Deformable Mirror Technology Roadmap (DMTR)

ExEP Technology Colloquium

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DMTR Working Group

June 7, 2024

Overall DM Technology Roadmap Task

Study to define the necessary steps to mature deformable mirror systems for future flagship exoplanet mission

The study will:

1. Define a possible roadmap
2. Factor in DM plans described in the HabEx/LUVOIR reports
3. Define provisional DM system requirements for the HWO
4. Update the ExEP DM Survey to capture any changes
5. Capture relevant DM flight experiences by the Roman Coronagraph
6. Engage with the top DM vendors to assess their interest and share provisional 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**

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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*Roman Coronagraph Instrument

Summary of the Study Deliverables (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
  - https://exoplanets.nasa.gov/internal_resources/2859/

- Updated the 2022 DM Vendor Survey that identified three promising candidate vendors:
  - **AOA Xinetics' electrostrictive DMs**
  - **Boston Micromachines' electrostatic MEMS DMs**
  - **French company ALPAO and their magnetic DM**

- Visited all three DM vendors at their manufacturing facilities

Summary of the Study Deliverables (2/2)

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

Study Findings (1/2)

- **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 vendors exist in important areas such as actuator count, resolution, pitch, surface figure, stability.
  - Possible that telescope/coronagraph system design and/or science requirements may have to trade against DM performance.

- **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

- **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 (2/2)

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

Note: This work was performed in absence of system design information and focused on continuous facesheet high-order DMs, no woofer/tweeter configuration.

Deformable Mirror Survey Update

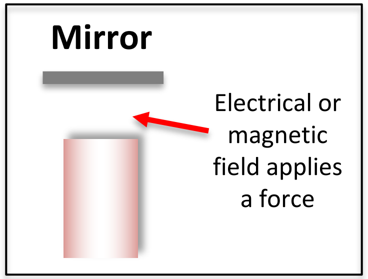
Eduardo Bendek
Jet Propulsion Laboratory – California Institute of Technology

NASA Exoplanet Exploration Program
May 9, 2023

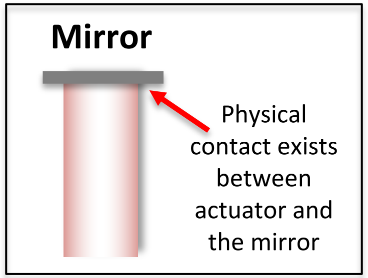
Technologies Overview

- 14 identified technologies
- 3 of the technologies deemed by group of subject matter experts to be closest to meeting HWO provisional requirements
  - **AOA Xinetics electrostrictive PMNs**
  - **Boston Micromachines electrostatic MEMS**
  - **ALPAO electromagnetic**
- Site visits made to the three DM companies during survey

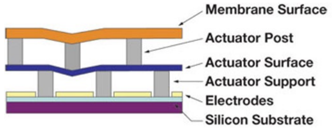
Contactless technologies



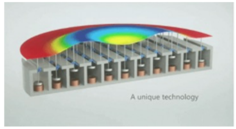
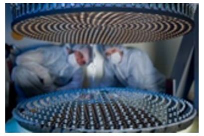
Contact technologies



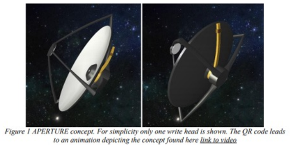
Electrostatic
BMC, Obsidian



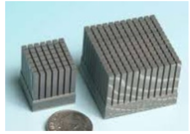
Electromagnetic
ALPAO, Microgate, TNO

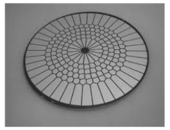
Magnetic
APERTURE

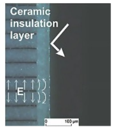


Electrostrictive
Xinetics, Microscale

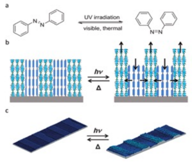



Piezo/monomorph
Cilas, PI+Fraunhofer (PICMA)





Photonic
Sparse DM



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

A First Cut at Deformable Mirror Performance Goals

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Tyler Groff (NASA Goddard Space Flight Center)
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We acknowledge the valuable contributions of the entire DMTR team.

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https://exoplanets.nasa.gov/internal_resources/2859/

CL# 23-4821

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

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:**
  - 2.5 pm and 1.9 pm for HabEx and LUVOIR respectively (Mennesson et al, table 2)
  - Roman CGI requirement is 15 pm resolution

	CGI CBE	CGI Design Spec.	HabEx Requirement	LUVOIR Requirement
Number of Actuators	48x48	48x48	64x64	A: 128x128, B: 64x64
Number of DMs per coronagraph channel	2	2	2	2
DM stroke range (nm)	>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 wavefront error	~ 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

- **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 neighbors.
- **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.

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

Possible relaxation? Unlikely

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

** The clear aperture should consider enough margin to prevent any pinned actuator outside the region from affecting the wavefront

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.

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

Possible TRL-5 Maturation Plan

Tyler Groff
Feng Zhao
Jeremy Kasdin
Ewan Douglas
Steve Kendrick

Parts redacted

TRL-5 Task Group

- **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 TRL-5 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
- **Infuse system in DM Characterization 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

Provisional 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	250nm	10nm	10nm
Telescope driven	10nm	30nm	10nm

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

*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	0.5pm	5pm	50pm
1 Hz	0.5pm	5pm	50pm
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

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)

Agreement between technology deliverer and customer:

1. What are the Critical Technology Elements (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?

- **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 device
- **Drive Electronics**
  - >16-bit resolution, high voltage, >18k channels
- **(Arguably) Thermal control system**
  - Thermal stabilization of device
  - Heat rejection if required for specific technologies

Question 3: What are the design requirements?

- **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?

- **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**

- **Critically for the DM: Observatory dynamic wavefront error**

Question 5: What are the Analysis Requirements?

- 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

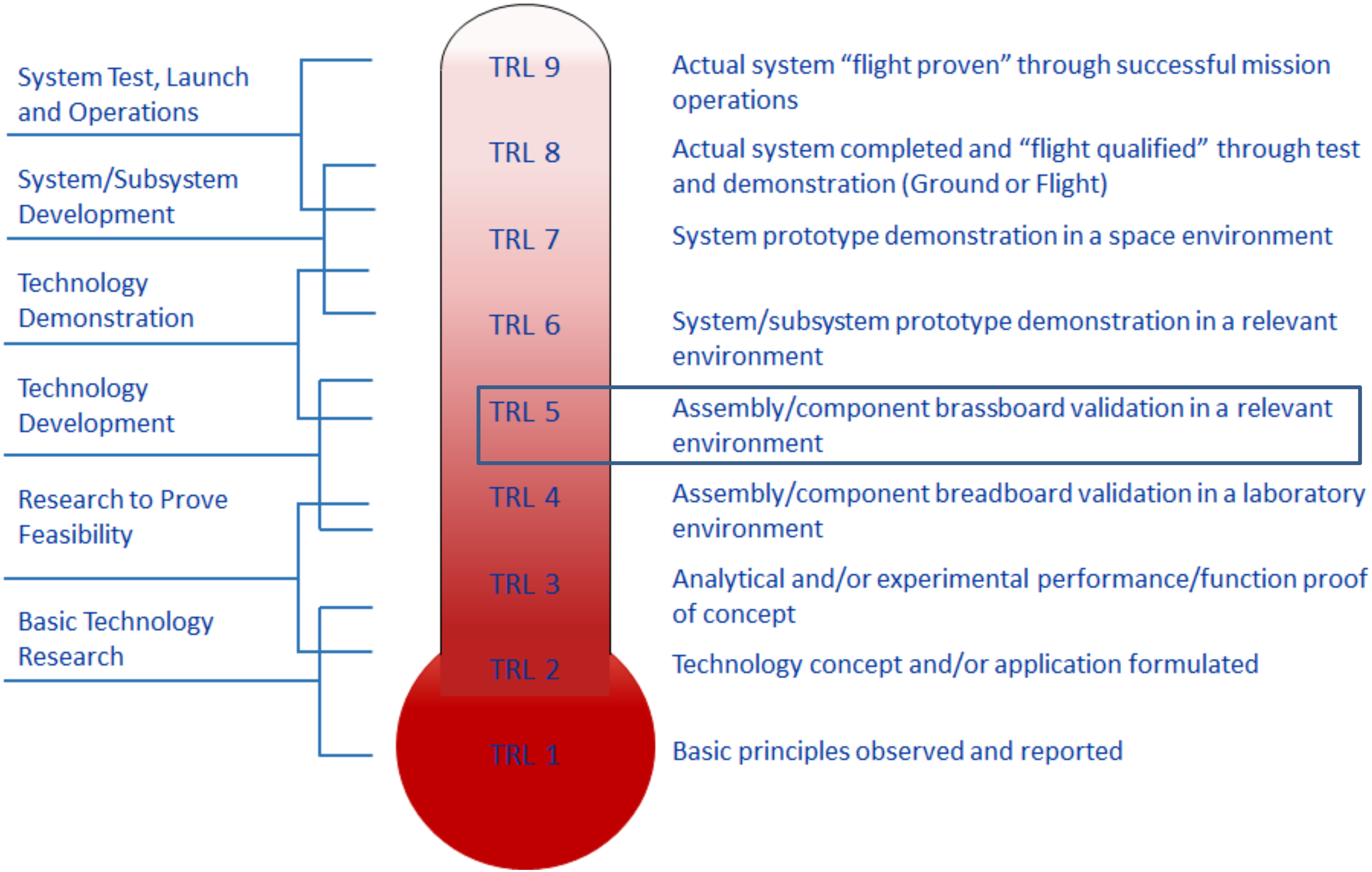
- Calibration accuracy for ”flattening” mirror and stroke range used for that; introduction of higher order errors when flattening or correcting “low order” errors

- 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: What are Integrated System Test Requirements

- **Performance/Function (Device)**
  - 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?
- **Performance/Function (Electronics)**
  - 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?

Thermometer Scale for NASA's TRLs



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

Prove flight electronics can drive device

Full Testbed TRL-4

Proving device meets spec with appropriate electronics

DM TRL4 and TRL5 Verification Architecture

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

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 demos

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-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*

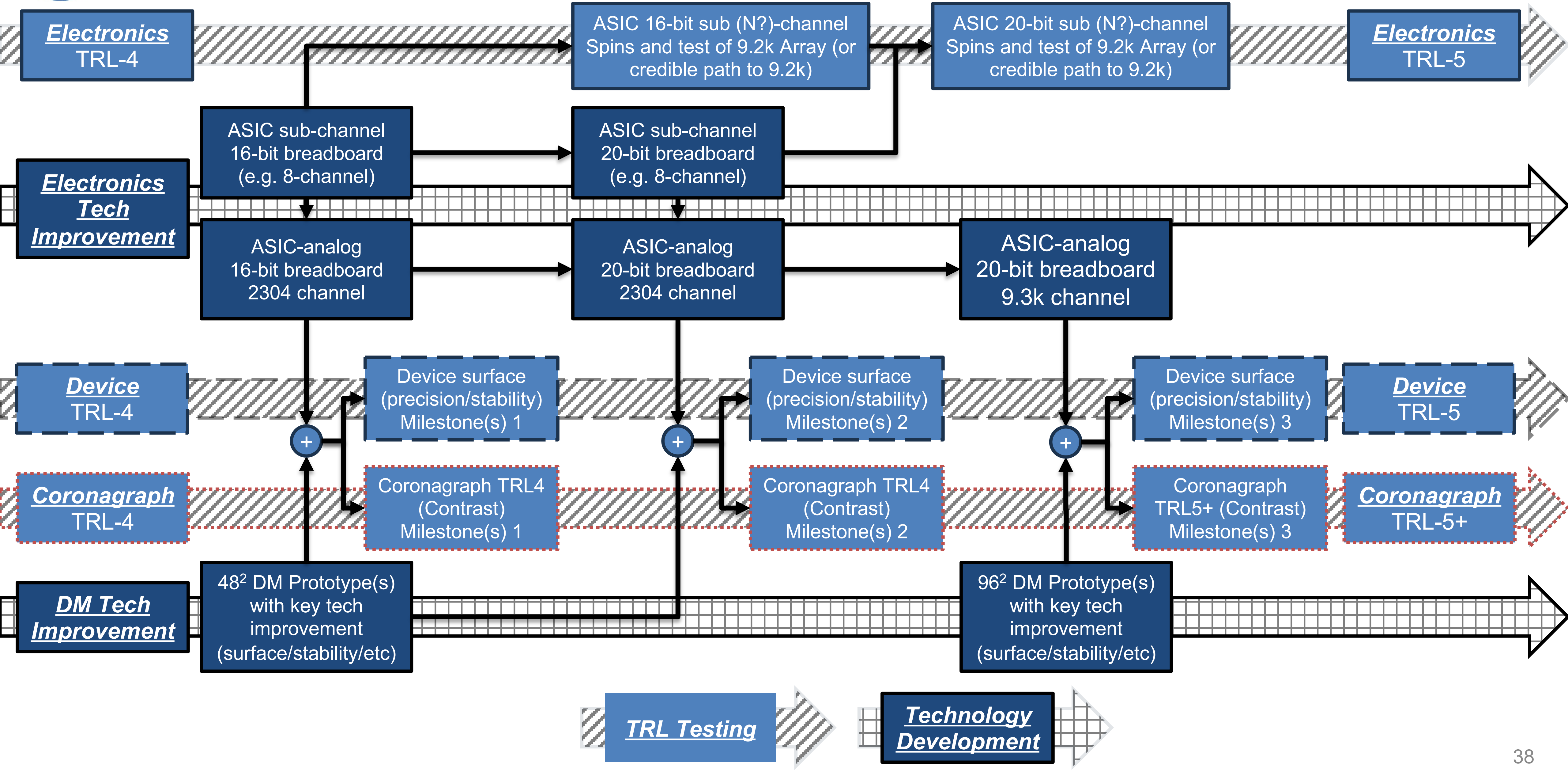
*Activity likely to carry through to TRL-6

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!)

Risks

- **Risks for DM development and characterization have been identified**
- **Working on how to buy down those risks on a per-technology basis**
- **Examples of technology risks**
  - Actuator/Surface Drift
  - Bad actuators near edges of devices (PARTICULARLY if tiling is needed to achieve full format)
  - Surface/Actuator print-through
  - Thermal loads, thermal sensitivities/surface instability
- **Examples of verification (non-vendor specific) risks**
  - OWA/large format DM risk. Testbed capability gap for characterizing large format DMs
  - Requirements on DMs may be more strict than provisional goals
  - Picometer verification of DMs as path to TRL-5
  - Many years to receive testable devices from any vendor that meet requirements
    - Highlights the need for these intermediate qualification milestones

Suggested Future Work and Trade Studies (1/2)

- **Consider how far the maturity is for each technology**
- **Consider what intermediate milestone development buys down the most risk**
  - (don't just send requirements for 96x96. e.g. 2-nm flatness on a kiloDM or a 2K)
  - Seed money where possible 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**
  - Simply 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 (2/2)

- **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**