HABITABLE WORLDS OBSERVATORY

TECHNOLOGY ROADMAP

2024 November 14

Exoplanet Exploration Program Office Webinar Series

Matthew R. Bolcar (GSFC) & Feng Zhao (JPL)

HWO Chief Technologists

Introduction

On August 1, 2024, the HWO Technology Maturation Project Office (TMPO) officially started at Goddard Space Flight Center

TMPO established a joint GSFC/JPL leadership team to define and implement project pre-formulation activities

- Primary goal is to develop HWO to a Concept Maturity Level (CML) 5 by Mission Concept Review in 2029

The HWO Science, Technology, and Architecture Review Team (START) and Technical Assessment Group (TAG) were re-organized into the new project office

HWO Project Office

* JPL ex officio
° Interim

Project Leadership

L. Feinberg, Principal Architect
S. Smith, Project Manager°
J. Ziemer, Pre-Formulation Architect*

Financial: P. Butler
Pub Affairs: C. Andreoli
Community Engagement:
Rob Zellem & Raissa Estrella*
Mentoring & Inclusion: N. Latouf, T.Kataria*

Science

G. Arney, Project Scientist°
A. Roberge,
Pre-formulation Scientist°
B. Mennesson*,
Pre-formulation Scientist

Deputy PS: Mike McElwain
Deputy PFS: Erin Smith
Deputy PFS: Pin Chen*
Coronagraph Instr Sci: Vanessa Bailey*
High Contrast Spectr. Sci: Neil Zimmerman
Camera Instr. Scientist: Tom Greene, Ames
UV Instrument Scientist: Paul Scowen
Exoplanet Theme Ld: Chris Stark
Exoplanet Theme Ld: Renyu Hu*
Astrophysics Theme Ld: Jason Rhodes*
Astrophysics Theme Ld: Allison Youngblood
Solar Systems Ld: Lynnae Quick

Testbeds

B. Sitarski,
Deputy Principal Architect
C. Baker*
JPL Testbed Lead

NASA HOST Lead: M. McElwain
HOST Systems: T. Groff
Keck Demo: M. Troy*

Systems

M. Menzel,
Mission System Engineer
A. Liu, Deputy MSE
M. Levine*, Systems Modeling

Servicing & Instrument Systems: J. Van Campen
High Contrast Systems: C. Noecker
Payload Systems: J. Abel
High Contrast Error Budgets: Brian Kern

Systems Design and Modeling Teams

Technology

M. Bolcar, Chief Technologist
F. Zhao*, Deputy Chief Technologist

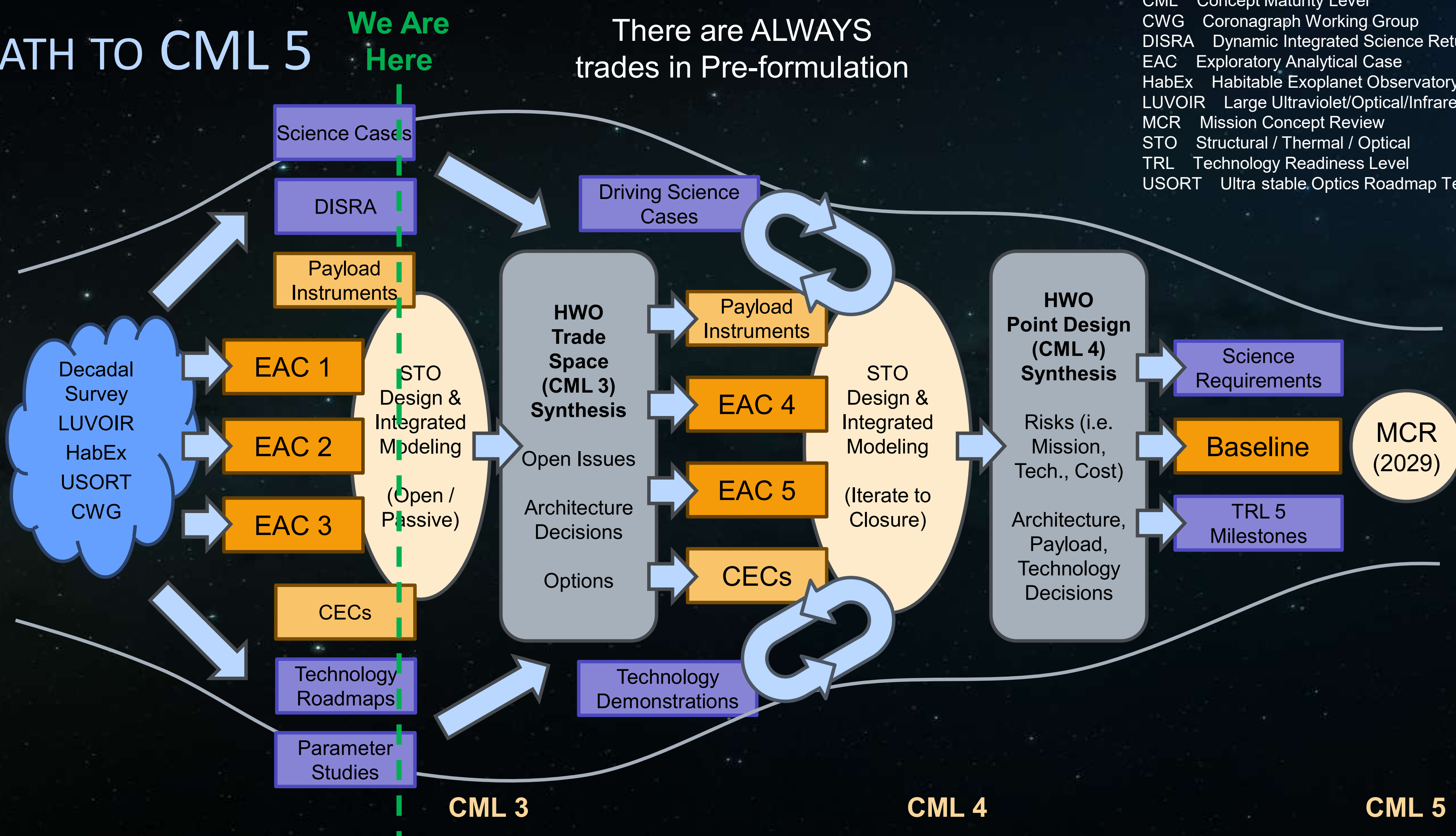
UV/Instrument Technology: Paul Scowen
SME: D. Redding*
SME: P. Stahl, MSFC
SME: R. Belikov, Ames

The Pre Formulation Project Development Team will encompass a broad group, including former START/TAG members.

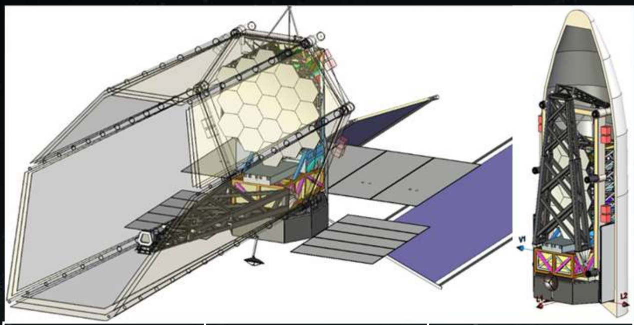
PATH TO CML 5

There are ALWAYS trades in Pre-formulation

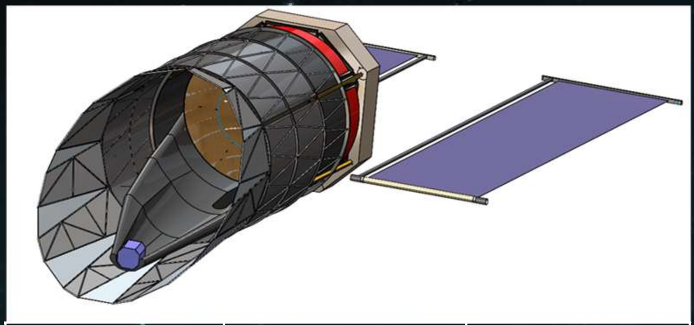
- CEC Coronagraph Exploratory Case
- CML Concept Maturity Level
- CWG Coronagraph Working Group
- DISRA Dynamic Integrated Science Return Analysis
- EAC Exploratory Analytical Case
- HabEx Habitable Exoplanet Observatory
- LUVOIR Large Ultraviolet/Optical/Infrared Surveyor
- MCR Mission Concept Review
- STO Structural / Thermal / Optical
- TRL Technology Readiness Level
- USORT Ultra stable Optics Roadmap Team



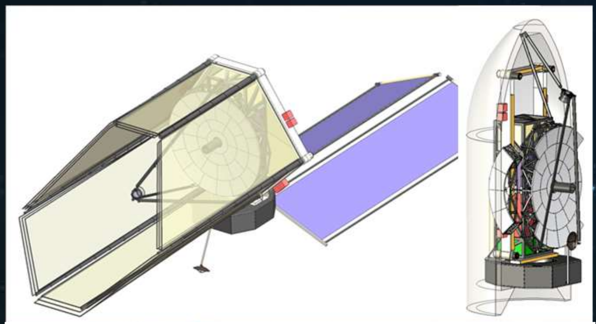
EXPLORATORY ANALYTICAL CASES



EAC1	Assumption	Comments
Launch Vehicle	New Glenn	7m diameter Fairing
Mass	Bottoms up estimate	
# of Mirrors	19 Hex Segments	1.65m point to point
Telescope Diam + Config	Off Axis, 6M ID/7.2m OD	
Deployment	JWST like Wings, Hinged SM Tower	



EAC2	Assumption	Comments
Launch Vehicle	New Glenn or Starship	9m diameter Fairing
Mass	Bottoms up estimate	
# of Mirrors	6+1	3m central mirror, 6 Keystone
Telescope Diam + Config	Off Axis, 6m Circ.	
Deployment	Fixed Primary, SM hinged, Barrel only	



EAC3	Assumption	Comments
Launch Vehicle	New Glenn or Starship	9m diameter Fairing
Mass	Bottoms up estimate	
# of Mirrors	34 Keystone	
Telescope Diam + Config	On Axis, 8m Circ.	Large FOV Hybrid OOFS Guider
Deployment	JWST like Wing, SM	

TECHNOLOGY DEVELOPMENT

OBJECTIVES

1. Identify technology, engineering, modeling, and facility/testbed gaps associated with the formulation and implementation of the Habitable Worlds Observatory.

2. Define roadmaps, milestones, and success criteria for the development of technologies and capabilities to close the identified gaps.

3. Scope the cost, schedule, and human resources needed to implement the roadmaps to achieve TRL 5 by March 2029, ahead of Mission Concept Review (MCR).

4. Execute the roadmaps.

ORGANIZATION

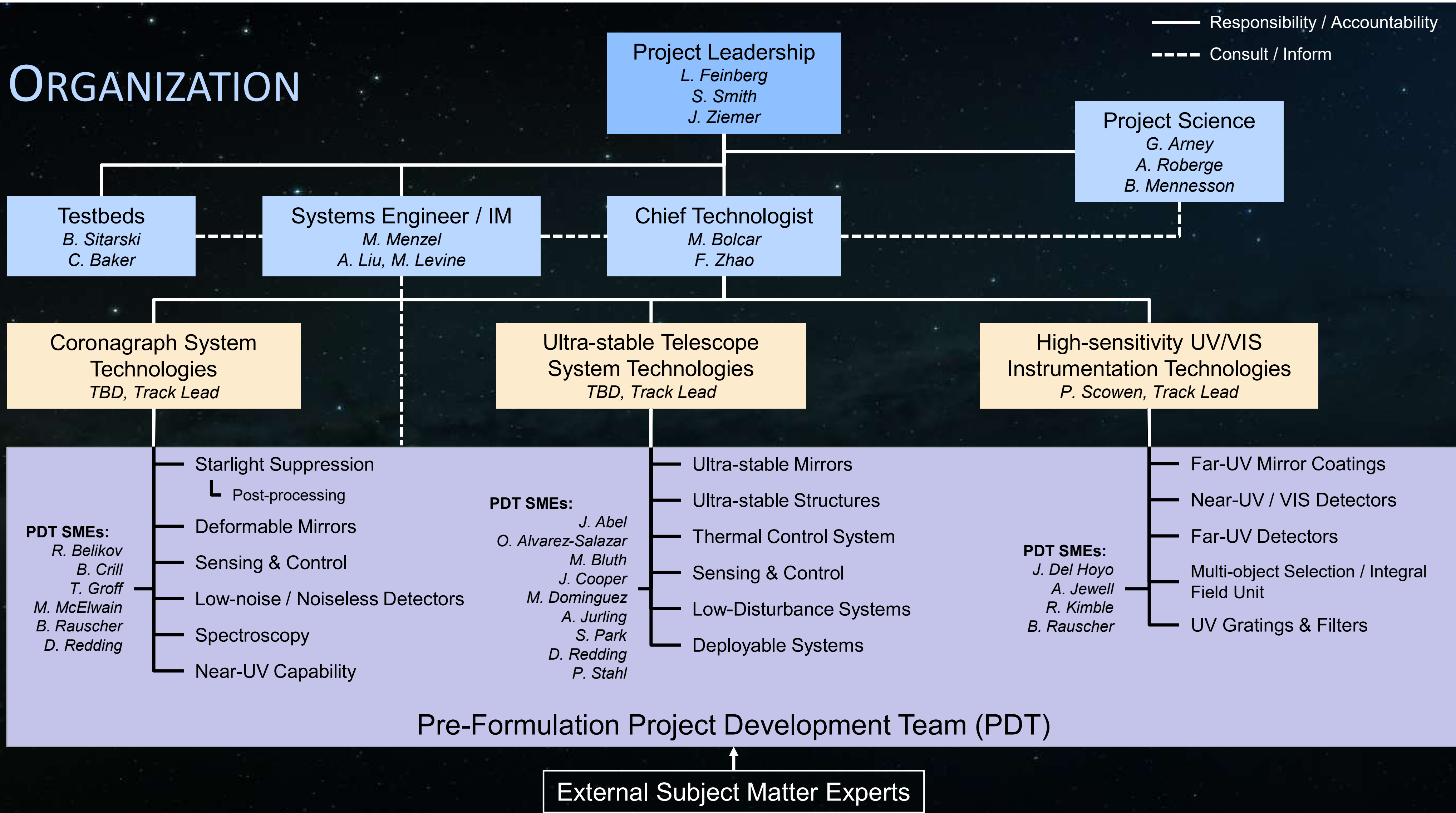
The HWO Technology Plan is organized along three ***tracks***:

- Coronagraph System Technologies (CST)
- Ultra-stable Telescope System Technologies (UTST)
- High-sensitivity UV and Instrument Technologies (HUVIT)

Each track is further divided into ***lanes*** associated with specific technology components or capabilities

- An initial set of lanes is shown on the next slide
- Lanes will be added or removed as needed

ORGANIZATION



TECHNOLOGY ASSESSMENTS

Gap Identification

An “element” is a component, assembly, sub-system, system, or capability that is required for an operational mission

- Elements and their associated functional/performance requirements are defined by the Systems team via the EACs

Gaps are classified as one of the following:

- ***Technology Gap:*** An element for which the required function/performance, form, fit, environment, or interface is novel or not bounded by existing demonstration.
- ***Engineering Gap:*** An element for which the required function/performance is bounded by existing demonstration, but not necessarily in the same form, fit, environment, or interface as needed for HWO.
- ***Modeling Gap:*** A computational, software, or analytical capability needed to adequately verify & validate an element’s performance.
- ***Testbed / Facility Gap:*** A capability needed to support the development of a critical technology element or improve the manufacturability, testability, yield, or reliability of an element.

****Note:*** An element that is not classified in one of the above gaps is considered “heritage”.

Gap Identification

Technology Gaps are further classified as one of the following:

- ***Threshold Technology:*** A technology that must be developed to enable the minimum viable (i.e., *threshold*) mission requirements. Threshold technologies should demonstrate TRL 5 prior to Mission Concept Review.

- ***Baseline Technology:*** A technology that must be developed to enable the baseline mission requirements. Baseline technologies should *at least* have a clear, low risk path to TRL 5 prior to Mission Concept Review.

- ***Enhancing Technology:*** A technology that would either substantially improve the science yield of the mission beyond the baseline or ease the development, implementation, test, and verification of the mission system.

START / TAG Identified Gaps (1/4)

In June 2024, the HWO START & TAG identified the gaps on the following slides

- Initial threshold/baseline/enhancing classification has been completed
- Estimated TRLs based on technology subgroup inputs

Track leads will continue to develop these assessments as road-mapping effort progresses

START / TAG IDENTIFIED GAPS (2/4) – CORONAGRAPH SYSTEM

Technology Track	Technology Lane	Candidate Technologies	Anticipated TRL5 Performance Need	Current State of the Art	(T)hreshold / (B)aseline / (E)nhancing	Estimated Current TRL
Coronagraph System	Starlight Suppression	CLC, HLC, VVC4, APLC, PAPLC, PIAA-CMC, etc.	Component fabrication tolerances demonstrated (e.g., polarization leakage, apodization shape error, film thickness uniformity, etc.) Includes post-processing concept and impacts on stability, sensing & control, and ConOps.	Some candidates achieve individual metrics, however simultaneous achievement by any one candidate of all metrics has not been demonstrated.	T	3-4
	Deformable Mirrors	Xinetics PMN, MEMs, AlpAO, etc.	96x96 stable, high-yield, low-creep actuators; High-precision electronics with robust interconnects.	CGI Xinetics PMN DMs with 48x48 actuators; actuator drift is an issue. MEMs DMs need better surface figure; Room temperature operation.	T	4
	Sensing & Control	LOWFS, OOBWFS, HOWFS, Photonic Lanterns, etc.	(1) Quasi-static contrast: >1e-10 contrast over 20% bandpass over specified IWA-OWA, core throughput with segmented apertures; (2) Contrast stability: Stabilize speckles to ~1e-11 level over specified temporal and spatial bandwidth -- residual from Telescope Sensing & Control	CGI low-order wavefront sensor, controlling tip/tilt and focus. CGI high-order wavefront sensor achieves ~1e-8 raw contrast.	T	3-5
	Low-noise / Noiseless Detectors	EMCCD, Skipper CCD, etc.	4k x 4k format, <0.1 e- read noise, <1e-4 e-/p/s dark current, >80% QE at H_2O detection wavelengths (e.g. 900 - 1000 nm), radiation hard	CGI EMCCD have 0 read noise, dark current of 7e-4 e/p/s, not rad hard and have poor QE at long wavelengths. Skipper CCDs count photons with low dark current, but readout times need improvement. Single Photon Sensing / Photon Number Resolving CMOS sensors have 0.2 e- read noise, <0.002 e/p/s dark current at ~240K and ar rad hard.	T	4
		H4RG, LM-APD, etc.	2k x 2k format, <0.1 e- read noise, <1e-3 e-/p/s dark current, >90% QE over 1-2 um band, ≥70 K operating temp.	Roman H4RG have single-digit read noise, 1e-3 e/p/s dark current and large format. LM-APDs have ~0.5 e- read noise; spurious counts dominated by ROIC glow at 0.01 e-/frame	T/B	3
		TES, MKID, SNSPD	1k x 1k array format with >90% QE at specified wavelengths, stable performance in radiation environment. If energy resolving, need to achieve R ~70/140 for VIS/NIR Note: These techs would supplant need for VIS/NIR Detectors as well as High-contrast Spectroscopy	MKID and TES have demonstrated energy resolving at 0.1 K and 0.05 K respectively. MKID QE~70% at 0.4 um, ~40% at 1.0 um; TES QE ~97% over band. Require cryo-cooling to achieve operational temperatures, which carries system-level thermal & stability impacts.	E	2-3
	Spectroscopy	IFS, Fiber-fed, Energy-resolving Detectors	Need R~70 for VIS, ~140 for NIR with high-throughput. Resolve questions around contrast gain and speckle chromaticity.	PISCES demonstrator for IFS; Some lab demonstrations of fiber-fed devices.	T	3-4
	Near-UV Capability	Coronagraphy, Starshade	Achieve R~5-7 high-contrast photometry between 250-450 nm to search for ozone features	Concepts from VIS coronagraph extend down to NUV, however, many questions pertaining to materials, coatings, scatter, etc. remain open. Starshade of appropriate scale for NUV is in-family with S5 program, however additional study needed to address questions on edges, contamination, and contrast for NUV.	E	2

START / TAG IDENTIFIED GAPS (3/4) – ULTRA-STABLE TELESCOPE SYSTEM

Technology Track	Technology Lane	Candidate Technologies	Anticipated TRL5 Performance Need	Current State of the Art	(T)hreshold / (B)aseline / (E)nhancing	Estimated Current TRL
Ultra-stable Telescope System	Ultra-stable Mirrors	Material: ULE, Zerodur, SiC, etc. Architecture: open back, close back, etc.	Stiff, thermally stable mirror segment of target areal density, 500 nm diffraction-limited surface figure, ~0.3 nm RMS surface roughness, ~1 mm edge roll-off; operational temperature 270-293K with required CTE knowledge and homogeneity to enable thermal performance prediction	MMSD program made 5 ULE 1.4m mirror segments, one full PMSA assembly, one finished to 8 nm RMS surface, one mounted and Flight qualified, three segments built on three-week centers to demonstrate fab process; operational temperature 270-293K. Roman and JWST thermal model correlation are SoA though do not meet level of performance needed for HWO.	T	4-5
	Ultra-stable Structures	Composite	<1e-9/K CTE uncertainty, low CME & creep. Key goal to screen, characterize, and verify piece-parts and sub-assemblies.	JWST, Roman both using composite metering structures with characterized CTE/CME; need ~order of magnitude better uncertainty in material property characterization	T	4-5
	Thermal Control System	Various	Need sub-mK control over 0.5-1 Hz rate; Low electronics noise; Need thermal system components (heaters, sensors, cables, straps, etc.) to have low impact on system stability.	Roman achieving ~1 mK level control on critical sub-systems. Sub-mk control demonstrated on small scale in ultra-stable systems lab with non-Flight-like electronics.	T	3
	Sensing & Control	Mechanical, Piezo, Hybrid	Low-creep, large stroke actuators with picometer resolution	JWST mechanical actuators achieve stroke and coarse-phasing requirements. PZTs demonstrate near capability for fine stage, but require integration with mechanical systems and electronics development.	T	4
		Edge Sensors, Laser Metrology, Phase Retrieval, etc.	Segment rigid-body sensing and global alignment sensing to picometer level at high bandwidths	Laser distance gauges, Capacitive, Inductive, and Optical edge sensors in development with varying degrees of sensitivity. Image-based techniques demonstrated on JWST, sub-nm stability measurement achieved with long data set.	T	3-4
	Low-disturbance Systems	Active & Passive Isolation, Microthrusters, low-disturbance cryo-coolers	Active, passive, or multi-stage isolation achieving ~40 dB suppression of disturbances > 1 Hz; Imported forces and moments well characterized to support dynamics modeling.	Disturbance free payload hardware is ~TRL4, and microthrusters have been used on missions with different requirements than HWO. Low/No-disturbance cryo-coolers require characterization and evaluation for impact to coronagraph performance.	T	4
	Deployable Systems	Deployable Membranes, Latches & Hinges.	Robust to micrometeoroids, low complexity deployment, low thermal impact on telescope; Stable interfaces once deployed.	JWST sunshield represents state-of-the-art.	T	3

START / TAG Identified Gaps (4/4) – High-sensitivity UV & Instrument Technologies

Technology Track	Technology Lane	Candidate Technologies	Anticipated TRL5 Performance Need	Current State of the Art	(T)hreshold / (B)aseline / (E)nhancing	Estimated Current TRL
High-Sensitivity UV/VIS Instrumentation	Far-UV Mirror Coatings	Various flavors of protected Al+LiF	>60-80% reflectivity 100-120 nm, robust to environments, no impact to coronagraphy	>50%-80% reflectivity below 120 nm. Major gaps are in environmental stability, and scale & uniformity needs for HWO, including measurements of impact on coronagraphy.	T	3-5
	Near-UV / VIS Detectors	CMOS, CCD, MCP	>8K x 8K pixels, <2.5 e- read noise, <0.002 e-/p/s dark current, >50% QE between 300-400 nm	Commercial CCD and scientific CMOS sensors exist, but would require improvements in noise. Low-noise detectors like EMCCD or Skipper CCDs require improvements in QE between 200-400 nm to be viable for NUV.	B	4
	Far-UV Detectors	MCPs, UV enhanced EMCCDs	>40% QE 100-200 nm; 100 mm array size with 40 um resels, 1e-5 OOB rejection >300 nm	FUV-optimized MCPs with peak QE of 50% between 100-180 nm exist. UV enhanced EMCCDs with sensitivity in the FUV require UV bandpass filters for out-of-band rejection.	B	4-5
	Multi-Object Selection	Next-gen MSAs, DMDs, reflective IFS	<100 mas spatial resolution, >500 simultaneous objects	MSA & DMD are TLR5+ for most missions, but require scaling and tile-ability for HWO; IFS requires additional study for scattered light and resolution	B	3-5
	UV Gratings & Filters	Filters: Reflective bandpass and dichroic filters, tuned photocathodes	Filters: 20 nm and 40 nm bandpass filters covering 100-200 nm that work on shaped optics; <0.0001% to 0.01% throughput > 300 nm (i.e. solar blind).	HST & Fuse are heritage designs, but lack solar-blindness or longevity. State-of-the-art reflective coatings require mutiple reflections to achieve out-of-band rejection.	B	4-5
		Gratings: KOH-etched echelles, holographic aberration-correcting gratings, ultra-low blaze angle	Gratings: R ≥ 50,000 with ≥80% efficiency, compatible with Far-UV coatings; aberration-correcting solutions on curved substrates.	HST & Fuse are heritage designs, but lack solar-blindness or longevity. KOH-etched echelle gratings have >60% efficiency; Custom low/medium resolution gratings are limited by recording wavelengths and assemblies.	B	3-6

TECHNOLOGY ROADMAPS

Roadmap Deliverables

Hardware demonstration requirements for each TRL up to 5

- i.e., what does a TRL 5 demo look like for Technology X?
- Performance / functional requirements, form & fit requirements, level of integration, relevant environment

Analysis requirements for each TRL up to 5

- Model fidelity and validation plan corresponding to each hardware demonstration

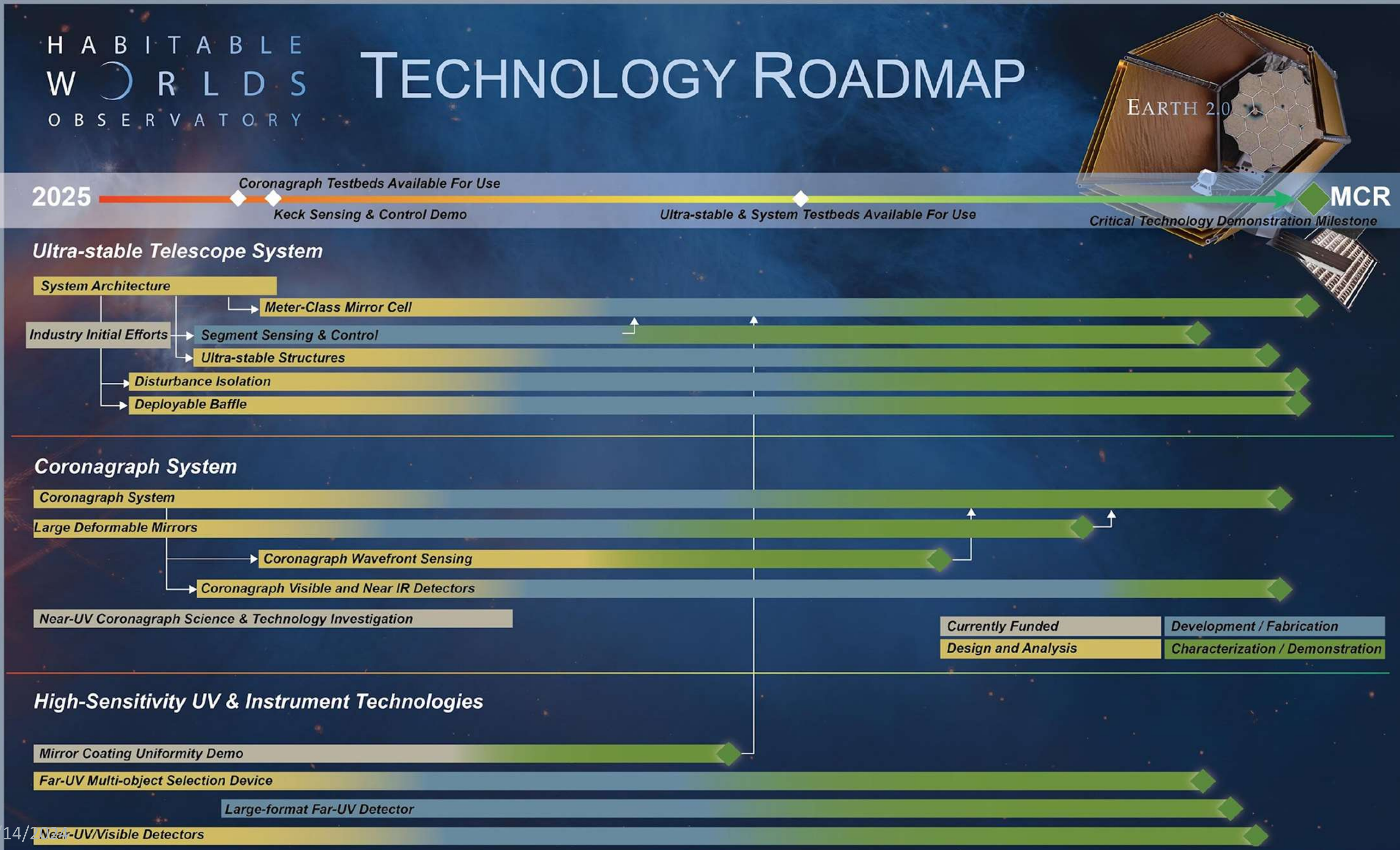
Risk assessment for the candidate technologies

- Define the risk or opportunity cost of investing in a low maturity technology that could potentially provide big science or technical gains
- Capture appropriate offramps for high-risk baseline or threshold technologies
- Incorporates input from science sensitivity curves

Road map timelines:

- TRL "Elevation" chart or high-level development flow
- Detailed development schedule

Cost and human resources estimate to execute plan(s)


HABITABLE WORLDS OBSERVATORY
TECHNOLOGY ROADMAP
EARTH 2.0
2025
Coronagraph Testbeds Available For Use
Keck Sensing & Control Demo
Ultra-stable & System Testbeds Available For Use
MCR
Critical Technology Demonstration Milestone
Ultra-stable Telescope System
System Architecture
Meter-Class Mirror Cell
Industry Initial Efforts
Segment Sensing & Control
Ultra-stable Structures
Disturbance Isolation
Deployable Baffle
Coronagraph System
Coronagraph System
Large Deformable Mirrors
Coronagraph Wavefront Sensing
Coronagraph Visible and Near IR Detectors
Near-UV Coronagraph Science & Technology Investigation
Currently Funded
Development / Fabrication
Design and Analysis
Characterization / Demonstration
High-Sensitivity UV & Instrument Technologies
Mirror Coating Uniformity Demo
Far-UV Multi-object Selection Device
Large-format Far-UV Detector
Near-UV/Visible Detectors

Feng Zhao

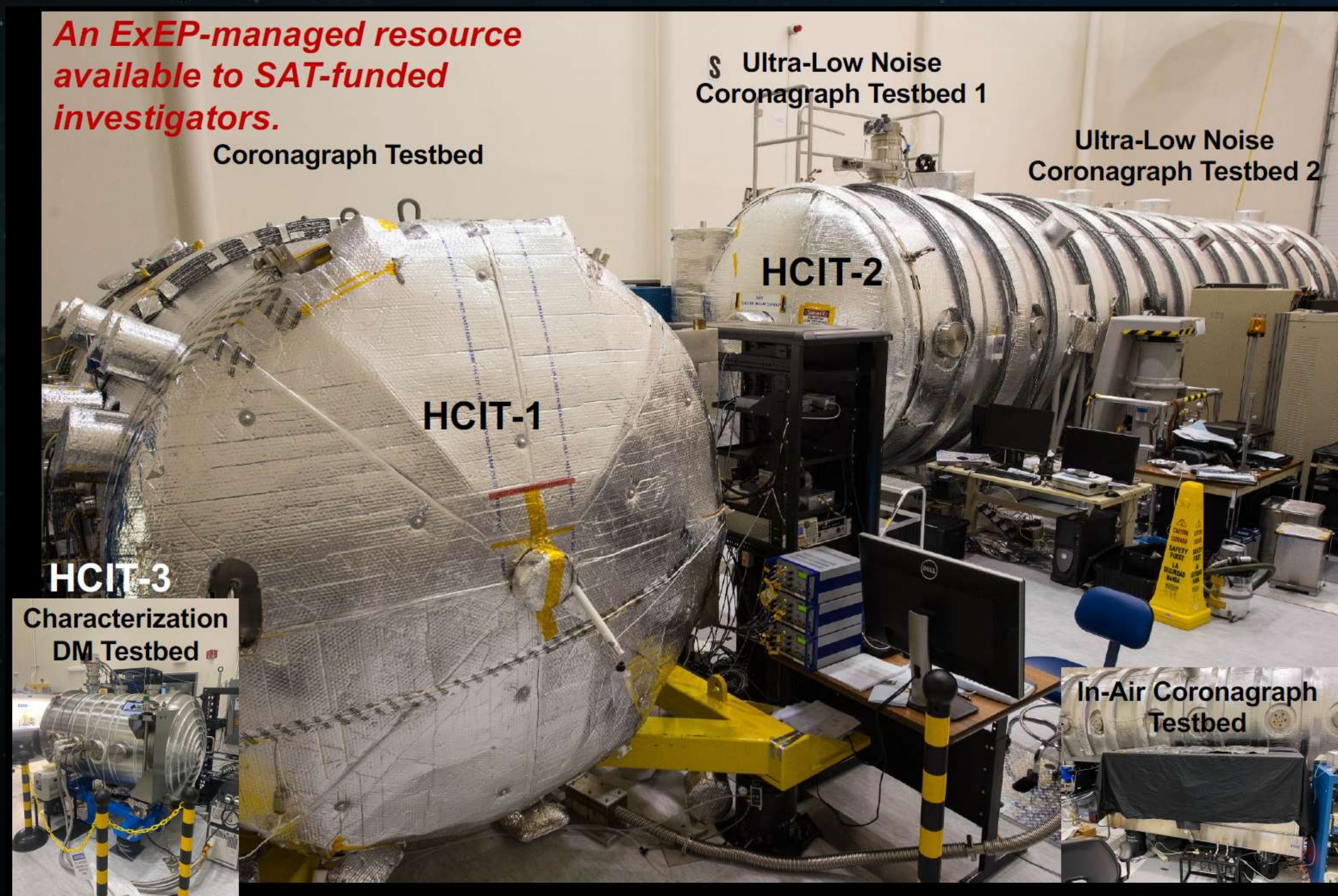
CORONAGRAPH & DM PROGRESS

NASA's High Contrast Imaging Testbed (HCIT) facility in JPL's Building 318 (Optical Interferometry Development Lab)

- ❑ HCIT-1 (aka OMC, PTB) was used by Roman (WFIRST) CGI for its TRL-5 demonstrations (2014 – 2017). Returned to ExEP ~ 2019

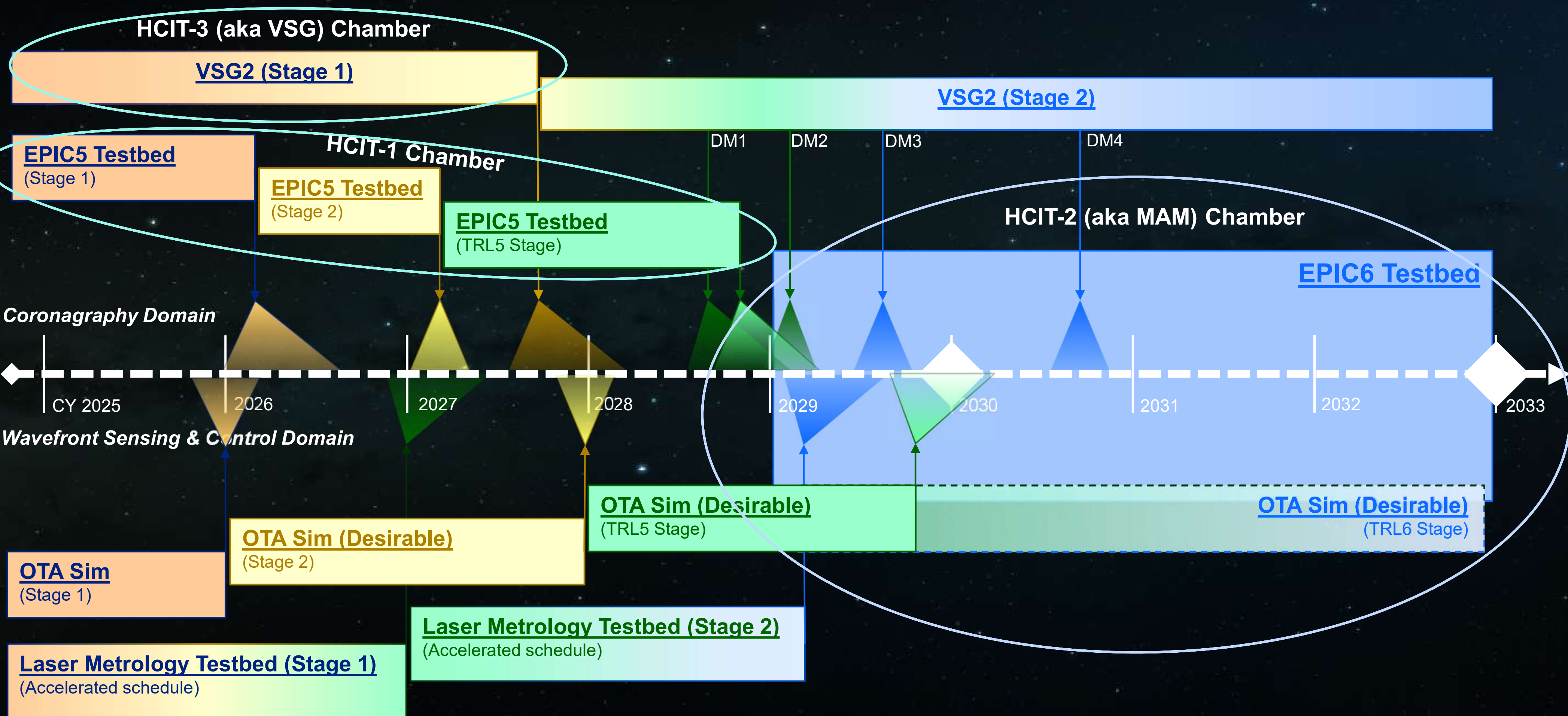
- ❑ DST-1 achieved our record contrast: ~4e-10 in a 10% spectral bandwidth.

- ❑ DST-2 recently commissioned.



Patterson et al., Proc. SPIE 111171U (2019)
Seo et al., Proc. SPIE 111171V (2019)
Meeker et al., Proc. SPIE 118230Y (2021)
Noyes et al., Proc SPIE, in prep. (2023)

OVERALL TESTBED ROADMAP (TIMELINE)



Courtesy of C. Baker, D. Redding

EPIC5 CURRENT STATUS:

- EPIC5 chamber (aliases "HCIT-1"; "OMC") now belongs to HWO
  - We do ***not*** plan to interrupt current Multi-Star SAT under Rus Belikov; no need to rush hardware work to meet EPIC5 milestones
- Contrast limitation studies ongoing.
  - Combined effort between HWO, HCIT, and CGI coronagraphy SMEs.
  - Will shape procurement strategy & some design/layout decisions for EPIC5 commissioning in CY25.
    - Procurement strategy will be limited with current budget.
  - Raw contrast error budget in draft form, currently being refined with feedback from CGI & HCIT SMEs (budget owned by Joon Seo.)

Contributions to Contrast Floor
10/26/2024
Best contrast so far on DST testbed is 4e-10

Credibility Codes
(1) = Confirmed
(2) = Most Probable
(3) = Credible-Likely
(4) = Credible-Unlikely
(5) = Non-Credible
(6) = Uncategorized

Ishikawa	Cause and Effect Description		Initial	Path forward / Actions
10.3	**Uncertainty of Contrast Measurement**		1	-
4.1.4	LSB		1	this is solved with new controllers
1.1.0	**Ghosts (occulter and other reflections**		2	model
1.1.1	Choose angle of incidence		2	model
1.1.2	Substrate coatings	E.g., incorrect pupil mask, double-pass factor, adopted	2	test & model
1.1.3	Pattern design		2	model
1.10.0	**DM Optical Properties, such as quilting and coating**		2	test
1.2.0	**Polarization**		2	-
1.2.2	include polarizer / analyzer		2	test
1.5.0	**birefringence in materials and coatings**		2	test and model
1.5.1	FPM substrate		2	test and model
1.5.2	FPM coatings		2	test and model
1.9.0	**Segmented Pupil**	How does segmented pupil affect testbed design choices?	2	test and model
3.1.0	Jitter		2	test and model
4.1.0	**DMs**		2	-
5.2.2	out of band spectrum		2	test, probably need to purchase/rent inst.
6.1.0	**Camera**		2	-
6.1.2	Dark Subtraction		2	test & model, build comparison matrix
6.1.3	persistence		2	test & model, build comparison matrix
6.2.2	DM high frequency		2	test
6.3.0	**Ground loops and other electronic noise**		2	test
7.7.0	**Photometry Uncertainty**	combination of camera, source, and method	2	
10.2	**Determine upper limits on dynamics we need to measure**		3	model
2.1.0	**STOP Modeling**		3	model, big effort
4.1.2	# of DM actuators		3	model
4.1.3	DM technology (MEMS, PMN, etc.)		3	test
4.1.5	# of dead actuators		3	model
5.1.1	Pinhole		3	test & model
5.1.1.2	polarization effect of pinhole (see 1.2)		3	test & model
6.3.1	pickup noise like the 500Hz noise seen on CGI		3	test
7.1.0	**Model Agreement**		3	model with model mismatch
7.2.3	mask characterization		3	test and model
7.3.0	**Affect of Field Stop edges on speckles near the edge of the dark hole**		3	test and model, choose appropriate model
7.5.0	**DM Gain Calibration**		3	test and model
7.5.1	Full gain cubes		3	test and model
7.5.2	nonlinear gain		3	test and model
8.1.0	Loop Rate		3	design

Ishikawa descriptor ratings feed into actionable survey tasks

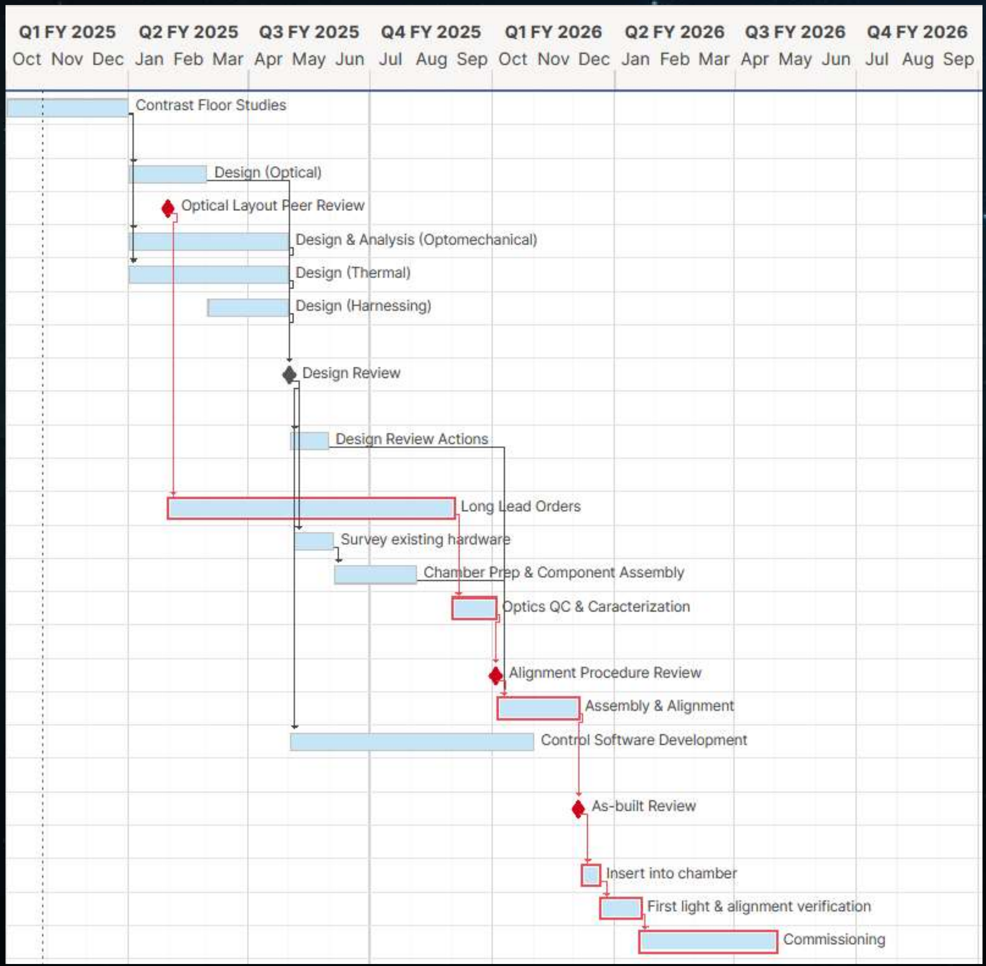
- Integrated Modelling team already involved
  - Received list of data product deliverables, hardware design/tolerancing inputs and points of critical involvement from modelling team.

#	Test / Analysis	Addresses ID	Can Do It Now	What's Needed	Priority	Who	Effort	Notes
1	Camera Testing	6.1, 10.3	on-going	Test list from Nathan ✅ EMCCD Camera qCMOS Camera ✅ OMC Camera	1	Susan & Nathan	1-2 FTE mo	see https://docs.
2	DME	6.2, 4.1.4	on-going	Teilch Electronics ✅ Time on DST to conduct dithering test	1	Camilo		test on DST1
3	Photometry Uncertainty	7.7.0	yes	Analysis Time	1	David & Susan		combination of s
4	FPM Pattern Tolerancing	1.5.3, 1.1	Early Nov	modeling team - full EM, e.g. FDTD	2	Dylan & Hanying	1 FTE mo	Dylan will be ava
5	FPM Substrate Tolerancing	1.5.1, 1.1	Early Nov	modeling team - full EM, e.g. FDTD, call Corning about	2	Dylan & Hanying	1 FTE mo	"Closer to perfec
6	FPM coating Tolerancing	1.5.2, 1.1	Early Nov	modeling team - full EM, e.g. FDTD	2	Dylan & Hanying	1 FTE mo	"Closer to perfec
7	Angle of Incidence	1.1,	Design problem	make a list of where AOI is a parameter	3	David		combination of o
8	DM Technology	1.10, 6.2.2, 4.1.3	on-going		4	Fang-AOX, Camilo-BMC		BMC DM modelir

Courtesy of C. Baker

EPIC5 NEAR-TERM PLANS

- "Complete" contrast study by end of CY24.
- Begin design work in Jan 25
  - ***Design for full TRL 5 coronagraph, fill in with dummy optics for 1e 10 commissioning.***
  - Want to accommodate SPC/APLC/Vortex modes, HWO pupil sim, color filters, LOWFSC, GSFC IFS, etc. without altering layout later.
- Have identified & ranked list of procurements for any budget windfalls.
- Proceed in lock-step with modeling team; ensure they have model inputs to get best agreement with testbed.
- Reach 1e 10 in first half of CY26.
  - Two primary non funding schedule drivers:
    - Contrast floor studies completion.
    - Optics lead times (est. 6mo for 5nm quality OAPs).



Courtesy of C. Baker

CORONAGRAPH TECHNOLOGY TRL-6 OUTLOOK

TRL-6 by PDR required by NPR 7120.5E

- Performance demonstration with Coronagraph Systems Testbed (EPIC6)
  - Demonstrate "Dark hole digging (static contrast)" in both VIS and NIR channels using polarization and dichroic beam splitters, in the presence of key optical interfaces (pupil geometry, closed-loop OTA dynamic WFE, etc)
  - Demonstrate "Static – dark hole digging" and "dynamic – dark hole maintaining" contrast concurrently
  - Demonstrate picometer WFS/C technologies including metrology
  - Demonstrate "Low flux tests" (key relevant environment in terms of performance)
  - Demonstrate spectral retrieval
- Environmental tests with key components (DM, masks, detectors, dichroic and polarization beam splitters, etc.)

Demonstrate a credible path for flight CI verification before launch

- The OTA-Sim will become flight Coronagraph Verification Stimulus

DM Study Contract Status

- 6-mo study subcontracts have been executed with the top three vendors from the ExEP DM Survey:
  - https://exoplanets.nasa.gov/internal_resources/3061/ExEP_DMTR_Final_Report_202405024_Redacted.pdf
- Deliverables: Development and Manufacturing Plan outlining vendor approach to fabricating two 96x96 DMs:
  - Development path
  - Estimated performance to 8 provisional performance goals
  - Key challenges, technical and programmatic risks
  - DM electronics and connectorization approaches
  - Estimated cost and schedule
- Plans due mid-February 2025 with final briefings to NASA SMEs (March 2025)
  - Groff (GSFC), Bendek (ARC), Baker, Trauger, Lindensmith, Liu, Chen (JPL) all with CGI experience
  - Will review received plans (April 2025)
  - Will inform Project Office of their assessment (May 2025)

AOA Xinetics / Northrop Grumman	Boston Micromachines Corporation — Shaping Light	bertin alpao
• Electrostrictive • USA • DMs are the main business • Part of Northrop Grumman • Supplier of Roman Coronagraph DMs	• Electrostatic • USA • DMs are the main business • Independent company • Several SBIRs, 1 SAT	• Electromagnetic • French • DMs are about 70% of business • Newly acquired by Bertin (French) • Development work with GSFC

Courtesy of N. Siegler

Ultra-stable Telescope System Technologies

In early 2024, three industry teams were selected under FY23 ROSES Appendix D.19 “Critical Technologies for Large Telescopes”

- Alain Carrier / Lockheed Martin: Technology Maturation for Astrophysics Space Telescopes (TechMAST)
- Laura Coyle / BAE Systems: Ultra-stable Telescope Research & Analysis – Critical Technologies (ULTRA-CT)
- Tiffany Glassman / Northrop Grumman: Systems Technologies for Architecture Baseline (STABLE)

All teams are now under contract and have held kick-off reviews

- See selection announcement for description of studies:

See: NSPIRES Solicitation NNH23ZDA001N-CT4LT

ULTRA-STABLE TELESCOPE SYSTEM TECHNOLOGIES

New FY24 ROSES D.19 “HWO System Technology Demonstrations and Mission Architecture Studies” call just released:

Proposals due 2/6/25

Solicits both system technology demonstrations ***and*** system architecture / parametric studies

See: NSPIRES Solicitation NNH24ZDA001N-HWOTAS

FY24 SAT & APRA

ROSES D.7 and D.3 calls are now both open

Proposals due 1/30/25

Focus on Tier-1 and -2 Technology Gaps identified in the Astrophysics Biennial Technology Report:

Tier-1 Technology Gaps

- Coronagraph Contrast and Efficiency in the Near IR
- Coronagraph Contrast and Efficiency in the Near UV
- Coronagraph Stability
- Cryogenic Readouts for Large-Format Far-IR Detectors
- Fast, Low-Noise, Megapixel X-ray Imaging Arrays with Moderate Spectral Resolution
- High-Bandwidth Cryogenic Readout Technologies for Compact and Large-Format Calorimeter Arrays
- High-Efficiency, Low-Scatter, High- and Low-Ruling-Density, High- and Low-Blazed-Angle UV Gratings
- High-Efficiency X-ray Grating Arrays for High-Resolution Spectroscopy
- High-Performance Sub-Kelvin Coolers
- High-Reflectivity Broadband Far-UV-to-Near-IR Mirror Coatings
- High-Resolution, Lightweight X-ray Optics
- High-Throughput, Large-Format Object-Selection Technologies for Multi-Object and Integral-Field Spectroscopy
- Integrated Modeling for HWO: Multi-Physics Systems Modeling, Uncertainty Quantification, and Model Validation
- Large-Format, High-Resolution Far-UV (100 - 200 nm) Detectors
- Large-Format, High-Resolution Near-UV (200 - 400 nm) Detectors
- Low-Stress, Low-Roughness, High-Stability X-ray Reflective Coatings
- Mirror Technologies for High Angular Resolution (UV/Visible/Near IR)
- Optical Blocking Filters for X-ray Instruments
- Scaling and Metrology for Advanced Broadband Mirror Coatings for HWO
- Segmented-Pupil Coronagraph Contrast and Efficiency in the Visible Band
- UV Multi-Object Spectrograph Calibration Technologies
- UV Single-Photon Detection Sensitivity
- Visible/Near-IR Single-Photon Detection Sensitivity

Tier-2 Technology Gaps

- Advanced Cryocoolers
- Broadband X-ray Detectors
- Compact, Integrated Spectrometers for 100 to 1000 μm
- Cryogenic Far-IR to mm-Wave Focal-Plane Detectors
- Far-IR Imaging Interferometer for High-Resolution Spectroscopy
- Far-IR Spatio-Spectral Interferometry
- Heterodyne Far-IR Detector Systems
- High-Performance Computing for Event Reconstruction
- High-Resolution, Direct-Detection Spectrometers for Far-IR Wavelengths
- High-Throughput Focusing Optics for 0.1-1 MeV Photons
- High-Throughput UV Bandpass Standalone and Detector-Integrated Filters and Bandpass Selection
- Improving the Calibration of Far-IR Heterodyne Measurements
- Large-Format, High-Spectral-Resolution, Small-Pixel X-ray Focal-Plane Arrays
- Large-Format, Low-Noise and Ultralow-Noise, Far-IR Direct Detectors
- Low-Power Readout and Multiplexing for CMB Detectors
- Millimeter-Wave Focal-Plane Arrays for CMB Polarimetry
- Optical Elements for a CMB Space Mission
- Starshade Deployment and Shape Stability
- Starshade Starlight Suppression and Model Validation
- Stellar Reflex Motion Sensitivity: Astrometry
- Stellar Reflex Motion Sensitivity: Extreme Precision Radial Velocity
- Warm Readout Electronics for Large-Format Far-IR Detectors

APRA

SAT

Future Technology Development Opportunities

Over next few months, Track Leads are gathering information from subject matter experts to develop long-term, detailed roadmaps

These roadmaps will be reviewed and released next spring, and will be part of the Project Pre-Formulation plan

We recognize that SAT and APRA will not fund all needed technology areas

- TMPO will address the expected gaps as part of Technology Roadmaps, including how and when future funding will be implemented

QUESTIONS?