Deformable Mirror Technology Roadmap

Path to TRL-5 For Future Exoplanet Direct Imaging Space Missions

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The DM Technology Roadmap Objective

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

- **Prepare a plan to mature the DM system technology to TRL-5 for a HWO mission**
  - DM System = Device, Electronics, Harness
  - Define the goals and exit criteria of the roadmap
  - Consider DM plans described in the HabEx/LUVOIR reports
  - Define placeholder DM system requirements for the HWO
  - Update the ExEP DM Survey to capture the latest updates
  - Document the DM system experience by the Roman Coronagraph
  - Consider all of the above to develop the maturation plan.
- **Inform NASA/EXEP the cost, schedule, and risks to execute the roadmap with all vendors (no down selection)**

Participants

- **Co-Leads:**
  - Eduardo Bendek (JPL)
  - Tyler Groff* (GSFC)

- **Team Members**
  - Kerri Cahoy (MIT)
  - Aki Roberge (GSFC)
  - Ruslan Belikov (ARC)
  - Ewan Douglas (UA)
  - Steve Kendrick (SK Consulting)
  - Pin Chen (ExEP)
  - Karl Stapelfeldt (ExEP)
  - Pierre Baudoz (Obs. de Paris)
  - Stefan Strobele (ESO)
  - Feng Zhao* (JPL)
  - Garreth Ruane (JPL)
  - Jeremy Kasdin* (Princeton)
  - Olivier Guyon (Subaru/UA)
  - John Trauger* (JPL)
  - Emiel Por (STScI)

*Roman Coronagraph Instrument Team Members

A DM Technology Roadmap: Why now?

The DM system is the critical component for any coronagraph direct imaging mission.

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

Achieving TRL 5 and 6: What does it Take?

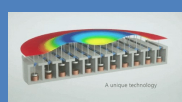
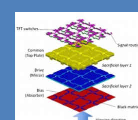
1. **Placeholder DM requirements including:**
   - Resolution, stroke, stability, actuator count and pitch, lifetime, mass, power and volume
2. **Manufacturing and testing**
   - Vendor site visit and joint research
   - Procure flight format units (DM, connectors, and electronics)
   - Preparing test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

Work Done to Date

- **Team Identified key elements of the DM "system" for which to establish requirements**
  - DM device, interconnect/harnessing, Drive Electronics
  - Identified how requirements drive different subsystems
    - e.g. stability – MEMS: drives electronics, PMN: drives device material
- **DM performance requirements and goals adopted**
  - Input from Coronagraph Technology and DM Technology Roadmap Working Groups,
  - Aggregated HabEx/LUVOIR reports
  - Format for high-order DMs: 96x96 actuator
  - Actuator pitch tracked as goal for high order DM.
    - Working with CTR to inform instrument constraints. Drives required DM separation
  - Stroke, Resolution, temporal stability
  - Static residuals: actuator print-through, surface WFE, power
- **2021 ExEP DM Survey updated**
  - Top three DM vendors for expected HWO performance unchanged
    - AOA Xinetics, Boston Micromachines Corporation, ALPAO (France)
- **Site visits of top three vendors**
- **Established the TRL-5 evaluation process**
  - Currently working on TRL milestones and development plan for a general DM system

DM Survey 2.0

- Detailed survey of vendor capabilities and performance against coronagraph instrument needs, lead by Eduardo Bendek
- Second major revision has been completed
- Provides assessment of maturity against NASA-specific needs for the deformable mirrors
- Currently focuses on the device itself
- Identifies where there is work to go, design in process, or demonstrated capability

DM Vendors / Features	ALPAO 	BMC 	Xinetics 	Obsidian 	SLM 	Parabolic 
Technology	Contactless electromagnetic	Contactless electrostatic	Contact PNM	Contactless electrostatic	LCOS	Contactless electromagnetic
Key advantages	Actuator count (128 in dev)	Actuator pitch, Stability	Surface quality	Actuator count, Pitch	Actuator count, Pitch size	Powered surface
Shortcoming and risks	Actuator pitch, heat dissipation	Surface error	Drift	Membrane issues, Programmatic	Polarization, Chromaticity, Radiation	Stability
Maturity for application	Medium	High	High	Low	Low	Medium

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

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.

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

Remaining Key Activities

- **Knowledge sharing with Roman CGI**
- **Provide representative HWO specifications to DM vendors**
- **Receive DM vendor technology development plans for a device to qualify to TRL-5**
  - Iterate on development plan, schedule, and requirements as necessary to inform scope
- **Plan to TRL-5**
  - Complete test plan and milestones to qualify electronics and device
  - Plan to infuse a complete system in a coronagraph testbed
- **Community Townhalls to be scheduled in Oct/Nov**
  - Opportunity for the community to hear details of the roadmap activities nd provide feedback
  - Another one will be scheduled at task completion
- **Integration of DM Roadmap with coronagraph technology and architecture roadmaps**
- **Final Roadmap report to ExEp, START/TAG teams**

DMTR Advice to START/TAG

- **Need to begin funded execution of feasibility studies with vendors**
  - Don't focus early on down-select.
  - Focus on development plan, schedule, and cost with the vendors to reach key milestone demonstrations
- **System development will be a hybrid effort with any DM vendor**
  - DM requirements will be iterative and evolve as vendor capabilities balance with mission implementation
- **Conduct trade studies to identify which DMs offer the highest probability of meeting requirements and have clear understanding of impact from DM requirement relaxation**
  - Descope, Requirement relaxation, and Risk acceptance will be very real even early in Phase A
- **Early planning on DM verification strategy and deliverables**
  - Don't write requirements on the DM that are really requirements on the coronagraph
  - Consider how we may need to verify DMs through instrument level knowing we may not be able to verify at payload level (e.g. lack of full aperture telescope tests)
- **Open Questions/Important Investigations**
  - Coupled architecture studies. DM technologies in particular drive instrument architecture
  - The DM+Electronics system verifications prior to coronagraph-level testing must be carefully considered
    - Contrast-driven instrument requirements point to picometer-level precision/stability
    - DM system verification testing and decomposition to device/electronics is difficult
    - Interconnect and harnessing will be an ongoing challenge for all high-density devices
  - Maintain an eye on less mature, but highly enabling DM technologies that enable different architectures

Additional Slides

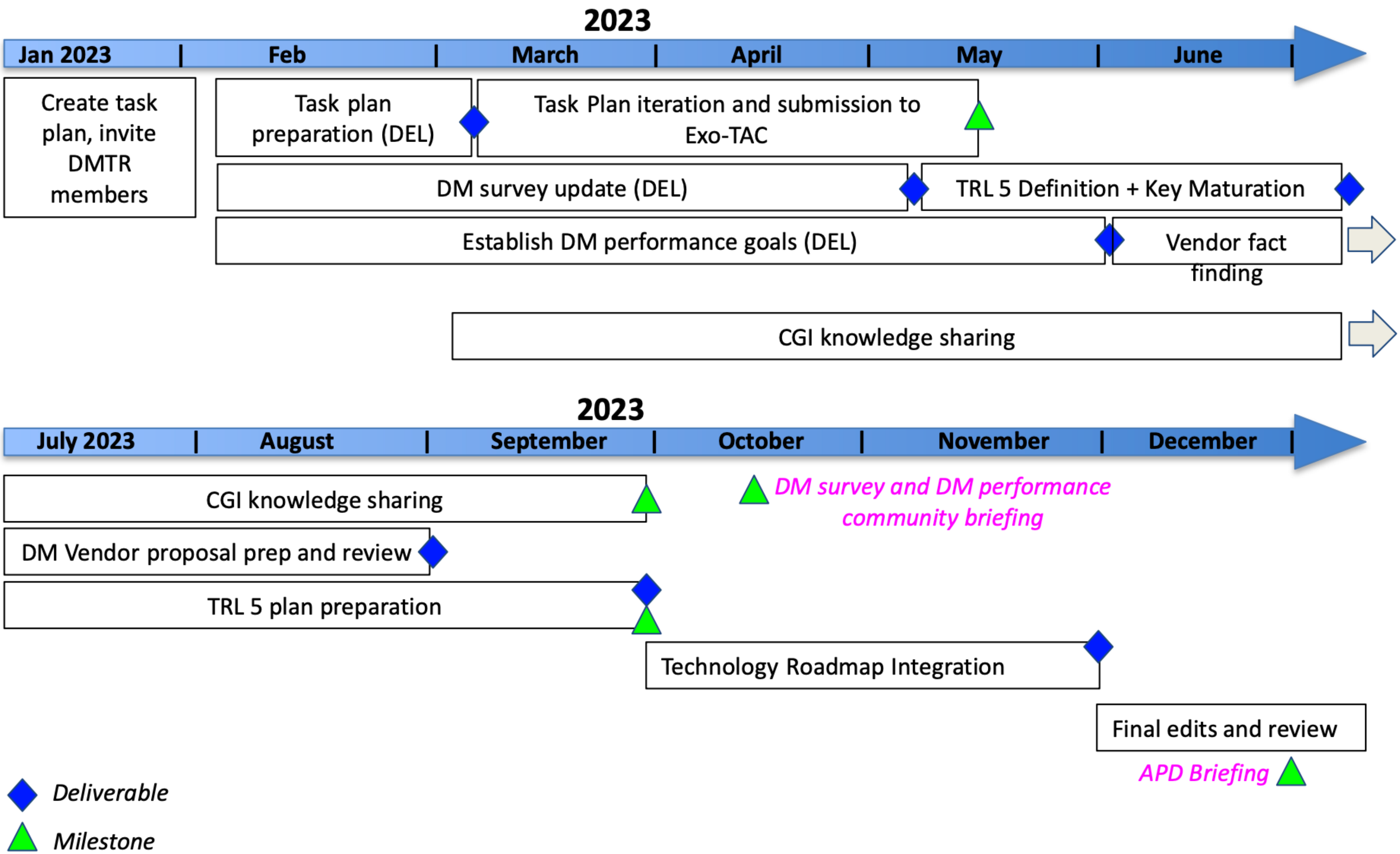
Requirements/Assumptions for CTR guiding DMTR

- **96x96 actuator DMs**
  - Informed by a balance of industry capability and needs identified in HabEx and LUVOIR studies
  - Does not exclude low-order devices in a woofer-tweeter type instrument
    - 96x96 considered driving and stability requirements are common to both high and low-order devices
    - Architectures with close-loop low-order stabilization could theoretically meet stability in closed loop with independent WFS measurement such as a LOWFS. Need to track with CTR if this would be necessary.
- **Stability requirements flow from CTR, treated as single "wavefront actuator". Examples:**
  - Single high order DM in pupil conjugate for half-dark hole
  - One high-order + one low-order pupil conjugate for half-dark hole
  - Two sequential high-order DMs (one out of pupil) for symmetric dark hole
  - One high-order + one low-order pupil conjugate + one high order out of pupil for symmetric dark hole
  - One high-order pupil DM + low-order parabolic DMs for symmetric dark hole
- **Instrument Requirement Rationale**
  - Static alignment (low order) wavefront error ~10 nm.
  - High frequency internal drifts are mostly driven by internal beam shear, assumed 1% of static wavefront.
  - Mid and Low frequency internal drifts are driven by thermal variations, assumed 10% of static wavefront
- **Requirement rationale from USORT team from Telesope**
  - Telescope drive static DM stroke: 37 nm rms = diffraction limited at 500 nm.
  - Time varying stroke depends on how much telescope drift the DM must correct
  - Fast (<10 sec) segment level variations cannot be sensed by coronagraph instrument, corrected at OTE level
  - Slow (>10 seconds) segment level variations corrected by DMs and will be offloaded to OTE every 100 seconds

Key Milestones and Deliverables

- Task Kickoff (02/23; MS)
- Task Plan Presentation to ExoTAC (03/23; MS)
- Roman Coronagraph DM Knowledge sharing (04 to 09 2023; Del)
- Update DM Survey (05/23; Del)
- DM Performance Goals Definitions: (06/23; Del)
- Community Town Hall 1: Present current status to a community gathering (6/23; MS)
- Community Presentation 1: Starlight Suppression Workshop, START/TAG
- Receive DM vendor technology development plans (09/23; Del)
- Community Town Hall 2: Present the final DM roadmap before final ExoTAC review (11/23; MS)
- Complete Final Roadmap Report (12/23; Del)
- Final Roadmap ExoTAC Review: Present the final DM roadmap to ExoTAC for review (2/24; MS)

Process and Original Timeline



Electronics Tests

- **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

DM Survey

- **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
  - No Contrast Requirements? to evaluate DM System TRL
    - Need to clearly identify how we support picometer level testing, particularly stability requirements

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