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

A First Cut at Deformable Mirror Performance Goals

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We acknowledge the valuable contributions of the entire DMTR team.

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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 is excluded from the stability definition.

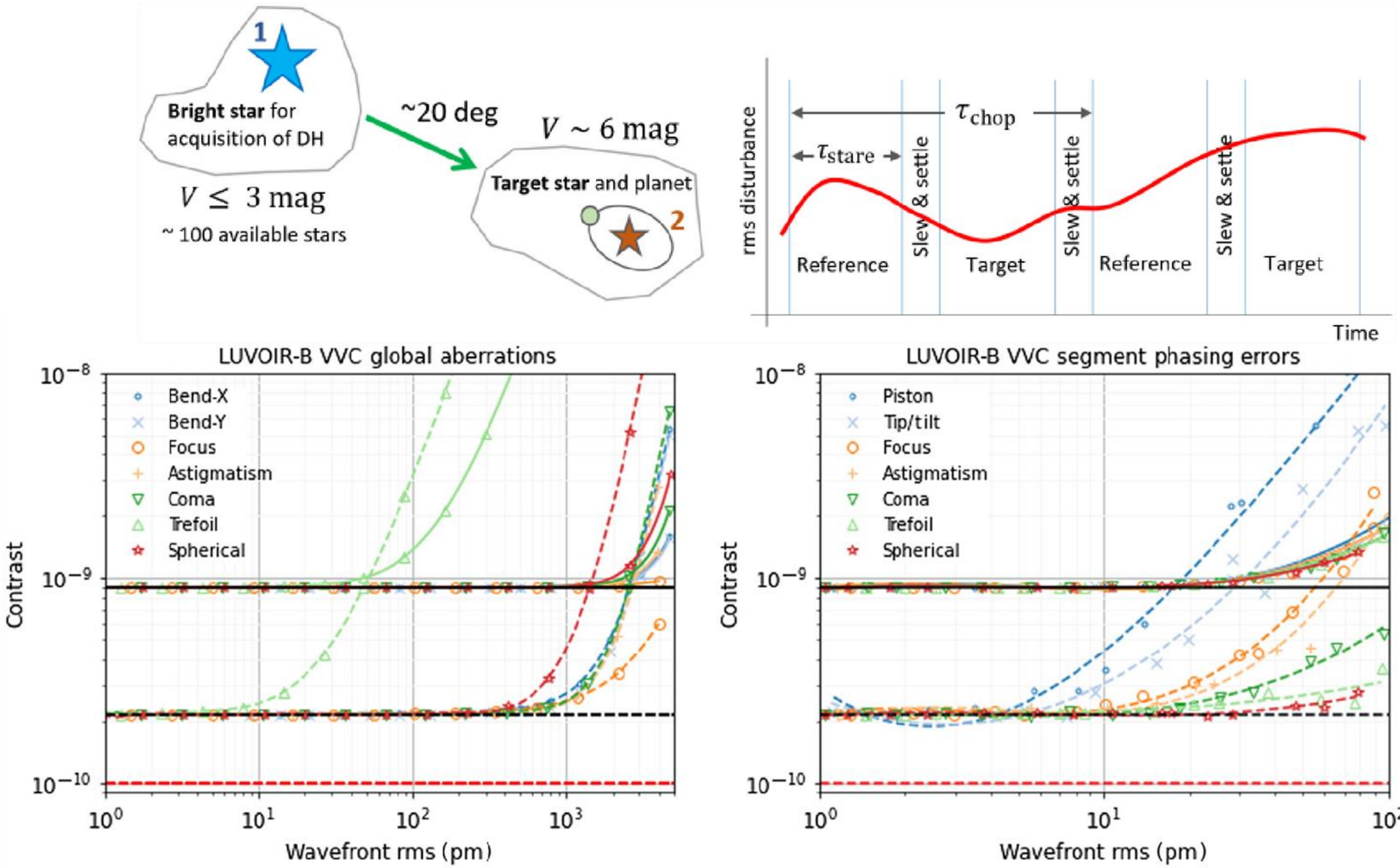
- **Actuator drift definition:** The rate of uncommanded motion of the DM excluding piston.

- **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.*

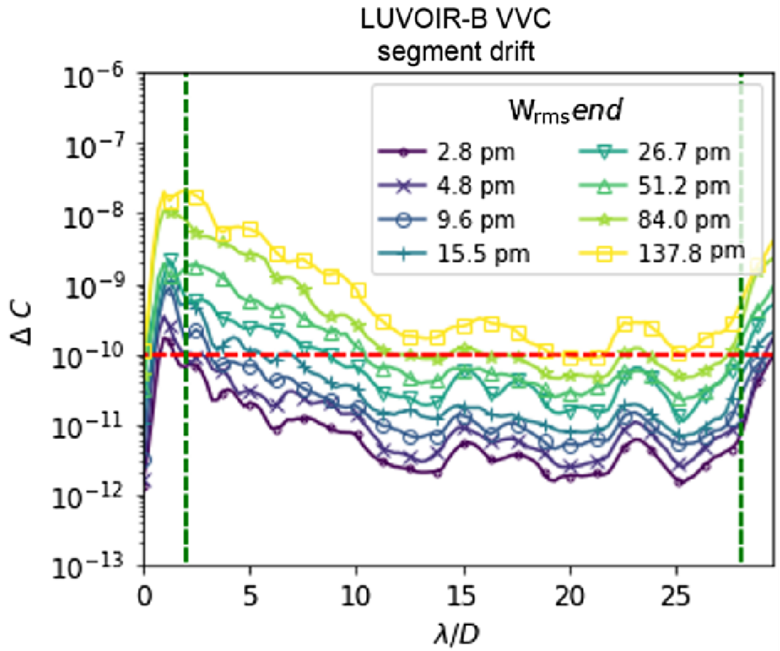


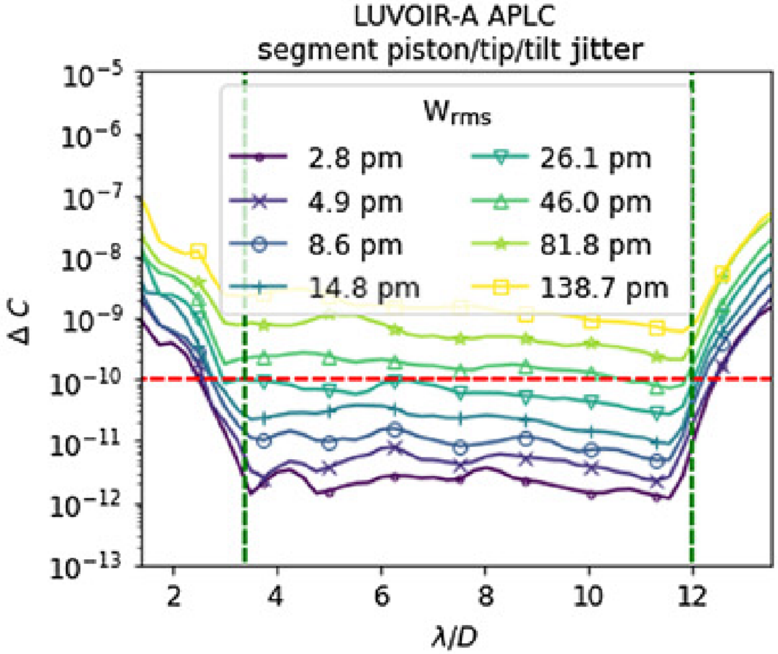
Nemati et al. (2020)

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 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
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

Lower Level Characteristics	CGI (CBEs)	CGI (Design Specifications)	HabEx Requirements	LUVOIR Requirements
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.

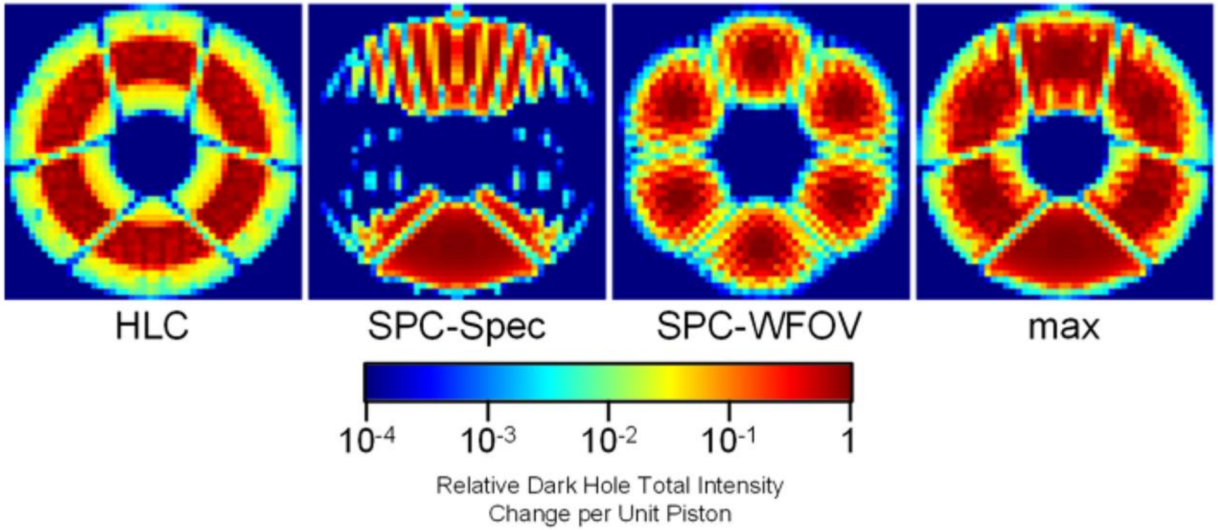


Figure 49. The "strength" of each DM actuator for each baseline coronagraphic mode. These maps were derived by separately pistoning each actuator by an equal amount and measuring the total change in simulated dark hole intensity. The maximum value for each actuator is shown in the "max" map, which is 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. Also the flight housing/carrier and electrical interconnect concepts must be explained.

- **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. Flight housing/carrier and electrical interconnect concepts must be explained.

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