Replace "Medium impact" with "High impact." Chris's calculations show that yield is a stronger function of efficiency than contrast. For this reason, I recommend changing impact to "high"	Leaving it as is for now. HWO should monitor this, and update if necessary, per mission requirements.
		p. 8, 4th bullet point: Change vis impact to medium. Lee has been asking us about photonic chips specifically for visible for some reason. Maybe we can clarify why he is interested.	Leaving it as is
		p. 10: Starlight suppression optics does not appear here. Perhaps we need to add “starlight suppression optics” to the label of the second matrix.	Will edit accordingly
		p. 13: Do we want to show an explicit on-ramp for emerging techs? Even ones that might not be at TRL5 by year 6 (even if that's too late for the initial batch of instruments, we don't want to start too late to develop instruments for servicing missions).	Good point, but deferring to HWO project.
		p. 13: Why not conduct vis, NIR, and NUV tests in parallel on multiple testbeds? (Maybe spread across multiple centers). We probably need different layouts and testbeds for different wavelength bands anyway, so this is a natural thing to parallelize	The "Key Findings" on p.16 states this point (without specifying whether or not the testbeds should be spread across multiple centers)
		p. 13: This is missing a potentially critical row: "AO system architecture design". (E.g. do we want to go with woofer-tweeter? Curved DMs? Are we sure 2 DMs per channel is the correct number, or is that possibly outdated common wisdom? Are we sure one of the DMs needs to be in a pupil plane, as opposed to pupil plane being in the middle? Are we sure we have the correct distance between DMs? Etc.)	Good points, HWO project should conduct such trades.
		p. 15: Opportunity: Post-processing + Coronagraph: opportunity for risk reduction (relaxing raw contrast requirements).	Agree with this opportunity, but not sure if it requires merging post-processing demonstration with the starlight-suppression testbed. The overall report does state importance of post processing in relaxing requirments

		p. 16, 1st bullet point: insert at end of 1st sentence, ", for segmented apertures (including the possibility of an on-axis segmented aperture)."	Will edit accordingly
		p. 16, 1st bullet point: insert at end of 1st sentence, " These testbeds need to be efficient and reliable to maximize the rate of tests per week. (Fully automatic calibration and fully automatic dark hole digging. Capable of reaching 1e-9 contrast in less than ~1 minute, and eventually 1e-10 in less than ~10 minutes)."	Seem too specific to state in general findings
		p. 16, 3rd bullet point: insert at the end ", especially better modeling of testbed environment itself (e.g. thermal and mechanical stability)"	Good point, but seems implicit as is
		p. 20, objective 2: I recommend saying "~1e-10" or "Xe-10", since we do not know for sure that 1e-10 is actually necessary -- this is a subject of an upcoming parameter study. Although perhaps demonstrating 1e-10 has value even if actual requirement ends up being 4e-10.	Not sure why we should be more specific when "we do not know for sure that 1e-10 is actually necessary"…
		p. 21, point 1: Replace "Any mission" with "The baseline"	This chart shows the going in assumptions at the start of our effort. We did not have a baseline mission architecture.
		p. 21, point 1: Insert at the end, " (other architectures could be studied for launch beyond first half of 2040s on servicing missions)"	Again, these are going-in assumptions, not recommendations. We will edit to clarify.
		p. 21, point 9: IIRC, EAC1 gap sizes are smaller (I forget the exact size).	Again, these are going-in assumptions. No EAC existed at that point.
		p. 21, point 9: EAC3 is on-axis	Same as above
	6/10/2024	p. 31: I think there are two more assumptions here: (a) no DM correction (or alternatively, this WFE is post-DM-correction residual); (b) no coronagraphic suppression (or alternatively, this WFE is post-coronagraph-suppression residual	Need clarfication
		p. 32: I think there are a few other factors that can relax requirements on WFE stability: (a) higher throughput (because it enables deeper post-processing in at least some scenarios, and/or faster loop rates); (b) relaxations in post-processed contrast requirements (which you may be able to trade against IWA and throughput, leaving expected science yield the same); (c) relaxations in raw contrast requirements (same reason as (b)).	Will consider

		p. 37: Is it worth noting that it might be possible to get to 1" with a 64x64 DM or even a 48x48DM? (Options: (a) use more than 2 DMs, spatially displaced by 1/2 actuator with respect to one another (and with thinner influence functions), or maybe there are better geometries; (b) use Super-Nyquist wavefront control; (c) use a woofer-tweeter architecture where the tweeter can be a sparse DM, which has a fundamentally simpler design and may be able to support more actuators easier.	Added future trade for HWO project to conduct
		p. 38: Wouldn't a woofer-tweeter architecture change these requirements? And, maybe these requirements also have some dependence on the distance between DMs? Maybe worth pointing out the possibility that some of the parameter studies we are planning for DM architectures could be game-changing here? Or do you believe there is no chance that these numbers can be significantly relaxed?	Same as above
		p. 51, re. print through of MEMS DM: This statement is coming from Krist et al. 2019, correct? I am not sure if the specific results of that paper can be extended to make a general statement like that -- too many things may be different on HWO. (For example, John assumed a 64x64 DM, and maybe with 96x96 this is no longer a problem? Or maybe with a more advanced EFC algorithm it can be solved? Or with a different coronagraph that has different chromatic levers? Or larger distance betwen DMs? Etc.) I recommend softening this statement to "past estimates of this effect on HabEx limited contrast to 1e-9, but requires a re-evaluation for HWO and a more thorough study"	Good points, will edit accordingly.
		p. 52: Add the following point, highlighted: "demonstrations with segmented apertures are ~5e-9 or brighter, lagging ~1 order of magnitude behind monoliths. Testing with segmented apertures is possibly the highest priority direction right now".	Good points, will edit a few slides down. Note an HCIT test showed a static segmented aperture making only a small difference in contrast at 1E-9 level. Agree that further work is necessary, but not top priority at this point.
		p. 56: Hmm, doesn't unresolved jitter that's present on all testbeds effectively create a star with finite diameter? So, in effect, all of the lab results had a star with some finite angular diameter? Maybe replace "finite angular diameter" by "precisely controlled finite angular diameter"	Good point, will edit accordingly

		p. 57: See the following link, especially lines 14-33. Let me know if you'd like me to generate an updated version of this that shows more recent designs, including for USORT apertures. https://docs.google.com/spreadsheets/d/1Z_D0H4VA1RWyBxuk5VzW4reOKAijnSUGaVjzP_vWWRQ/edit#gid=2138297368	Will add reference to the link.
		p. 58: Earlier slides show that 3e-10 may be sufficient for raw contrast. Should this be changed to "<3e-10, and possibly <1e-10 (to be determined by a future trade study)"	Good point, will edit accordingly
		p. 63: There is a 1e-6 result in 2016 we may want to cite here, albeit it is with MZIs rather than PLNs: https://opg.optica.org/ol/fulltext.cfm?uri=ol-41-22-5318&id=354452 . A team at Stanford also just demonstrated 1e-8. I just pinged Stanford to see if they would be willing to share a draft of their results. There is a long way from 1e-8 nulling demo to a practical coronagraph of course, but it appears that contrast may no longer be the tall pole for photonics. (1e-8 nulling is very roughly speaking equivalent to 1e-10 contrast since the first airy ring is 1e-2)	Added slide on photonic nulling chips to incorportate this information + more. Thanks to Dan Sirbu's input!
		p. 65: I agree 60mas is challenging, but it is mitigated by the fact that stellar sizes and LO aberrations are also easier in NIR in units of l/D. If IWA is limited by stellar size and LO aberrations, I think maybe NIR IWA is not any more challenging? Also, maybe we do not need 60mas in IR in the first place? I mean, if we have a perfectly good coronagraph at 120mas that can do great science on half of our exoEarth targets, and it gets descoped simply because it does not satisfy the 60mas requirement, that would be a shame...	Good point, addressed by response in Row 40.
		p. 69: Highlight this point. I think this point also holds true from a coronagraph design PoV, not just AO PoV. (We can design coronagraphs to be insensitive to specific modes, at least for some architectures.) There are also a couple of related points, though they may be getting too far into the weeds: (a) make modes as "spatially monochromatic" as possible (in order to localize their effect in the image plane as much as possible); (b) make the mode "occupancy factor" as small as possible. For example, there are 4*pi*k Fourier modes with spatial frequency k. If all of them are vibrating, we cannot detect planets at spatial frequency k. But, if only a fraction of them are vibrating, we only suffer a throughput loss on those planets.	Good points, will find the right place to add them

		p. 75: I recommend adding the following point: at 3e-11 level, most of the modeling effort will be about modeling the testbed rather than the coronagraph (judging by slide 53).	Will add a point about testbed modeling
		p. 82: Maybe move the "coronagraph designs" into the list of first 3 sub-bullets?	Will edit accordingly
		p. 83, re. NIR IWA: recommend adding ("although this is mitigated by the fact that stellar sizes and LO aberrations are easier for NIR in units of l/D")	Will edit accordingly
		p. 83, last bullet point: I hesitate to suggest this because it is self-serving, but please consider adding the following if you judge it important enough: "starlight suppression for binary stars has not yet been fully demonstrated"	Good point we will include this.
		p. 84: add and highlight: "especially segmented apertures!"	Good point we will include this.
		p. 84: Add and highlight: "very few demonstrations with segmented apertures"	Good point we will include this.
		p. 85, 1st bullet point: add "with segmented apertures"	Good point we will include this.
		p. 85: 2nd bullet point: If you judge it to be important enough, please consider adding "binary star suppression technologies" to the list of recommendations. [I won't be offended if you skip it -- I know I may have a conflict of interest here.]	Good point, under consideration
		p. 87: Add: invest in a thorough study of WFC architectures to optimize performance vs. DM maturity, risk and cost (e.g. woofer-tweeter, 3+ DMs, curved DMs, drizzle DM registration, sparse DMs, Super-Nyquist WFC)	Added bullet point in recommendations
		p. 88, Description: I recommend adding "coronagraph throughput, bandwidth, IWA" in addition to dichroics -- those all impact efficiency in roughly comparable ways? Also, detector QE, coating reflectivity, observing strategy / schedule optimizations?	Edited accordingly
		p. 88, Impact: Add: This gap, if not closed, can also drive other requirements higher (telescope diameter, coronagraph throughput, wavefront stability) -- in general, most parameters can be traded off against one another under the constraint of a fixed science yield.	Good point we will include this.

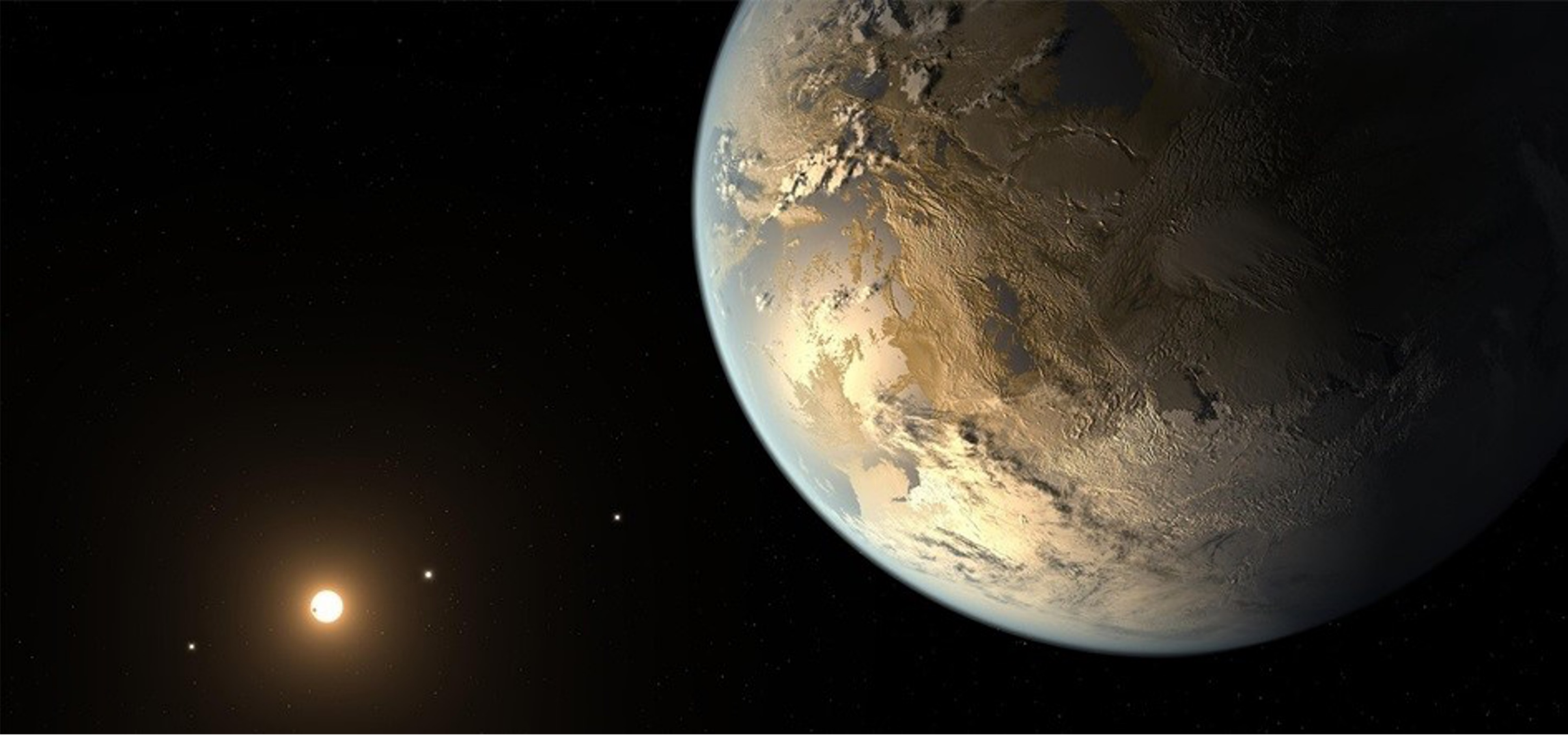
		p. 88, Gap Size: It's not immediately obvious to me why this is the main/only bullet describing this gap size. Shouldn't it say something like "mission efficiency is a factor of X away from requirements and/or from theoretical limits?"	Good point we will include this.
		p.89: If you agree with my statements in the previous slide, I would add the following bullets (and maybe cull or combine the previous ones to make space): perform a thorough analysis of: (a) reducing # of optical elements; (b) on-axis apertures (which may enable a larger aperture for the same cost); (c) more efficient coronagraph designs; (d) more robust coronagraph designs (which would enable shorter integration times b/c post-processing wouldn't need to work as hard to beat down speckle noise); (e) DRM optimizations; (f) [if you judge it important enough] binary star suppression technologies and DRMs using binary stars (ability to target binary stars makes the average star brighter, reducing exposure times, and maybe allows more efficient post-processing b/c you can calibrate two nearby stars on each other).	Good point, under consideration
		p. 93: Mature next-generation WFC algorithms, such as dark hole maintenance, and [if you judge it important enough] super-Nyquist wavefront control, and multi-star wavefront control. Also, next-generation post-processing algorithms (HRHCI?)	Edited accordingly
		p. 94: may not mature in time for the first generation set of instruments for HWO.	Edited accordingly
		p. 94: I hate to be self-serving again, but if you judge it important enough, you may want to cite Sirbu et al. 2024 (let me know if you'd like to see a draft of Dan's SPIE paper or ECI proposal). Also, you may want to add PIAA-Vortex and PAPLC (which enable potentially cost- and risk-saving on-axis segmented apertures). We have more discussion of emergent technologies in the CDS report (Belikov, Stark, et al. 2024).	Good point. Sticky note to PO to update this based on SPIE proceedings.
		p. 94, Key Issues: See my comment on slide 63. I think the key issue is no longer contrast, but throughput and # of channels. Though it really depends on what exactly we are talking about.	Good point, under consideration

		p. 94, last bullet point: Hmm, I would consider this an advantage, rather than an issue. Nulling technologies by their nature can be designed to "snipe" unwanted modes more easily than coronagraph technologies.	Slide removed. Emergent technology gap is incorporated as NIR gap for starlight suppression optics.
		p. 95, Impact: PICs can in theory boost yield by a factor of 2-4 (see slide 51 on the following link). In addition, they can in theory snipe modes, relaxing stability requirements by a large factor. Finally, they can miniaturize the coronagraph, saving considerable volume, and enabling a large number of spectral channels. This represents an impact that seems much greater than for almost any other technology (but the gap is also correspondingly large of course). Due to this potential impact, I would change impact to "high" on both, or at least "medium on Vis, and high on NIR". On-axis coronagraphs also have at least a medium impact, because on-axis apertures make many other requirements easier. https://exoplanets.nasa.gov/internal_resources/3037/CDS_ExEP_Colloquium_05_20_2024v6.pptx.pdf	Slide removed
		p. 95: Please consider adding the following bullets: (a) conduct a thorough study of on-axis aperture: benefits, requirements relaxations, and coronagraph designs such as PAPLC and PIAA-Vortex; (b) conduct a thorough benefit / maturity cost analysis of photonic chips; (c) create a "tiger team" to thoroughly consider the potential of all emergent technologies, as well as unconventional approaches to HWO using mature technologies (e.g. alternative DM system architectures, relaxations of raw contrast, etc.)	Good point, under consideration. We tried to keep recommednations a bit more generic, but for this we might need more specific statements.
		p. 96: A large number of testbed effects manifest themselves at <1e-10 contrast and are not currently modeled (see slide 53). More modeling effort may need to be dedicated to the testbed itself rather than the coronagraph at those contrast levels.	Good point we will include this.
		p. 107, point a: Add "(x4 or even x5)". I don't know how much detail we want to add here. (Are you envisioning vacuum facilities at GSFC, ARC, and UofA in addition to HCIT? Should they have separate use cases, maybe different layouts testing different architectures, or simply enable many of the same kinds of tests to be conducted in parallel? Do you think we should list an SSTF specifically for PICs?)	We have no vision regarding physical location. Separate use cases and layouts are our recommendation. Dediated SSTF for PICs is needed to advance PIC readiness.

		p. 108: If we are thinking in terms of multiple SSTFs at different geographic locations that have potentially different use cases, I would state this as "The combined set of SSTFs must enable the following functionalities (not necessarily all at every SSTF):"	Good point we will include this.
		p. 108: The very first bulletpoint on this list should be "segmented apertures", and this should be highlighted. I know this is obvious and perhaps implied, but the purpose is to bring to attention the fact that to date, there have been only very few segmented demos in vacuum. I also recommend adding "binary star source capability" and "finite star source capability".	Good point we will include this.
		p. 110, 2nd bullet point from bottom: Insert after "sensitive to WFEs": "(and, by the same token, have more theoretical design levers to make them more insensitive to WFEs than traditional coronagraphs)."	Slide removed
		p. 111: It's not obvious to me why "closing gaps" (the title of this slide, and the y-axis) should result in any motion along the x-axis. I think this may be a holdover from when these diagrams had "risk" on the x-axis? Defining "impact" more precisely is needed to avoid confusion. In my mind, "impact" is the level of benefit to the mission that results from closing the gap. (Same comment for all the subsequent slides like this.)	Closing a gap in one category does not move the x axis in said catergory. However there are some interactions between categories: say maturing a high throughput coornagraph reduces the impact of not closing gap on detector noise.
Kasdin	7/13/2024	You know that Ewan Douglas is building a UV vacuum testbed, right? Not sure if you want to mention that, but thought I'd bring it up.	PO needs to go over our slide deck and update SOTA with accpeted SATs . We will add sticky note.
		You had a good discussion of risk mitigation approaches. But to me, the big risk is that we simply don't close on the requirements in 6 years. That is, we can't reach TRL 5 on certain components. What then? I think this is most likely for the NIR channel. That depends a great deal on a major improvement of new technology.	Not sure. I think the more accurate statements is "IR yield will be very low without major tech improvement". We should leave it out to PO to map that yield to tech.
	7/15/2024	I did finish a pass through the report this weekend. I think it is excellent and very thorough. I did note that dark hole maintenance was discussed there. But I'll be honest, the conclusions that we need all of those testbeds, and in parallel, is frightening. Will the money and resources really be there? I thought the roadmap was very clear but I think accomplishing all of that in 6 years is daunting. Not sure I see an alternative, though.	Received lound and clear. One of the thigs we tried to highlight is how can things be accelerated (of course that requires funding, we are punting on that).

Juanola-Parramon	6/7/2024	In the list of deliverables, how specific do you want to be? I did present the UV coronagraph design at the UV Workshop, and I will be presenting as well in Yokohama (poster). Not sure if this should be included in the list.	Added deliverable item
		I might have missed it, but I couldn't find anywhere in the document that the UV coronagraph could/should be a separate instrument. At this point, given that it has been set that the main coronagraph instrument will only be visible and NIR, should we consider adding a slide or two about developing a UV coronagraph instrument concept?	Good point. The rationale is that our charter of a "roadmap" did not cover "where to put the instrument". But at this point we should put it back in. Note that we do mention in the "Gap: Starlight-Suppression-Optic Subsystem" section that "A possible pathway is to utilize separate UV and vis/IR instruments and different types of coronagraphs to get the job done." Added text in "Executive Summary" about standalone UV instrument.
Siegler	6/9/2024	"Emergent technologies" is not a gap; it is a potential solution	Removed "emergent technologies" gap. It is a potential solution to the static performance gap in the IR.

10. Appendix



ExEP

Estimate of UV Throughput for Target-List Calculations

Pin Chen
June 26, 2023

Reflective Losses

- Using Exo-C as a telescope-coronagraph optical layout driven by coronagraphy (per J. Trauger's suggestion)
- Number of reflections
  - Telescope: 2
  - Downstream: 13
    - 1 tertiary mirror
    - 1 FSM
    - 2 pupil re-imaging mirror
    - 2 DMs
    - 1 focusing mirror
    - 1 collimating mirror (to form Lyot pupil conjugate)
    - 1 focusing mirror (for field stop)
    - 1 collimating mirror (for filters)
    - 1 fold mirror
    - 1 focusing mirror
    - 1 flip mirror
  - TOTAL: 15 reflections
- Reflection throughput, Al coating (R = 0.92): 0.92^{15} = **0.29**

Exo-C Instrument Layout

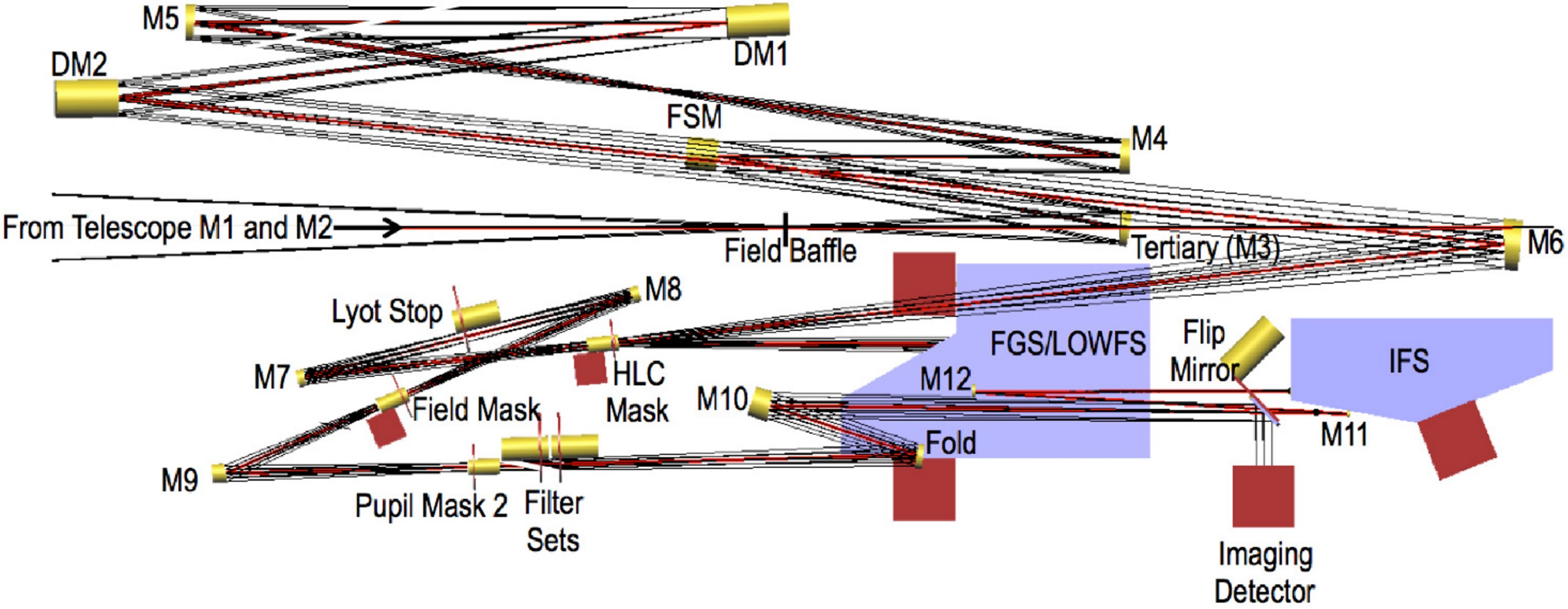


Figure 5.5-1. Instrument bench optical layout. The elements are distributed into two planes to provide a compact package, so there are no interferences between elements and light paths even where apparently conflicting in the figure.

SSTF initial experimental plan

A. Demonstrate *repeatable* raw contrasts that are sufficiently deep for compelling science yield and achievable contrast stability.

- In this case the raw contrast goal ought to ultimately be set following analyses from START and TAG.

- While waiting for the outcome of such analyses, an immediate goal is to improve upon the contrast floor of this experiment by tracking the limiting factors identified in Seo et al. (2019) .

- In order to establish repeatability, it will be important to identify the root cause of the contrast instabilities reported in Seo et al. (2019), and in particular investigate the hypothesis that these drifts are driven by DM settling.

SSTF initial experimental plan

B.Change/add key components one at a time and repeat step A.

- Possible changes of components are, in no particular order:
  - Add a UV coating on one of the optics.
  - Change the coronagraph mask for one optimized at smaller inner working angles, or for higher throughput.
  - Introduce a dichroic in the optical train.
  - Introduce a segmented pupil without residual static segment phasing errors.
  - Introduce a segmented pupil with residual static segment phasing errors.
- In between each experiment with a new component, stable contrast (step A) should be reproduced in order to re-establish the baseline.
- Experiment prioritization ought to be set following analyses from START and TAG.

SSTF initial experimental plan

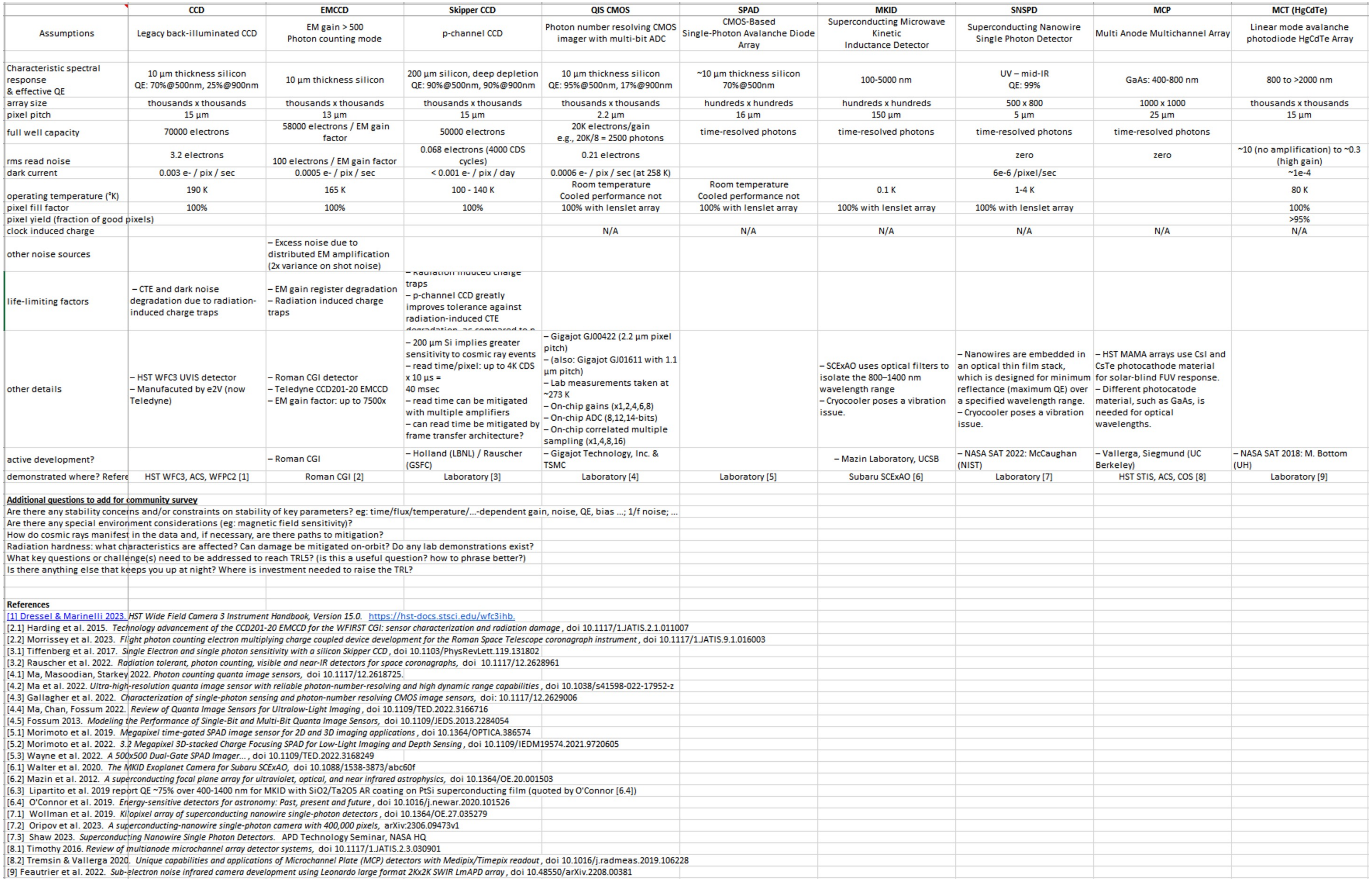
C. For architectures tested in A, and B, once the required contrast is reached, the modulated (e.g. coherent) sensitivities to wavefront errors should be measured using the procedure reported in Zhou et al. (2020, Proc. SPIE)

Possible wavefront sensitivities to measure, in no particular order:

- Low order wavefront errors at the entrance pupil.
- Coronagraph mask misalignment.
- Pupil misalignments, magnification, beam shear, and beam walk.
- Wavefront error due to segmentations (segmented pupil with residual static segment phasing errors).

- In case of limited resources, prioritization of the most pressing sensitivity measurements, as well as actual magnitude of wavefront changes for these experiments, ought to be set following analyses from START and TAG.

Detector Fact-Finding Spreadsheet (J. Trauger, V. Bailey, B. Dube)



	CCD	EMCCD	Skipper CCD	QIS CMOS	SPAD	MKID	SNSPD	MCP	MCT (HgCdTe)
Assumptions	Legacy back-illuminated CCD	EM gain > 500 Photon counting mode	p-channel CCD	Photon number resolving CMOS imager with multi-bit ADC	CMOS-Based Single-Photon Avalanche Diode Array	Superconducting Microwave Kinetic Inductance Detector	Superconducting Nanowire Single Photon Detector	Multi Anode Multichannel Array	Linear mode avalanche photodiode HgCdTe Array
Characteristic spectral response & effective QE	10 µm thickness silicon QE: 70%@500nm, 25%@900nm	10 µm thickness silicon	200 µm silicon, deep depletion QE: 90%@500nm, 90%@900nm	10 µm thickness silicon QE: 95%@500nm, 17%@900nm	~10 µm thickness silicon 70%@500nm	100-5000 nm	UV – mid-IR QE: 99%	GaAs: 400-800 nm	800 to >2000 nm
array size	thousands x thousands	thousands x thousands	thousands x thousands	thousands x thousands	hundreds x hundreds	hundreds x hundreds	500 x 800	1000 x 1000	thousands x thousands
pixel pitch	15 µm	13 µm	15 µm	2.2 µm	16 µm	150 µm	5 µm	25 µm	15 µm
full well capacity	70000 electrons	58000 electrons / EM gain factor	50000 electrons	20K electrons/gain e.g., 20K/8 = 2500 photons	time-resolved photons	time-resolved photons	time-resolved photons	time-resolved photons	
rms read noise	3.2 electrons	100 electrons / EM gain factor	0.068 electrons (4000 CDS cycles)	0.21 electrons			zero	zero	~10 (no amplification) to ~0.3 (high gain)
dark current	0.003 e- / pix / sec	0.0005 e- / pix / sec	< 0.001 e- / pix / day	0.0006 e- / pix / sec (at 258 K)			6e-6 /pixel/sec		~1e-4
operating temperature (°K)	190 K	165 K	100 - 140 K	Room temperature Cooled performance not	Room temperature Cooled performance not	0.1 K	1-4 K		80 K
pixel fill factor	100%	100%	100%	100% with lenslet array	100% with lenslet array	100% with lenslet array	100% with lenslet array		100%
pixel yield (fraction of good pixels)									>95%
clock induced charge				N/A	N/A	N/A	N/A	N/A	N/A
other noise sources		– Excess noise due to distributed EM amplification (2x variance on shot noise)							
life-limiting factors	– CTE and dark noise degradation due to radiation-induced charge traps	– EM gain register degradation – Radiation induced charge traps	– Radiation induced charge traps – p-channel CCD greatly improves tolerance against radiation-induced CTE degradation, as compared to n						
other details	– HST WFC3 UVIS detector – Manufacuted by e2V (now Teledyne)	– Roman CGI detector – Teledyne CCD201-20 EMCCD – EM gain factor: up to 7500x	– 200 µm Si implies greater sensitivity to cosmic ray events – read time/pixel: up to 4K CDS x 10 µs = 40 msec – read time can be mitigated with multiple amplifiers – can read time be mitigated by frame transfer architecture?	– Gigajot GJ00422 (2.2 µm pixel pitch) – (also: Gigajot GJ01611 with 1.1 µm pitch) – Lab measurements taken at ~273 K – On-chip gains (x1,2,4,6,8) – On-chip ADC (8,12,14-bits) – On-chip correlated multiple sampling (x1,4,8,16)		– SCExAO uses optical filters to isolate the 800–1400 nm wavelength range – Cryocooler poses a vibration issue.	– Nanowires are embedded in an optical thin film stack, which is designed for minimum reflectance (maximum QE) over a specified wavelength range. – Cryocooler poses a vibration issue.	– HST MAMA arrays use CsI and CsTe photocathode material for solar-blind FUV response. – Different photocatode material, such as GaAs, is needed for optical wavelengths.	
active development?		– Roman CGI	– Holland (LBNL) / Rauscher (GSFC)	– Gigajot Technology, Inc. & TSMC		– Mazin Laboratory, UCSB	– NASA SAT 2022: McCaughan (NIST)	– Vallerga, Siegmund (UC Berkeley)	– NASA SAT 2018: M. Bottom (UH)
demonstrated where? Refere	HST WFC3, ACS, WFPC2 [1]	Roman CGI [2]	Laboratory [3]	Laboratory [4]	Laboratory [5]	Subaru SCExAO [6]	Laboratory [7]	HST STIS, ACS, COS [8]	Laboratory [9]

Additional questions to add for community survey

Are there any stability concerns and/or constraints on stability of key parameters? eg: time/flux/temperature/...-dependent gain, noise, QE, bias ...; 1/f noise; ...

Are there any special environment considerations (eg: magnetic field sensitivity)?

How do cosmic rays manifest in the data and, if necessary, are there paths to mitigation?

Radiation hardness: what characteristics are affected? Can damage be mitigated on-orbit? Do any lab demonstrations exist?

What key questions or challenge(s) need to be addressed to reach TRL5? (is this a useful question? how to phrase better?)

Is there anything else that keeps you up at night? Where is investment needed to raise the TRL?

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