Habitable Worlds Observatory

Technology Roadmap

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Greenbelt, MD

Matthew R. Bolcar (GSFC) – HWO Chief Technologist

Feng Zhao (JPL) – HWO Deputy Chief Technologist

Paul Scowen (GSFC) – UV/VIS Instrument Track Lead

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

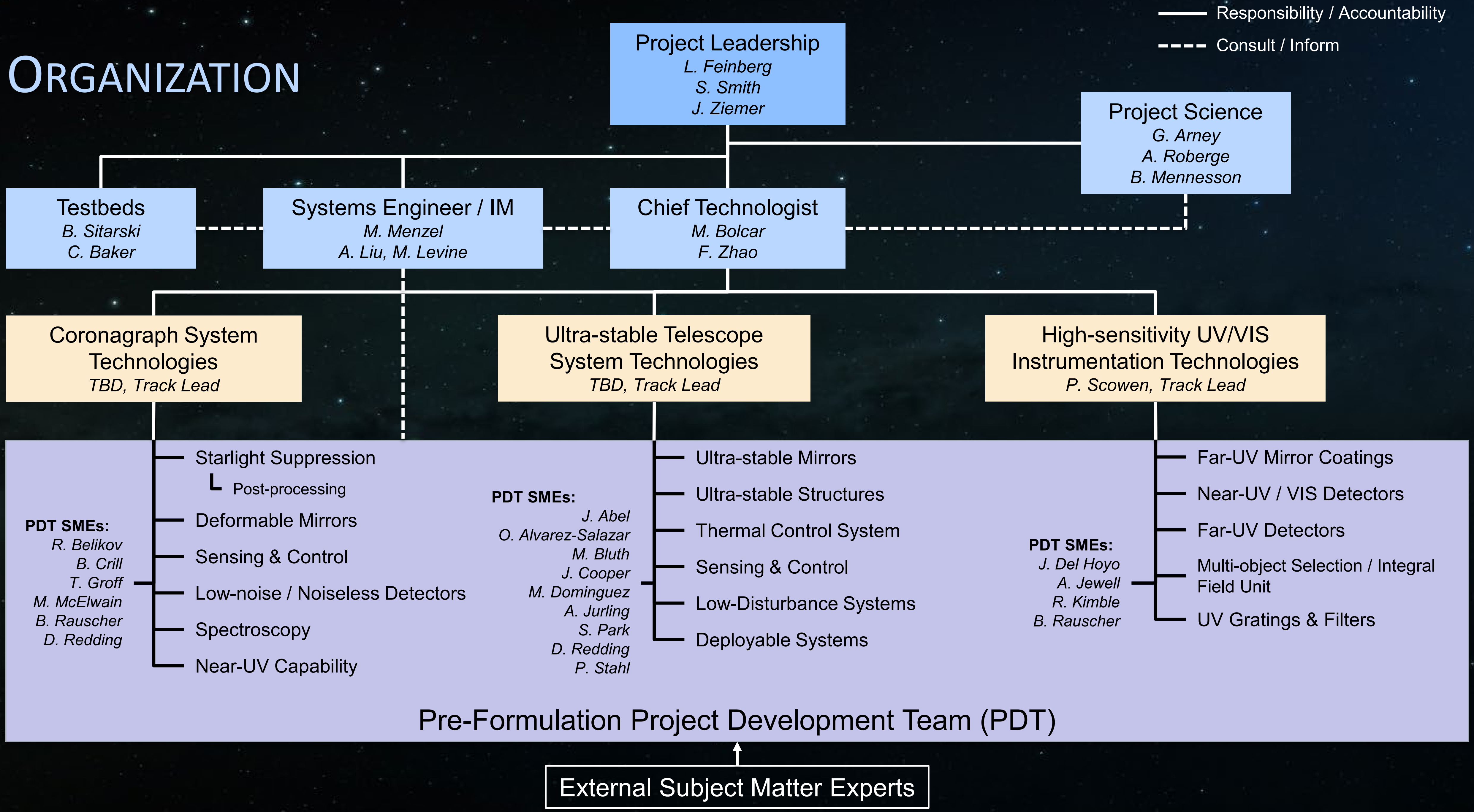
The HWO Technology Plan is organized along three ***tracks***:

- 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 H2O 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

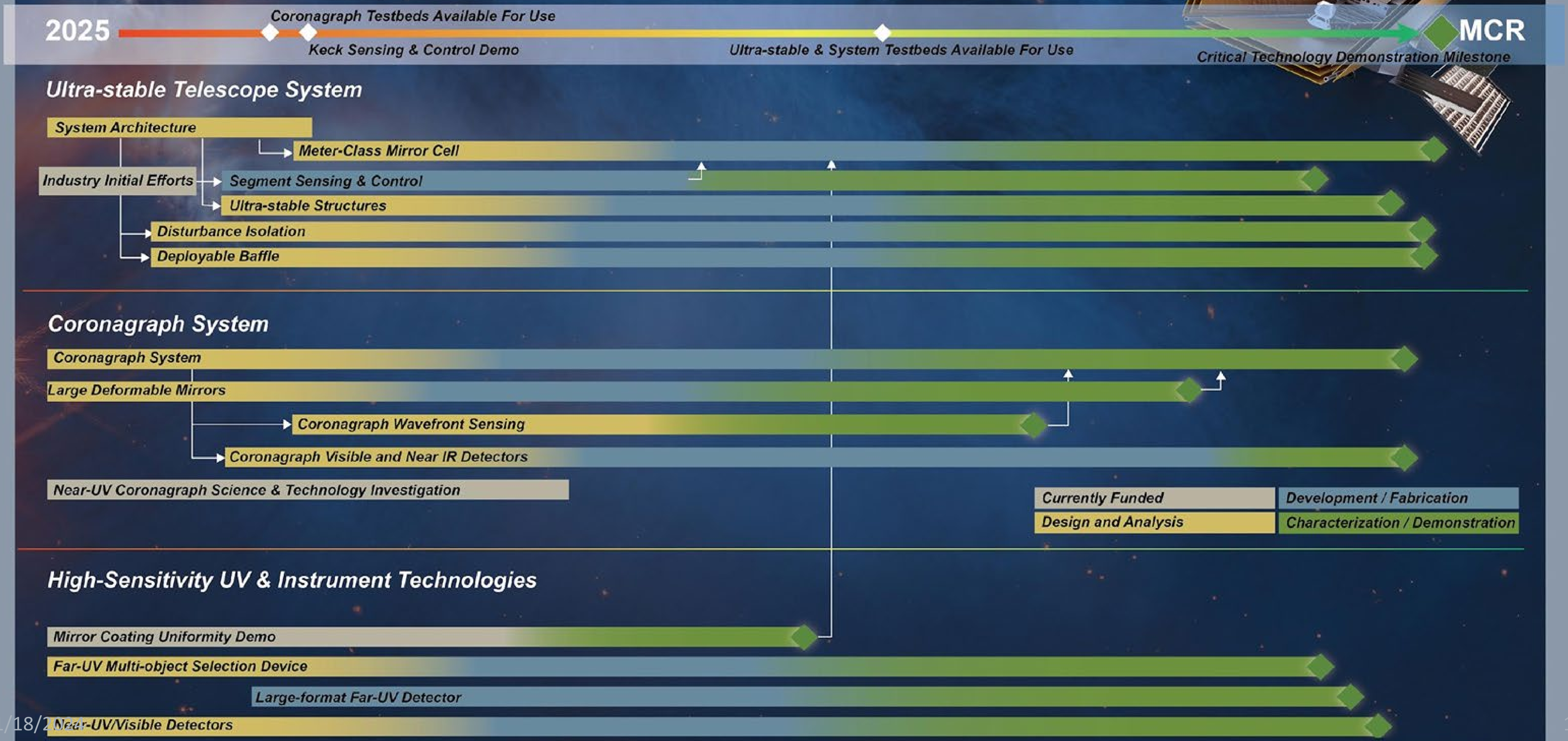
Road map timelines:

- 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



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?