Development path and verification for HabWorlds deformable mirrors

SPIE Astronomical Telescopes and Instrumentation

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HABITABLE WORLDS OBSERVATORY

Overview

Objective: Achieve TRL-5 Device Demonstrations by Mission Confirmation Review

- **February 2023: NASA's ExEP initiated a technology roadmap for a deformable mirror system**
- **April 2025: Vendor study findings presented to the HWO Technology Maturation Project Office**
  - Three DM vendors were identified as having the capabilities and interest to develop and fabricate 96x96 devices that will meet expected HWO requirements.
- **Fall 2026: NASA to fund some Phase 1 development efforts towards TRL-5**
  - Putting contracts in place to begin credible and thorough development and fabrication plans to conduct risk mitigation and tech development activities
- **Critical systems-level trades through Exploratory Analytic Cases, which will help finalize the DM requirements, such as:**
  - The allocation of wavefront control between the DM, the coronagraph, and the telescope
  - DM actuator count, pitch size, and lab-demonstrated dark hole size (outer working angle)
- **NASA facilities being developed to test and characterize large format DMs to their HWO performance levels**

Key Provisional DM Requirements

- **Actuator count**
  - Goal: 96x96
  - Possible Relaxation? Not desired, will have to mature understanding through Exploratory Analytic Cases
- **Actuator Resolution**
  - Goal: 2.5 pm and 1.9 pm for HabEx and LUVOIR respectively (Mennesson et al, table 2)
  - Possible Relaxation? Unlikely. Roman CGI requirement is 15 pm resolution
- **Actuator Stability**
  - Goal: 5 pm RMS per control cycle (target 1 hr)
  - Possible Relaxation? Possible but difficult
- **Actuator Stroke**
  - Goal: 500 nm
  - Possible relaxation? Yes, when considering systems trades such as woofer tweeter, static compensators, etc.
- **Pinned actuators**
  - Goal: No pinned actuators within the pupil
  - Possible Relaxations:
    - Pinned actuators may be acceptable if behind an obscuration or on the DM corners. Very case-by-case
    - Floating actuators could be acceptable as the fraction is very small and they are not adjacent.

https://assets.science.nasa.gov/content/dam/science/astro/programs/exep/exopag/announcements-2023/files/DMTR_Final_Report_20240518.pdf

DM Development Status

- **For the next several years, testbed verifications will involve existing AOX modules in 32x and 48x formats, and 2k BMC modules that will be upgraded on a rolling basis over the next few years**
  - Includes contrast demonstrations up to mission confirmation review
  - Includes DM verification and integrated modeling validation testbeds
- **Parallel technology Phase 1 efforts will soon be underway to address the shortcomings of the respective technologies against the HWO provisional requirements**
  - Notable gaps among vendors are actuator count, resolution, surface figure, stability
  - Phase 1 effort is focused on process improvement, not delivering components
  - Completion of Phase 1 triggers readiness to fabricate TRL-5 verification devices
- **Drive electronics are not sourced directly from the DM Vendors**

Risks

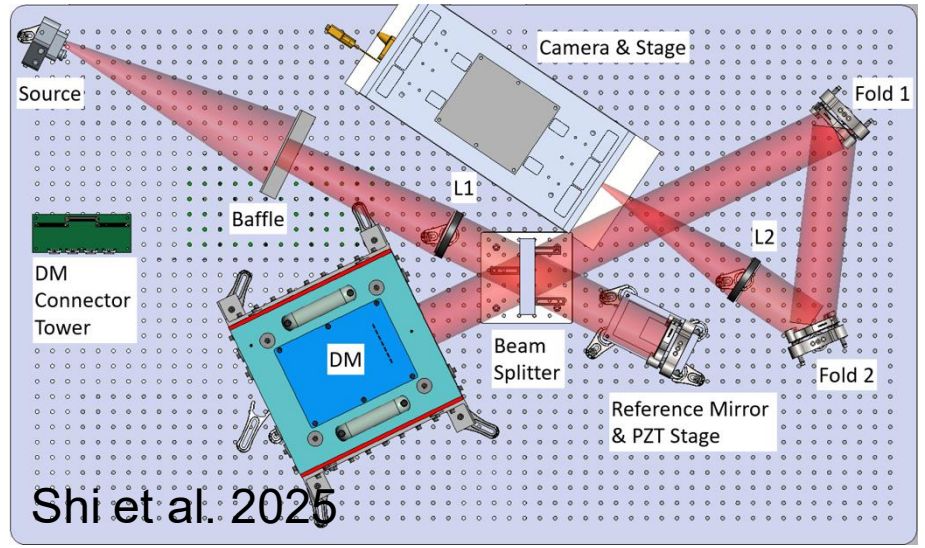
- **Risks for DM development and characterization have been identified**
- **Working on buying down those risks on a per-technology basis as funding permits**
- **Examples of technology risks**
  - Actuator/Surface Drift
  - Bad actuators near edges of devices (PARTICULARLY if tiling is needed to achieve 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

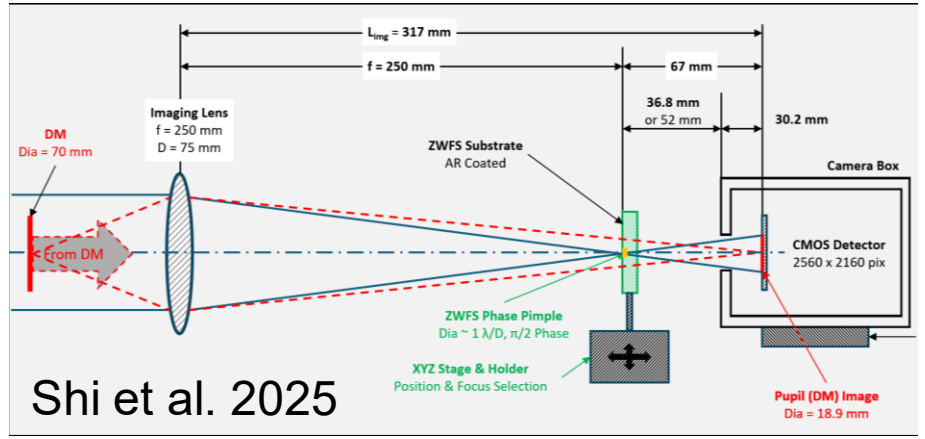
Overall Technology and Testbed Plan

- **Phase 1**
  - Vendors are executing process improvements to address key technology risks
  - 1-2 64x64 devices delivered in 2028
- **Phase 2**
  - Chance for second attempt at a full TRL5 verification
  - Two 64x64 TRL 5 devices in late 2029/early 2030
- **Phase 3**
  - Two 96x96 TRL 5 devices (delivery TBD, largely based on success of Phase 1)
- **As mission design matures and DM technology development is realized, possibility that 96x devices will be descoped to the 64x format**
- **Primary verification path is the vacuum surface gauge measurements at JPL**
- **Complementary verifications and Integrated Modeling validation done on testbeds in development at Goddard**

VSG2: Vacuum Surface Gauge 2

- **Primary deformable mirror verification testbed at JPL**
- **Dedicated vacuum Twyman-Green interferometer for characterizing deformable mirrors. Originally built to calibrate flight DMs for Roman Coronagraph Instrument (CGI)**
- **Notable upgrades VSG2 in preparation for the upcoming HWO coronagraph testbed effort**
  - Accommodate DM mount and beam height for expected HWO DM formats
  - Additional thermal stabilization
    - 6 layers Astro-Foil reflective insulation on outside chamber
    - Multi Layer Insulation (MLI) around entire optical bench inside the chamber.
  - Improved thermal sensors, heaters, and coolant system
  - Adding strain gauge closed loop controller to the reference mirror PZT scan stage
  - Adding a classic Zernike Wavefront Sensor Mode
    - Reference arm blocked, transmissive Zernike deployed

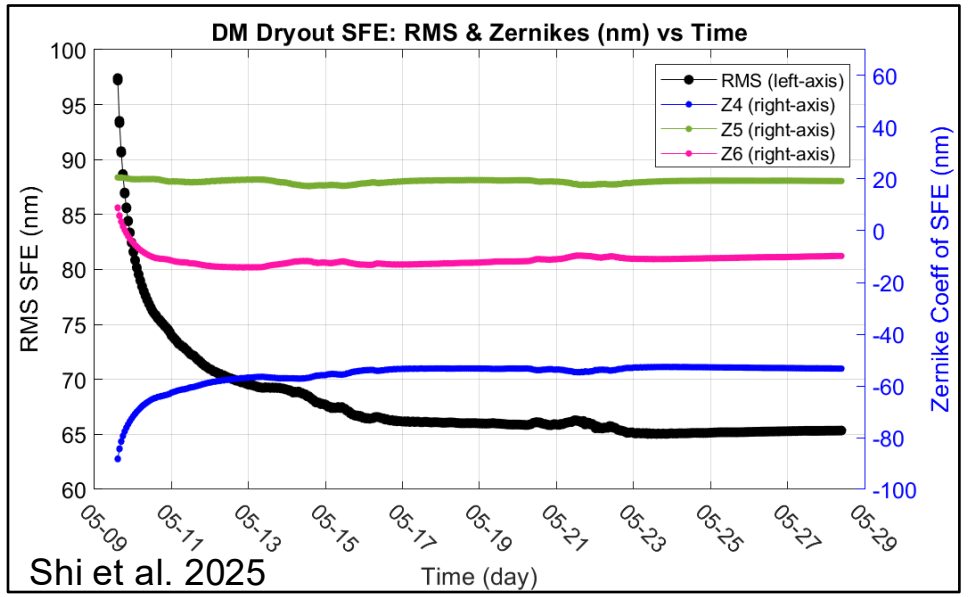


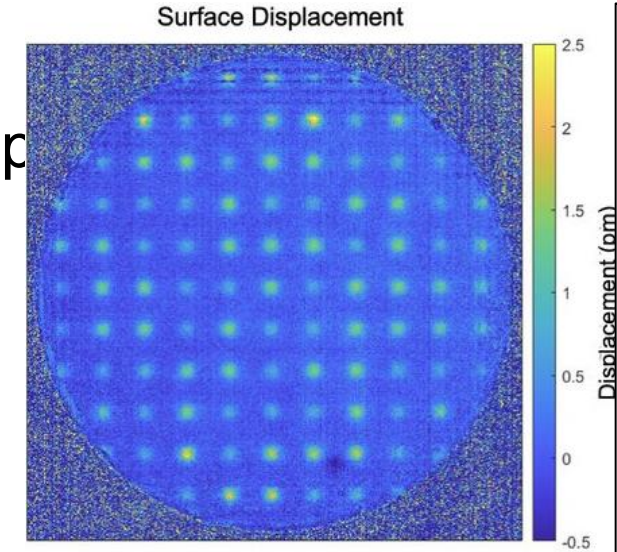


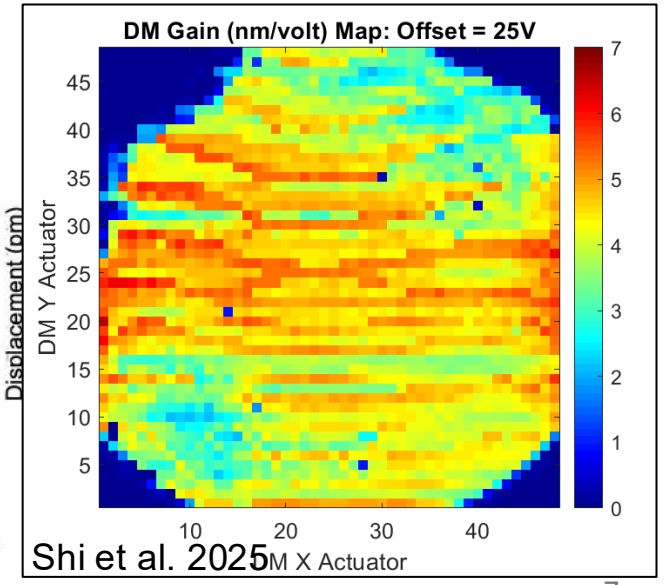
Major shout out to Fang Shi, Alex Walter, and Caleb Baker

VSG2 Historical Measurements

- **VSG2 DM measurement and calibration include:**
  - actuator mapping
  - actuator gain
  - actuator influence function
  - DM stability
  - actuation repeatability
  - long term drift and post-actuation creep
- **Zernike sensing has demonstrated picometer level sensing of DMs in the past**

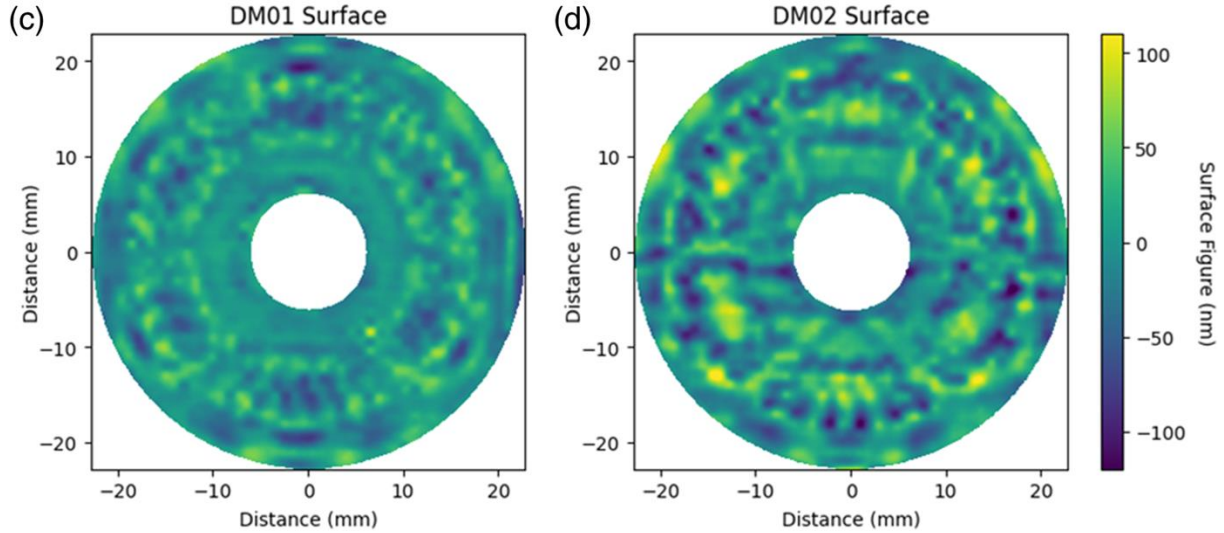




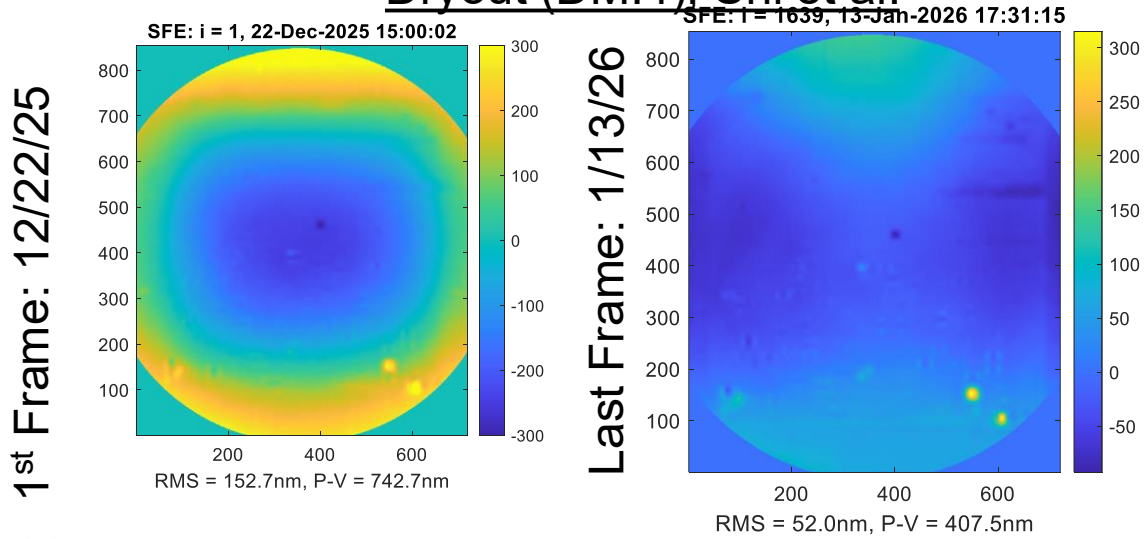


Example VSG2 Measurements of CGI DMs

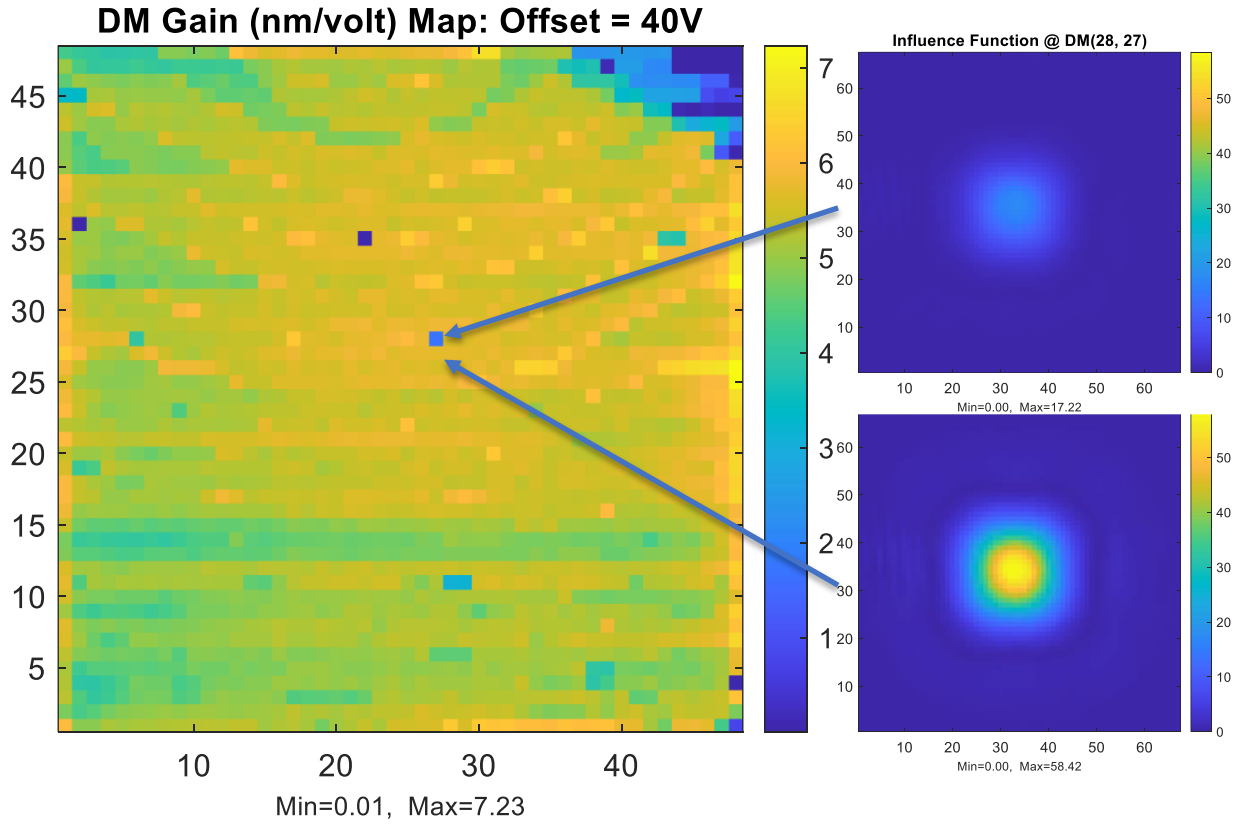
CGI HLC Nominal Map Measurements, Baker et al. 2025



Dryout (DM.4), Shi et al.



DM.4 Gain As Function of Offset. Shi et al.

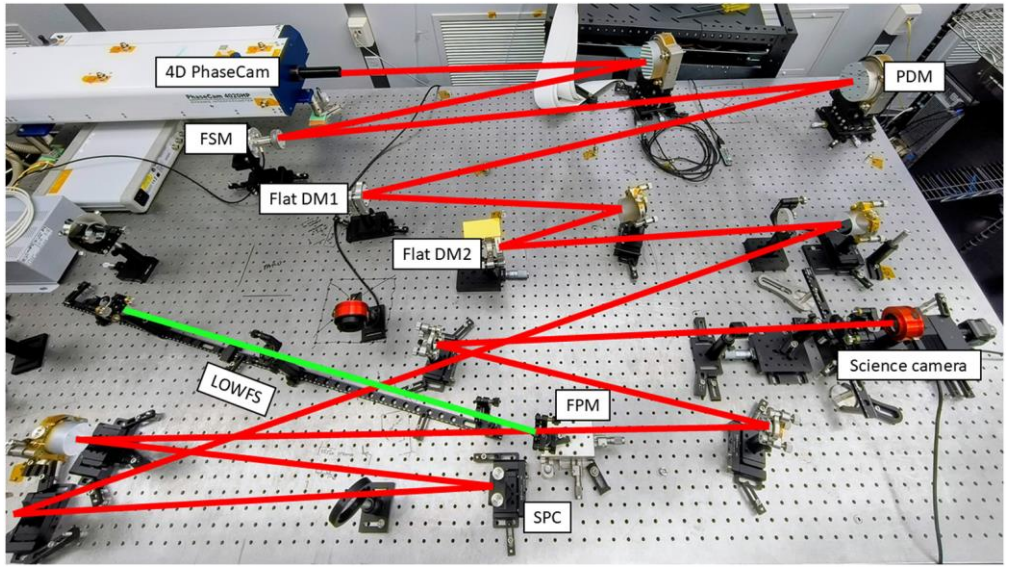


NTRPRISE:Necessary Testbed Revisions for PRoving Integrated Systems Engineering

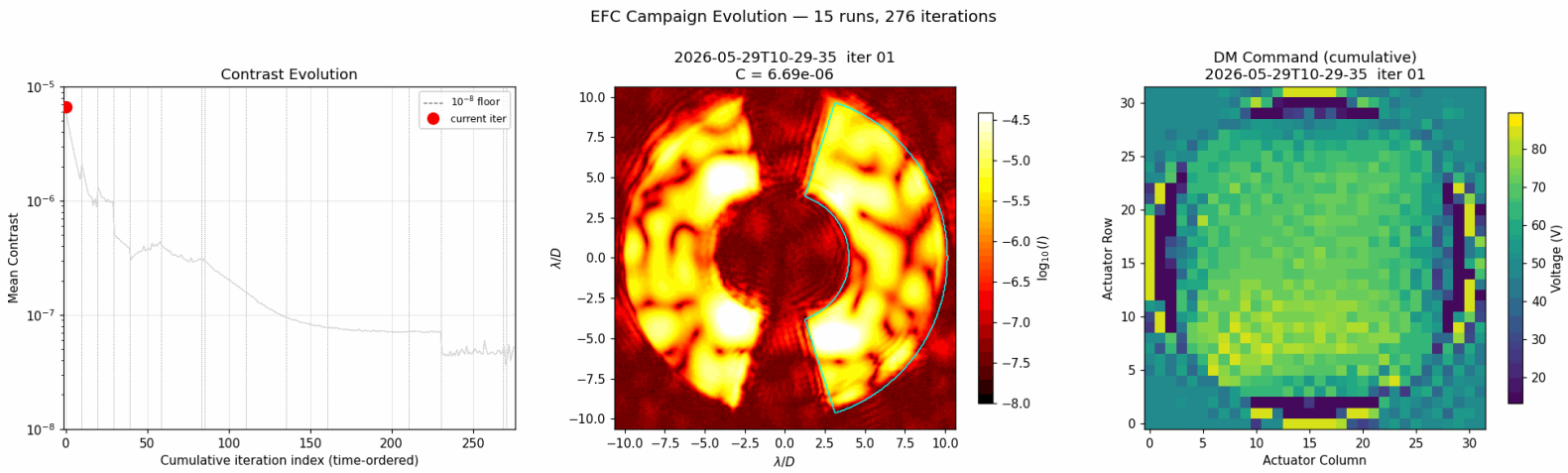
- **Much like Roman, HWO will rely heavily on modeling predictions of performance**
- **Minimizing (and knowing) model uncertainty is are critical for performance verification**
  - Wavefront error/contrast stability during an observation, post-processing performance
- **Goddard testbeds are focusing on supporting the high contrast model validation and stability predictions that are necessary for characterizing Earth-like planets**
- **Taking a phased approach, building up the model validation process**
  - Simple, single optic test configuration with the greatest stability and fewest components. Allows for Speckle and Pupil Optical Correlation (SPOC) to validate models.
  - A single off-axis reimaging configuration that would be considered a Key Element of a Reimaging Coronagraph (KERC)
  - General support and parallel development activities are supported by the ExoSpec testbed (in addition to its parabolic DM support)
- **Both SPOC and KERC will be configured with apodizers, static, and deformable mirrors for these demonstrations**

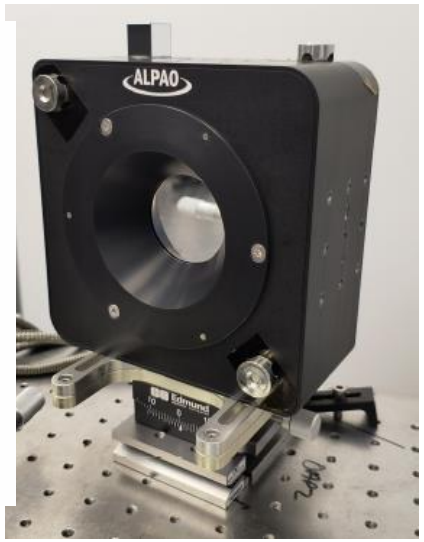
ExoSpec Testbed

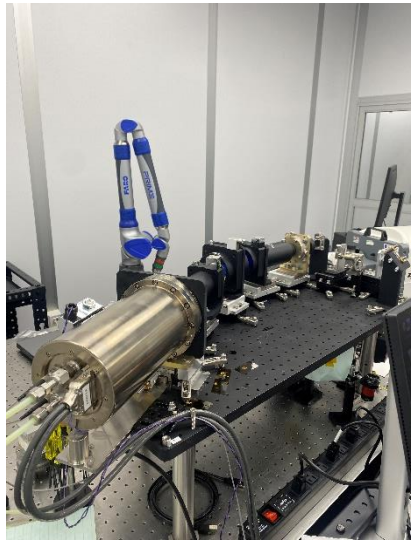
- **Testbed for Versatile DM Architecture Evaluation**
  - Provides a controlled basis for evaluating performance differences between DM architectures
  - Used for algorithm development and test prototyping for SPOC and KERC
- **Current Hardware Status**
  - One (of two) BMC kilo-DMs currently installed
  - Shaped Pupil Coronagraph
  - Generation 1 parabolic DM is currently being characterized
  - LOWFS tip/tilt control
  - PISCES IFS will be integrated soon for broadband EFC



High Contrast testbed (above) and PDM, *Groff et al., JATIS, 2026* (below left) and PISCES IFS (below right).





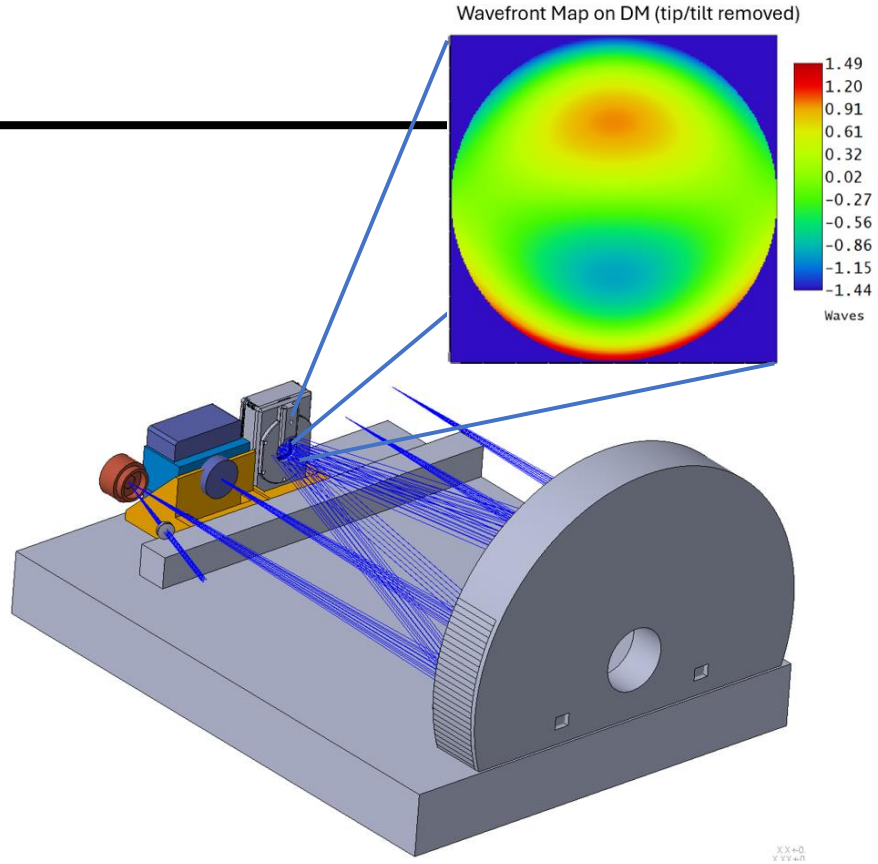


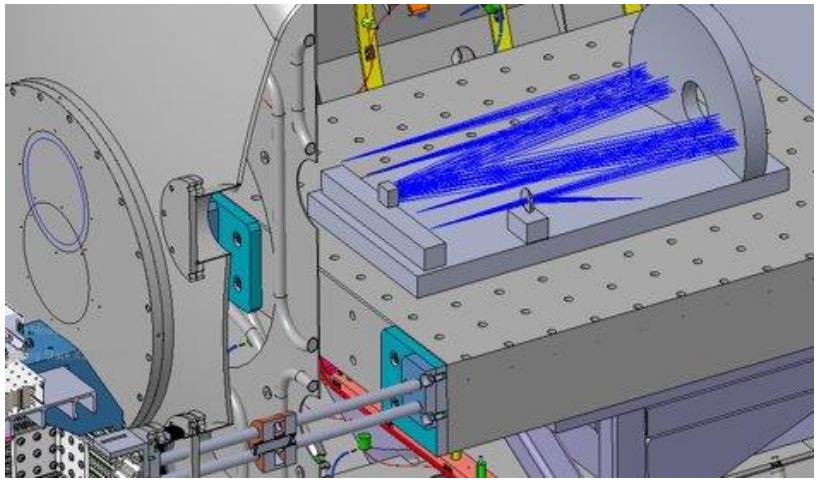
SPOC: Speckle and Pupil Optical Correlation Testbed Concept

- **Keep it simple and build up capability**
  - Best possible chance for integrated modeling performance validation in a high contrast observatory
- **Design Concept and Objectives**
  - Create a testbed capable of ultrastable drift measurements
  - Minimize all verification equipment to as few optics as possible while still ensuring high contrast measurements
  - Wavefront characterization by correlating speckle images to a Zernike measurement of the pupil
  - Performance is verified via a power spectrum in space and time
- **Allows for independent verification of deformable mirror performance that complements the vacuum surface gauge**
- **KERC initial design in parallel with SPOC**
  - Unfolded version of SPOC with off-axis mirrors
  - Extends design principles, modeling prediction, and control to more flight-like instrument design

SPOC Design

- **Offner design concept with compensating aberrations**
  - System has 8nm RMS WFE despite ~340nm RMS WFE at test article
- **Single optic testing of a DM**
- **Bench and mirror made from ZeroDur or ULE (currently being traded)**
  - Belt and suspenders approach to holding things stable
- **On axis independent surface metrology**
- **Speckle imaging combined with Low and Mid-Order Zernike wavefront sensing**
- **Performance estimates and Model Correlation with the MRSCOTT package (Modeling a Really Simplified Coronagraph for Optical Telescope Testing)**





Conclusions

- **DMs are one of the single most critical technologies for HWO Coronagraphy**
- **DM Technology Development roadmap for HWO is officially underway**
  - Currently working to a set of provisional requirements
  - Some will likely relax, some may get harder
  - Mission architecture and design trades will close this as we move to our Mission Confirmation Review
- **Testbeds at JPL and GSFC are specifically being built to demonstrate technology readiness of the deformable mirror system**
  - Upgrades to the Vacuum Surface Gauge at JPL to verify DM performance is underway
  - Goddard testbeds are being built to augment TRL advancement and support validation of integrated modeling predictions