Deformable Mirror Technology Roadmap (DMTR) Final Report

(Redacted 5/21/2024)

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Scope of DM Technology Roadmap

Study to define the necessary steps to mature deformable mirrors systems for a future flagship exoplanet mission to TRL-5.

The study will:

a. Define a possible roadmap
b. Consider DM plans described in the HabEx/LUVOIR reports
c. Define provisional DM system requirements for the HWO
d. Update the ExEP DM Survey to capture any changes
e. Capture relevant DM flight experiences by the Roman Coronagraph
f. Engage with the top DM vendors to assess their interest and share provisional requirements

Executive Summary (1/2)

The DMTR working group was initiated in February 2023 by NASA's ExEP to get an early start on providing a technology roadmap for the most challenging component of a space coronagraph – a deformable mirror system. Here's what was achieved:

- **Completed "A First Cut at DM Performance Goals" that can be used as provisional requirements for vendors until a future flight mission can establish them. They cover:** (1) Actuator count, (2) Actuator stability, (3) Actuator resolution, (4) Actuator stroke, (5) Actuator pitch, (6) Residual WFE, (7) Actuator yield, and (8) Path to flight
- **Updated the 2022 DM Vendor Survey that identified three promising candidate vendors** – AOA Xinetics' electrostrictive DMs, Boston Micromachines' electrostatic MEMS DMs, and the French company ALPAO and their magnetic DM.
- **Visited all three DM vendors at their manufacturing facilities**
- **Received preliminary responses from the top three vendors to the provisional requirements document for their feedback.**
  - None received NASA funding so the responses were very preliminary and incomplete

Executive Summary (2/2)

- **Collected shared lessons from the Roman CGI DM team**
- **Laid out a plan to bring readiness of HWO DM technology candidates to TRL-5**
  - TRL-5 Plan (05/2024)
- **Created a one-page roadmap to develop HWO DM to TRL-5**

Study Findings

1. **Three DM vendors were identified as having the capabilities and interest to develop and fabricate 96x96 devices that will meet expected HWO requirements.**
   - However, large gaps among the vendors currently exist in many important areas such as actuator count, resolution, pitch size, surface figure, and stability.
   - It is possible that the telescope/coronagraph system design and/or the science requirements may have to be traded against expected DM performance.

2. **NASA will need to provide initial seed funding to the top vendors to receive credible development and fabrication plans.**
   - These plans are needed to inform a future project office which vendors to fund through a prototype phase

3. **Critical systems-level trades need to be conducted early to finalize the DM requirements, such as:**
   - the allocation of wavefront control between the DM, the coronagraph, and the telescope
   - DM actuator count and lab-demonstrated dark hole size (outer working angle)

Study Findings

4. **Early vendor feedback regarding development was consistent - approximately five years to deliver a TRL-5 96x96 device.**
   – Hence, NASA needs to get started early in the HWO program (also Roman CGI recommendation)

5. **Early and significant NASA vendor involvement is required to achieve TRL-5 and path to flight goals.**

6. **A NASA facility is required to test and characterize large format DMs to their HWO performance levels.**
   – Develop test facility required to test DMs with fidelity required to verify flight requirements

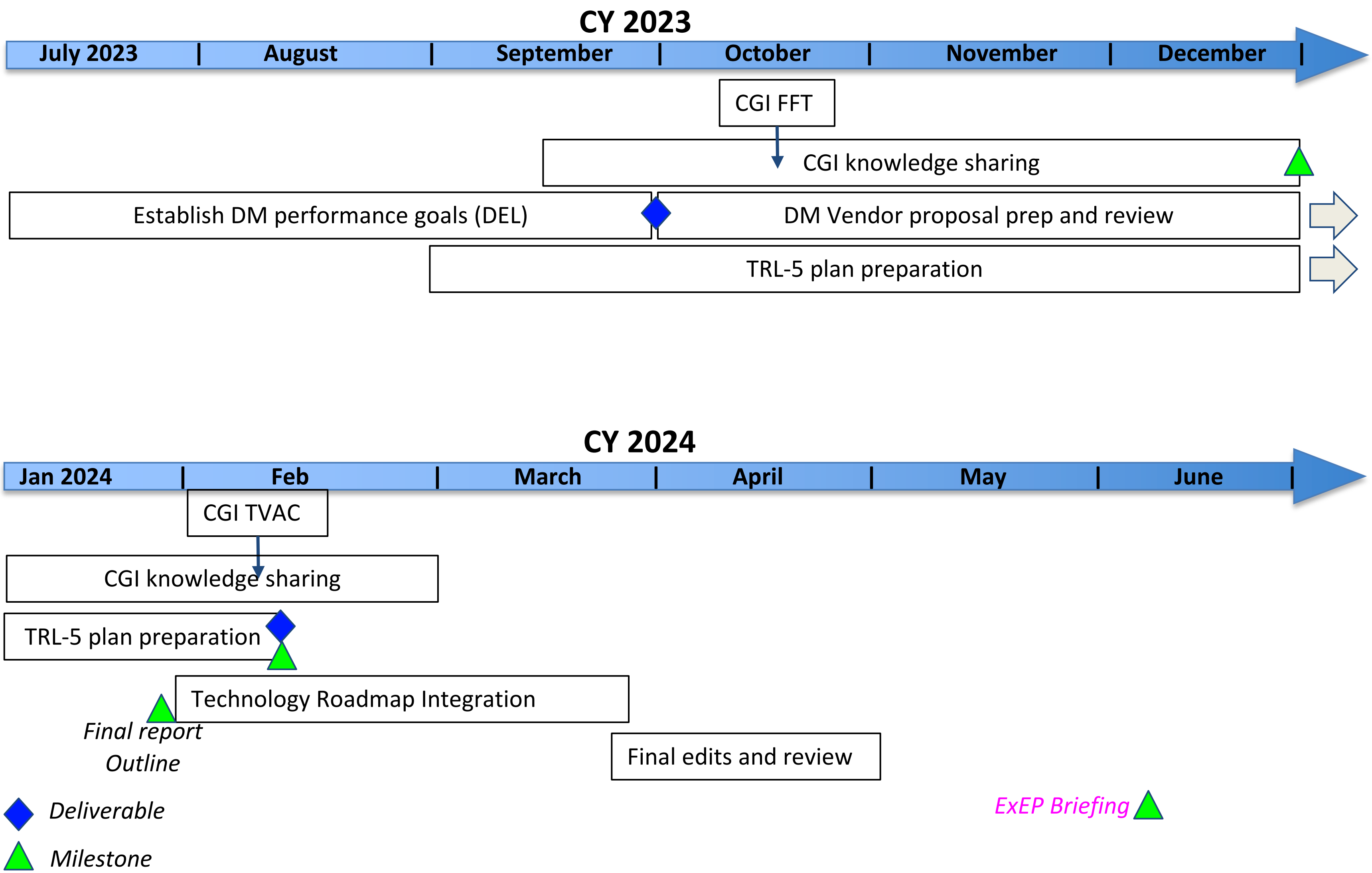
Study Assumptions

- **The DMTR will have a duration of 15 months.**
- **DM will be treated as a system that performs wavefront control in a coronagraph.**
  - This includes the DM device, the control electronics, and cables/connectors
- **The ExEP Coronagraph Technology Roadmap (CTR) will define the provisional DM requirements.**
  - Consideration will be given to match HabEx and LUVOIR requirements
  - Community consensus will be incorporated
- **The observatory is the major contributor to the relevant environment.**
- **Given that the HWO pre-Phase A activity hadn't commenced but a desire existed to move out on planning for DM maturation, this work would be performed in absence of system design information**
- **The study acknowledged that woofer/tweeter configurations could be worth analyzing but requires a systems perspective and hence the study only focused on two continuous facesheet high-order DMs working in tandem.**
- **No down-selecting**

Key Milestones and Deliverables

- **Task Kickoff** (02/2023)
- **Task Plan Presentation to ExoTAC** (05/2023)
- **Roman Coronagraph DM Knowledge Sharing** (04/2023 to 02/2024)
- **Update DM Survey** (05/2023)
- **DM Performance Goals Definitions:** (06/2023)
- **Receive DM Vendor Technology Development Plans** (09/2023 – 4/2024)
- **Complete Final Roadmap Report** (4/2024)
- **Final Roadmap ExEP Briefing** (06/2024; venue will be a public ExEP Technology Colloquium Series and recorded)

DMTR Timeline and Process



DMTR Working Group Participants

Co-Leads				
Duncan Liu	(JPL)			
Tyler Groff*	(GSFC)			
Eduardo Bendek				
Group Members				
Feng Zhao*	(JPL)		Pierre Baudoz	(Obs. De Paris)
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Aki Roberge	(GSFC)		Garreth Ruane	(JPL)
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Steve Kendrick	(SK Consulting)		John Trauger*	(JPL)
Pin Chen	(ExEP)		Emiel Por	(STScI)
Karl Stapelfeldt	(ExEP)			

*Roman Coronagraph Instrument

Deformable Mirror Survey Update

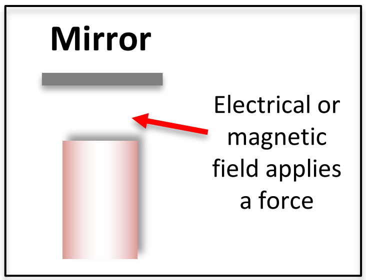
Eduardo Bendek
Jet Propulsion Laboratory – California Institute of Technology

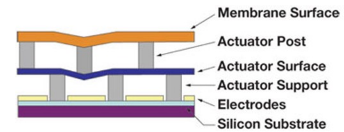
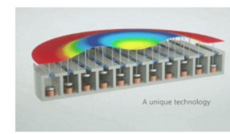
NASA Exoplanet Exploration Program
May 9, 2023

Technologies Overview

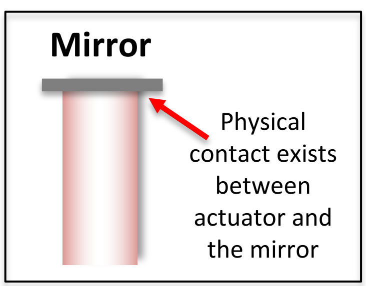
Actuation type

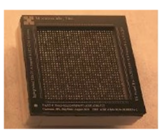
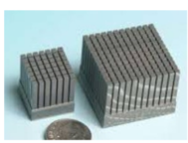
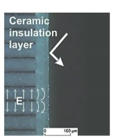
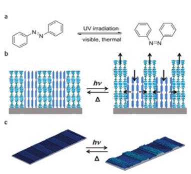
Contactless technologies



Technology	
Electrostatic BMC, Obsidian	
Electromagnetic ALPAO, Microgate, TNO	 
Magnetic APERTURE	 *Figure 1 APERTURE concept. For simplicity only one write head is shown. The QR code leads to an animation depicting the concept found here link to video*

Contact technologies

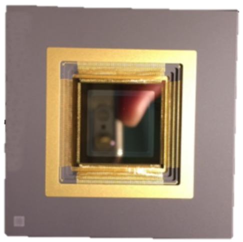


Technology	
Electrostrictive Xinetics, Microscale	 
Piezo/monomorph Cilas, PI+Fraunhofer (PICMA)	  
Photonic Sparse DM	

Technologies Overview

Small format v/s large format

Resolution, Pitch



Small format (Coronagraph level)

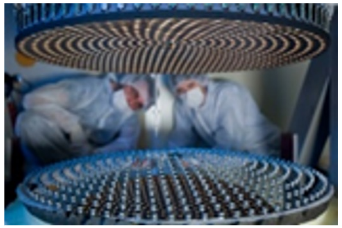
- BMC
  15 pm, 0.3 mm
- Xinetics
  8 pm, 1.0 mm
- ALPAO
  <120 pm, 0.8 – 20.6 mm
- Cilas
  <300 pm, >2.0 mm

U.S. and European vendors

Large format (Telescope level)

- TNO
  ~500 pm, 5.0 – 50mm
- Microgate
  ~300 pm, 16 – 39 mm
- Cilas
  <300 pm, > 2.0 mm

Mostly European vendors



Provisional DM Performance Goals for HWO

https://exoplanets.nasa.gov/internal_resources/2859/DM Performance goals_External_9_30_2023.pdf

Note: These performance goals were conducted in anticipation of the HWO START and TAG teams. A multi-institutional working group called the ExEP Coronagraph Technology Roadmap Working Group co-led by Laurent Pueyo (STScI) and Pin Chen (JPL) provided inputs into these provisional goals in absence of an observatory system design.

Deformable Mirror Technology Roadmap (DMTR) for Future Exoplanet Direct Imaging Space Missions

A First Cut at Deformable Mirror Performance Goals

(redacted 5/13/2024)

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Nick Siegler (NASA Exoplanet Exploration Program; Jet Propulsion Laboratory, California Institute of Technology)

We acknowledge the valuable contributions of the entire DMTR team.

September 30, 2024

CL# 23-4821

Introduction

- **This document provides early guidance about key DM performance goals for on-going feasibility studies. It does not provide a comprehensive set of requirements.**
- This document describes first-cut, best-estimate performance goals for the DM systems needed for the HWO. The goal is to start understanding vendors’ capabilities for manufacturability and scalability of such devices and develop a plan to mature them to TRL-5 for infusion in the coronagraph to eventually achieve TRL-6.
- For the purposes of this work we will consider the **DM as a system,** therefore the performance and noise of the electronics, cables, and connectors should be considered. Outsourcing subsystems such as the electronics or cables can be assumed if preferred.
- We aim to work together with the vendors to clarify capabilities so as to inform discussions on future DM requirements and test plans. We expect an iterative process as any one device may not meet all of the targeted performance goals captured in this document
- We share performance target relaxation comments as expected to be possible and indicate where engineering trades with other performance goals could be considered.

A DM Technology Roadmap

Why now?

The DM system is <u>the</u> critical component for any coronagraph direct imaging mission.

- **State-of-the-art: There are no DM devices today that meet the expected Habitable Worlds Observatory (HWO) wavefront control requirements.**
- **Need:** A robust, reliable, larger format, demonstrable, and manufacturable DM system for the HWO.
- **Knowledge sharing:** The Roman Coronagraph flight build has shown technology gaps to meet future DM requirements for the next-generation space coronagraphs.
- **Time critical:** Lead times can be half a decade or more to develop and test a new wavefront control device. We need to start soon to retire that risk.

Methodology

- **Background:** Having initial and estimated DM performance goals are necessary to begin interactions with key DM vendors to gain an early understanding of their manufacturing capabilities and challenges.

- **Two sources for estimating these early goals definitions:**
  - **ExEP Deformable Mirror Technology Roadmap (DMTR) Requirements Subgroup:** Has generated a set of performance goals interpolating the HabEx and LUVOIR mission concept DM requirement recommendations.
  - **ExEP Coronagraph Technology Roadmap (CTR) Working Group:** Has generated a set of performance goals based on their analyses

  No effort was made to optimize their suggestions; this is a first-cut.

- The estimated needed performance goals will be in a **green box.** They represent the consensus of the DMTR working group at this time. Please use this as the initial target value.

- **Relaxation:** For each item there will be comments about the expected likelihood of relaxing the goal if necessary.

Requested Feedback from DM Vendors

The information gathered from the vendors and the community will provide NASA first-cut guidance about the funding and schedule needed to close the DM technology gap for the HWO.

We request feedback from the vendors in the following areas:

1. High-level plan for development, manufacturing, and verification
2. Feasibility of meeting the performance goals, scaling information and cliffs
3. Environmental requirements for the DM to meet the goals. i.e. thermal stability, maximum exposure to humidity, etc.
4. Key challenges that require new engineering or manufacturing methods
5. Risks that, if realized, may prevent delivery
6. Any new infrastructure needed
7. Any support requested from NASA for manufacturing or characterization
8. Plan for the DM electronics (including the option of outsourcing) and connectorization
9. Rough timeline to deliver flight units including the following steps: a) develop manufacturing process, b) manufacture qualification units, c) perform TRL-5 qualification, d) deliver TRL-5 units.
10. Expected cost range for the entire project breaking down the main cost allocations.

The information received will be kept within JPL and NASA civil servants covered by NDAs and meet the "need to know" rationale. No information will be shared between the vendors.

Technical Scope

Possible HWO Wavefront Control Needs

1. Correct the nearly-static **mid-spatial frequency errors** arising from all of the mirrors in the OTA, and the coronagraph beam train, and their non-uniformities in its reflective coating
2. Correct the dynamic small amplitude **low-order WFEs** caused by drifts in telescope alignment and warping of the primary mirror, excepting tip/tilt which will be corrected by a fine steering mirror
3. Likely need to correct for dynamic **drift in primary mirror segments** in tip, tilt, and piston

The actuator stability and resolution performance goals will be the same for all the above, but the DM format, stroke, and needed update timescale will differ for each application.

Hence, different requirements are expected for each control region. Key question for the future HWO design teams will be: “Can a single DM handle all three tasks, or will multiple sequential DMs be needed?” This is a likely future trade.

We will provide anticipated performance goals derived from cases 1 and 2 only.

Performance Goals

1. Actuator count
2. Actuator stability
3. Actuator resolution
4. Actuator stroke
5. Actuator pitch
6. Residual WFE
7. Actuator yield
8. Path to flight

1) Actuator Count

- **Definition:** The number of actuators across the DM diameter if circular or across the DM if square.

- **CTR Input:**
  - The number of actuators across the pupil is 96.

- **DMTR Inputs:**
  - Extrapolating the HabEx science OWA requirement to a 6m aperture and allowing for the OWA to be smaller than the control radius, results in a 108x108 DM, whereas the extrapolating the LUVOIR-B OWA requirement from a 6.7m to a 6m aperture results in a 58x58 DM.
  - A 96x96 DM, providing a usable OWA of 756 mas @0.5 um on a 6 m telescope, seems like a prudent compromise as the minimum format requirement for HWO.
  - It is important to consider that a 96x96 DM will only have 92x92 actuators available to allow for actuator padding at the edge.

Goal: Actuator count is 96x96

Possible relaxation? Not desired, need to understand limitations.

2) Actuator Stability and Drift (1/6)

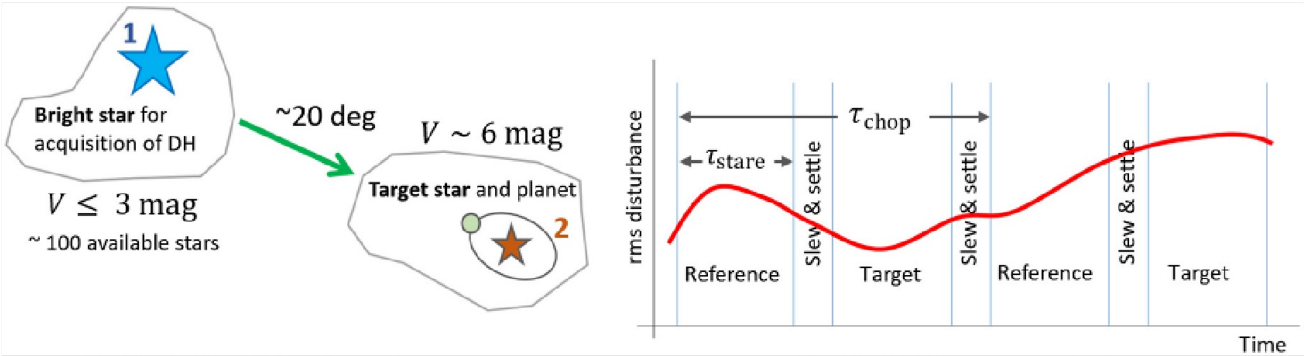
- **Actuator stability definition:** The rate of change of the position of one or more actuators with respect to the DM flat shape when operating in open loop. Piston of the flat surface shape is excluded from the stability definition.

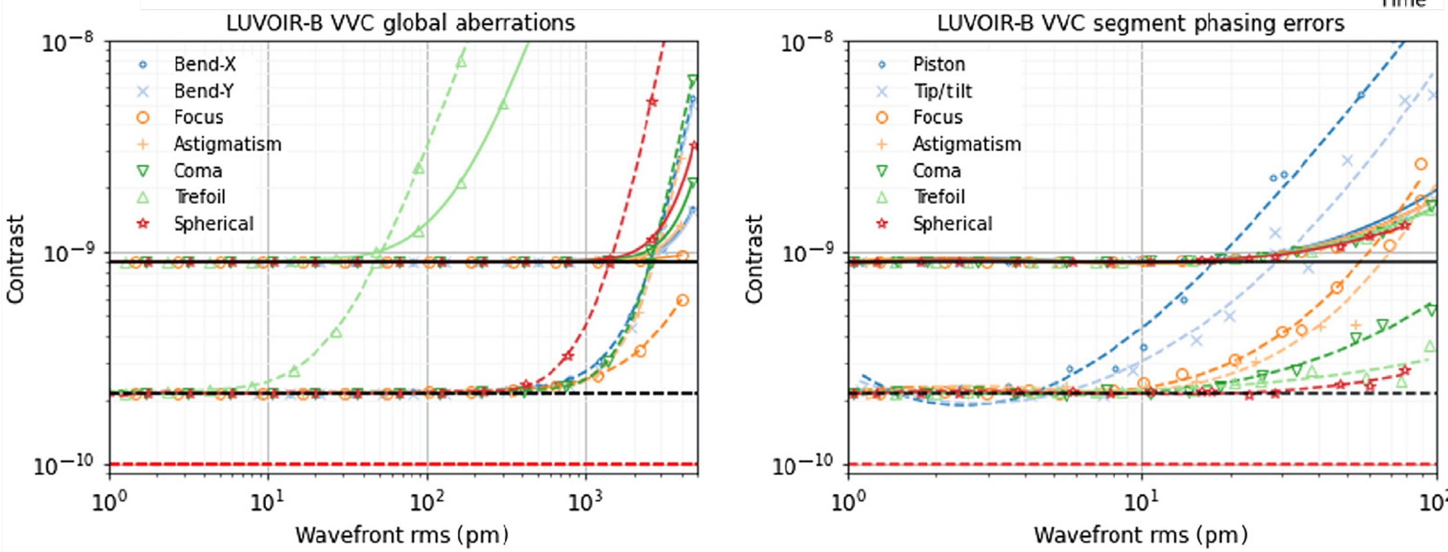
- **Actuator drift definition:** The rate of uncommanded actuator motion with respect to the mean flat surface shape.
- **CTR Input:**
  - *DMs are (almost) the last optics before coronagraph removes bulk of starlight. Requirements will be driven by contrast in science images.*
  - *Requirements will depend on observing scenario and whether or not DMs are updated during science sequence.*
  - *Goals here assume no DMs updates. CTR will develop another set of requirements assuming DMs updates. DMTR team will discuss with vendors whether their technology fits one or more observing scenarios.*
  - *We are talking about a system with multiple DMs as a single "wavefront actuator"*
  - *From CTR standpoint these placeholder requirements can be met using as many physical devices as needed.*

2) Actuator Stability and Drift (2/6)

CTR Input:

- ***Dark hole stability during slew and target observation:*** *At slow timescales requirements are driven by residual post differential imaging: dominated by coronagraph sensitivities.*



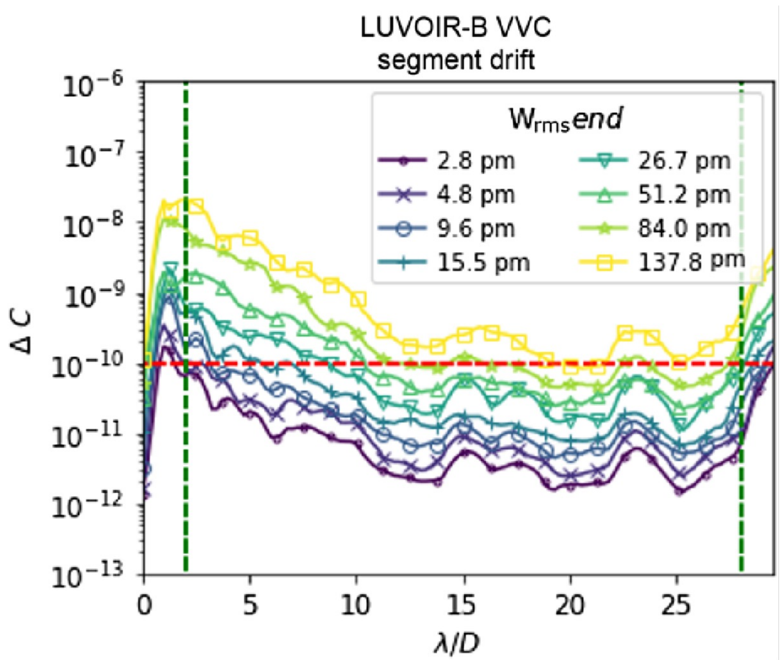


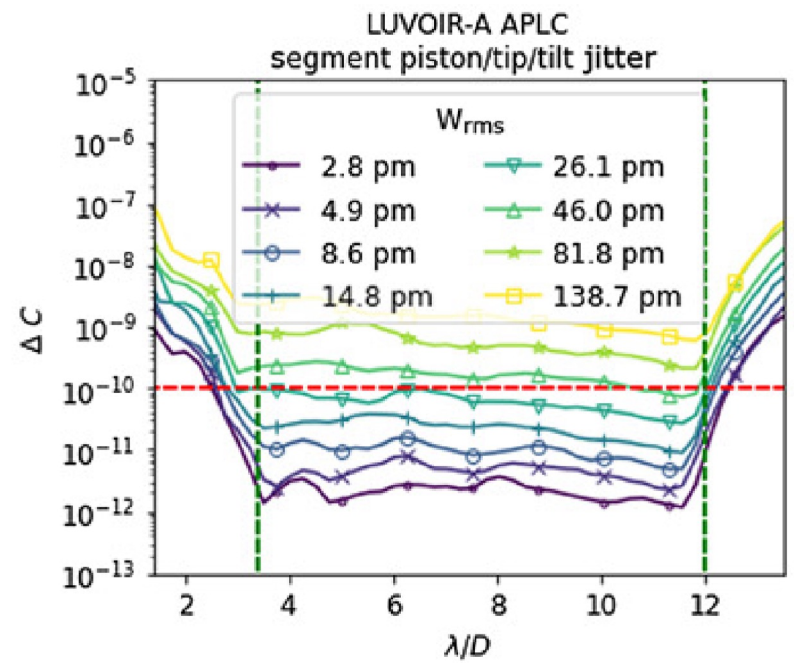
Nemati et al. (2020)

2) Actuator Stability and Drift (3/6)

CTR Input:

- ***Dark hole stability during slew and target observation:*** *At slow timescales requirements are driven by residual post differential imaging: dominated by coronagraph sensitivities.*
- *At fast timescales requirements are somewhat relaxed by averaging over a science exposure (we assume here a factor of ~2)*





Juanola-Parramon et al. (2021)

2) Actuator Stability and Drift (4/6)

CTR Input:

- ***Scenario: No DM updates during science observations***

Frequency (Hz)	Time (s)	1 actuator and less (high SF) (pm)	10 actuators (mid SF) (pm)	Global modes (low SF) (pm)
50	0.02	0.5	5	50
1	1	0.5	5	50
0.1	10	1	10	100
0.001	1000	1	10	100

SF = spatial frequency

2) Actuator Stability and Drift (5/6)

DMTR Input

- HabEx "expected contrast stability performance" of 1.45x10^-11 @ 0.45 um would imply 5 pm stability (no time scale specified). Mennesson et al, Table 2, lists the HabEx wavefront temporal rms stability requirement after correction. 10 pm / hr net stability is needed regardless of how it breaks down between the DM and telescope, this is probably the most stringent case of no control system acting*.

Lower Level Characteristics	CGI (CBEs)	CGI (Design Specifications)	HabEx Requirements	LUVOIR Requirements
Wavefront Sensing and Control			Assumes VVC6	LUVOIR A: APLC; LUVOIR B: VVC6
Residual Defocus drift (pm)	3 (temporal rms in OS9)	< 15 (NFOV)	< 1315	A: < 33, B: < 7
Residual Astigmatism drift (pm)	3 temporal rms in OS9)	< 47 (NFOV)	< 157	A: < 50, B: < 14
Residual Coma drift (pm)	2 (temporal rms in OS9)	< 4 (NFOV)	< 94	A: < 1, B: < 8
Residual Spherical drift (pm)	2 (temporal rms in OS9)	< 2 (NFOV)	< 76	A: < 2, B: < 4
High order wavefront drift in pm after any correction (weighted sum of all Zernikes with n+|m| >=6)	5 (temporal rms in OS9)	< 50	< 5	< 5

Table 2. Mennesson et al. 2020

*For context JWST OTA stability is 110 pm/hr

2) Actuator Stability and Drift (6/6)

Goal: 5 pm RMS per control cycle (target 1 hr)

Notes:

1) The goal refers to the RMS of the difference of wavefront maps.
2) This number is a preliminary design point.
3) This value assumes open loop operation (see possible relaxation below)

Drift: The DM drift should converge to equal or less than the stability requirement after 10 s for small commands

Possible relaxation?

- Likely if the coronagraph has DM metrology.
- Drift convergence will depend on amplitude of the command.

NOTE: Verification by analysis by vendor, and by test by NASA.

3) Actuator Resolution

Definition: The actuator resolution is defined as the minimum controllable incremental motion of each actuator surface. We assume that the DM is in the middle of the stroke (after flattening) and the neighboring actuators have the same voltage as the test actuator.

- **CTR Input:**
  - None
- **DMTR Input:**
  - HabEx allocation for resolution is 2.5 pm and 1.9 pm for LUVOIR Mennesson et al, table 2.
  - Roman CGI requirement is 15 pm resolution

Deformable Mirrors (DM)				
Number of actuators	48 x 48	48 x 48	64 x 64	A: 128 x 128, B: 64 x 64
Number of DMs per coronagraph channel	2	2	2	2
DM stroke range (µm)	>0.5	>0.5	>0.5	> 0.5
DM stroke resolution (pm)	7.5	<15	2.5	1.9

Actuator resolution: 2 pm

Possible relaxation? Unlikely

4) Actuator Stroke (1/3)

Definition: The actuator stroke is defined as the maximum motion of an actuator after flattening the DM. The stroke should be measured for one actuator in the center of the DM, and for an actuator adjacent to the actuators on the perimeter.

- This stroke definition assumes that the neighbor actuators will be allowed to move to respect the specific DM neighbor rule.

CTR Input:

Static	1 actuator and less (High SF) (nm)	10 actuators (Mid SF) (nm)	Global modes (Low SF) (nm)
Stroke requirement, static, instrument driven.	250	10	10
Stroke requirement, static, OTE driven.	10	30	10

SF = spatial frequency

4) Actuator Stroke (2/3)

DMTR Input:

Scenario for stroke requirement	Stroke requirement value (nm) (note: values below assume no margin)	Justification
Correction of static end-to-end wavefronterror	~ 150	From LUVOIR and HabEx WFE requirements [1], [2]; note that these are a few times more aggressive than JWST actual performance [3]
Dark hole digging / high order wavefront control	~ 50 (10% band) ~ 100 (20% band) ~ 200 (multi-star wavefront control)	From typical testbed demos (e.g. see [4]), and assuming linear scaling with bandwidth
Coronagraph design (i.e. stroke required to get to 1e-10, for the case of no WFE)	Highly coronagraph dependent. Some coronagraphs require 0, some ~250	Krist et al. 2019 (HabEx) and 2024 (Roman), see [5] and [6]
Telescope WFE + coronagraph design + EFC + telescope drift +LOWFS	> 500 PV	See Appendix in DMTR spreadsheet. Can be made available upon request.

Taking the most stringent goals we converge to actuator stroke > 500 nm PV

[1] HabEx final report, section B.1.1.1, Wavefront Error Budget: “Wavefront Error (WFE) not exceed 30nm rms in the UV and visible instruments” Using a typical conversion factor of 5x between p-v and rms, stroke required for 30nm rms is 150nm.
[2] LUVOIR final report, section 1.10.1: “end-to-end wavefront error (<35 nm RMS); also, table 8-7, ECLIPS specifications for rms wavefront error: 14, 37, 71nm for UV, VIS, and NIR).
[3] McElwain et al., 2023, Table 5, JWST Static P-V ranges from 61-134nm rms, depending on instrument.
[4] Kasdin et al., 2014, section 8.3: with stroke minimization, strokes required were < 15.4V (assuming BMC DMs and a bias voltage of 100V, this corresponds to a stroke of ~50nm)
[5] Krist et al., 2024, Section 3.1 (HLC): “The DMs create a highly structured wavefrontpattern, intentionally introducing ~76 nm RMS (root mean square) of WFE with ~184 nm peak-to-valley actuator stroke, before adding corrections for aberrations.
[6] Krist et al., 2019, Section 5.4 (HLC): “P-V of 248nm”

4) Actuator Stroke (3/3)

Surface stroke after flattening: > 500 nm PV*

Possible relaxation? Yes, with the following considerations:

1) If a woofer tweeter architecture is implemented, for which the woofer corrects low order modes
2) A static compensator optic could be installed to free up the bulk of the stroke used to flatten the DM
3) If the telescope and instrument are very stable (~10 pm/hr) and the wavefront has only medium to high spatial frequency errors

*Value measured after flattening and assumes that the neighbor actuators will be allowed to move to respect the specific DM neighbor rule.

5) Actuator Pitch

Definition: The distance between actuators assuming a 100% fill factor.

- **CTR Input:**
  - None

- **DMTR Input**
  - HabEx considered a 64x64 BMC 400 um
  - Suggestion from coronagraph designers to stay below 1 mm
  - CGI experience: 1 mm

Actuator pitch: ≤ 1 mm

Possible relaxation? Possible, but will significantly impact mission design

6) Residual WFE

Definition: The WFE* of the DM caused by quilting or other surface finish features that cannot be corrected by actuating the DM.

- **CTR Input:**
  - < 1 nm RMS

Frequency	1 actuator and less (High SF)	10 actuators (Mid SF)	Global modes (Low SF)
0 Hz	<1 nm	<stroke/10*	<stroke/10*

- **DMTR Input:**
  - Riggs et al. includes experimental data and additional modeling argues for < 1 nm RMS

Surface residual WFE: < 1 nm RMS**

Possible relaxation? Unlikely

*The WFE must be measured using interferometry and in open loop after flattening

**A PSD will be specified later in the development of HWO. A guideline PSD can be provided

NOTE: Verification by analysis by vendor, and by test by NASA.

7) Actuator Yield (1/3)

Definition: Number of weak or non-operational actuators, defined as those that cannot be moved (pinned) or their gain prevents the actuator to match the position of their neighbours.

- **CTR Input:**
  - None
- **DMTR Input:**
  - (From Krist et al 2023) No pinned actuators within the pupil*. Pinned actuators may be acceptable if they are located behind an obscuration or on the DM corners. Depends on the influence function, coronagraph design, and proximity to illuminated area.
  - Floating actuators that move with the neighbours could be acceptable as the fraction is very small and they are not adjacent.

*Pupil is defined as a circular area inscribed in the DM area

7) Actuator Yield (2/3)

DMTR Input

- Based on CGI experience and simulations (Krist et al 2023) To reach 10^{-11} contrast no dead actuators in red region is going to be absolutely mandatory, but it could be acceptable in green area. Exact answer depends on DM/Mask/Overall design for HWO.

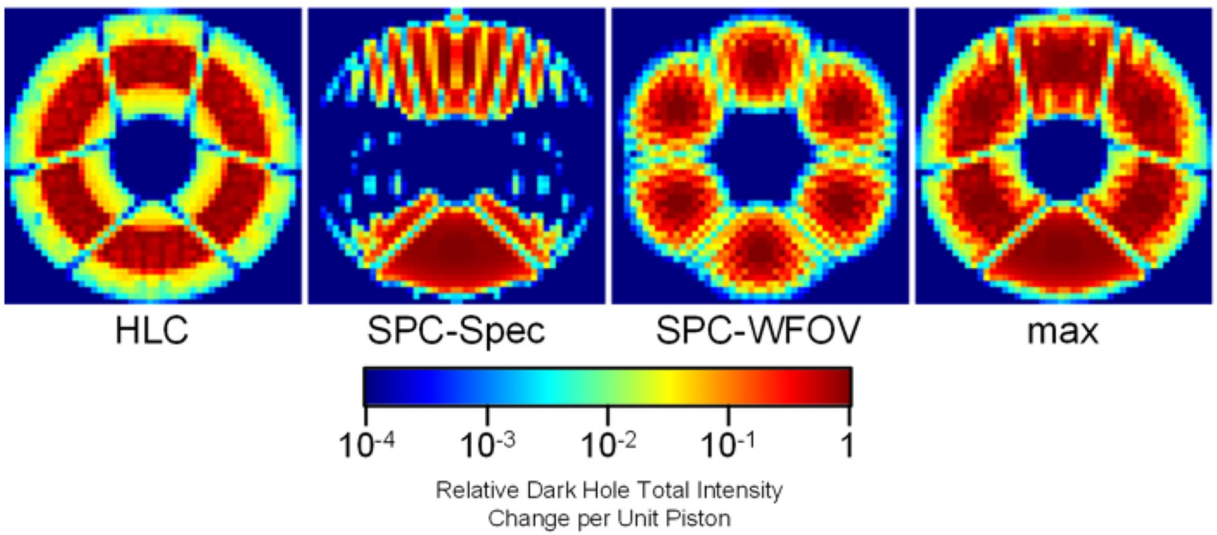


Figure 49. The "strength" of each DM actuator for each baseline coronagraphic mode. These maps were derived by separately pistoning each actuator by an equal amount and measuring the total change in simulated dark hole intensity. The maximum value for each actuator is shown in the "max" map, which is used to determine which actuators need to be individually controlled. Each map is 48 × 48 actuators.

7) Actuator Yield (3/3)

Actuator yield: No weak or non-operational actuators within the inscribed circular clear aperture* as defined by the telescope.

Possible relaxation? Unlikely

* The clear aperture should consider enough margin to prevent that any pinned actuator outside the region does not affect the wavefront inside the clear aperture,

8) Path to Flight

Definition: The system must have a path to flight and survive General Environmental Verification Standard (GEVS) launch and orbit (Sun-Earth L2) environment. Radiation events that may damage the DM must be understood.

- **CTR Input:**
  - None

- **DMTR Input:**
  - No known showstoppers in flight environment (radiation, thermal, vibration, acoustic)

DM should have a path to flight and be able to survive launch and orbital environment.

Possible relaxation? Will depend on instrument shielding and thermal control.

TRL-5 Maturation Plan

Redacted 5/21/2024

Tyler Groff

Feng Zhao

Jeremy Kasdin

Ewan Douglas

Steve Kendrick

Key Areas of Work

1. **DM survey update**
   - Ongoing (Updates from BMC, Obsidian, and ALPAO)
2. **CGI**
   - To be started soon
3. **DM Requirements (Performance goals)**
   - Input from CTR + community consensus
4. **Identify DM systems shortcomings**
   - Electronics, connectors, WFE, etc.
5. **Interaction with vendors**
   - Electronics, connectors, WFE, etc.
6. **Plan to TRL-5 and infusion to 6**
   - Define TRL-5 test plan and hardware + Infuse system in CTR testbed
7. **Community engagement**
   - Define TRL-5 test plan and hardware + Infuse system in CTR testbed

Overall DM Technology Roadmap Task

Study to define the necessary steps to mature Deformable Mirrors Systems for future flagship exoplanet mission

The study will:

1. **Prepare a plan to test and qualify any DM system technology to TRL-5, and subsequently TRL 6 as integrated with the coronagraph:**
   a. Define the goals and exit criteria of the roadmap
   b. Consider DM plans described in the HabEx/LUVOIR reports – Note: studies did not detail DM TRL5 qualification to this depth
   c. Utilize placeholder DM system requirements for the HWO
   d. Update the ExEP DM Survey to capture the latest updates
   e. Document the DM system experience by the Roman Coronagraph
   f. Consider all of the above to develop the maturation plan.

2. **Inform NASA/EXEP the cost, schedule, and risks to execute the roadmap with all vendors (no down selection)**

TRL-5 Working Group Task

- **Assess what qualifies a DM system as TRL-5**
- **DM System = Device, Electronics, Harness**
  - thermal control system? Leave this as a device requirement
- **Harnessing will likely be device specific**
- **Electronics may be evaluated as common solution but unique requirements for a technology must be identified**
  - i.e. inductive vs. capacitive loads, feedback concepts
- **Should focus on the testing for delivering a TRL5 DM system**
  - Device, Electronics, Harness level testing
  - Contrast Requirements to evaluate DM System TRL
    - Need to clearly identify how we support picometer level testing, drift in particular

Achieving TRL-5

- **Using definitions defined with concurrence from Coronagraph roadmaps**
  - DM requirements including:
  - Resolution, stroke, stability, actuator count and pitch, lifetime, mass, power and volume
- **Manufacturing and testing**
  - Vendor site visit and joint research
  - Procure units flight format (DM, connectors and electronics) and preparing test facilities
  - Define vendor test program
  - Acceptance tests
  - Environmental tests
  - Performance tests
- **Iterate**
  - Discuss with vendors shortcomings and improvements
  - Repeat #2
  - TRL-5 review
  - Deliver TRL-5 unit
- **Path to TRL-6**
- **Infuse system in CTR testbed**

System Requirements and TRL-5 Tests

Design Requirements

- **Design Requirements**
  - Performance/Function
    - Stability
    - Resolution
    - Total stroke
    - Gain stability and knowledge
  - Form/fit (mass, volume, layout, etc.)
    - Actuator Pitch and count (96x96)
    - Harness and enclosure volume. Bezel area
  - Interfaces
    - Power dissipation
    - Temperature stability
  - Operating environments
  - Lifetime
    - Performance degradation
    - survival

Integrated System Tests

- **Performance/Function**
  - Picometer-stability of test
  - Control resolution of device control
  - Influence function and failed actuator tests
    - Quantity and type of actuator failure
  - Actuation speed
  - Actuator coupling (proof of capability)
  - Lifetime tests
    - Performance degradation from use
    - Survival (fatigue/cracks etc)
  - Contrast test of device?
- **Relevant environments**
  - Radiation environment
  - Thermal-Vacuum
  - ?Vibration-Shock? GEVS analysis?
  - Electromagnetic
  - Life limit survival tests

Stroke and Stability Requirements

Requirement Flow-Down from Coronagraph Technology Roadmap Working Group

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

Stroke

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.

USORT: HWO Control Scenarios Impacting DM Requirements

A. Correct the quasi-static mid-spatial frequency errors
   - Telescope and coronagraph surface and reflectance non-uniformity

B. Correct the dynamic low-order WFEs caused by drifts in telescope
   - Telescope alignment and warping of the primary mirror*

C. Correct for dynamic drift in primary mirror segments tip/tilt/piston

Each scenario drives different requirements:

- Same actuator stability & resolution requirements for all 3 scenarios
- DM format, stroke, needed update timescale, gain stability will differ

Key question:

- Can a single DM handle all three tasks, or will multiple DMs be needed?

Moving forward with DM definitions:

- We will provide requirements to the vendors now, derived from Case A
- The DM WG needs to continue work to identify how requirements change between cases A, B, C

* tip/tilt will be corrected by a fine steering mirror

Path Forward

- **✓ Review the Technology Assessment Best Practices guide (SP-20205003605)**
- **✓ 6/12 Get a primer from Feng on CGI TRL raising activities and path to TRL-5 and 6**
- **Identify key requirements for device performance that must be tested**
- **✓ Performance (Decision: do we verify the device only or contrast)**
- **Environmental**
  - Map to driving requirements for any individual technology
  - Expectation that some performance requirements are more difficult to meet than others for a particular technology
- **Identify what each technology needs to be considered a medium fidelity unit**
- **Identify relevant testing or analysis to claim TRL-5**
- **Iterate and Document TRL-5 criteria across technologies**

Some Notes on Technology Readiness Assessment (TRA)

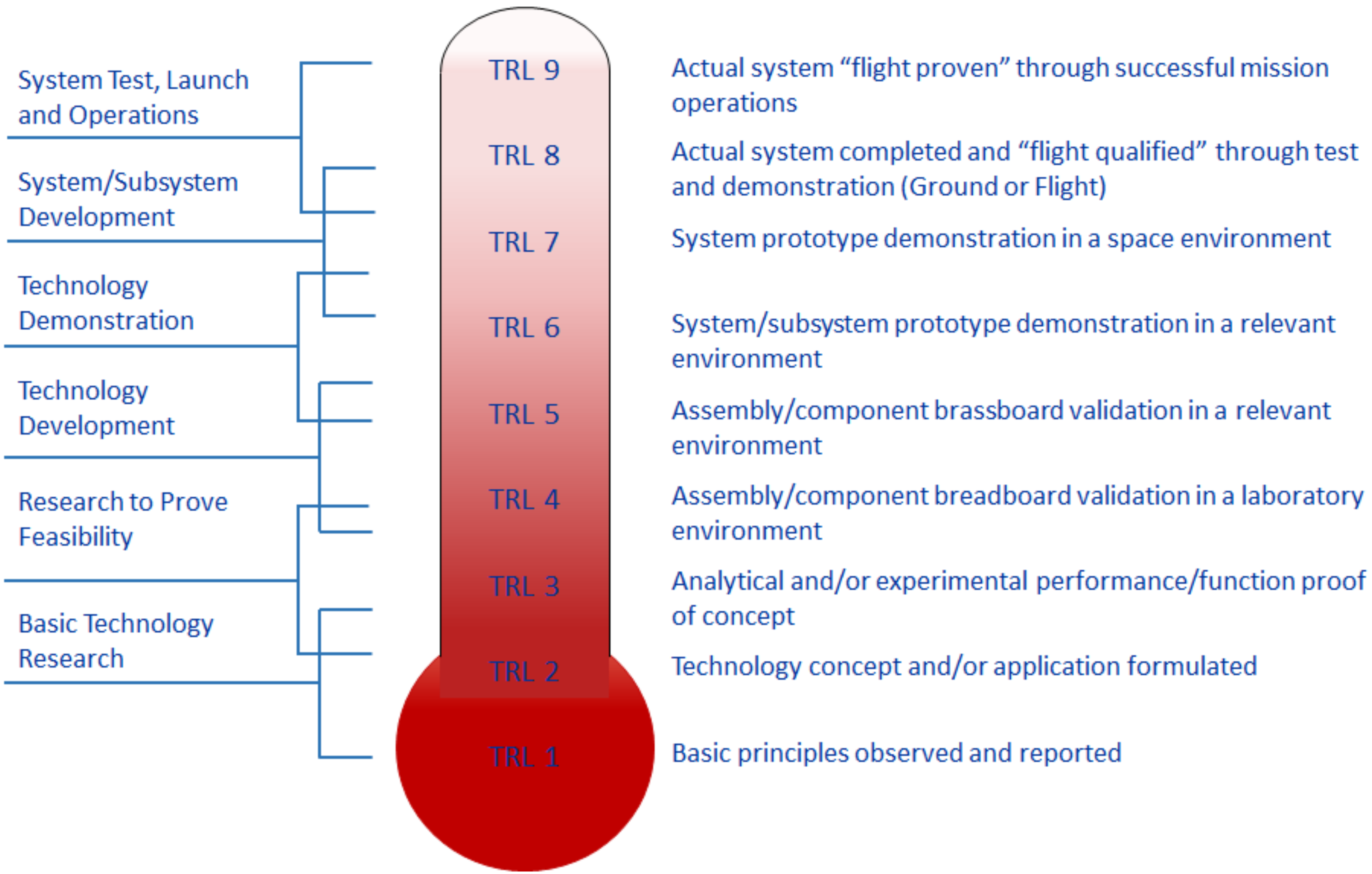
- **TRL definition is agency level (oversight?) SP-20205003605**
  - Technology Readiness Assessment Best Practices Guide
  - Sec. 3.1.4 Defines Key questions to support TRL review (15 for TRL-5)
- **TRA is NASA center-driven and NASA center-dependent**
  - Appendix A provides examples of processes three NASA Centers use to conduct TRAs.
  - Each Center can tailor its process for implementing TRAs to the distinct needs of each Center. TRL assessment teams can reference these processes as examples for how to design, modify, and conduct their own TRAs.
  - Implementation can vary, but the definitions provided in the best practices guide—such as the TRL definitions—are standard across NASA Centers.

TRL-5 Questions for TRA Reviewers

For each of the three critical technology elements, consider the following:

- **Have Critical Technology Elements been identified?**
- **Fidelity of Build**
  - Did the team develop and operate a medium fidelity test article, with realistic support elements?
- **Fidelity of Analysis**
  - Did the team develop a medium-fidelity analysis
  - Is the team's error budgeting at an appropriate level of fidelity?
  - Have life-limiting factors been considered?
- **Environments**
  - Is the choice of relevant environments correct?
- **Performance**
  - Did the team demonstrate performance in critical areas?
- **Success Criteria**
  - Did the team document test performance and show agreement with analytical predictions?
  - Did the team document a definition of scaling (via models)?
- **Path to flight**
  - Does the team have a credible path to TRL-6?

Thermometer Scale for NASA's TRLs



Brassboard vs. Breadboard

- **Breadboard: A low fidelity unit that demonstrates function only, without respect to form or fit. It often uses commercial and/or ad hoc components and is not intended to provide definitive information regarding operational performance.**
- **Brassboard: A medium fidelity functional unit that typically tries to make use of as much of the final product as possible and begins to address scaling issues associated with the operational system. It does not have the engineering pedigree in all aspects but is structured to be able to operate in simulated operational environments in order to assess performance of critical functions.**

Important notes from "Table 2.5.-1: Fidelity of Build"

- Environmental testing (e.g. survival/performance post survival levels): TRL-5 brassboard must be designed to meet relevant environments. TRL-6 prototypes must be tested to meet relevant environments.
    - Device and Electronics don't necessarily have to meet performance requirements post-environmental testing
    - That said, electronics and device should probably meet TRL-5 after driving environments
        - Electronics: Radiation/EMI
        - Device: Vibe/Shock/Thermal
- Scalable: TRL-5 brassboard form/fit is approximate with with scale factors understood. TRL-6 prototype must be representative form/fit with scaling factors understood.
    - Electronics: If one ASIC chip only has subset of control channels that is okay. E.G. if one chip has 128 channels a fully integrated set of 72 chips is not required to qualify TRL-5 *if* there is clear way to integrate on a full backboard
    - Device: scalability not particularly straightforward, must be a full-scale array

Assumed Encompassing TRL Milestones at Coronagraph Testbed Level

- **When instrument performance tests are done, we must be able to identify the limiting subsystem or how subsystems interact to limit the entire instrument system**
  - This becomes more difficult and complex as TRL increases
- **Fundamental tenet of DM system verifications is to systematically test performance constraints and the extent to which the DM system limits instrument/observatory performance**
- **Rely on in-air coronagraph testbeds to qualify up to TRL-3**
- **Subsystem breakouts begin at TRL-4 and are integrated in TRL-5**
  - TRL 4 must prove the DM is not the limiting factor in ideal conditions and make performance predictions against various optical stimulus
  - TRL-5 must prove the DM is not the limiting factor in the presence of relevant disturbances and control loops

Context: Coronagraph Level Verification

TRL 1-3

Coronagraph Testbeds in Air
~ 1x10^{-8} Contrast Demos
< 16-bit electronics
≥ 10% Broadband
Single or Two-sided DHs

DM TRL Clear from these tests in coronagraph testbeds
✓ Device
✓ Electronics
✓ Harness

TRL 4 Breadboard, Laboratory

Air or Vacuum
~1x10^{-10} Contrast Demos
? ≥ ?-bit electronics
≥ 10% Broadband
Single or Two-sided DHs

DM TRL with coronagraph less clear
- Electronics can be in air and of arbitrary size/power draw
- What limits best contrast performance under ideal conditions?
- Sensitivity to various stimulus can be tested (wavefront dynamics, LOWFS feedback, etc.)

TRL-5 Brassboard, Relevant Environment

Vacuum
≥ 16-bit electronics
≥ 10% Broadband
Two-sided DHs
Relevant Aperture

DM TRL must be demonstrated beforehand
- Electronics must have flight-like form and fit, at least feasibly operates in vacuum
- Interconnects/harness arguably also of flight format. Likely must be negotiable with instrument architecture trades
- What limits robustness to relevant disturbances, the control architecture, the coronagraph, or the DM itself?

Breaking out DM Device and Electronics Testing for TRL-5

DM TRL4 and TRL5 Verification Architecture

Prove flight electronics can drive device

Full Testbed TRL-4

Proving device meets spec with appropriate electronics

Electronics TRL-4

Functional Electrical Performance
- Can drive DM to tolerance
- Must Inform ASIC design
- Supported by series of scaled milestones up to 96x96 channels. e.g. an ASIC with subset of channels reaching 14→16→20 bit-depth and a feasible design path to 96^2 channels with target power, volume, and mass

Electronics TRL-5

- Likely ASIC solution
- Meeting full form and fit for a 96x96 array
- Vacuum compatible design
- Meets performance post-survival environments, even if by agreed upon analysis or subsystem test: EMI, Shock, Acoustic, Vibration, Thermal
- Suitable flight-like interconnect to device

Device TRL-4

Verify Functional Surface Performance
- Static/dynamic surface quality
- Prove lab electronics limit performance
- Supported by series of scaled milestones that span key technology gaps from smaller to larger formats. e.g. incremental 32^2→48^2→96^2 formats to meet flatness, tiling, or drift requirements. Devices must also inject into coronagraph testbed

Device TRL-5

- Use of TRL-4 Electronics
- Must have DM-side flight format harness solution
- Meets surface metrics at final form and fit
- New Requirement/Verification Approach: Tiered PSD+actuator verification method to meet picometer surface tolerances using VSG + Zernike sensor/'Fiducial' coronagraph

Full Testbed TRL-5

Ongoing interconnect and harness environmental testing and trades*

*Activity likely to carry through to TRL-6

Components Path to TRL-5

Prove flight electronics can drive device

Electronics TRL-4

Functional Electrical Performance

- Can of drive DM to tolerance
- Must Inform ASIC design
- Scaled development up to 96x96 channels

Electronics TRL-5

- Likely ASIC solution
- Meeting full form and fit for a 96x96 array

Proving device meets spec with qualified electronics

Device TRL-4

Functional Surface Performance

- Validates dynamic surface performance
- Prove lab electronics are limiting performance
- Static surface quality metrics
- Scaled milestone plan from e.g. 48x48 to 96x96

Device TRL-5

- Use of TRL-4 Electronics
- DM-side harness solution
- Meeting surface metrics at final form and fit
- VSG, Zernike sensor, ‘Fiducial’ coronagraph

Full Testbed TRL-5

- Relevant Coronagraph
- Relevant Aperture
- ≥10% Broadband
- Two-sided DHs

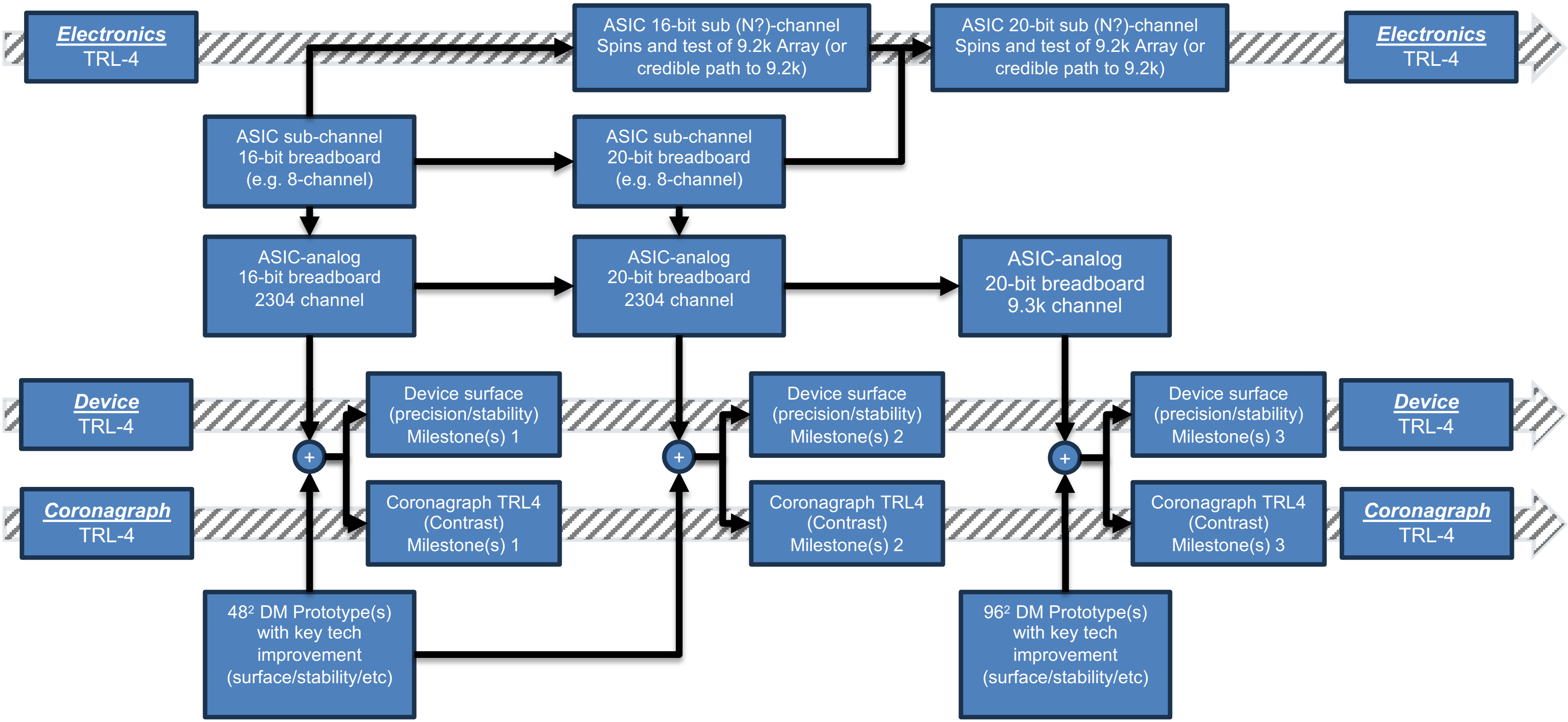
Ongoing interconnect and harness environmental testing and trades*

*Activity likely to carry through to TRL-6

Mapping DM TRL Raising to Hardware Development

- **Verification Architecture highlights overall phasing of DM subsystems to qualify a full-format device to TRL5 that meets all specifications**
- **Hardware-centric development and verification flow should be based on risk mitigating milestones that buy down technology-specific risks and support both technology lifts and down-selects**
  - These developments and milestones translate to phased device deliverables from the vendors and possibly on-site testing of intermediate hardware throughout the project
    - Coronagraph testbeds need newly improved devices to continue progress in high contrast demos
    - Device and Electronics verification and the associated resources to do so will be developed alongside the DM. (e.g. a testbed for any kind of 10-100 picometer jitter verification at 50Hz doesn't exist)
  - Special note: Budget/schedules tend to force focus on down-selecting, but performance opportunities unique to each technology merit strategic "lifts" of systems that allow them to meet the demands of a flight coronagraph unique to NASA needs

Supporting Tests and Required Components Example Test Flow



Vendor Qualification

- **We have provided very strict requirements, particularly in stroke/resolution/stability**
  - Some of these requirements are on the bleeding edge of measurement capabilities
- **DM manufacturers are not full-up optical test facilities**
  - Some vendors lack even basics such as cleanrooms, interferometers, optical test equipment
  - Most vendors do not and will not sign up to building flight electronics
- **Need to consider carefully the development and verification structure, milestones, and deliverables**
  - Key and driving requirements that require specialized testing vendor supports by analysis
  - Intermediate deliveries of devices targeting specific milestones for testing by NASA
  - Backstop (one way or another) on supply chain to meet these milestones and deliverables

Device Verification GSE

- **Best verification to-date in the VSG with 20-bit dithering electronics required a full week of data collect**
- **The current GSE is not adequate to verify milestone demonstrations of DMs as we develop them to full 96x96 format**
- **Requirements are *almost* written as a function of spatial frequency and temporal frequency, but at device level we continue to suffer from death-by-decomposition**
- **Recommend new requirement and verification approach that does not focus on actuator-type decomposition, but rather power spectrums in space and time. Define new GSE that can verify such requirements**
  - Current thinking by Tyler Groff is in addition to VSG, have single actuator picometer demonstrations, as well as develop a ”fiducial coronagraph” with a highly simplified and ultrastable apodizer, LOWFS, and speckle imaging setup for correlated trending of pupil and focal plane speckle. This will allow for correlated space and time-domain verifications of the device as-relevant to coronagraph speckle stability (our *REAL* requirement!)

Overview of TRA Questions for TRL-5

- **Agreement between technology deliverer and customer:**
  1. What are the CTEs?
  2. What are the benefits of the new technology?
  3. What are the design requirements? These typically include the following:
    . Performance/Function (concept of operation, calibration, modes, autonomy, etc.)
    b. Form/Fit (mass, volume, layout, etc.)
    c. Interfaces a (thermal, mechanical, power, electrical, data, signal/sample input, etc.)
    d. Operating environments (mechanical, dynamics, thermal, radiation, EMI/EMC, etc.)
    e. Lifetime
  4. What are the relevant environments?
  5. What are the analysis requirements? This includes the following:
    a. Key performance parameters and life limiting factors
    b. Model with "first order" equations
    c. Validation that provides moderate accuracy analysis uncertainty factor and limitations
  6. What are the test requirements? Note: Not all design requirements are tested. These include at minimum the following:
    a. Performance/Function
    b. Relevant environments
  7. What is the level of integration and test configuration? For TRL-5, at minimum, the component/assembly level is demonstrated by means of a brassboard in the relevant environment.
  8. What data is used to capture the agreements and results?
- **Analysis results:**
  9. What performance is predicted for the key parameters and life limiting factors for the test conditions? Note: these are put in place prior to the test.
  10. What are the analysis uncertainty factors and limitations?
  11. Are the analyses updated based on the test results?
- **Test results:**
  12. Are the test requirements successfully demonstrated?
  13. Are the variances between the test results within the analysis uncertainty? If not, are the variances understood?
  14. Were there any unpredicted behaviors? If so, was root cause determined and impact found to be acceptable?
- **Data Products:**
  15. Are the data products, agreed to in Question 8, above, complete?

Question 1

What are the Critical Technology Elements (CTEs)?

- **Deformable Mirror Device**
  - Specifically, for HOWFS&C loops to generate contrast. Devices for e.g. tip-tilt offloads of primary mirror segments would be assessed against completely different set of requirements
- **Harness and interconnects**
  - Carrying analog signal from drive electronics to
- **Drive Electronics**
- **(Arguably) Thermal control system**
  - Thermal stabilization of device
  - Heat rejection if required for specific technologies

Question 2

What are the benefits of the new technology to Habitable Worlds Observatory?

- **Enables Coronagraphic Imaging of Exoplanets**
  - Enabling for general astrophysics for better wavefront stabilization. Non-exoplanet science using coronagraph instrument?
- **Increase Yield of exoplanet discoveries**
- **Reduce cost and risk of the instrument and mission**
- **Any device-specific enabling capabilities**
  - Surface polishing Post-actuator integration for better mid-spatial frequency surface performance (Quilting)

Question 3

What are the design requirements? These typically include the following:

- **Performance/Function (concept of operation, calibration, modes, autonomy, etc.)**
  - Stability
  - Resolution
  - Total stroke
  - Gain stability and knowledge
  - Reflectance minimum over spectral range and derived requirements on optical coatings (if any)
- **Form/fit (mass, volume, layout, etc.)**
  - Actuator Pitch
  - Harness and enclosure volume. Bezel area
- **Interfaces (thermal, mechanical, power, electrical, data, signal/sample input, etc.)**
  - Power dissipation
  - Temperature stability
  - Operating voltage; voltage bias (e.g., for PMN actuators)
- **Operating environments**
  - Vacuum; room temperature +/- 20 C TBR (assumes HWO will be biased slightly below RT and controlled with heaters); radiation env. at L2
- **Lifetime**
  - Performance degradation - Graceful degradation (number of allowed non-functional actuators);
  - number of lifetime cycles - TBR
  - Survival

Question 4

What are the relevant environments?

- **DM**
  - Vacuum
  - RT+/- 20 C TBR operating; +/- 55C TBR storage
    - assumes HWO will be biased slightly below RT and controlled with heaters to meet stability requirements; DM may require separate temperature control
    - Note: need to understand materials, outgassing, max. allowed temp. of any coatings/epoxies etc. and take that into consideration when doing bake-outs for contamination control
  - Radiation at L2 for 5 years TBR
  - Acoustics, vibration, shock
  - WFE (Wave Front Error) and stability
    - We expect the HWO observatory static WFE and WFE stability might be on the order of 10’s nm and 10’s – 100’s pm, respectively.

Question 5

What are the analysis requirements? These include the following:

Key performance parameters and life limiting factors

Model with "first order" equations

Validation that provides moderate accuracy analysis uncertainty factor and limitations

- **DM**
  - Influence functions. Stroke at adjacent actuators a factor in analyzing impact of dead, mechanically broken, or pinned actuators and ability to compensate or accept degradation.
  - Leakage impact when passive during observation; required refresh rate
  - Calibration accuracy for "flattening" mirror and stroke range used for that; introduction of higher order errors when flattening or correcting "low order" errors
  - Dynamics impact – can we assume that if operating closed loop any induced dynamic perturbations are negligible at pm level? If always passive during observations this isn't relevant. Would be interesting to analyze if this is a limitation at some stability performance level.

Question 6 – Integrated System Test

What are the test requirements considered here? Note: Not all design requirements for Habitable Worlds Observatory are tested. These include at minimum the following:

- **Performance/Function**
  - Picometer-stability of test
  - Control resolution of device control
  - Influence function and failed actuator tests
    - Quantity and type of actuator failure
  - Actuation speed
  - Actuator coupling (proof of capability. Device always must be screened)
  - Lifetime tests
    - Performance degradation specifically from use
    - Survival (fatigue/cracks etc)
  - Contrast test of device
    - Spatial frequency tests showing speckle control of 10-10 amplitude?
- **Relevant environments**
  - Radiation environment
  - Thermal-Vacuum
  - ?Vibration-Shock? Need a GEVS analysis to meet TRL-5?
  - Electromagnetic
  - Life limit survival tests

Question 6 – Electronics Tests

What are the test requirements considered here? Note: No design requirements for Habitable Worlds Observatory have been established. These include at minimum the following:

- **Performance/Function**
  - Commanded voltage stability
  - Least-significant-bit output voltage
  - Control speed under representative load
  - Actuator coupling (proof of capability. Device always must be screened)
  - Lifetime tests
    - Performance degradation specifically from use
    - Survival (fatigue/cracks etc)
  - Contrast test of device
    - Spatial frequency tests showing speckle control of 10-10 amplitude?
- **Relevant environments**
  - Radiation environment
  - Thermal-Vacuum
  - ?Vibration-Shock? Need a GEVS analysis to meet TRL-5?
  - Electromagnetic
  - Life limit survival tests
  - WFE and stability of OTA: We expect the HWO observatory static WFE and WFE stability might be on the order of 10's nm and 10's – 100's pm, respectively.

Question 7

What is the level of integration and test configuration? For TRL-5, at minimum, the component/assembly level is demonstrated by means of a brassboard in the relevant environment.

Question 8

What data products (and measurements) capture the agreements and results?

Question 9

What performance is predicted for the key parameters and life limiting factors for the test conditions?

Question 10

What are the analysis (modeling) uncertainty factors and limitations?

Question 11

Are the analyses (aka modeling) updated based on the test results?

Question 12

Are the test requirements successfully demonstrated?

Question 13

Are the variances between the test results within the analysis uncertainty? If not, are the variances understood?

Question 14

Were there any unpredicted behaviors? If so, was root cause determined and impact found to be acceptable?

Question 15

Are the data products, agreed to in Question 8, above, complete?

TRL 0 thorough 5

- **Maturation plan for much lower TRL devices**
- **DMs on curved surfaces**
- **Drizzle architecture for 2+ DMs**
  - Sub-pixel Lateral displacement of actuators
- **Sparse DMs**
- **Diffractive patterns on DMs**
  - Super-Nyquist EFC enabling

Concerns/Risks

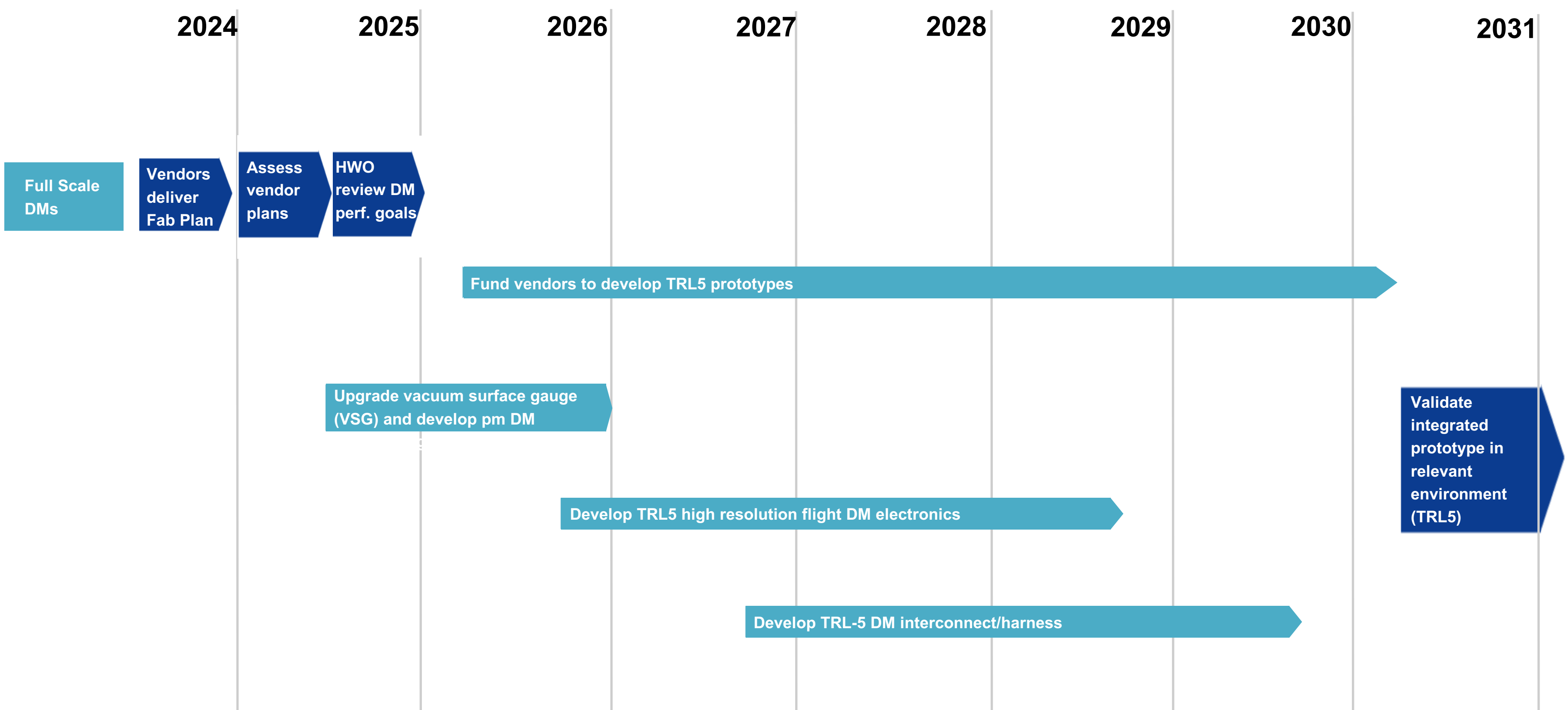
Risks Captured by the Working Group

- Are we missing something? Are there more risks than those listed in the table.
- Non-vendor risks. OWA/large format DM risk. Testbed capability gap for characterizing 96x96 DMs. When does this needs to be retired?
- There is a risk that DM requirement may be even more strict than those captured in the provisional performance goals document. That risk spreads out into all areas of HWO.

Additional Working Group Concerns

- **Picometer verification of DMs as part of path to TRL-5**
- **Many years (≥ 5) to receive testable devices from any vendor that meet the requirements**
  - Development needs/risks are technology dependent
  - In addition to requirements, need to establish a development plan with vendors for intermediate qualification milestones and risk reduction
    - Some specific examples:
      - surface flatness/actuator print-through
      - Stability/Actuator precision

Deformable Mirror Technology Roadmap



Suggested Future Work and Trade Studies

- **Consider how far the maturity is for each technology**
- **Consider what intermediate milestone development buys down the most risk with top vendors**
  - (don't just send requirements for 96x96. e.g. 2-nm flatness on a kiloDM or a 2K)
  - Seed money for the vendors to develop more detailed development plan
- **Rigorous decomposition of instrument requirements to DM so system-level trades can be made against DM specs that are difficult to achieve or test**
  - just setting a challenging bar for the device without trading real instrument impacts will not be successful
- **In addition to device requirements, we need to define a full qualification program with scaled performance milestones**
  - e.g. stability and surface flatness at intermediate actuator counts, interconnect on smaller devices, what to send to HCIT for contrast demonstrations
- **Reconsider how we define the stability/precision requirement for the DM and how to verify it**
  - What DM verification facilities are needed to prove how/if DM limits the instrument

Suggested Future Work and Trade Studies

- **Electronics design**
  - ASICS, required LSB/stability (driven by bluest wavelength), bit-dithering vs. true >16-bit (20?), harnessing vs. direct connection
- **NASA should be more involved with the DM vendors (collaboration), including QA and MA**
- **Interconnect**
  - AOX: resolve interconnect induced astigmatism (e.g. change symmetry of interconnect or wire bond)
- **More rigorous study and trades in pairing high order DMs with low-order and parabolic DMs**