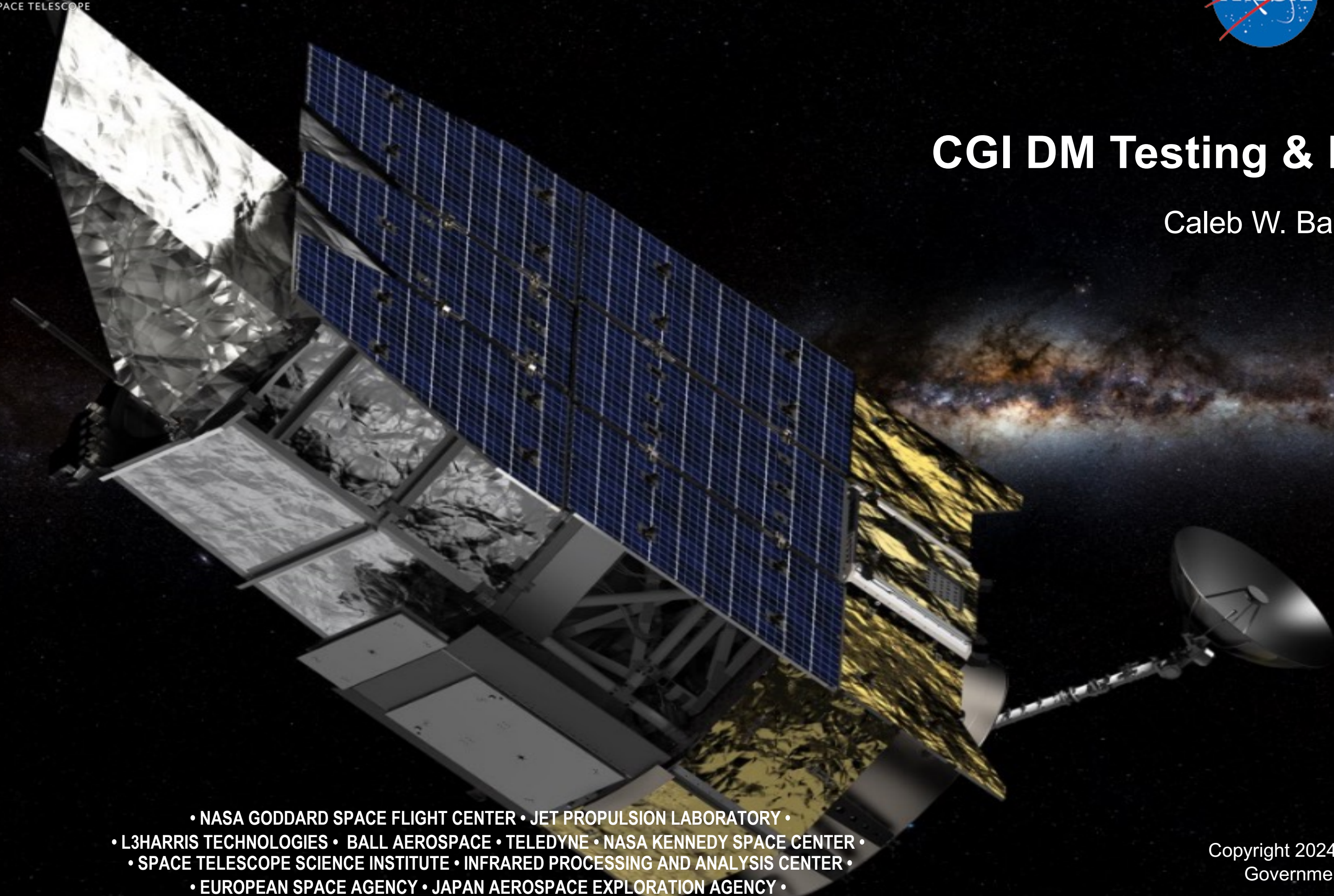

CGI DM Testing & Performance

Caleb W. Baker

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109
August 26, 2024

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Government sponsorship acknowledged

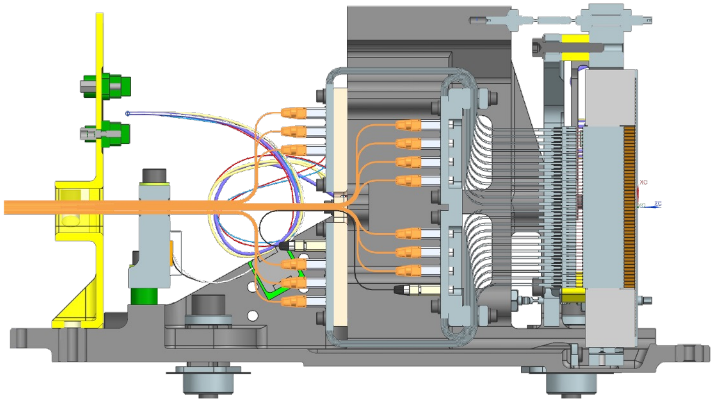
Presentation Outline

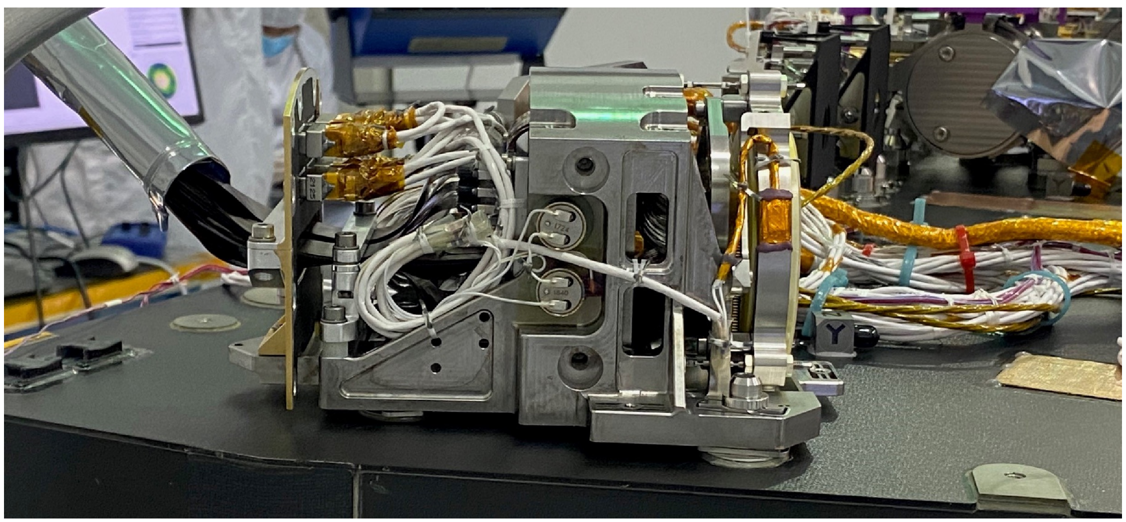
- DM Overview & DM Team Credits
  - Notes on Data in This Presentation
- DM I&T
  - I&T Flow
  - Critical GSE
- Risk Reduction Testing
  - PMN Module Stage
  - Front-End Assembly Stage
- Optical Performance Testing
- DM Lessons Learned

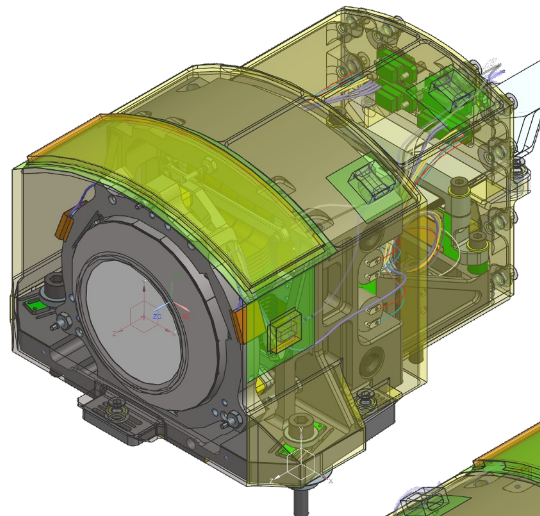
CGI DM OVERVIEW

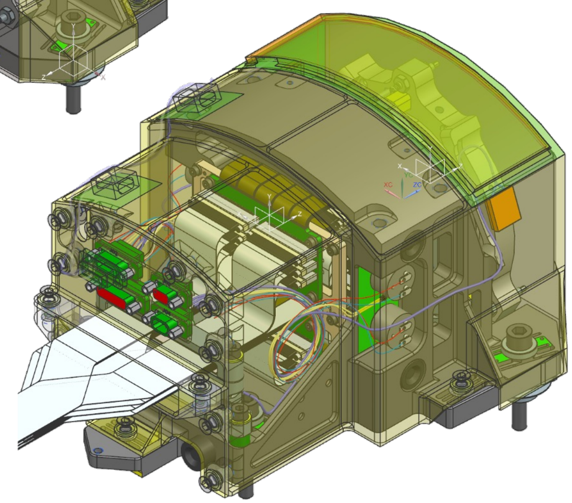
(Glam Shots and Credit Reel)

CGI DM Overview

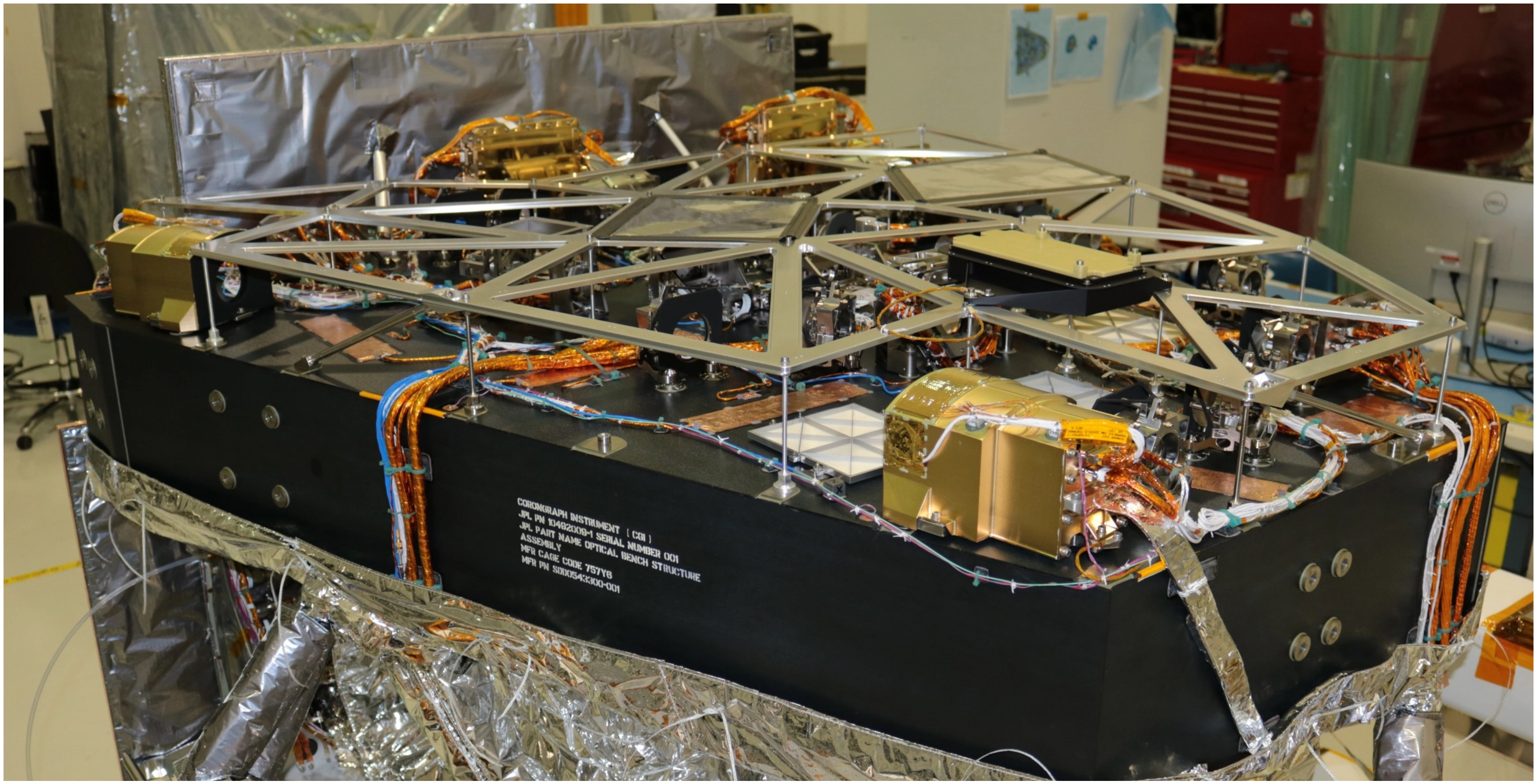






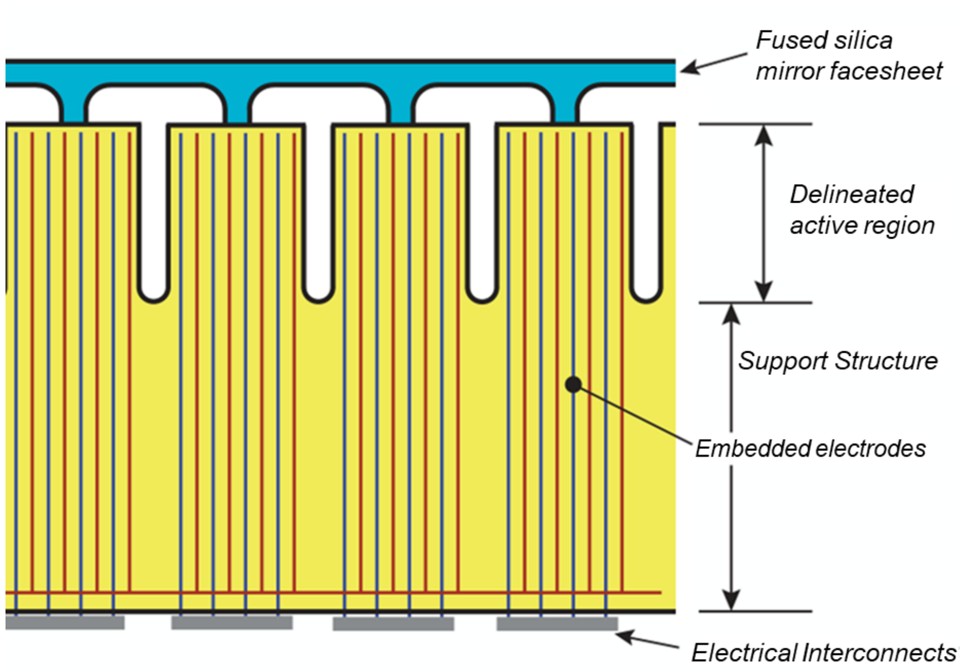


CGI DM Overview



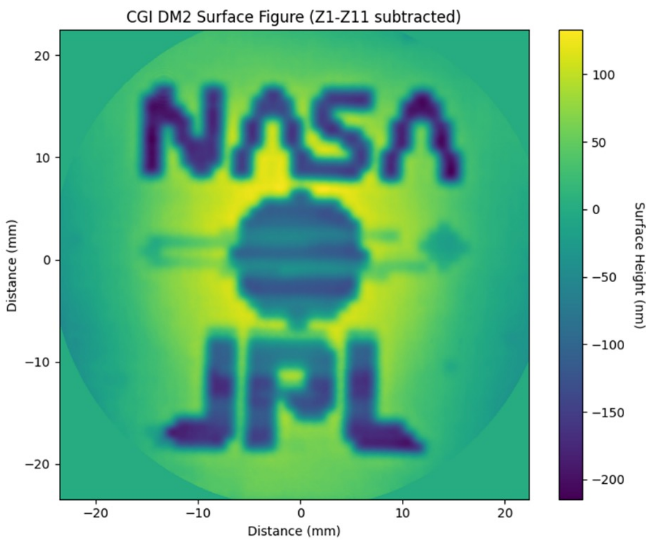
CGI DM Overview

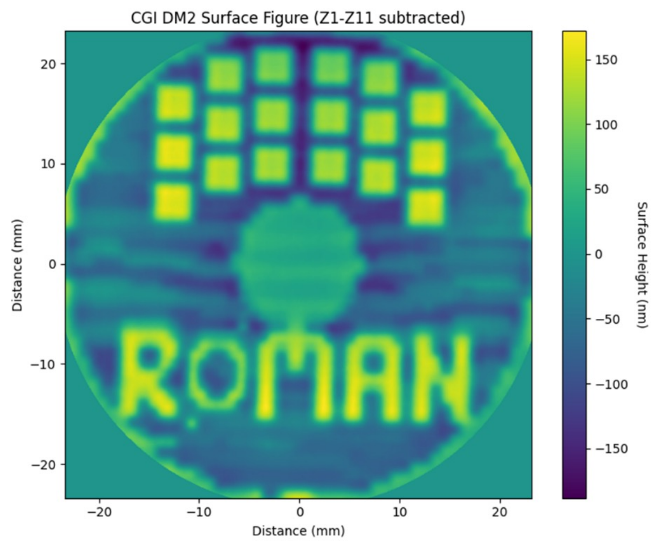
- Actuator module is based on Lead Magnesium Niobate (PMN) with embedded platinum electrodes.
- Each actuator is spot-bonded to a small pillar of glass (a "pusher pad") extending from the fused silica face sheet.
- Actuator modules were provided by Adaptive Optics Associates - Xinetics (AOX; subs. Northrop Grumman).
  - Xinetics has been building actuator modules for JPL since WF/PC-II articulated fold mirrors (Hubble - 1994).

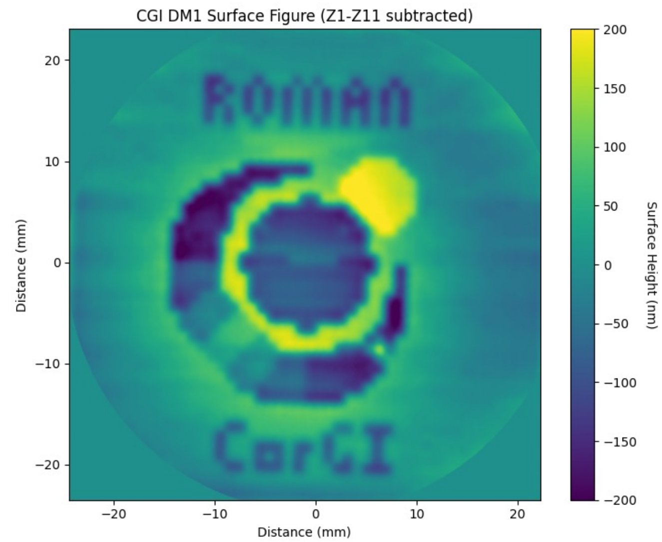


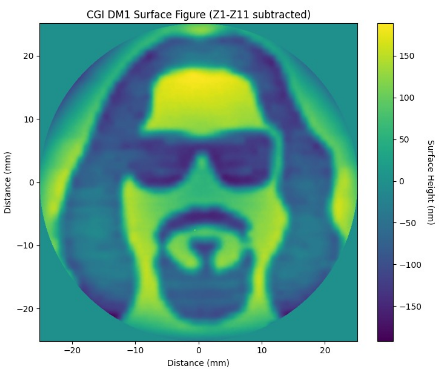
C/O J. Trauger (2016)

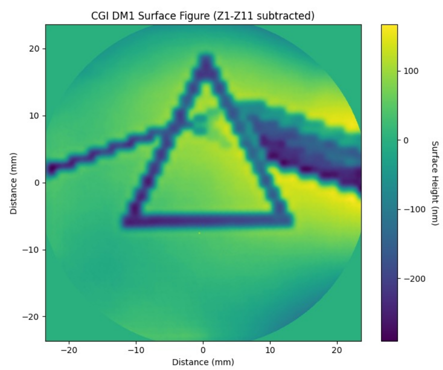
CGI DM Overview

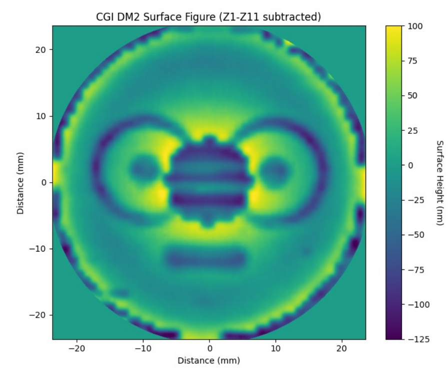


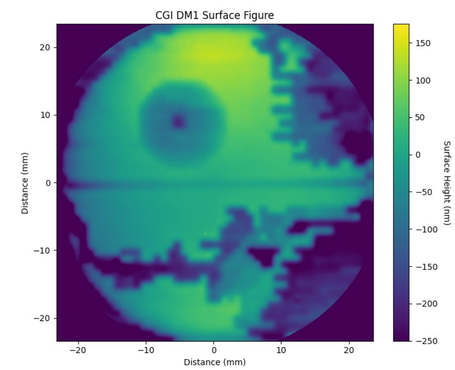












DM Development Team

DM Core Team

Fai Mok	(PDM)
Duncan Liu	(I&T Lead; Nailpin TRL6 Lead)
Warren Holmes	(SE Lead)
Chris Lindensmith	(AOX CTM)
Tony Turner	(SE & Metallization)
Kelly Wang	(Mechanical/Thermal SE)
Caleb Baker	(Electrical/Optical SE; VSG Lead)
David Aldrich	(I&T)
Dan Preston	(I&T)

DM SMEs

John Trauger	(DMs; Coronagraphy)
Saverio D'Agostino	(Materials)
Rob Calvet	(Optomech)
Josh Kempenaar	(Thermal)
Brian Kern	(Coronagraphy)
Joon Seo	(Coronagraphy)
Frank Greer	(Metallization)
Bob Scully	(EMI/EMC)
Kevin Pham	(EMI/EMC)

Mount Design & Analysis

Otto Polanco	(Optomech Lead)
Zensheu Chang	(Structural Analysis)
Anthony Bautista	(Thermal Analysis)
Vance Valenzuela	(Drawings)

DM Electronics Interface

Rembrandt Schaefer	(DME Cog E)
Dena Giovinazzo	(DME Test Lead)
Erin Kubo	(DME Test Eng.)
David Barr	(Rigidflex Harness)
Mark Hetzel	(Flexprint Assy)

VSG

Dwight Moody	(Software)
Phil Irwin	(Software)
Deniz Celik	(Software)
Wes Baxter	(Optical Eng.)
Cole Meyers	(Eng. Technician)

Quality Assurance

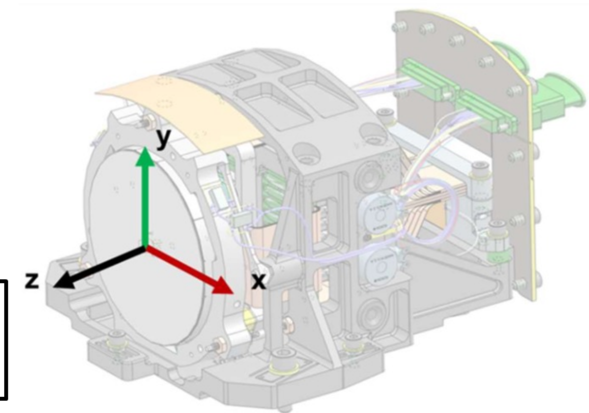
Rigo Garcia	(HQA)
Sam Zingales	(HQA)

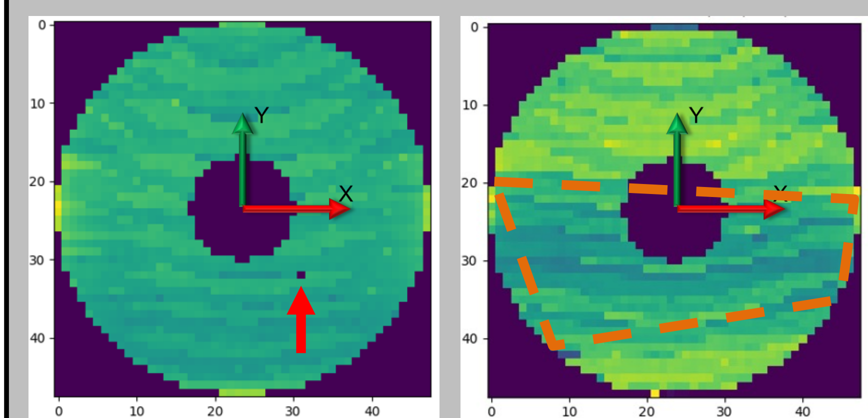
Contractors

AOA Xinetics	(DM Core Modules)
Topline	(Nailpin Assembly)
JMC Design	(Rigidflex Harness Design)
Pioneer	(Rigidflex Harness Fab)
Surface Optics	(Surface Coating)

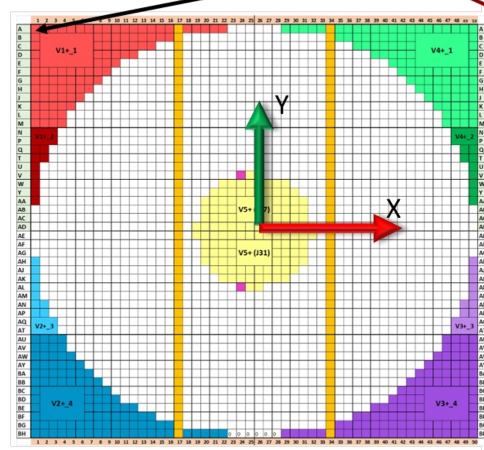
Notes on Data in this Presentation

- **<u>All</u>** surface figure, wavefront error, voltage map, etc. data is presented in the orientation of an upright DM viewed from the front.
  - Features to orient yourself if in question:
    - **DM1's dead actuator** should be in the bottom right quadrant.
    - **DM2's crosstalk region** should be in the bottom half of the mirror and larger on the left side.

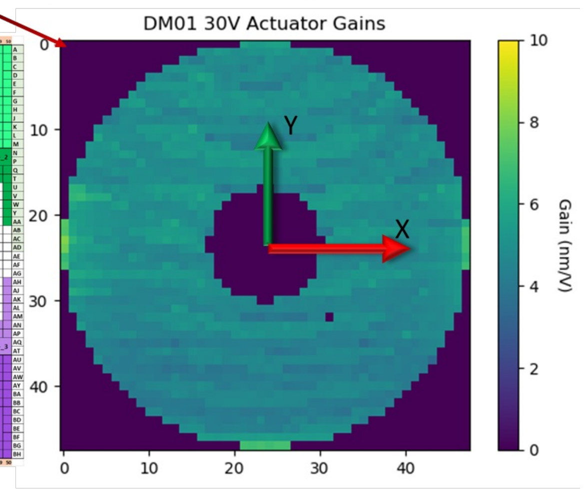




(0,0) of array is also Actuator A1 on DM



CGI DM Actuator Map



Example Gain map from DM01

Notes on Data in this Presentation

- Unit conventions can be confusing.
  - I will do my best to be clear slide-to-slide which units are involved.

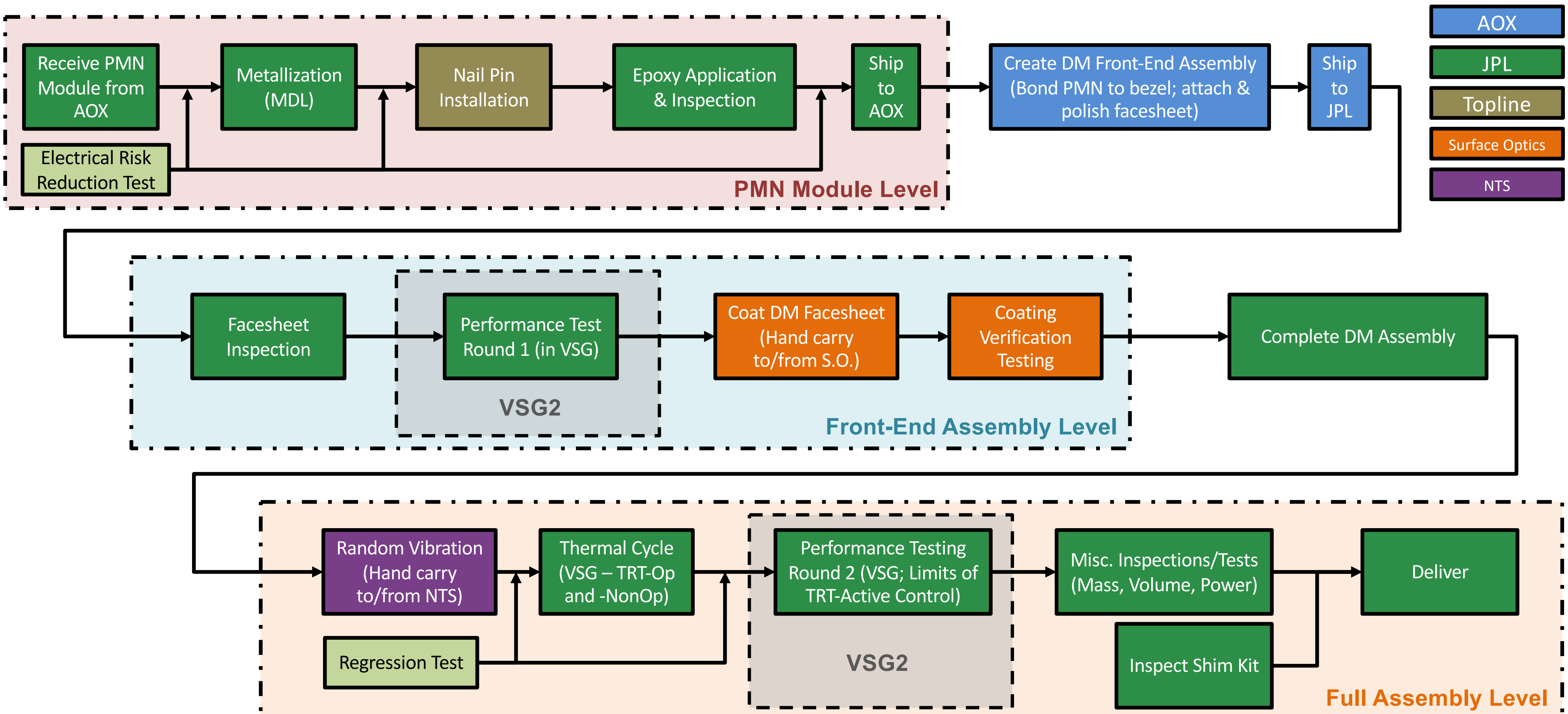
- <u>Surface vs Wavefront</u>
  - DM requirements are written in terms of Surface Figure Error (SFE)
  - Most CGI system level performance is book kept as WaveFront Error (WFE)
    - WFE = -2.0 * SFE

- <u>Stroke, Gain, and Free Stroke Ratio</u>
  - All gains presented here are calculated via peak-displacement from an isolated poke (±5.0 V from a given bias voltage).
  - All stroke values here are presented in free stroke, which is calculated by integrating gains across voltage, ***with*** Free Stroke Ratio applied.
    - Free Stroke Ratio (FSR) is the ratio of peak displacement from an isolated poke to integrated area under the poke divided by square of actuator pitch.

CGI DM I&T

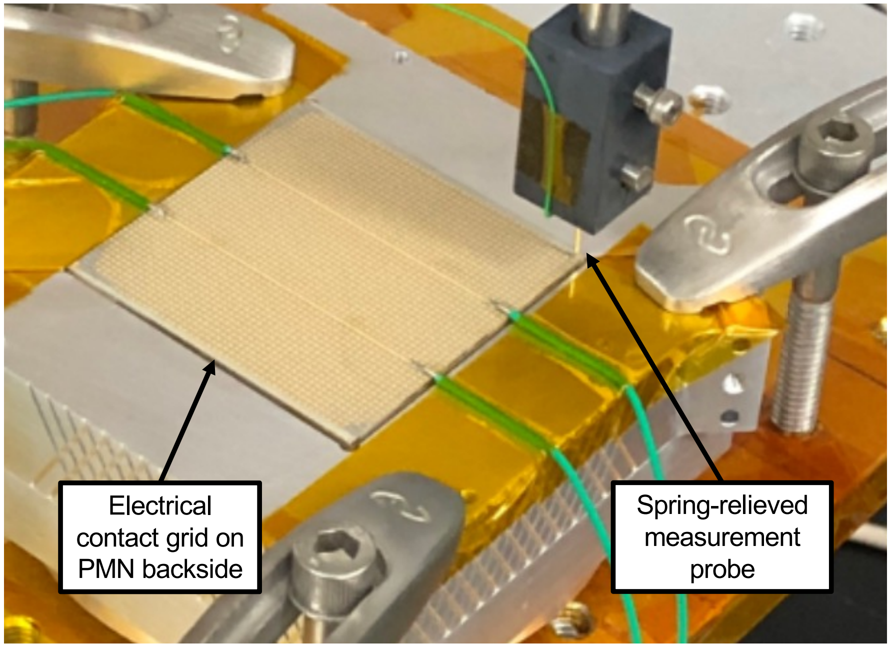
(Hope you like block diagraaaaaaaaaaaams)

CGI DM I&T Flow



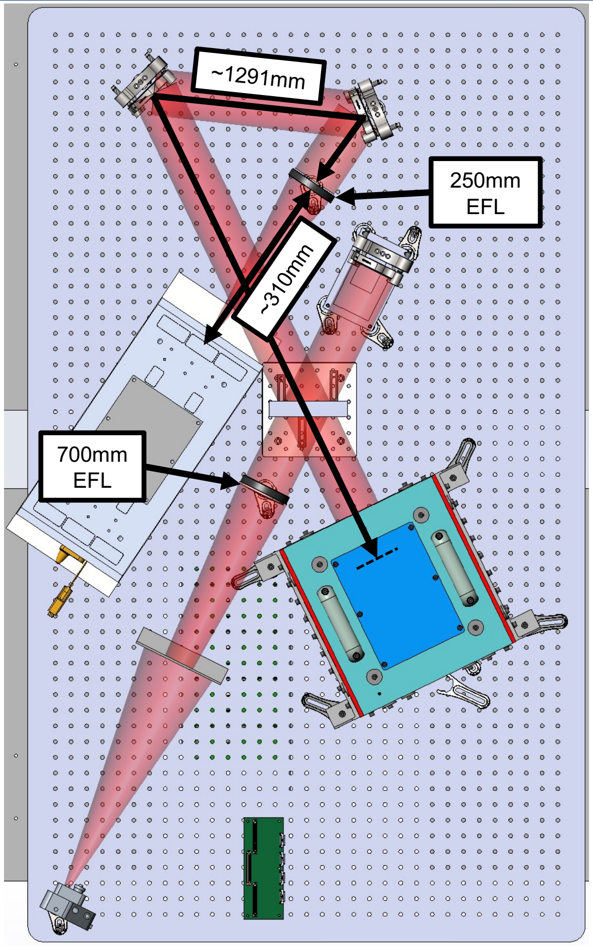
CGI Testing Major GSE

- **Electrical testing gantry**
  - Used for capacitance, series resistance, and parallel resistance measurements.
  - Had to be customized to probe different stages of assembly:
    - metallization pads.
    - soldered nailpins.
    - pins inside rigidflex nano-d connectors.
  - Needs to be capable of accurately measuring up to ~10^{11} Ω during parallel resistance tests.



CGI Testing Major GSE

- **Vacuum Surface Gauge (VSG) 2**
  - Descended from VSG1 heritage by John T. et. al.
  - Twyman-Green interferometer inside a 4' diameter vacuum chamber.
    - Andor-NEO sCMOS camera.
    - Custom-design double-walled thermal control shroud.
      - Supports DM Proto-flight range of -5 to 52 °C.
    - Supports both GSE ("Gen 5") DM driving electronics and CGI's EDU DME.
    - ~30 μm imaging resolution gives ~10x10 pixels per actuator.
    - Retrieved surface measurements have ~8 nm objective accuracy and ~100 pm precision*.
  - This was the test venue for all major optical performance tests of the two CGI DMs.



*across timescales relevant to CGI DM requirements

CGI DM RISK REDUCTION TESTING

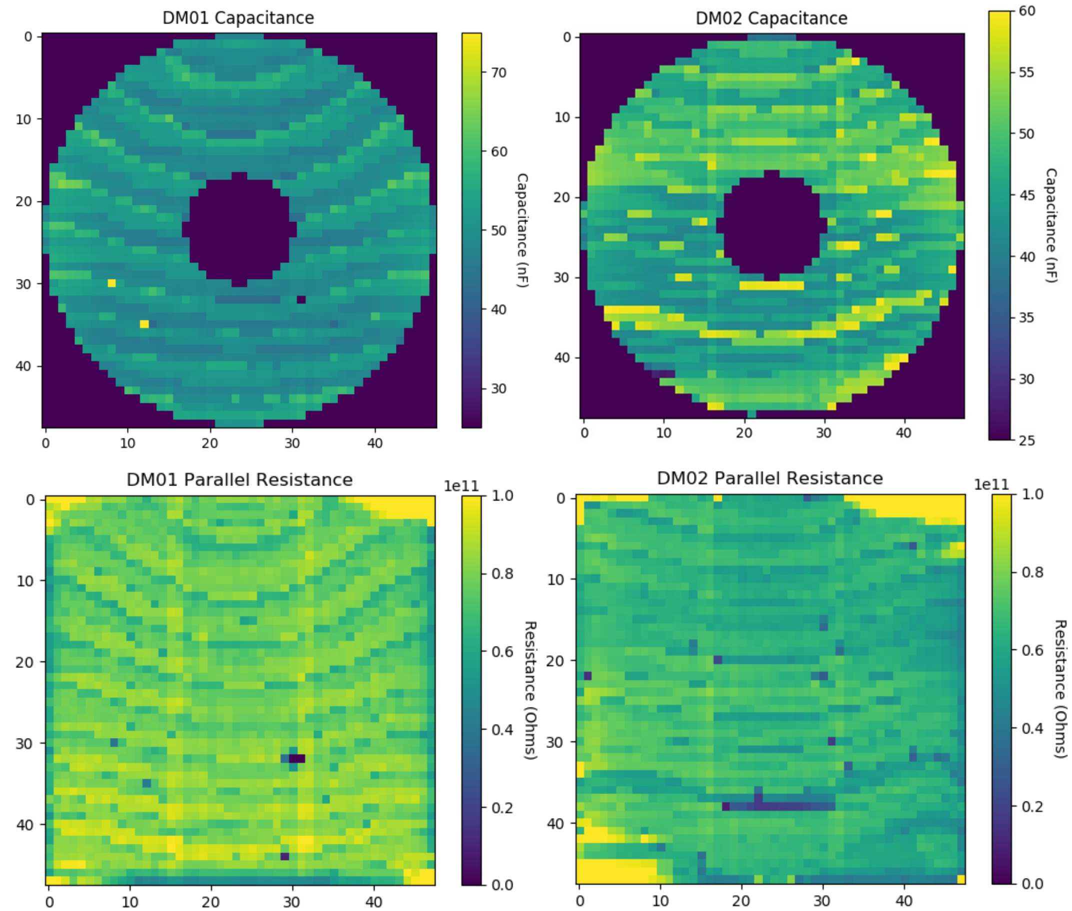
(Putting the “Cheese” in the Swiss Cheese Model)

Electrical Testing Results

- On average actuator electrical characteristics were as expected:
  - 40-60 nF capacitance
  - 10^{10}-10^{11} Ω parallel resistance
  - 300-500 Ω series resistance

- Some variation pre- and post-metallization; very little variation across all other interconnect processes.

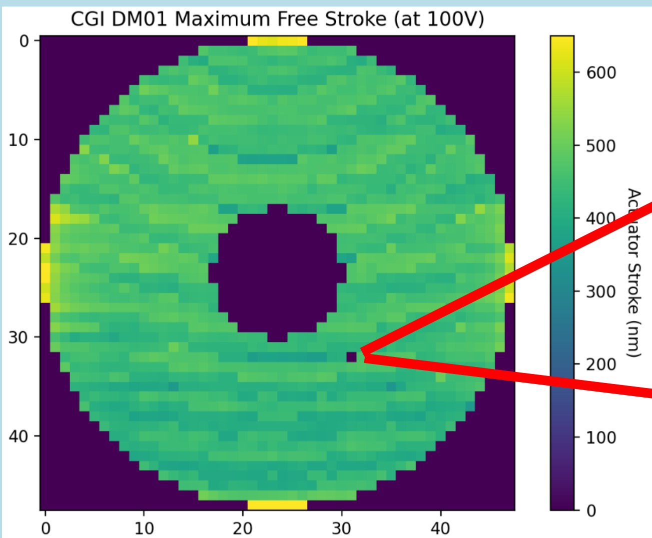
- There were 7 modules fabricated by AOX; project down-selected to 2 flight + 1 spare using electrical test data.

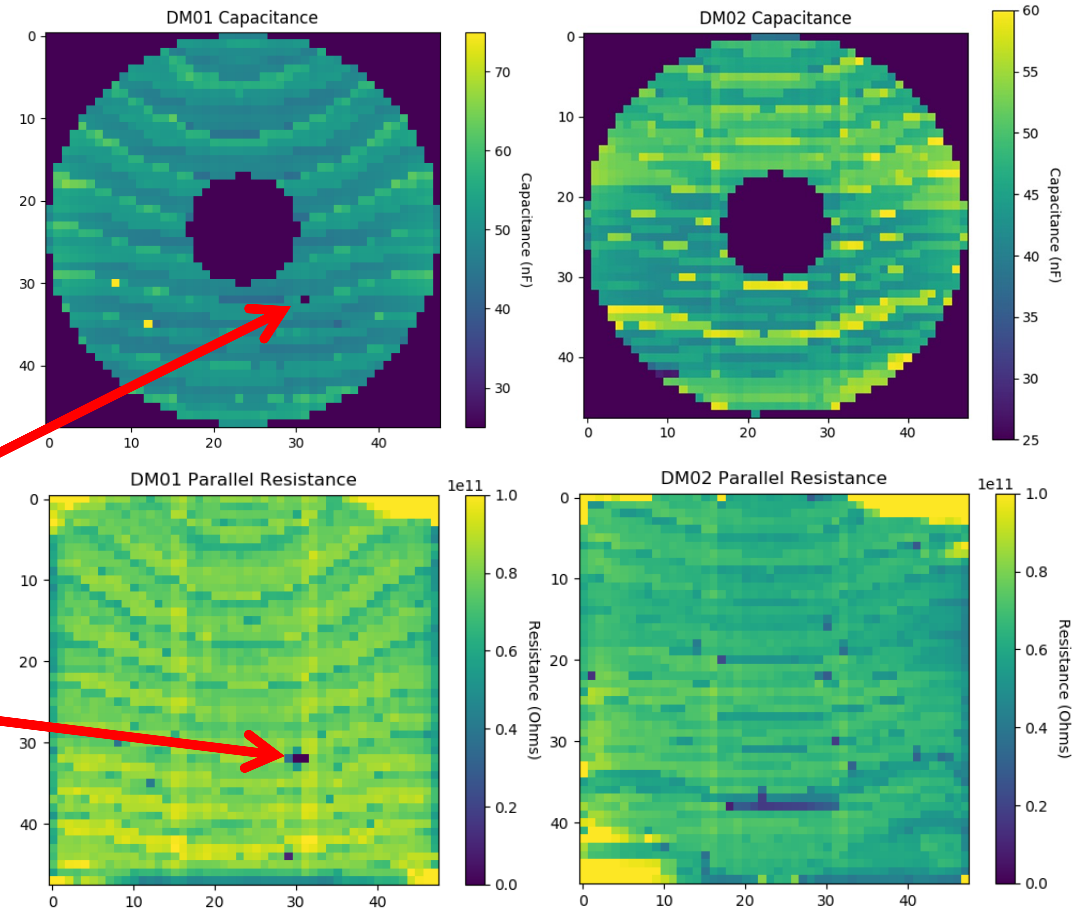


Electrical Testing Results

- Capacitance and Parallel Resistance in particular wound up being quite prescient for CGI DMs.

Capacitance & Parallel Resistance measurement on DM1 accurately captures dead DM1 actuator.

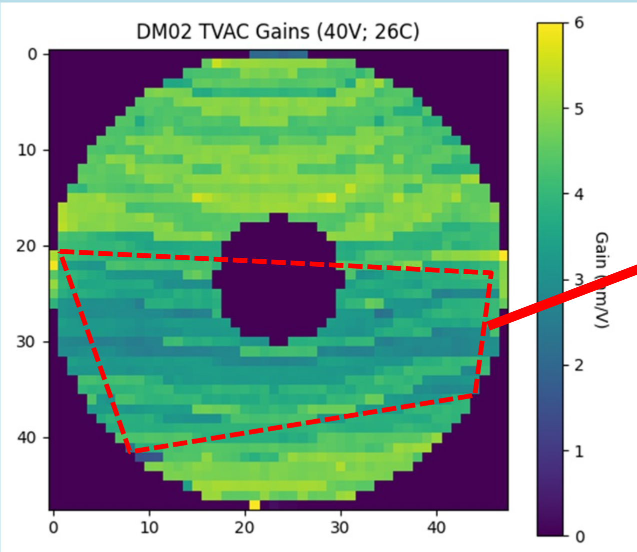


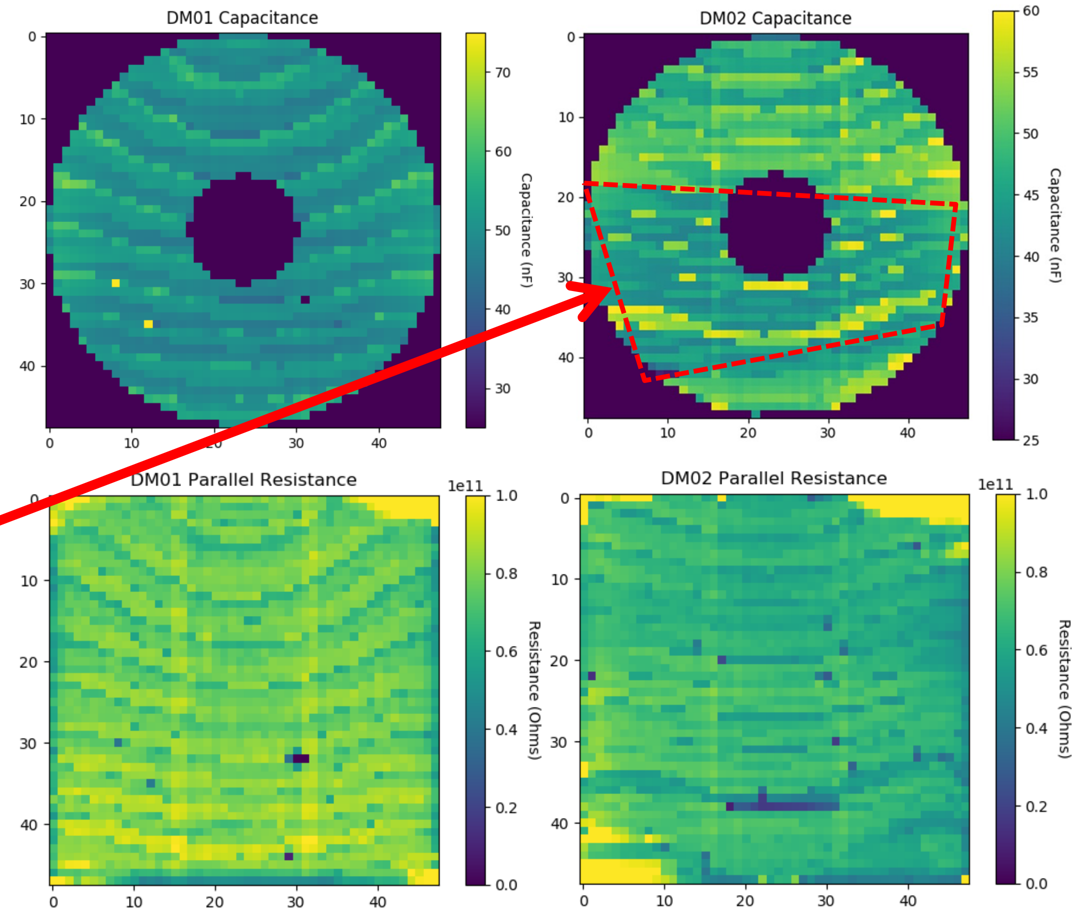


Electrical Testing Results

- Capacitance and Parallel Resistance in particular wound up being quite prescient for CGI DMs.

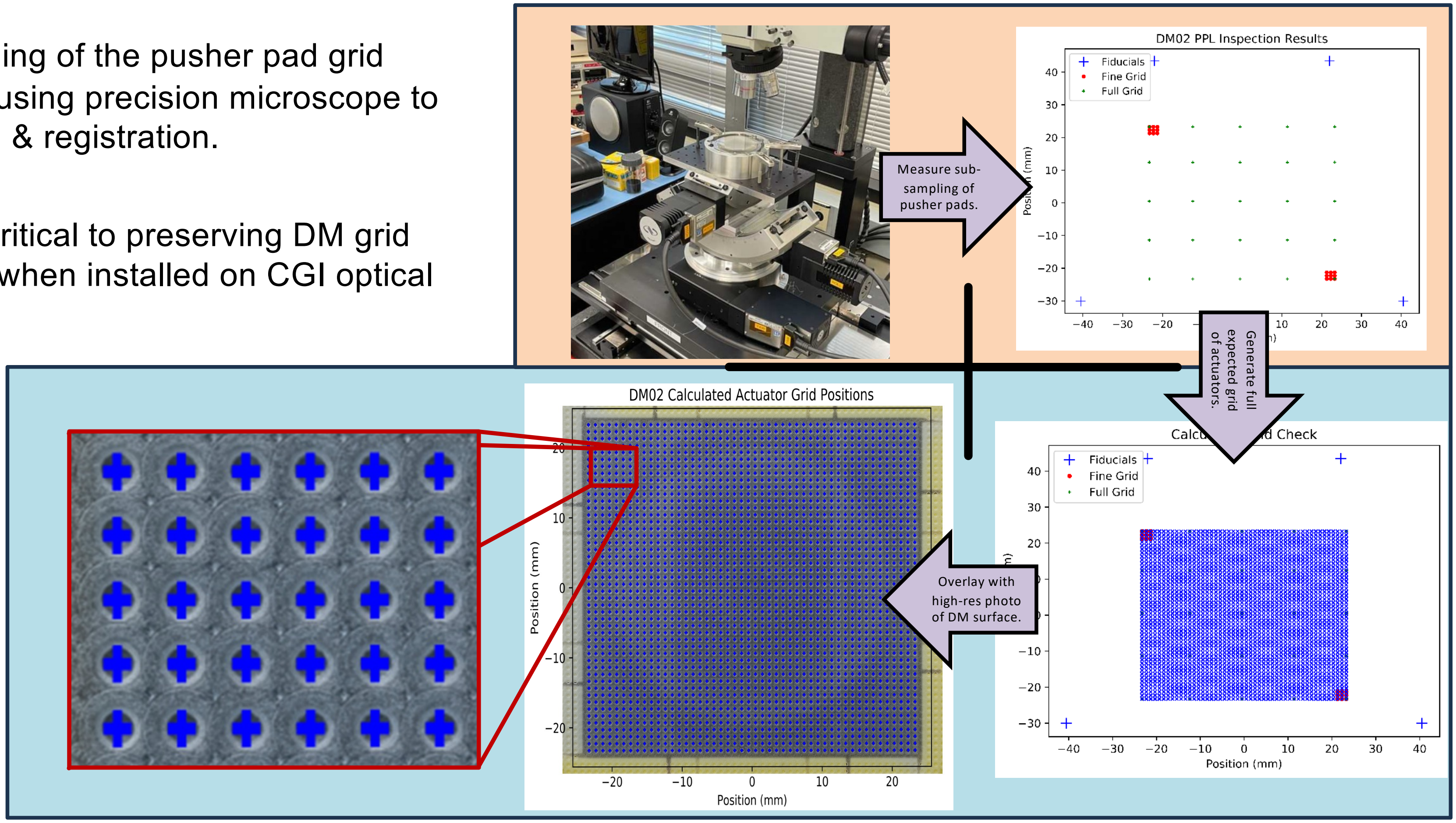
Capacitance measurement on DM2 shows ample evidence of DM2 crosstalk region.





Facesheet Inspection

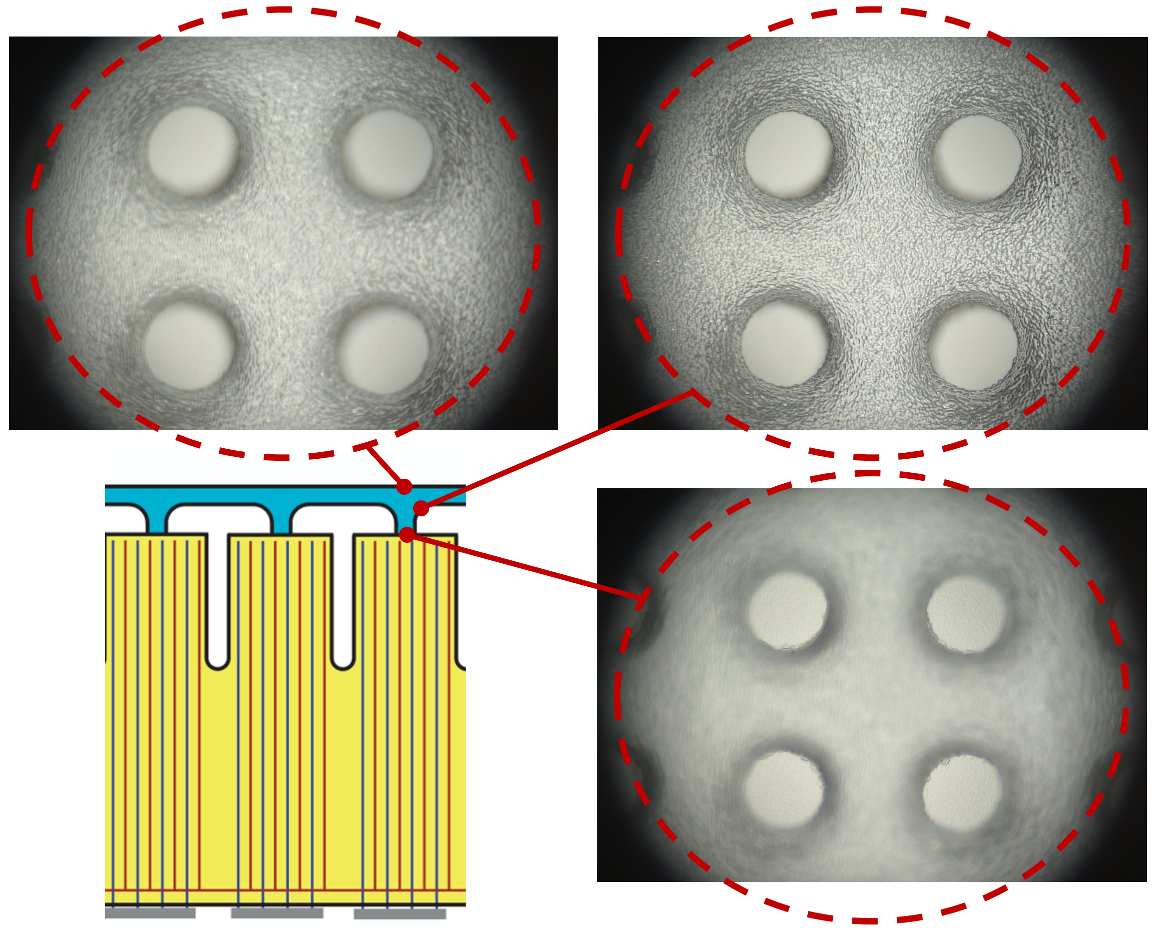
- Sub-sampling of the pusher pad grid inspected using precision microscope to verify pitch & registration.
- This was critical to preserving DM grid alignment when installed on CGI optical bench.

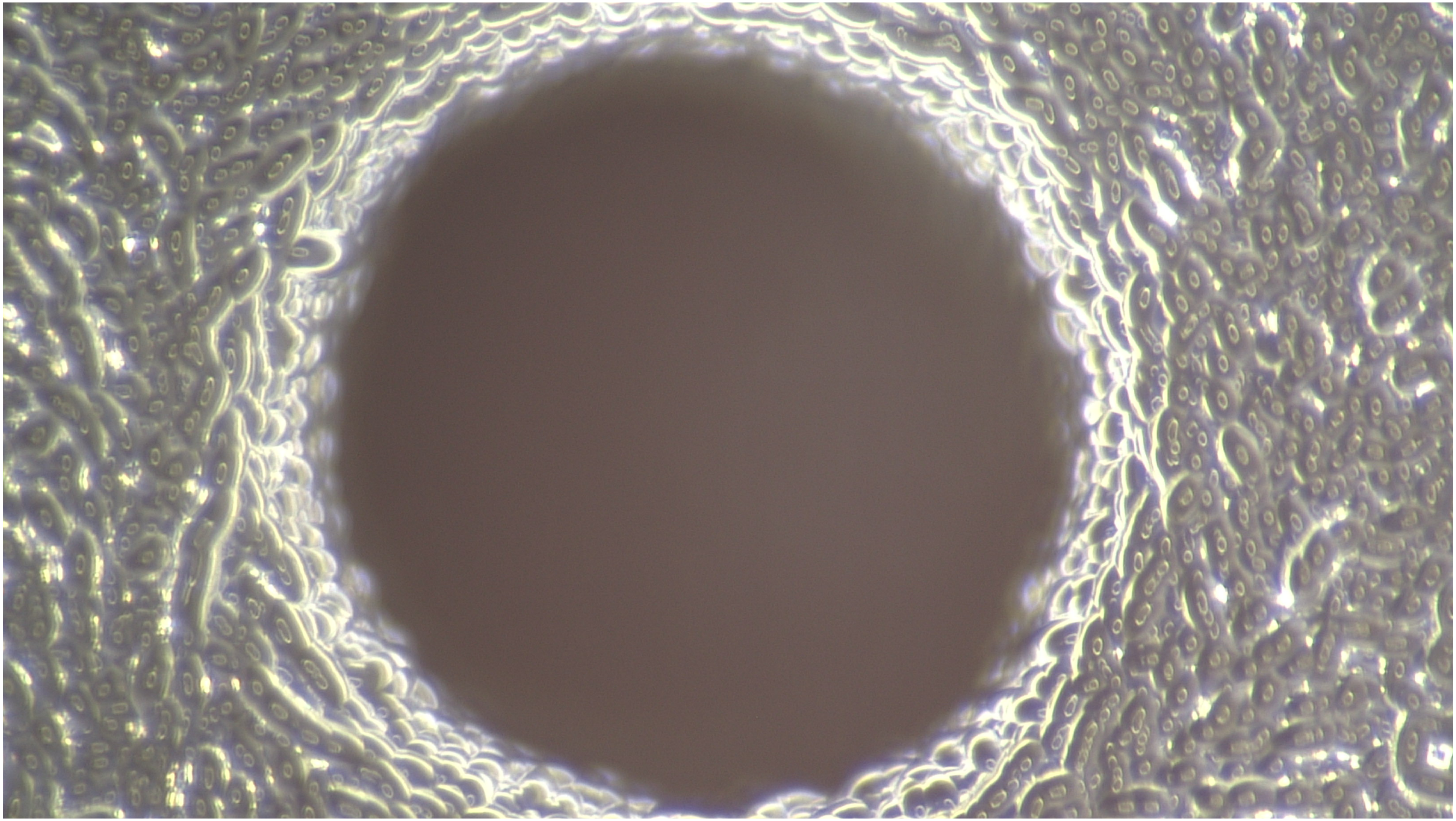


Facesheet Inspection

- Same measurement setup determined facesheet thickness and surface height relative to bezel fiducials.
- Thickness of the facesheet directly leads to the shape of the influence function each actuator exerts on the optical surface.

Same inspection was leveraged for assessment of contamination or any indication of other issues with facesheet bonding.



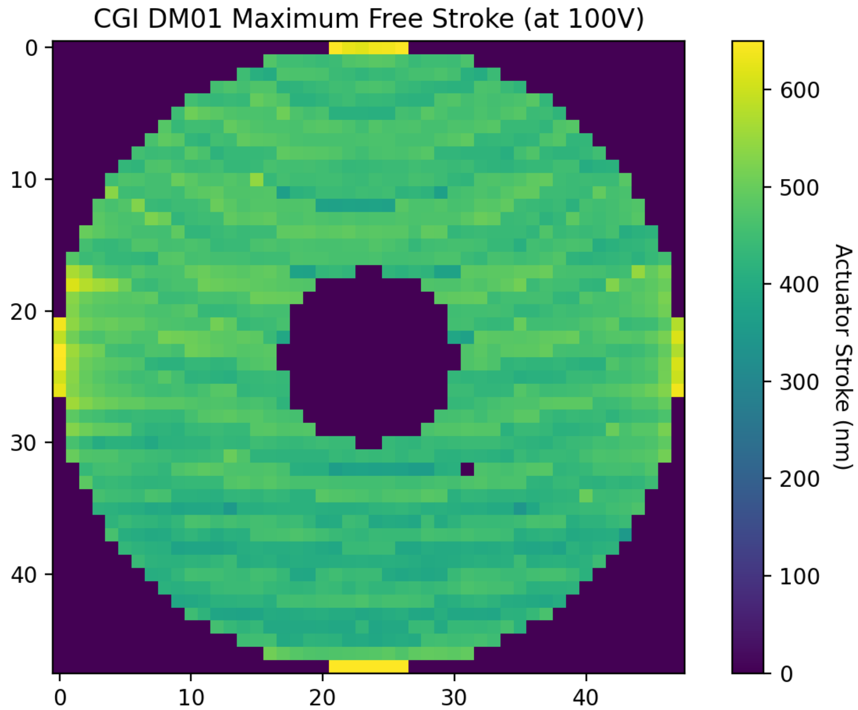


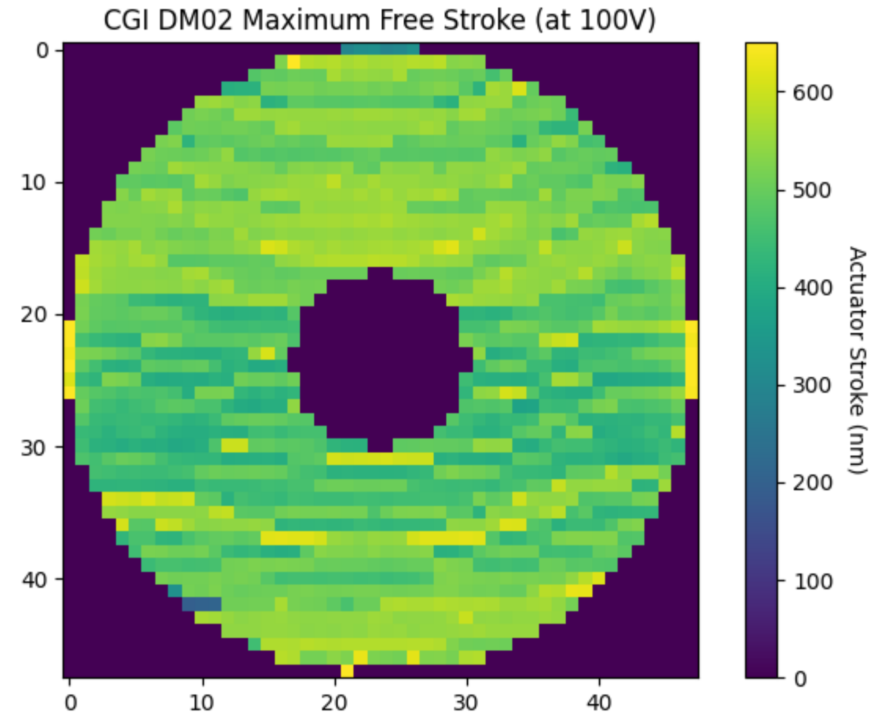
CGI DM OPTICAL PERFORMANCE TESTING

(NO PAIN NO GAIN…map)

Actuator Stroke

- 2D view of per-actuator DM stroke for both DMs:

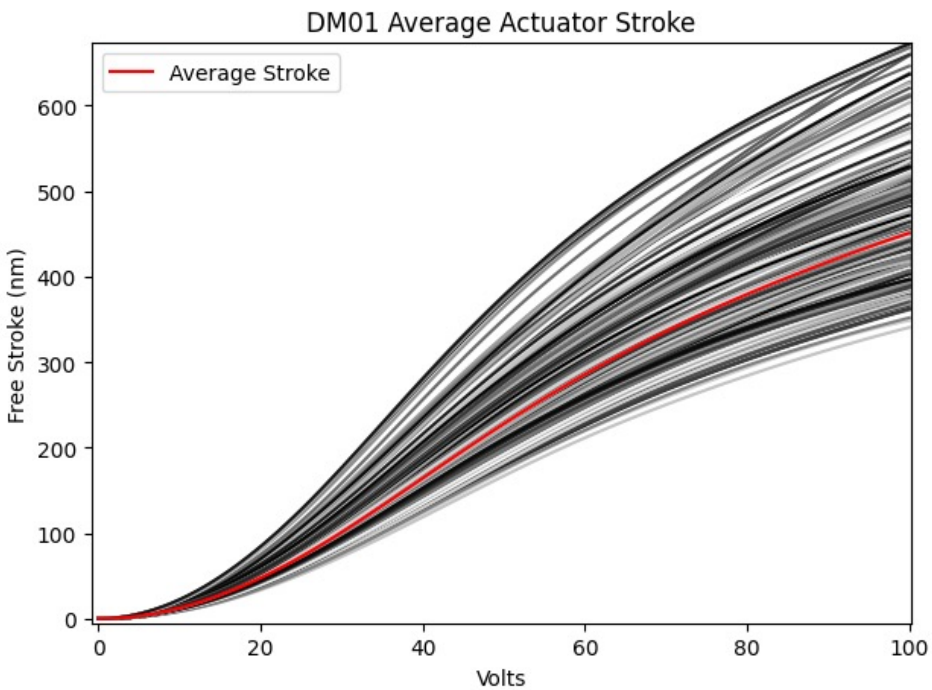


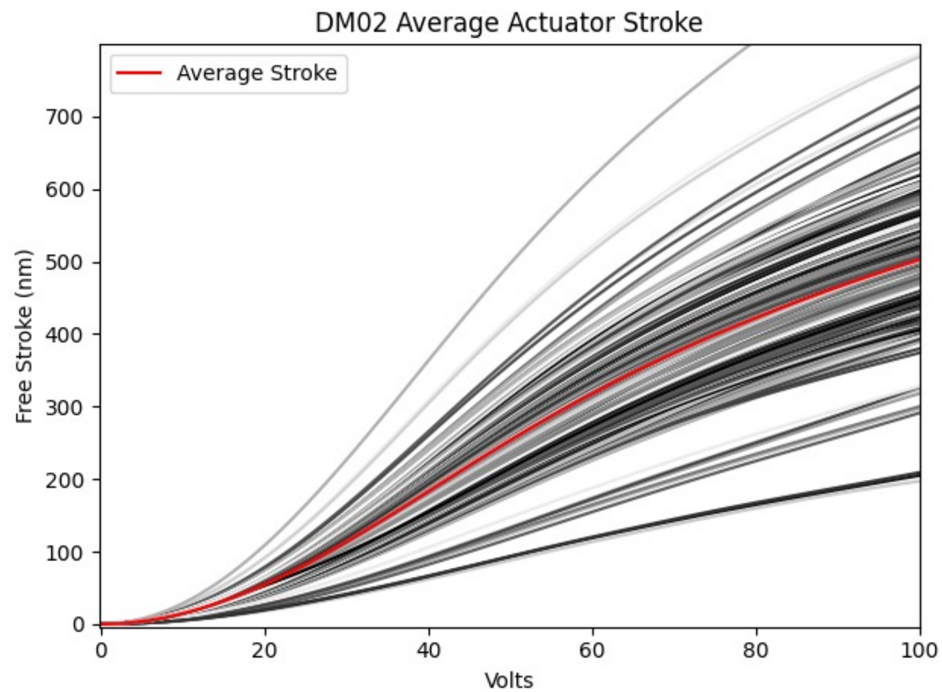


DM02 stroke is crosstalk-corrected (IE stroke from cross-coupled drive channel is *included* in the calculation)

Actuator Stroke

- Typical S-curve view of each DM's individual and average actuator stroke:





DM02 stroke is crosstalk-corrected (IE stroke from cross-coupled drive channel is *included* in the calculation)

Actuator Stroke (Crosstalk)

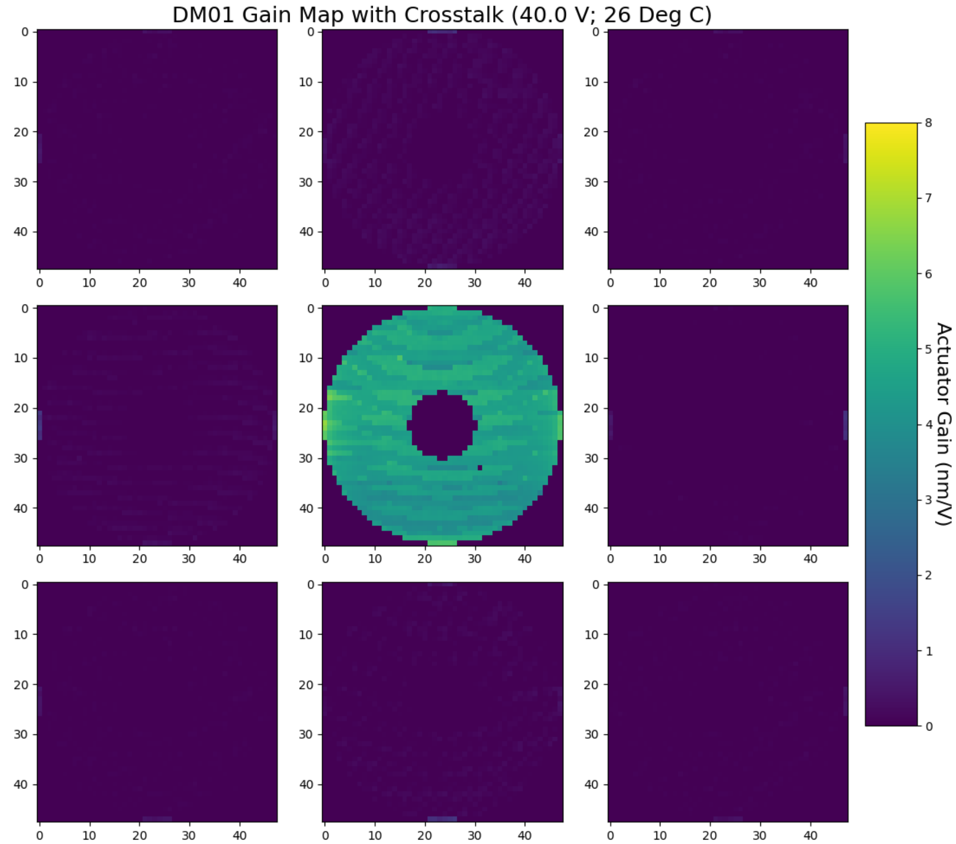
- On DM1, no significant crosstalk was detected.
  - Every actuator cleanly controls its own local portion of the facesheet and no drive channels are cross-coupled.

*3x3 grid displays gain of neighboring actuators due to drive voltage applied to center channel.

Example:

Center plot (1,1) shows gain of actuator (i,j) due to drive channel (i,j) (IE, the intended behavior).

Top Center plot (0,1) shows gain of actuator (i-1,j) due to voltage on drive channel (i,j)



Actuator Stroke (Crosstalk)

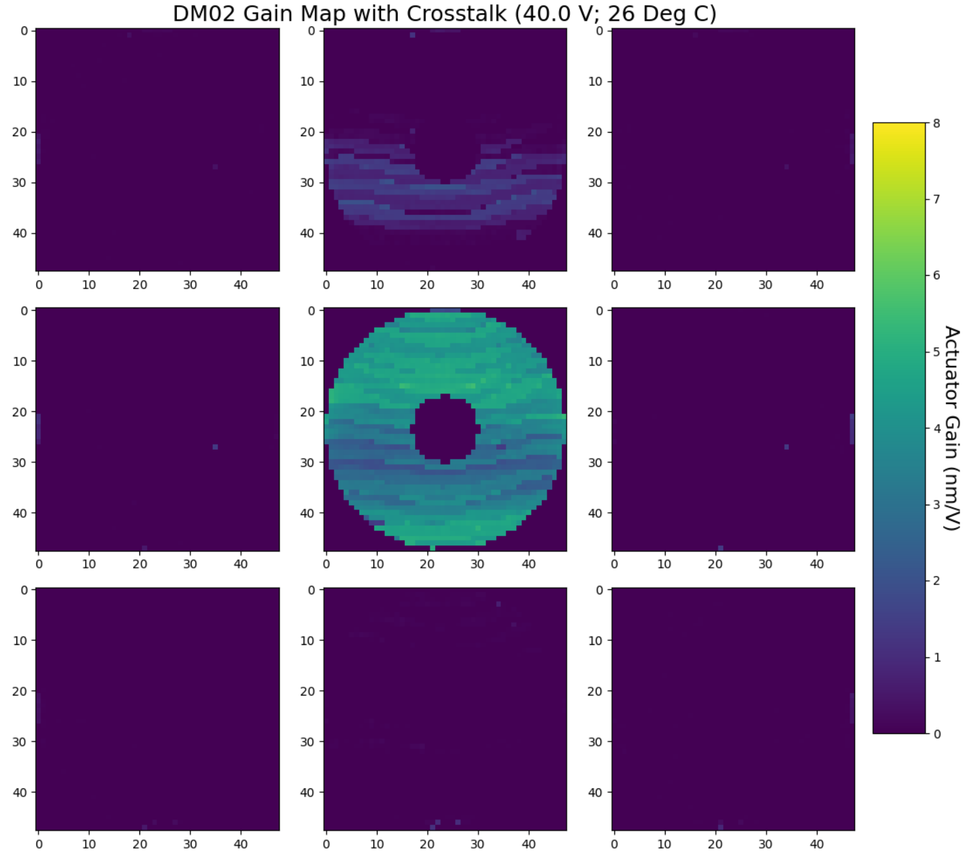
- On DM2, there is significant vertical crosstalk.
  - This is the result of cross-coupled electrical drive channels stemming from mismatch between electrode grid and metallization pad grid.

*3x3 grid displays gain of neighboring actuators due to drive voltage applied to center channel.

Example:

Center plot (1,1) shows gain of actuator (i,j) due to drive channel (i,j) (IE, the intended behavior).

Top Center plot (0,1) shows gain of actuator (i-1,j) due to voltage on drive channel (i,j)



Surface Temperature Dependence

- DM control surfaces show notable thermal dependence.

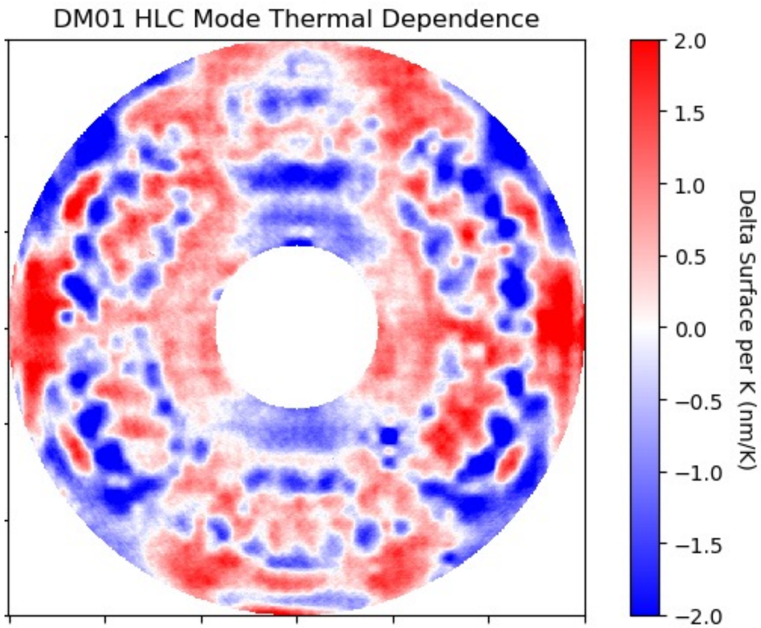
- DM01: 0.98 nm/K
- DM02: 1.15 nm/K

The most significant result here is that print through of the HLC control pattern is easily seen in the thermal dependence.

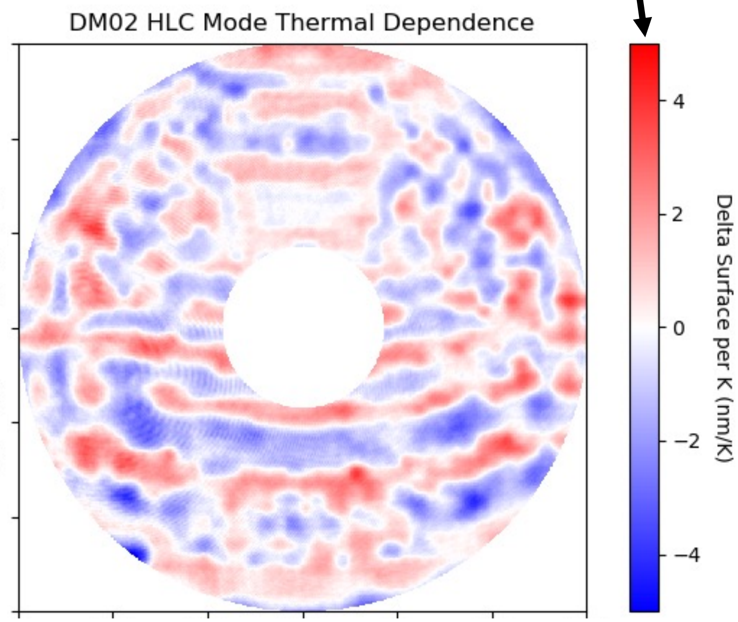
<u>This performance is fine for CGI at baseline and threshold performance requirements</u>, but temperature dependence in the DM control solution is the largest error term in the HOWFSC FRN Error Budget.

If CGI thermal control performed at its requirement level (10 mK stability), this would comprise a 7E-9 effect in contrast across 3-9 λ/D (-B. Kern)

Note the scale change here



***DM01 HLC data from a difference of two surfaces measured at average bezel temperatures of 20.5C and 25.5C**

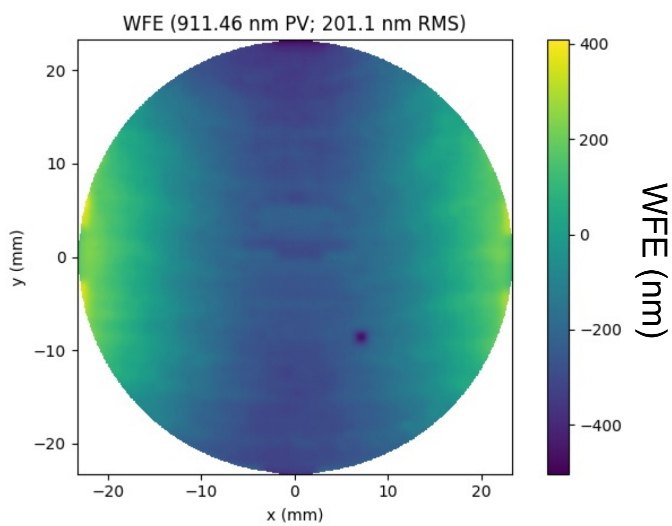


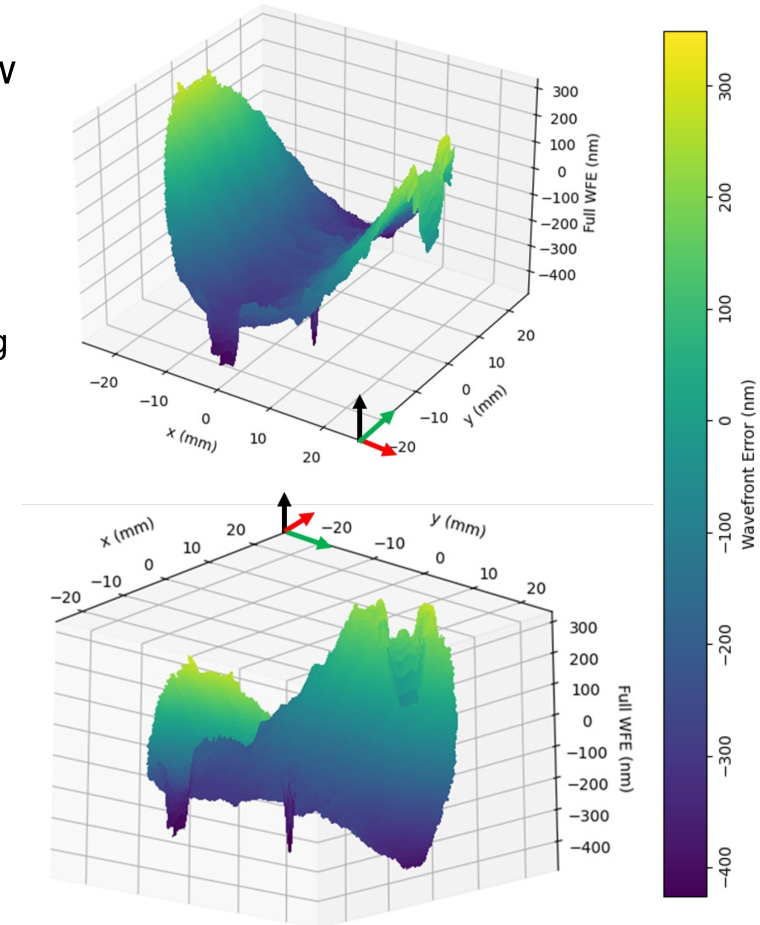
*** DM02 HLC data from a difference of two surfaces measured at average bezel temperatures of 20.4C and 24.2C**

Desiccated WFE & Desiccation Drift

- When fully desiccated in vacuum, both DM1 and DM2 show significant cylindrical error terms.
  - Convex surface ⇒ concave wavefront
  - Effect is exacerbated by voltage bias application.
  - WFE here is taken at 40V “Pure Piston”
    - Slight improvement over naïve 40V bias application at preserving initial, unpowered surface figure.

<u>DM01 Desiccated WFE</u>
- **<u>P-V</u>** = 911.4 nm
- **<u>RMS</u>** = 201.1 nm



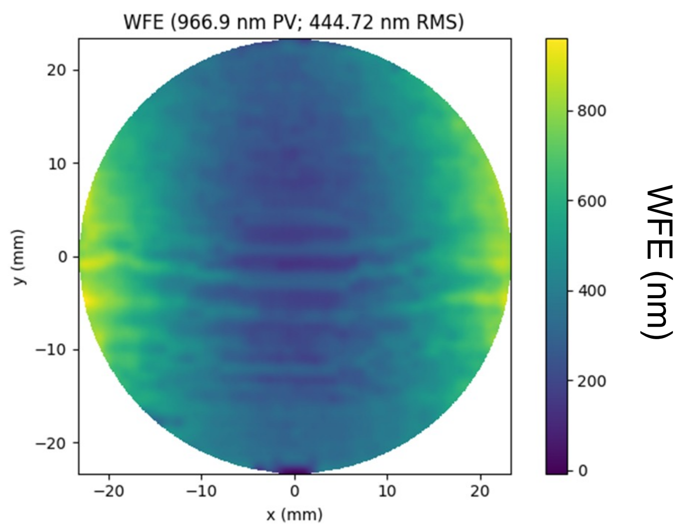


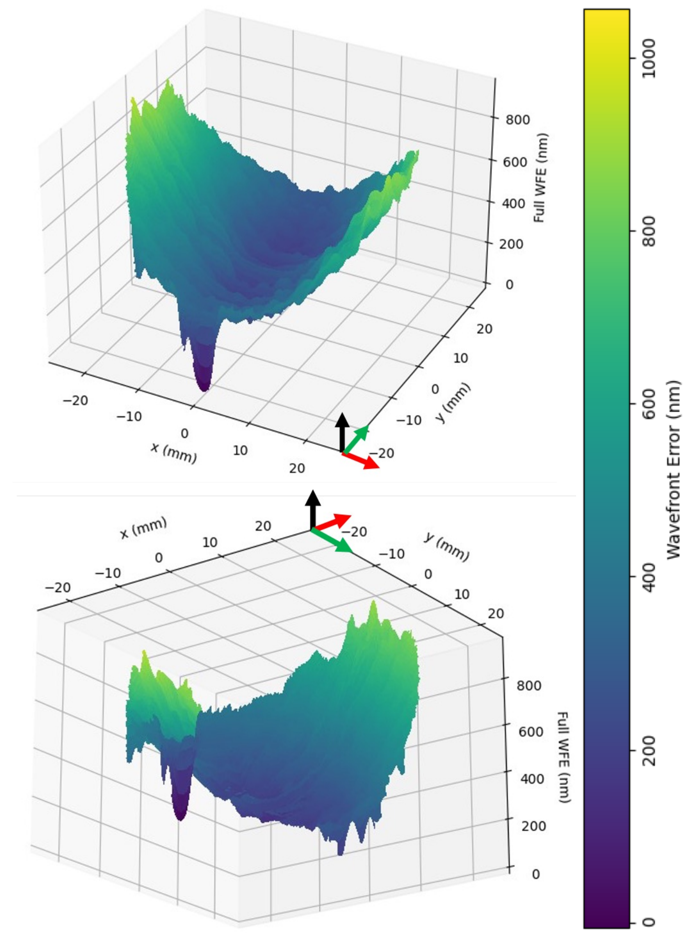
Desiccated WFE & Desiccation Drift

- When fully desiccated in vacuum, both DM1 and DM2 show significant cylindrical error terms.
  - Convex surface ⇒ concave wavefront
  - Effect is exacerbated by voltage bias application.
  - WFE here is taken at 40V "Pure Piston"
    - Slight improvement over naïve 40V bias application at preserving initial, unpowered surface figure.

DM02 Desiccated WFE

- **P-V** = 966.9 nm
- **RMS** = 444.7 nm

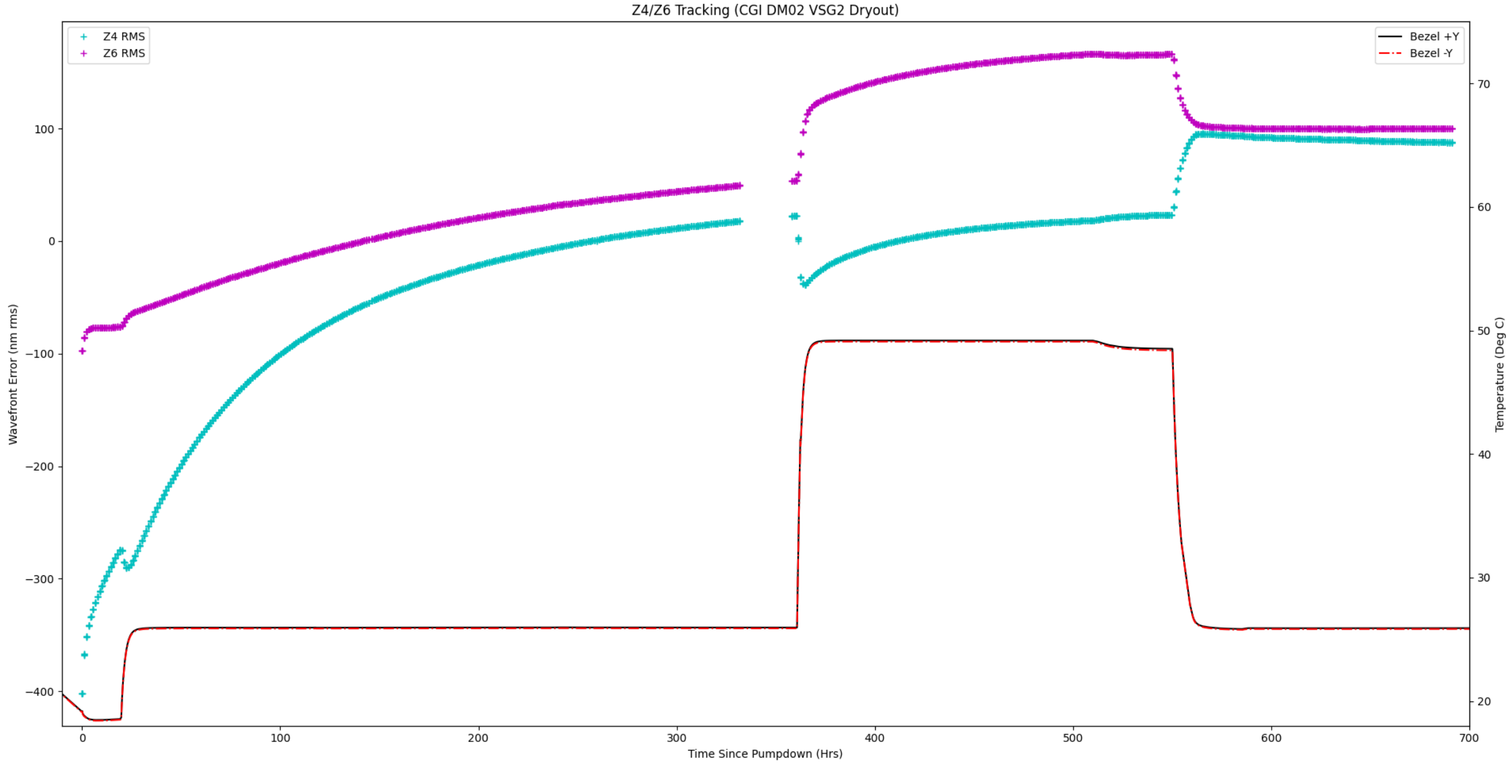




Desiccated WFE & Desiccation Drift

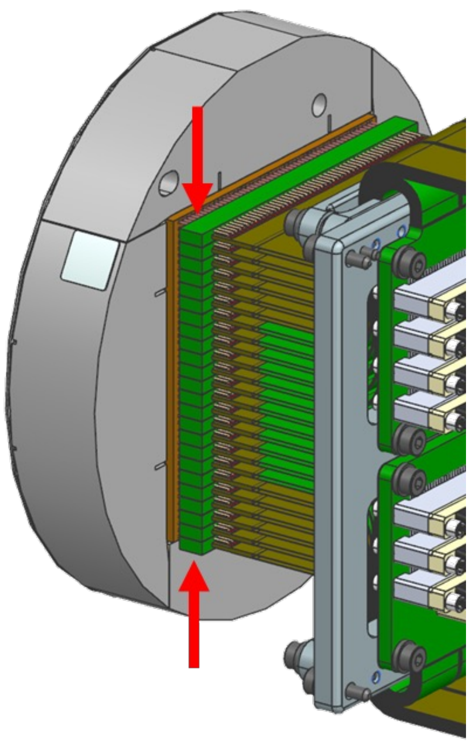
- Timescale for desiccation was painful for CGI system TVAC, but should not pose problems during/after on-orbit commissioning simply due to time gap before CGI is operational.

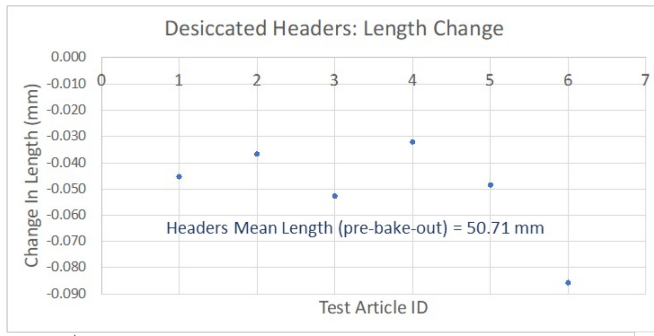
DM02 dryout data (right) also includes a period of accelerated dryout via elevated DM temperature.



Desiccated WFE & Desiccation Drift

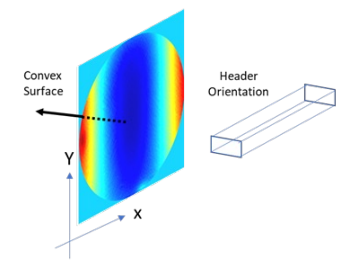
- Root cause: constriction of headers and reinforcing epoxy under vacuum desiccation.

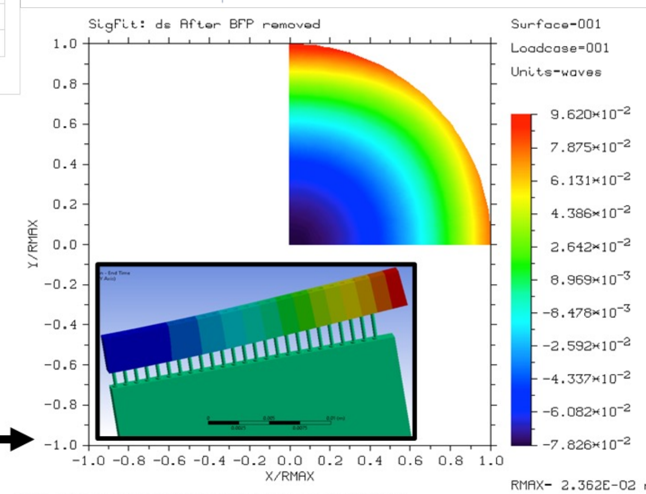




Hardware tests on spare headers show they do shrink under desiccation

Modeling efforts show this stress can propagate through to optical surface

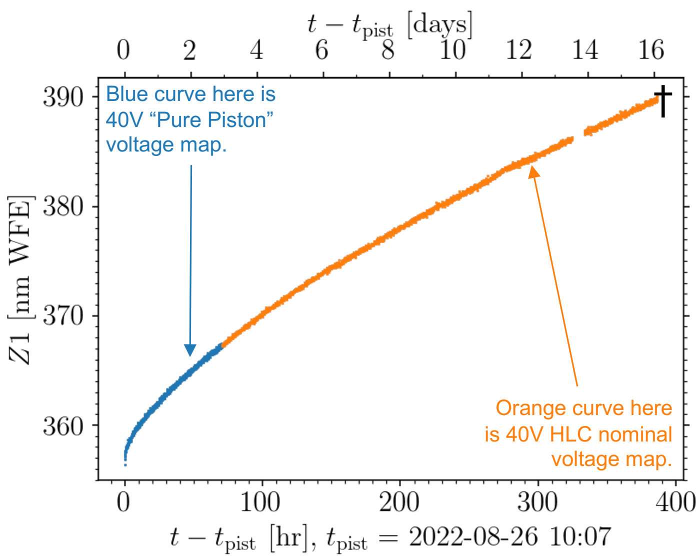


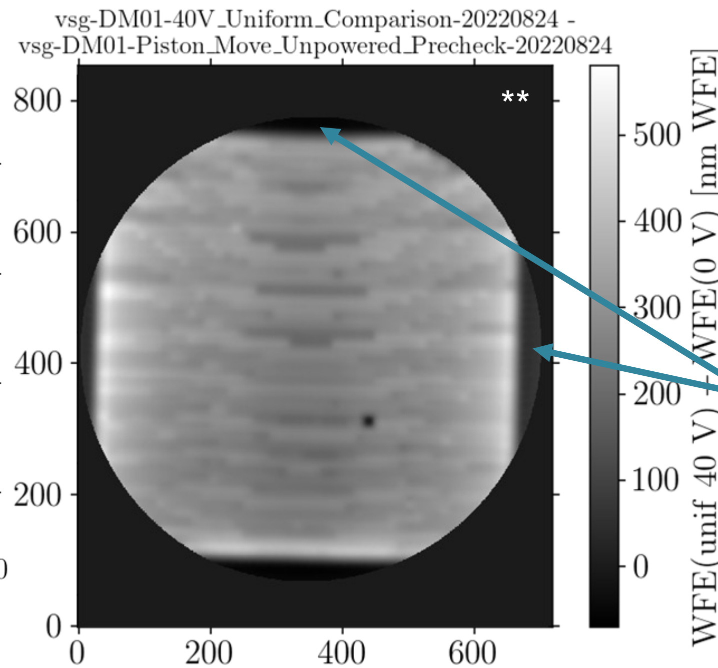


Long Timescale Control Surface Drift

- Longer-term drift characterization with mean-40V control maps gives insight into drift behavior of CGI DMs under applied voltages.

This plot of referenced DM01 piston does not display expected log-drift behavior.





Regions outside active area provide VSG reference for piston, if properly controlled for VSG effects.

*All these analyses c/o Brian Kern (7/8/2022)

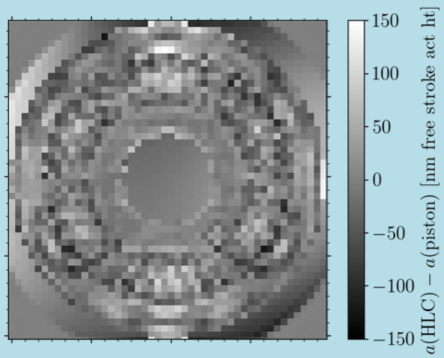
†Also published in John E. Krist, et. al., "End-to-end numerical modeling of the Roman Space Telescope coronagraph," J. Astron. Telesc. Instrum. Syst. 9(4) 045002 (11 October 2023) https://doi.org/10.1117/1.JATIS.9.4.045002

**Image parity here flipped vertical from source presentation to correct for the somewhat heretical placement of origin at bottom left

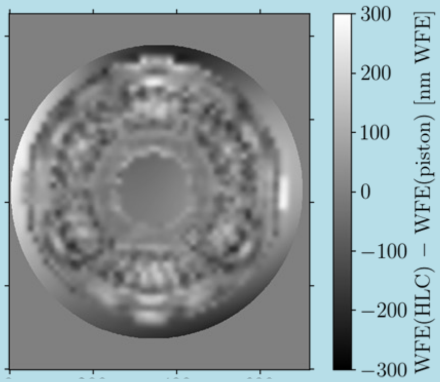
Long Timescale Control Surface Drift

- Behavior ***does*** affect control maps (IE it is not purely bulk piston).

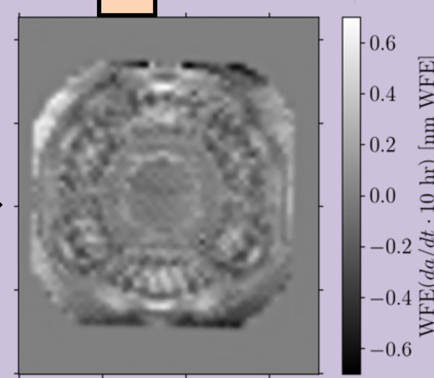
This actuator height difference map shows the transition into an HLC control map from a 40V "Pure Piston" map.



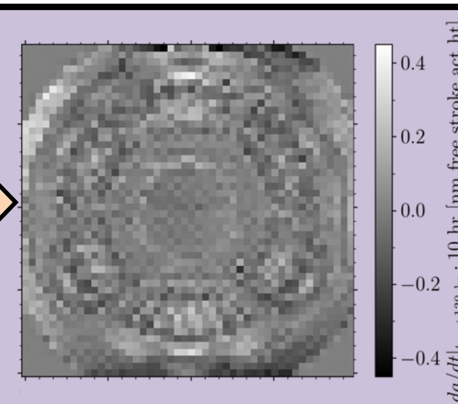
And it produced this measured DM WFE. (≤ Z11 removed)



That DM surface drifted over 10 hours to produce this ΔWFE.



Which decomposes into this change in actuator heights.



The notable part, again, is that we see the HLC pattern emerge in the 10-hour drift delta.

***All these analyses c/o Brian Kern (7/8/2022)**

****Image parity here flipped vertical from source presentation to correct for the somewhat heretical placement of origin at bottom left**

DM LESSONS LEARNED

(Need to write all these down so we can ignore them later)

Summary of Performance-Based Lessons Learned

- **Build with enough time to properly cherry pick modules**.
- Rely on early risk reduction testing w/ SME oversight to gauge module health.
- Decouple interconnect from active module as much as possible.
- Pay close attention to thermal environment & local stability of DM surface & active region.
- Invest in truly picometer-precision testbed w/ high data rate.

Planning for HWO

Project Role

Customer/User of CGI

CGI Impact from DM1 Dead Actuator

- DM1’s dead actuator was a near-miss for the technical performance of CGI.
  - It sits (almost entirely) behind the Lyot stop in HLC mode and is partially occluded in both SPC modes, allowing all modes to still achieve threshold and baseline requirement performance.

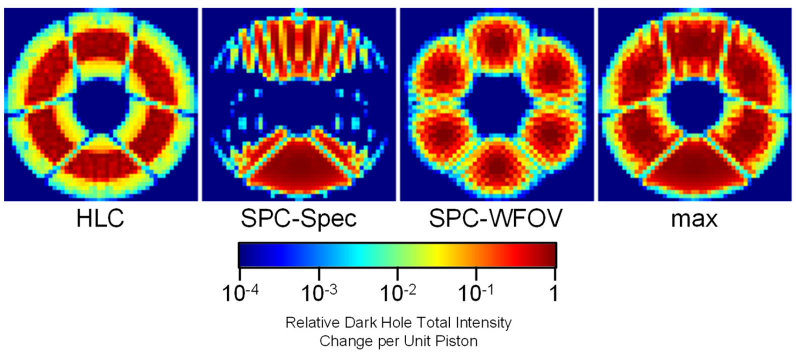


Figure 49. The “strength” of each DM actuator for each baseline coronagraphic mode. These maps were derived by separately pistoning each actuator by an equal amount and measuring the total change in simulated dark hole intensity. The maximum value for each actuator is shown in the “max” map, which is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

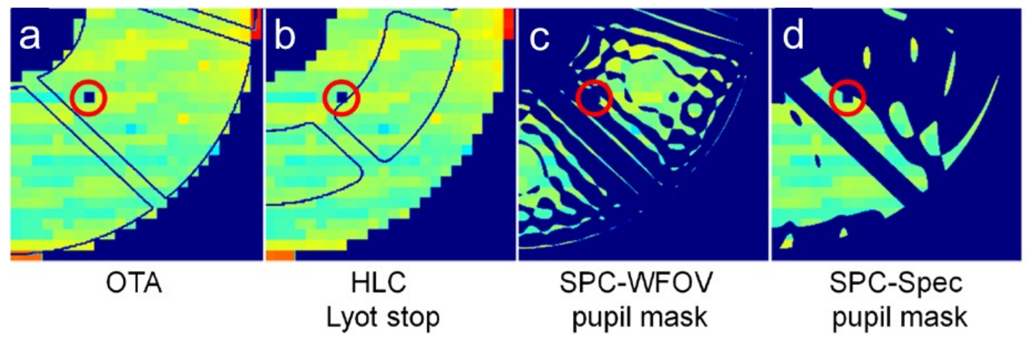


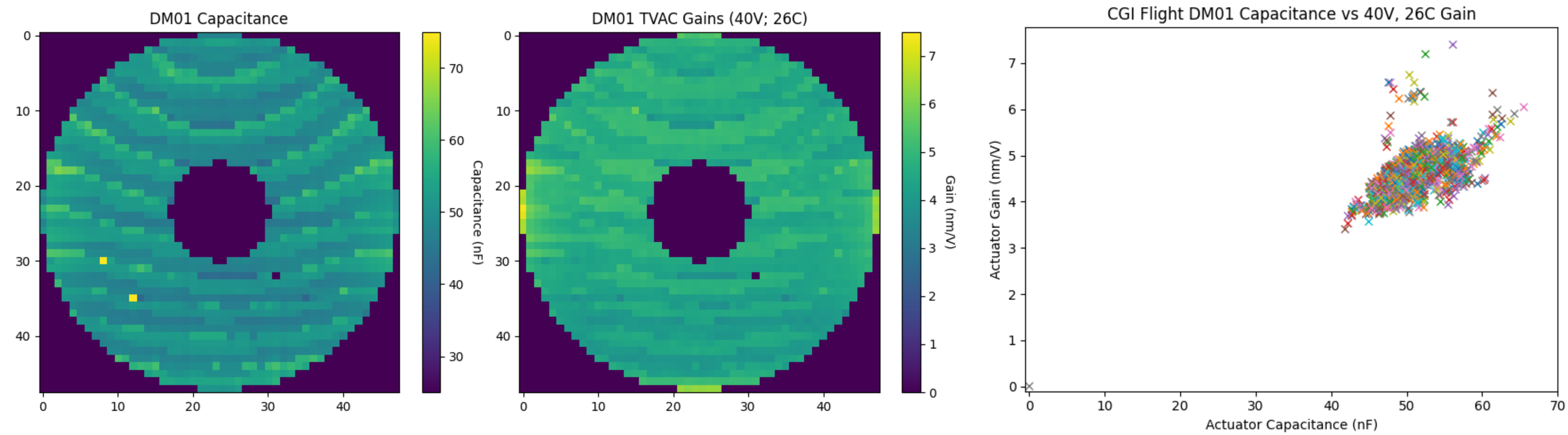
Figure 60. Maps of maximum actuator stroke over one-quarter of DM1 with obscuration patterns superposed and the dead actuator circled. (a) The OTA obscurations outlined; (b) the HLC Lyot stop openings outlined; (c) the SPC-WFOV pupil mask; (d) the SPC-Spec pupil mask.

***John E. Krist, et. al., "End-to-end numerical modeling of the Roman Space Telescope coronagraph," J. Astron. Telesc. Instrum. Syst. 9(4) 045002 (11 October 2023) https://doi.org/10.1117/1.JATIS.9.4.045002**
****Although I have, again, corrected orientation on the right plot for heretical placement of the origin.**

Viable Screening Tests

- Due to the high demands on actuator yield and DM performance, robust screening tests and module cherry picking are highly recommended during HWO DM development.

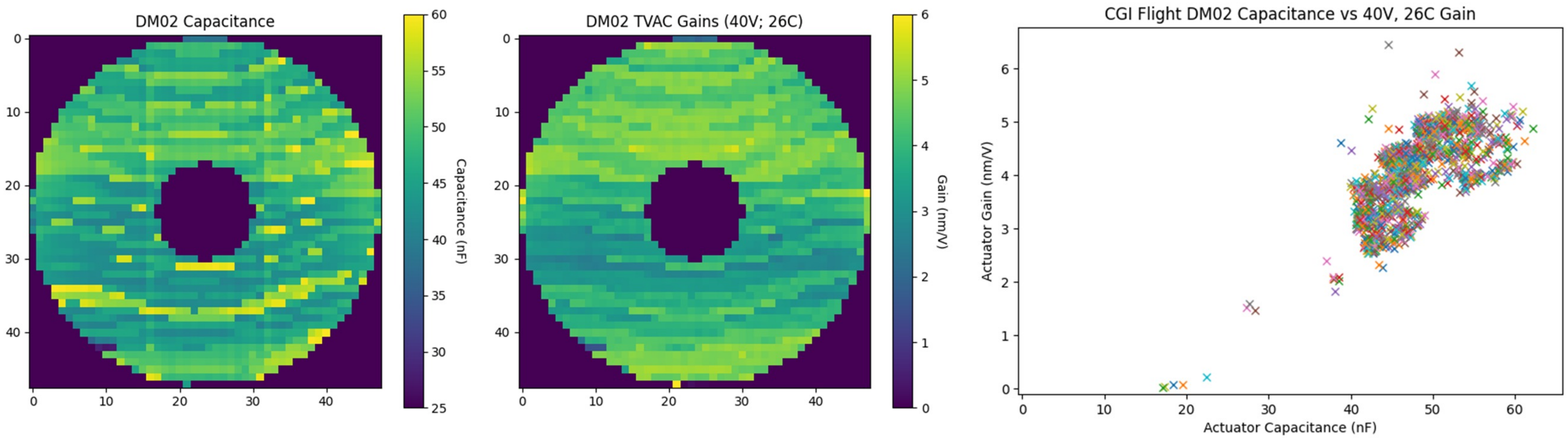
- Early capacitance measurements are actually a reliable method for determining aliveness and general actuator health.



Viable Screening Tests

- Due to the high demands on actuator yield and DM performance, robust screening tests and module cherry picking are highly recommended during HWO DM development.

- Regions of likely crosstalk like CGI DM2 can also be seen (at least retrospectively) in early module capacitance measurements.



Summary of Performance-Based Lessons Learned

- **Build with enough time to properly cherry pick modules**.
- Rely on early risk reduction testing w/ SME oversight to gauge module health.
- Decouple interconnect from active module as much as possible.
- Pay close attention to thermal environment & local stability of DM surface & active region.
- Invest in truly picometer-precision testbed w/ high data rate.

Planning for HWO

Project Role

Customer/User of CGI

Summary of Performance-Based Lessons Learned

- **Build with enough time to properly cherry pick modules**.
- Rely on early risk reduction testing w/ SME oversight to gauge module health.
- Decouple interconnect from active module as much as possible.
- Pay close attention to thermal environment & local stability of DM surface & active region.
- Invest in truly picometer-precision testbed w/ high data rate.

Planning for HWO

Project Role

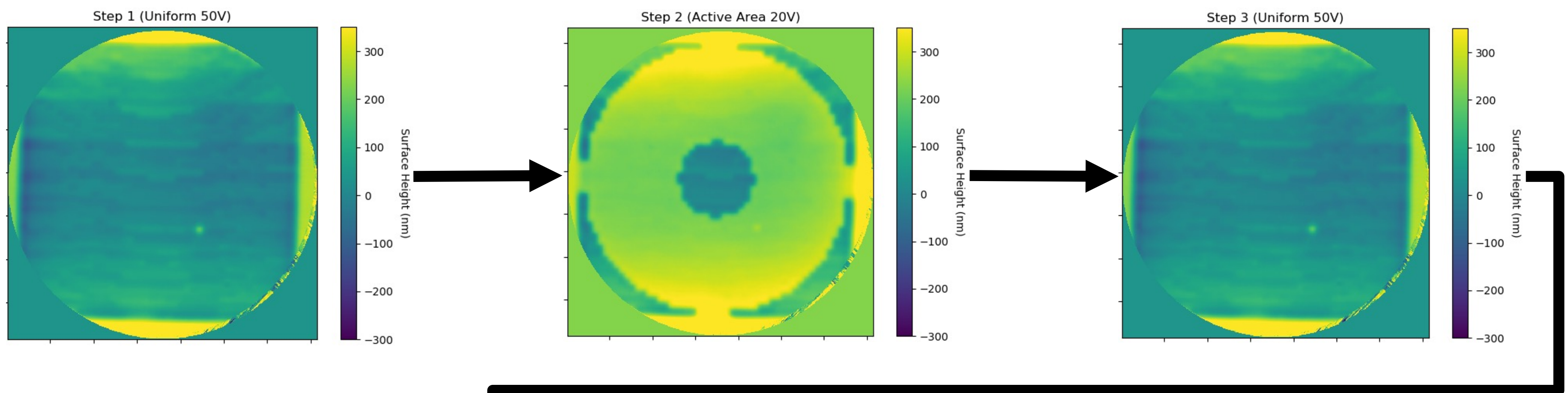
Customer/User of CGI

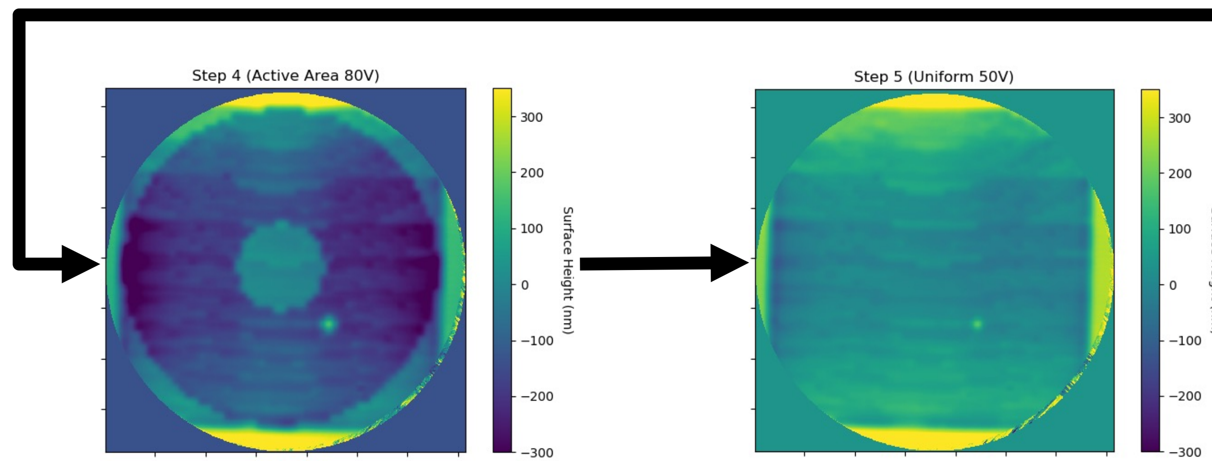
- Maintain awareness of:
  - DM02's crosstalk region
  - Neighbor rule concerns near edges & DM1/DM2 dead actuators
    - CGI Ops team has already produced software tools to handle these and crosstalk!
  - Native Z4/Z6 terms and stroke loss for self-flattening.
  - Drift timescales
    - ~12-24 hours for "rogue" drifters.
    - ~5-15 days for control map drift.
  - DM models are included in the coronagraph diffractive optics model (should be released now, if not soon).

BACKUP

(Nothing is hidden in here, I swear)

Actuator Hysteresis

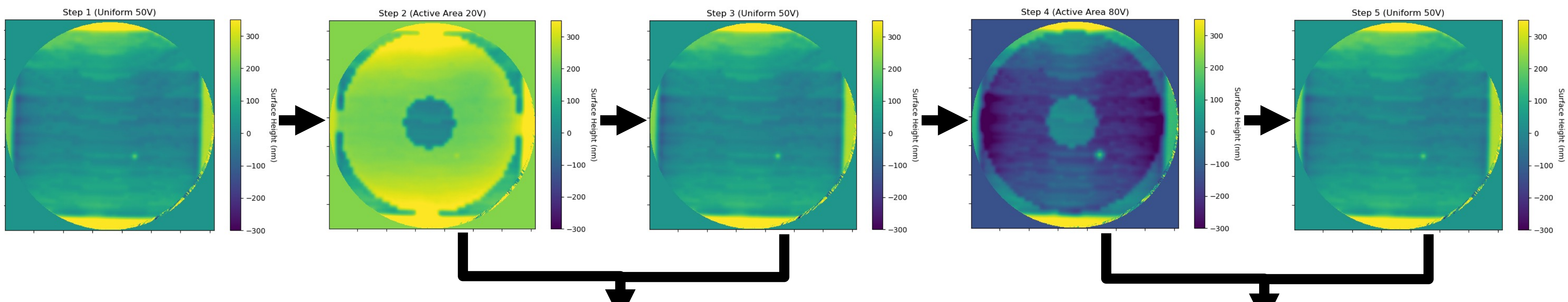


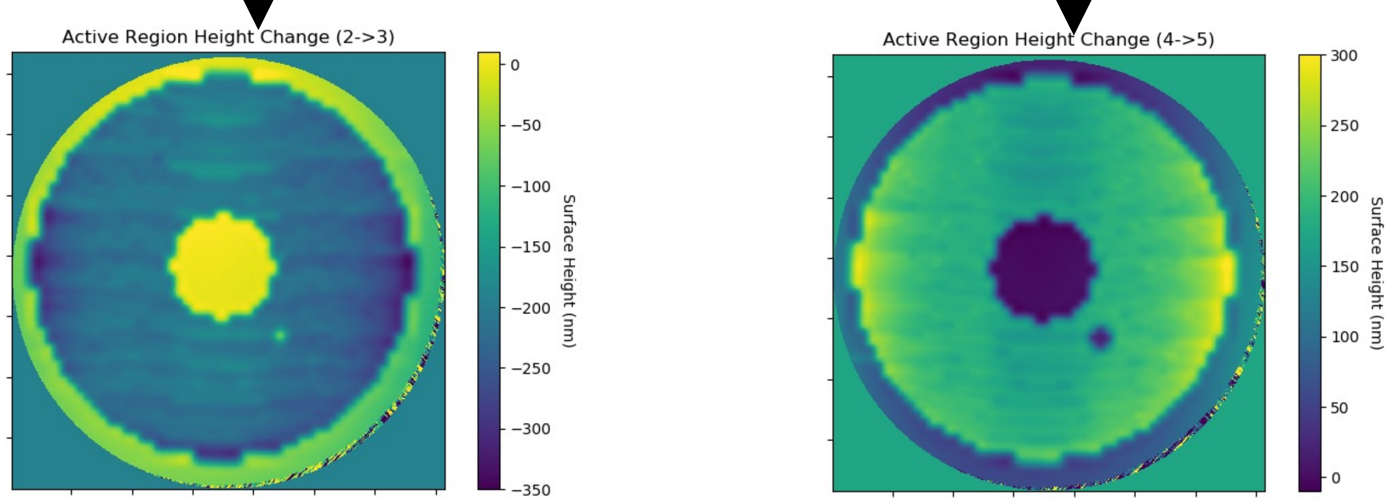


General Hysteresis Procedure

- Set series of 5 voltage maps in specific sequence.
  - Set active annulus to 20V and 80V, returning to 50V after each change.
- Hold center ganged region at 50V for piston reference.
- Measure difference in piston-referenced surface height for active annulus between Uniform 50V surfaces.

Actuator Hysteresis

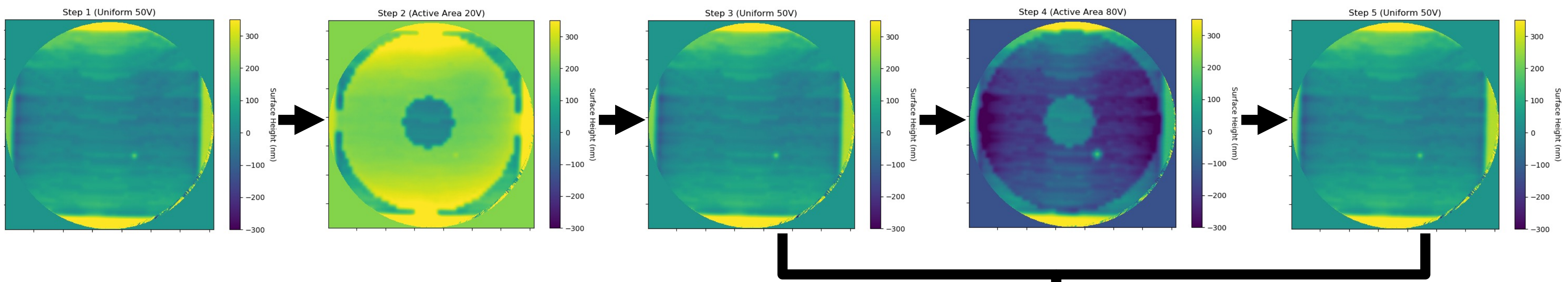


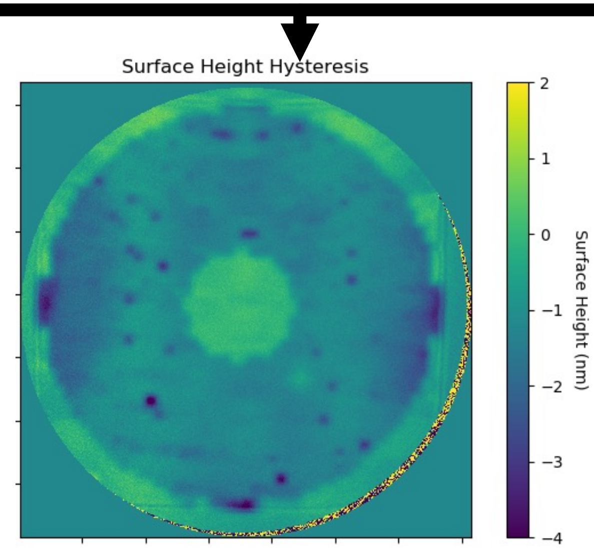


General Hysteresis Procedure

- Difference between surfaces 2&3 and 4&5 gives surface height change.

Actuator Hysteresis





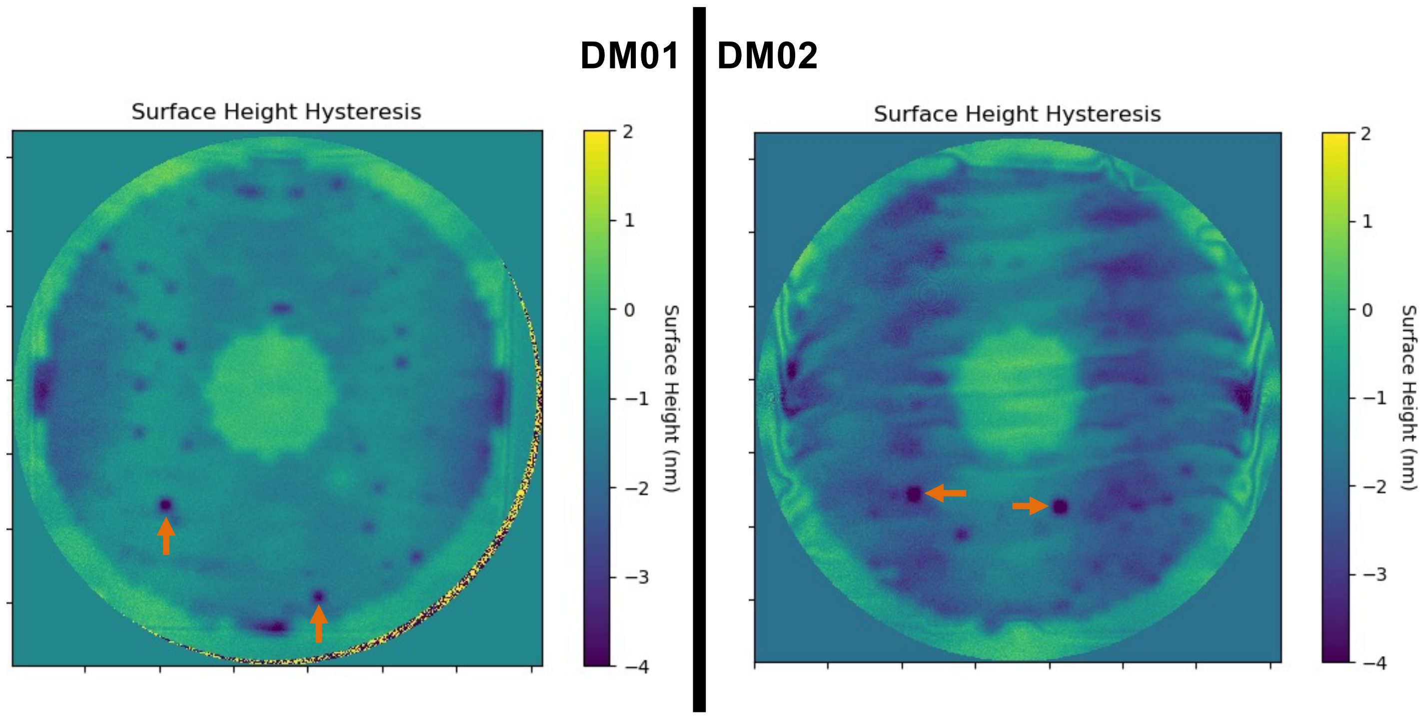
General Hysteresis Procedure

- Difference between surfaces 3&4 gives hysteresis of surface height between the two motions

Actuator Hysteresis

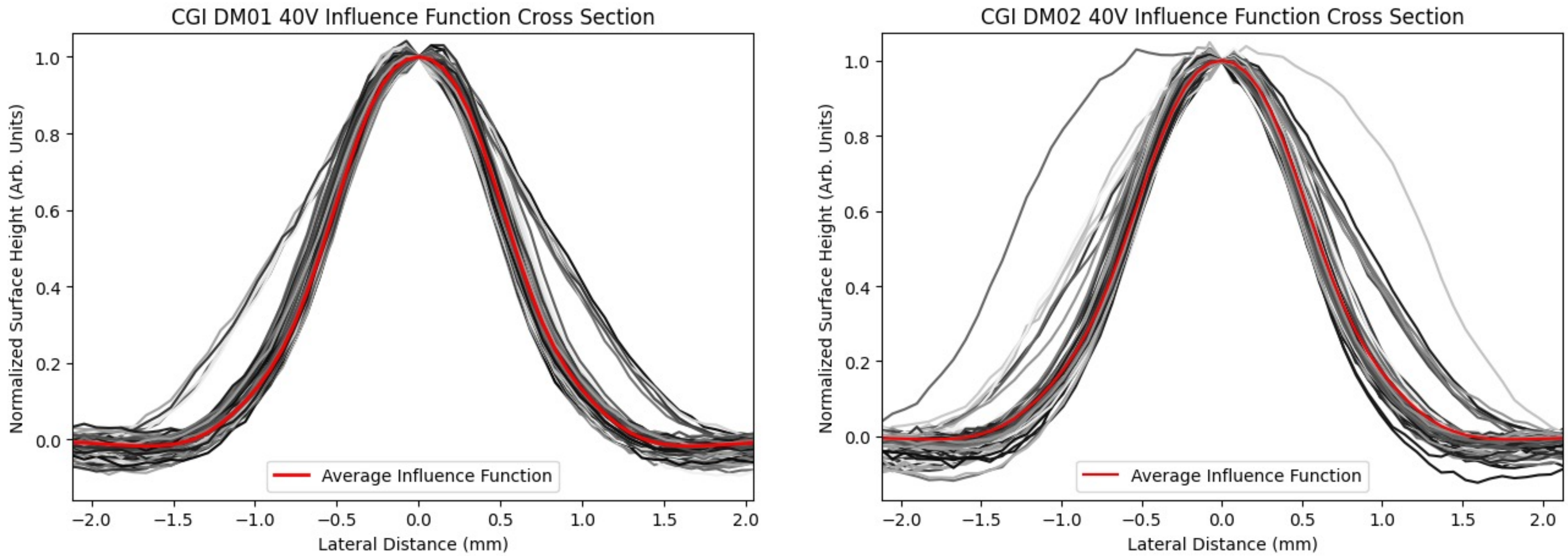
- Both DMs passed hysteresis requirement (<1% of commanded motion for 30nm):
  - <u>0.65%</u> of ~200nm command for DM1
  - <u>0.97%</u> of ~200nm command for DM2

Attention should be brought to “rogue” actuators, however. These *were* noted by coronagraphers during CGI wavefront flattening, although any impact was overtaken by lengthened Con Ops to account for control voltage drift.



Influence Function Shape

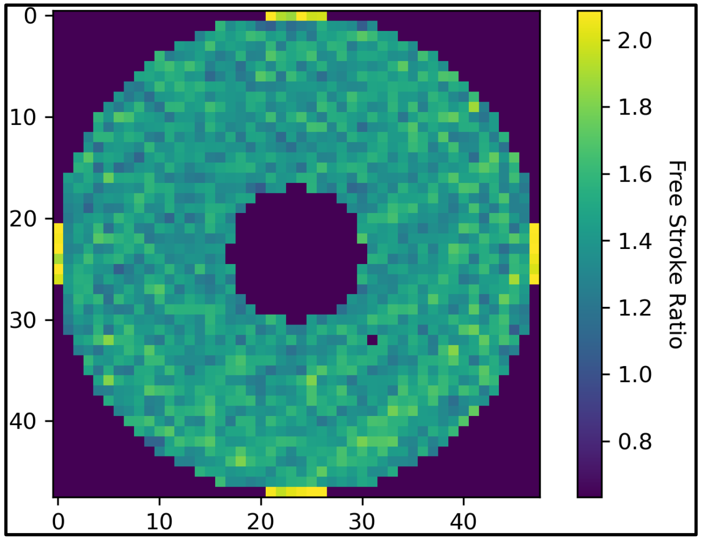
- Influence function requirement focuses largely on the Free Stroke Ratio.
  - Requirement: **FSR of <2.1** for all actuators in active region

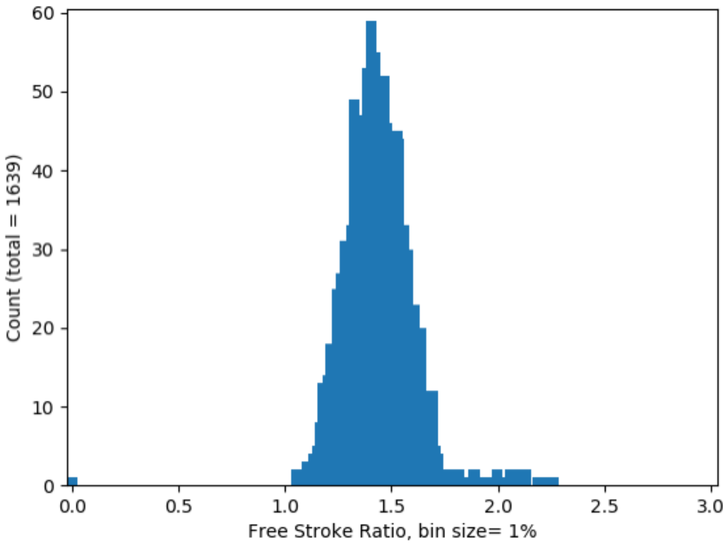


***Greyscale here is a cross section of every poke image on the respective DM. CGI FSW utilizes an average influence function for each DM (red curve) for HOWFSC implementation.**

Influence Function Shape

- Influence function requirement focuses largely on the Free Stroke Ratio.
  - Requirement: **FSR of <2.1** for all actuators in active region
  - DM01 has ideal facesheet thickness.
    - Median FSR: **1.4** (ideal FSR)

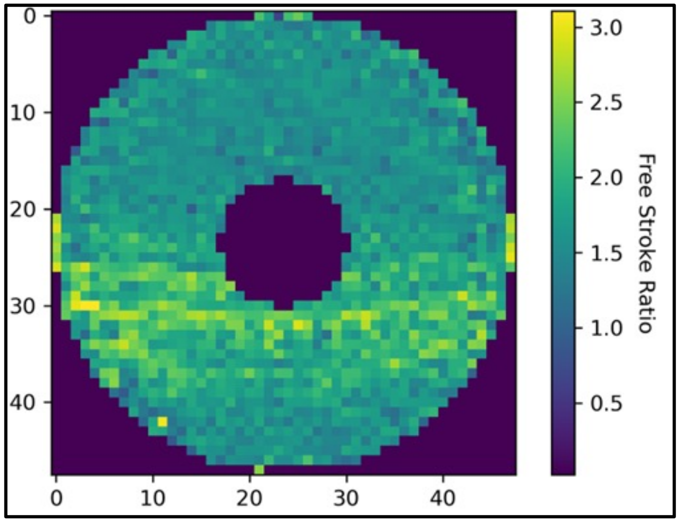


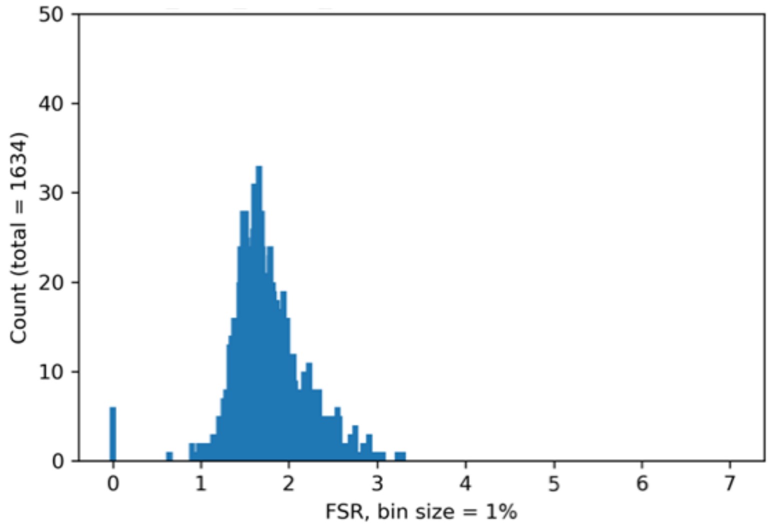


(above) FSR for all actuators on DM01, colorscaled by FSR. (left) Histogram of FSR for DM01. Only a handful of actuators (on the edges) fail the FSR < 2.1 requirement, which is inconsequential.

Influence Function Shape

- Influence function requirement focuses largely on the Free Stroke Ratio.
  - Requirement: **FSR of <2.1** for all actuators in active region
  - DM02 wound up with thicker than ideal facesheet.
    - Median FSR: **1.7** (higher than ideal FSR)

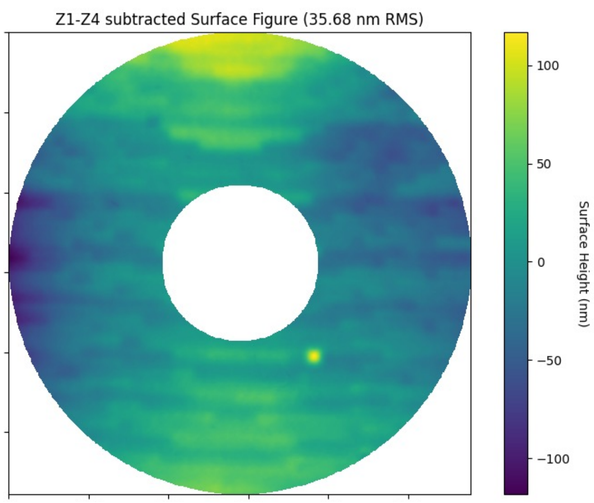




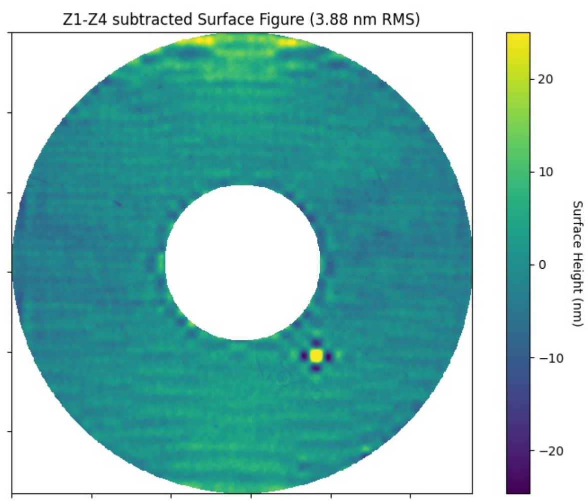
(above) FSR for all actuators on DM02, colorscaled by FSR. (left) Histogram of FSR for DM02. In addition to edge actuators (again inconsequential, now also significant amounts of actuators in the crosstalk region show increased FSR due to the crosstalk (issue book kept elsewhere in CGI DM V&V).

DM Self-Flattening Capability

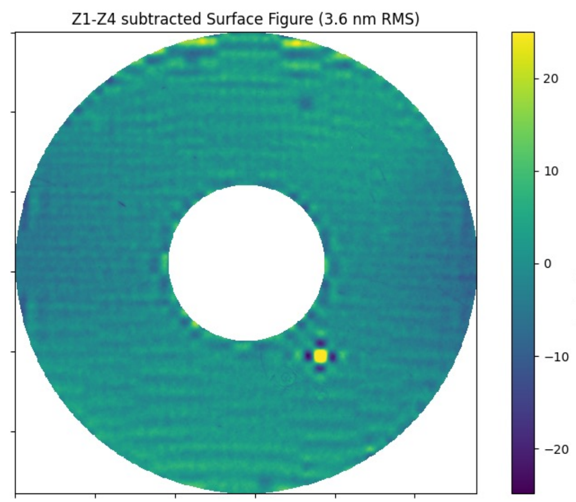
- DM01 capability for self-flattening is generally around 3-4 nm surface rms.



DM01 40V uniform Bias



DM01 after 1 self-flattening iteration

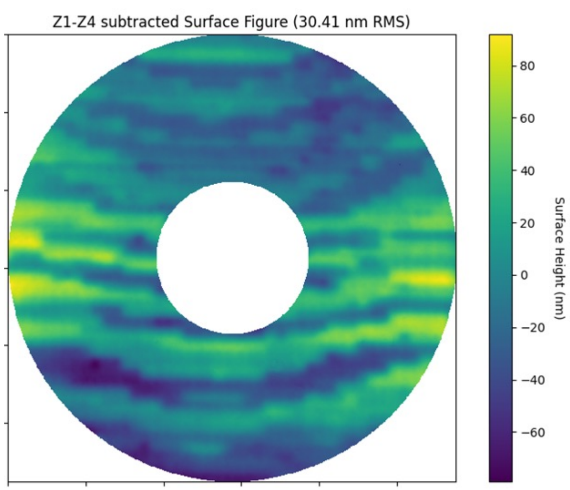


DM01 after 2 self-flattening iterations

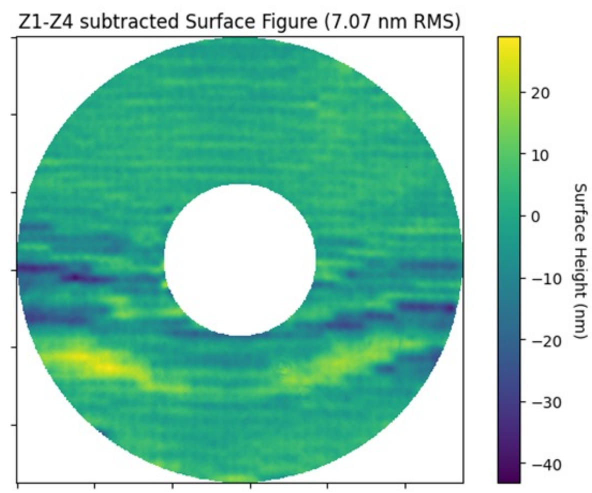
***All data here taken in TVAC at 26C**

DM Self-Flattening Capability

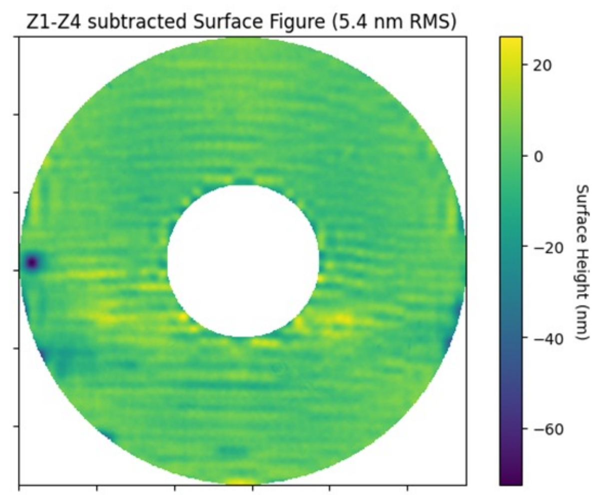
- DM02 capability for self-flattening is generally around 5 nm surface rms and requires multiple iterations to account for crosstalk region.



DM02 40V uniform Bias



DM02 after 1 self-flattening iteration



DM02 after 2 self-flattening iterations

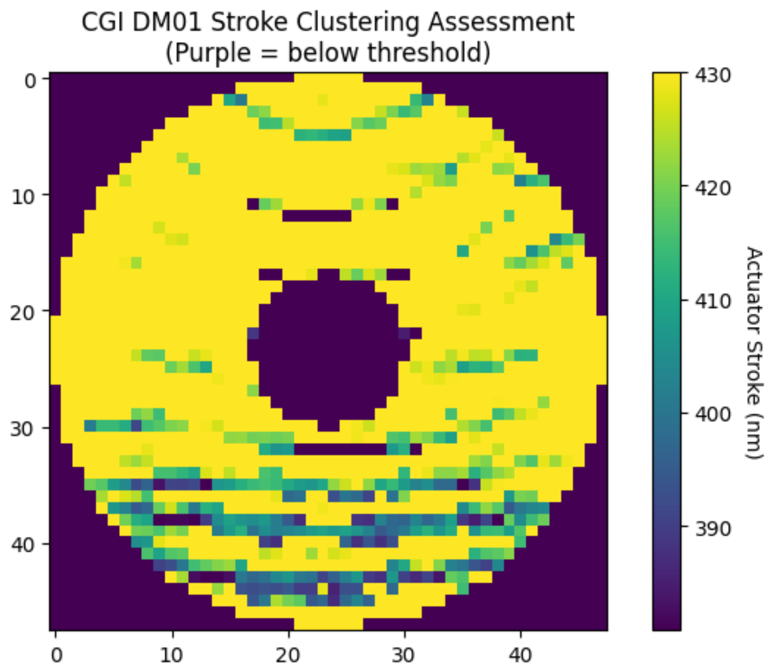
*All data here taken in TVAC at 26C

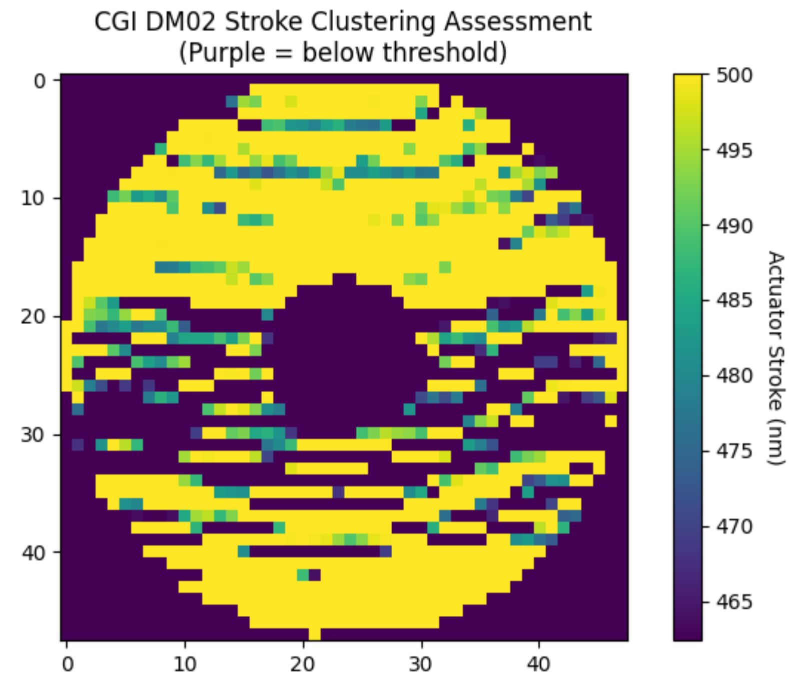
Stroke: Clustering of Low Stroke Actuators

- Requirement: No clusters of 10 or more low-stroke actuators (threshold set at 95% level) within any given 5-actuator radius.

DM02 crosstalk region does show clustering of lower-stroke actuators – potential weakness in control of lower spatial frequencies.

DM01 does not possess any similar regions.



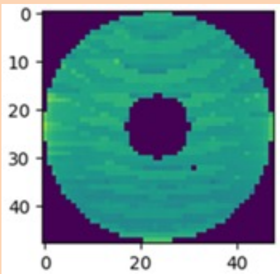


Z11+ Stability – Temperature Dependence

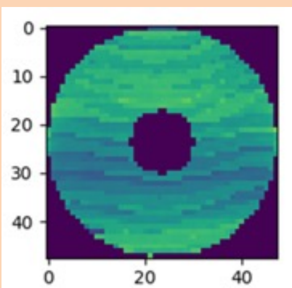
- Another look at temperature dependence, with flat surface solutions instead of HLC control map.

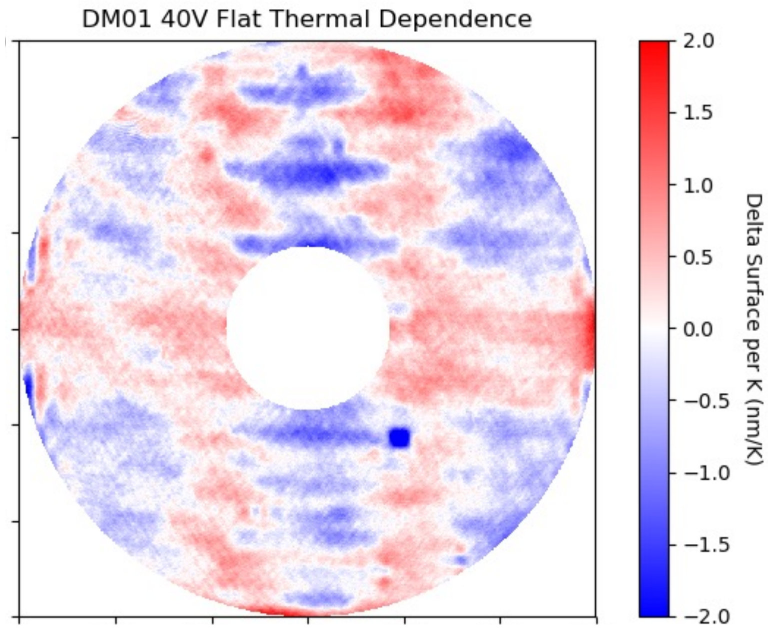
Thermal dependence of flat surface solutions show print through of the respective gain maps for DMs 01 and 02.

DM01:

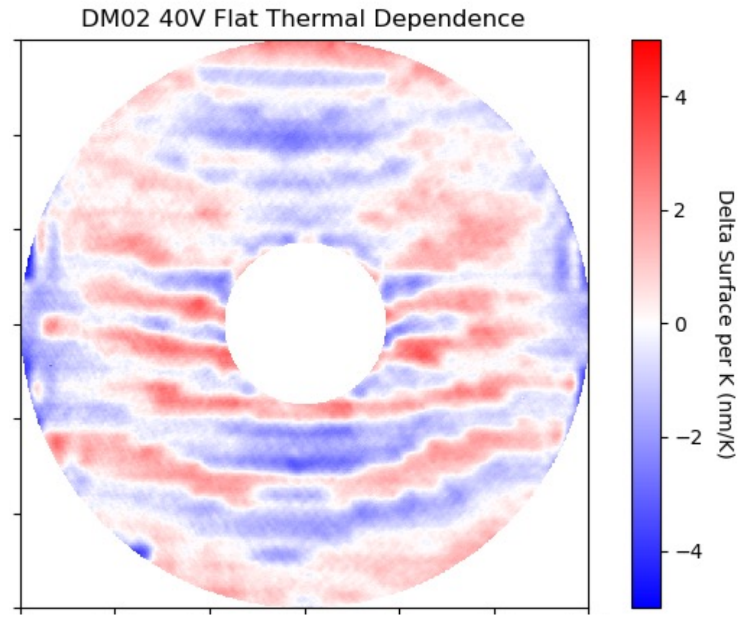


DM02:





***DM01 flat data from a difference of two surfaces measured at average bezel temperatures of 14.0C and 19.0C**

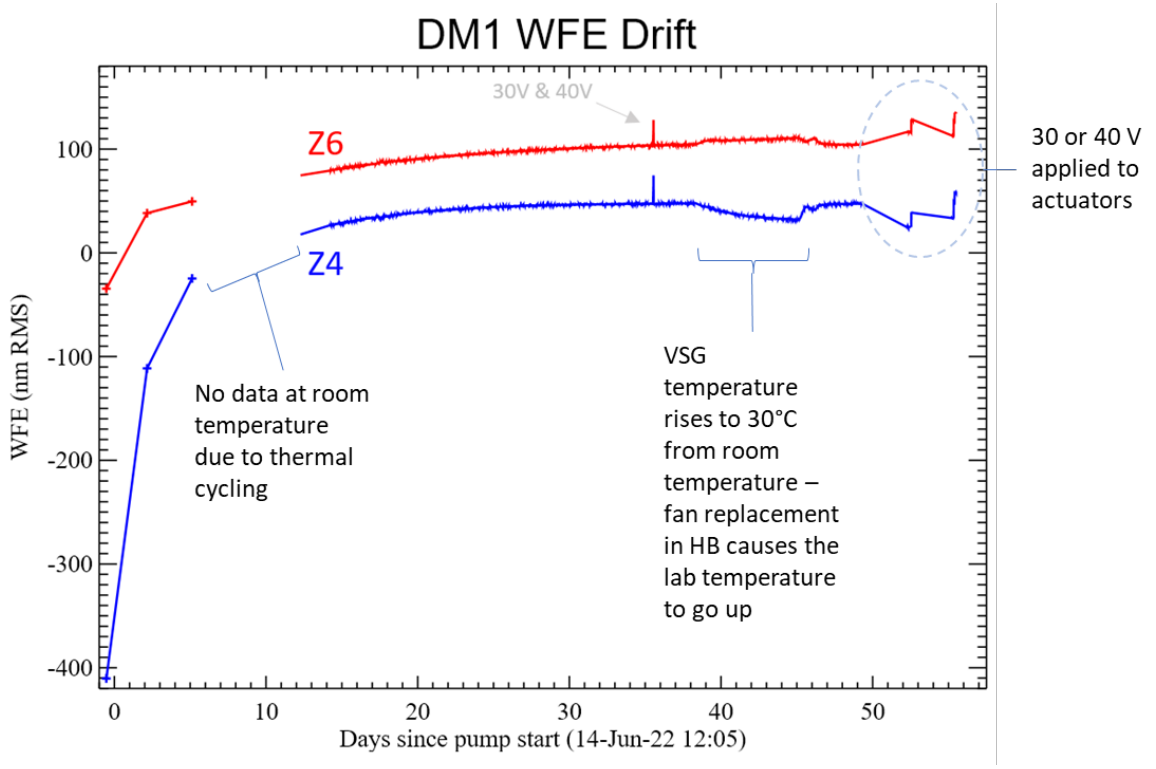


***DM02 flat data from a difference of two surfaces measured at average bezel temperatures of 10.0C and 15.0C**

Desiccation Drift
(Flatness: Z4 & Temporal Stability - Z4-Z11)

- Timescale for desiccation was painful for CGI system TVAC, but should not pose problems during/after on-orbit commissioning simply due to time gap before CGI is operational.

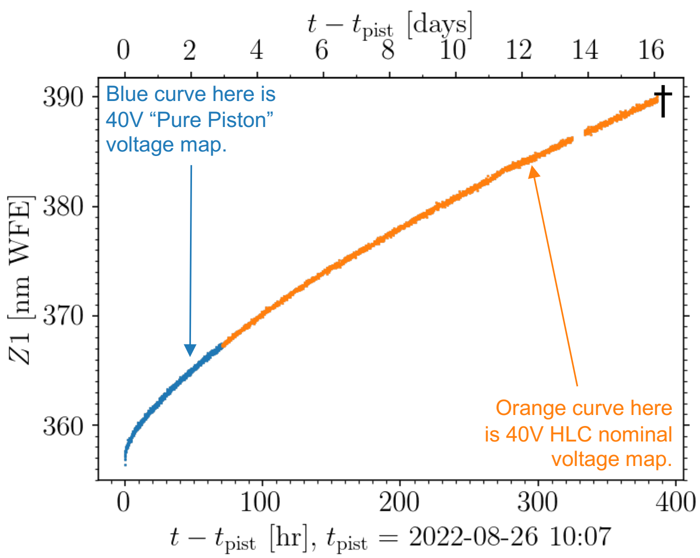
DM01 dryout data is fairly sparse at beginning as drift issue was discovered after other data collection (gain maps, etc.) was completed and those tests confounded the bulk of the early drift behavior.

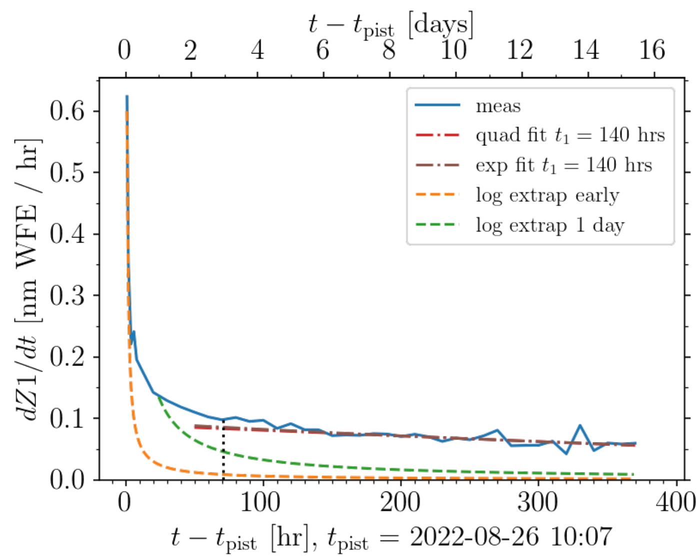


Long Timescale Control Surface Drift

- Longer-term drift characterization with mean-40V control maps gives insight into drift behavior of CGI DMs under applied voltages.

This plot of referenced DM01 piston does not display expected log-drift behavior.



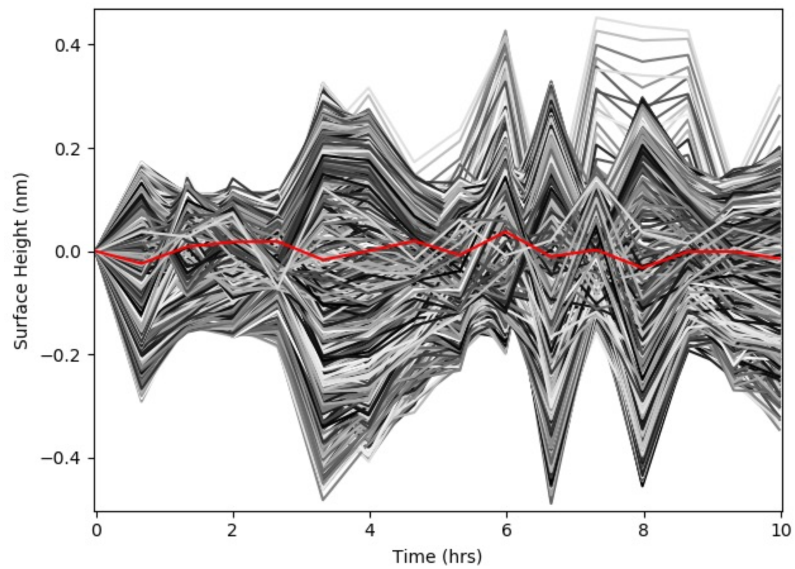


Derivative plot reinforces piston behavior is not close to any extrapolated logarithmic behavior.

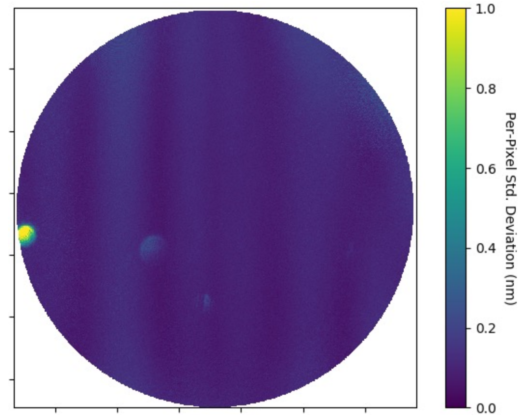
***All these analyses c/o Brian Kern (7/8/2022)**
†Also published in John E. Krist, et. al., "End-to-end numerical modeling of the Roman Space Telescope coronagraph," J. Astron. Telesc. Instrum. Syst. 9(4) 045002 (11 October 2023) https://doi.org/10.1117/1.JATIS.9.4.045002

Testing Venue Precision

- Improvements to VSG are required to adequately test HWO DMs.
  - Data per-pixel or per-actuator (IE all resolvable spatial frequencies) in VSG2

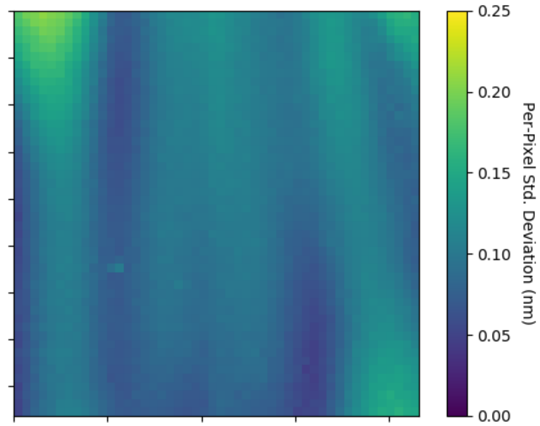


(Above) "Actuator" surface heights of a 2" flat tracked over a series of measurement sets, each set a 5-measurement average. Each greyscale curve is the surface height of a specific 10x10 pixel region. Red curve is the average for each measurement.



***Data here are standard deviations in surface height taken from a 10-hour stability test with a sampling rate of 1 set of 5 averaged surfaces every 30 minutes**

Mean precision across all pixels: 110pm



Mean precision across spatially-averaged "actuators": 98pm

Testing Venue Precision

- Improvements to VSG are required to adequately test HWO DMs.
  - Data for low-order spatial frequencies (Z4-Z11) in VSG2

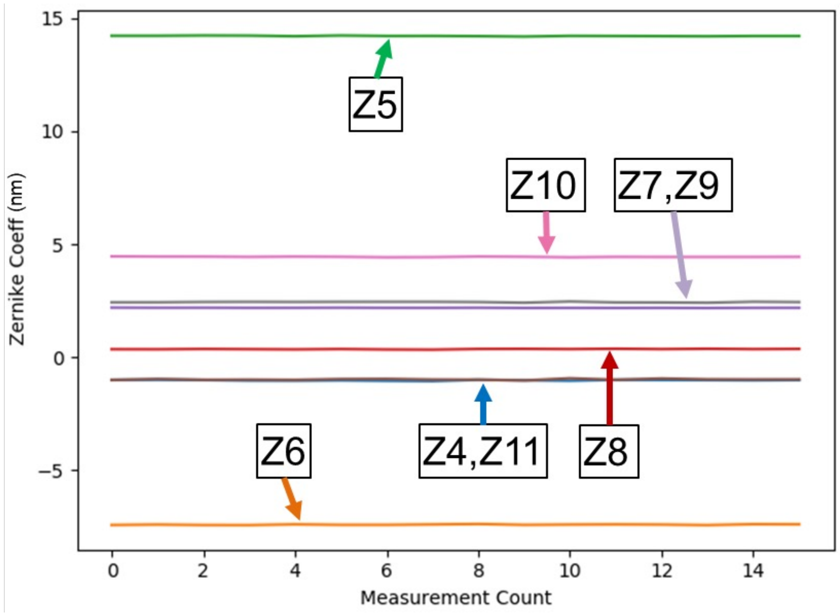
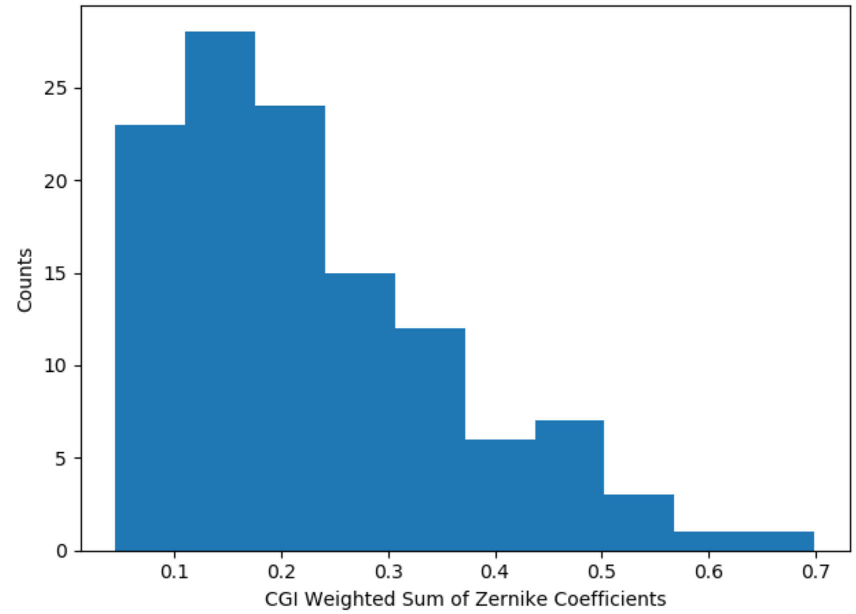


Table 338478: Weights defining weighted sum, $S = (\Sigma_i \Delta Z_i^2 w_i)^{1/2}$ for $i = 4$ to 11

	Zernike weight							
Noll index	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11
w_i	1	0.4	0.4	10	10	4	4	50

Histogram of CGI weighted-sum results across temporally-averaged measurement sets in a 10-hour data collection

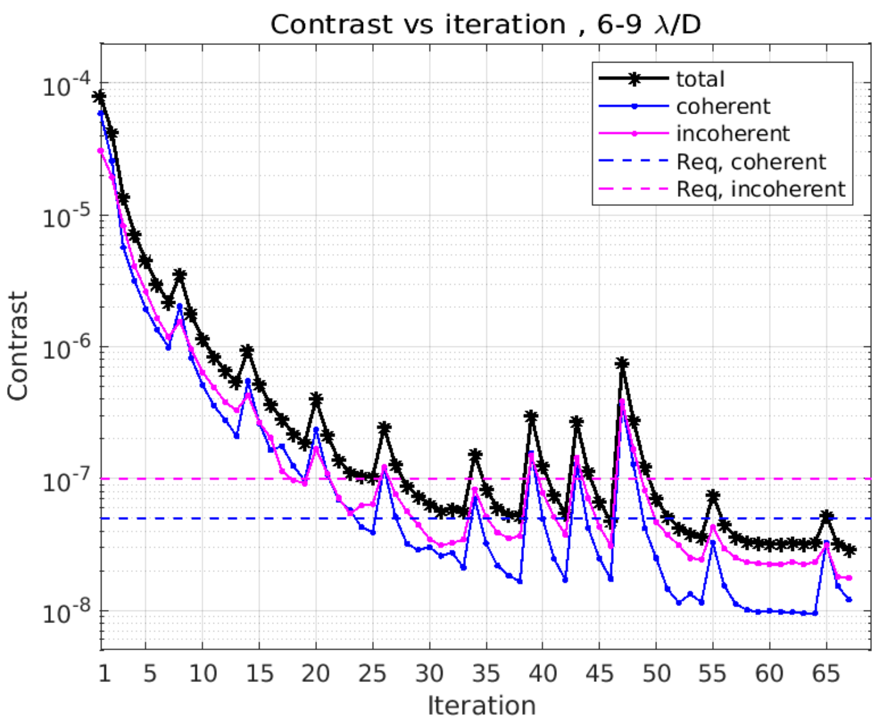


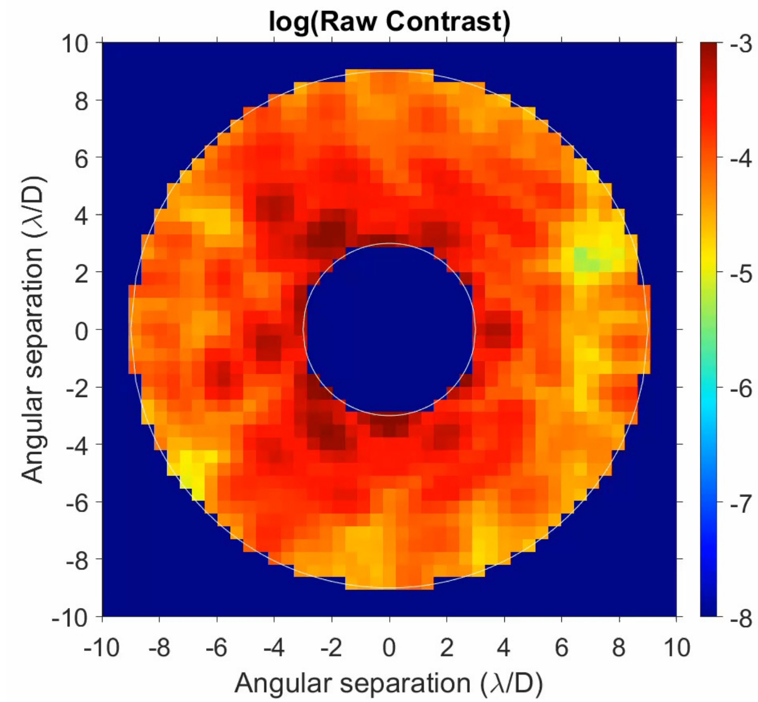
DM PERFORMANCE DURING CGI TVAC

(Just in case people want to see things)

CGI Demonstrated Raw Contrast

- Hybrid-Lyot Coronagraphy Mode demonstration during CGI TVAC (<u>3.3×10^{-8}</u> @ 6-9 λ/D).

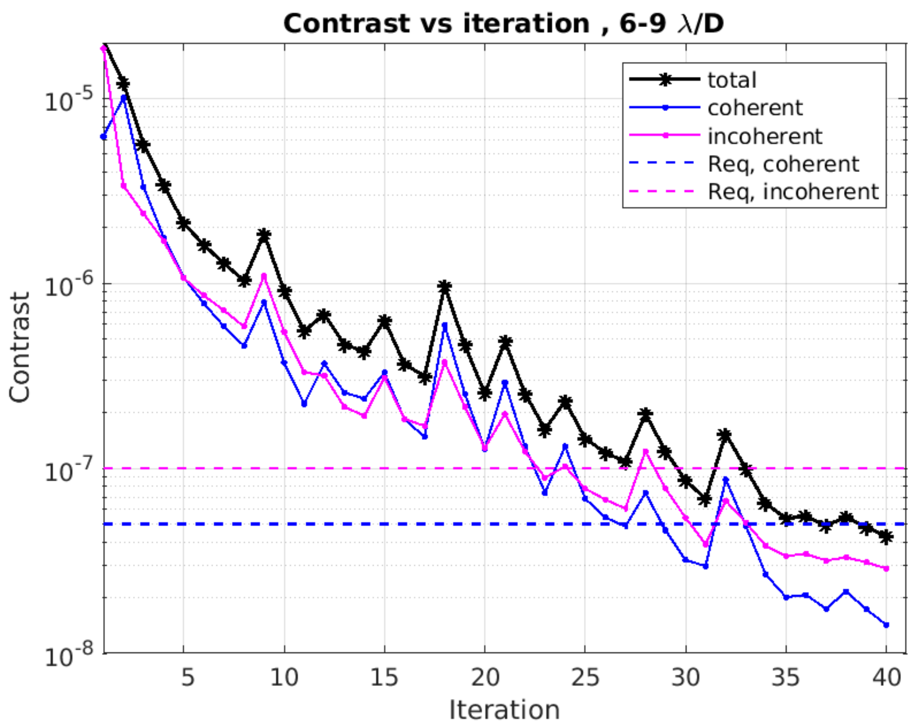


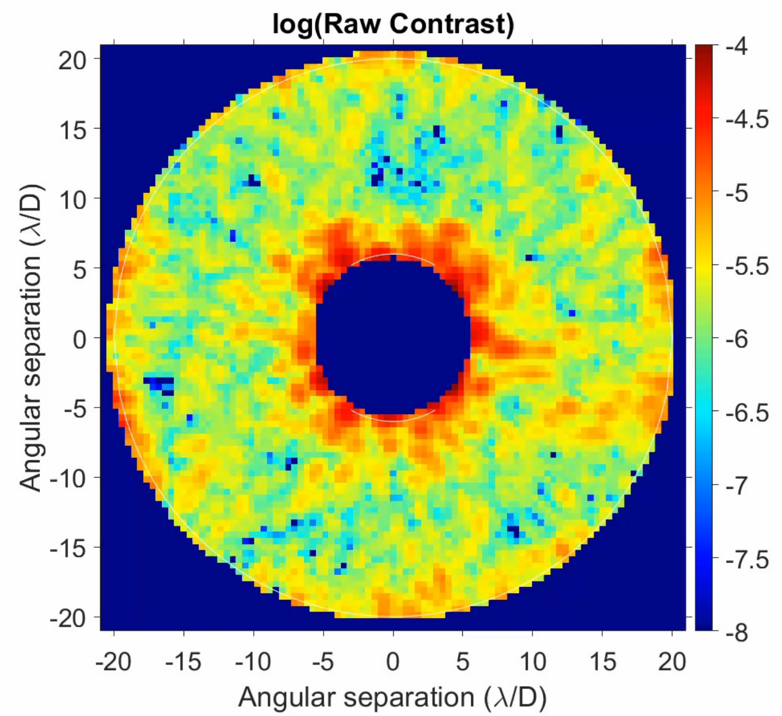


*Data c/o Ilya Poberezhskiy, Matt Smith, and the rest of CGI PSE. Taken from CGI Pre-Ship Review (5/2/2024)

CGI Demonstrated Raw Contrast

- Shaped Pupil Coronagraphy Mode demonstration during CGI TVAC (4.3x10^{-8} @ 6-9 λ/D).



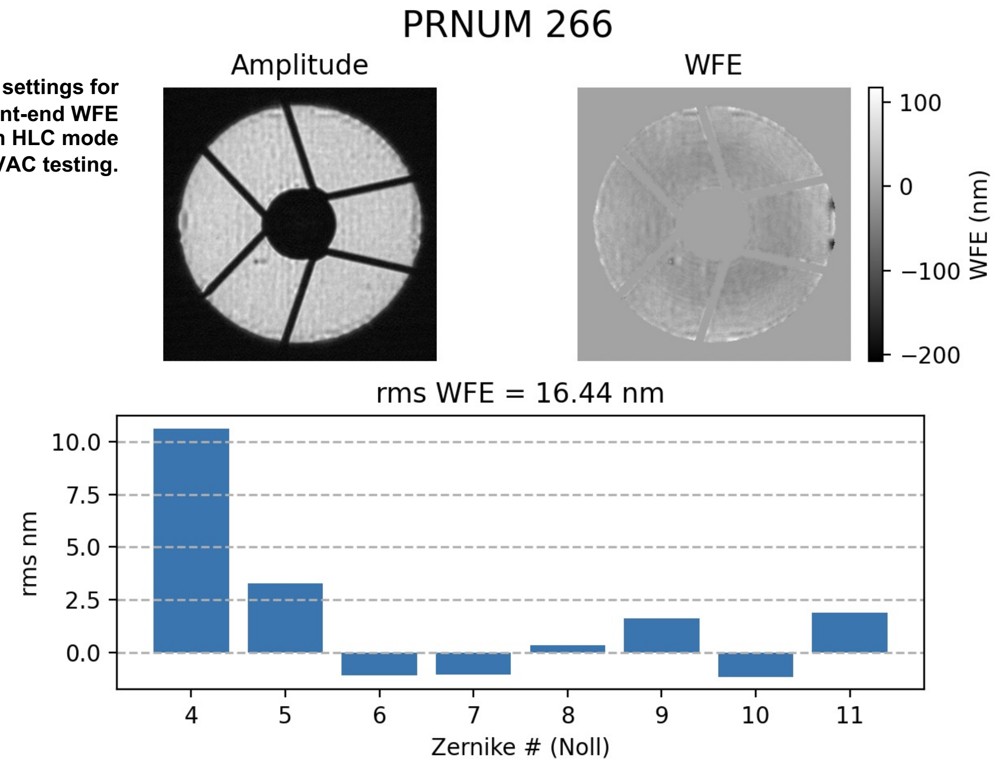


*Data c/o Ilya Poberezhskiy, Matt Smith, and the rest of CGI PSE. Taken from CGI Pre-Ship Review (5/2/2024)

CGI Wavefront Flattening

- DMs were able to acceptably flatten CGI front-end WFE during TVAC.

Result of final DM settings for flattening CGI front-end WFE entering HOWFSC in HLC mode during CGI TVAC testing.



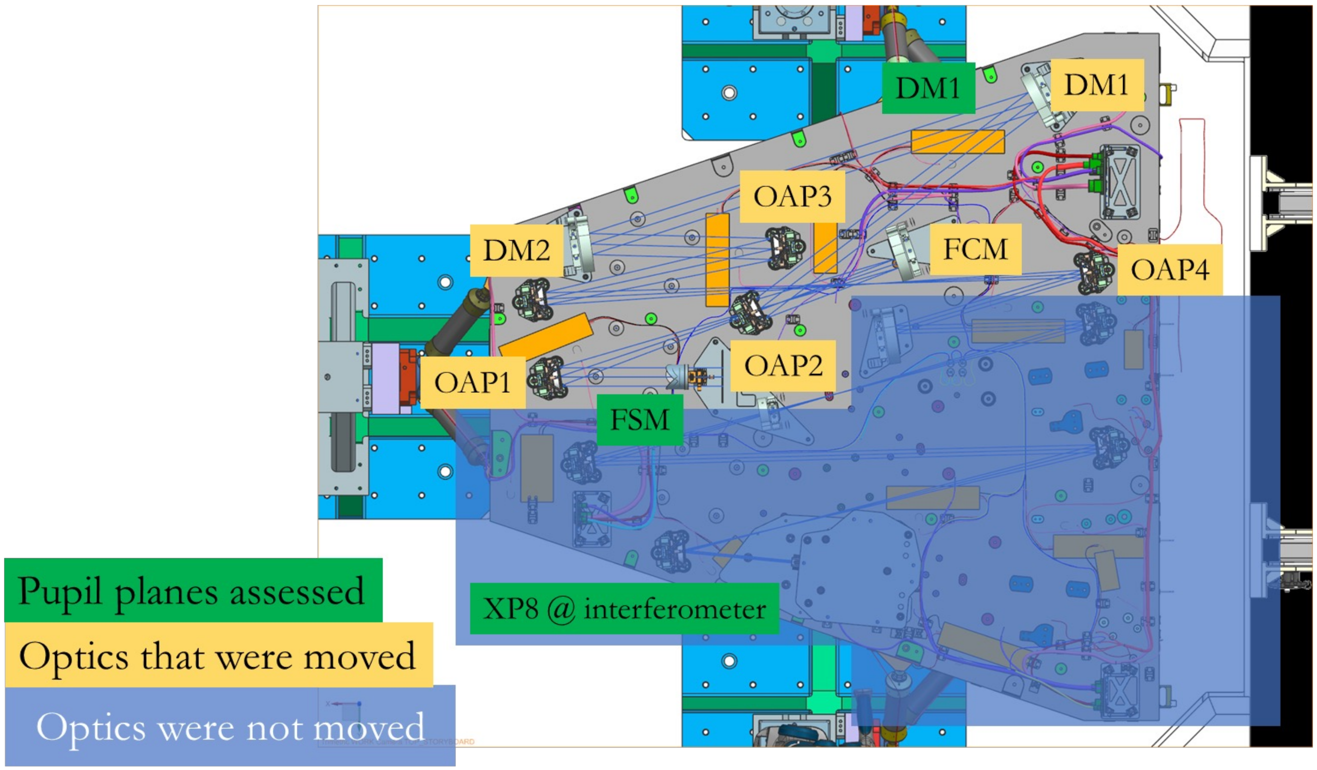
Per comment by AJ Riggs:

- End-to-end WFE at flat setting was perfectly fine for HLC, which throws a large amount of WFE into the system anyway.
- SPC would ideally have flatter wavefront at the beginning of HOWFSC iterations.
  - Initial flattening not the main limitation to SPC during CGI TVAC, but likely did slow down SPC iterations.

***Data c/o AJ Riggs & CGI PSE (7/19/2024)**

CGI Mitigations for Desiccation Drift

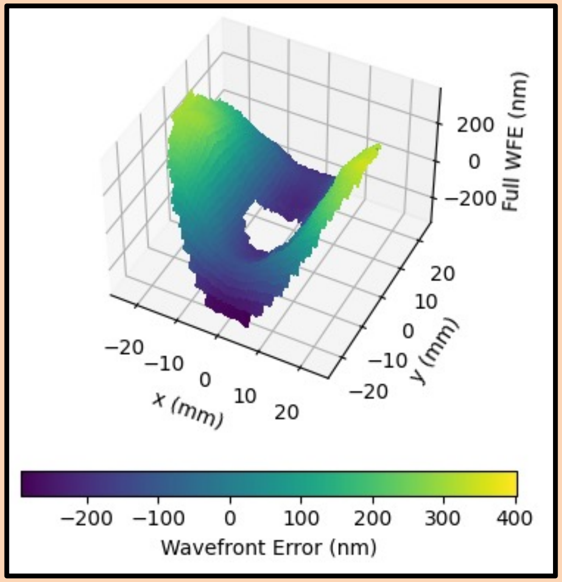
- Moisture desiccation drift is cylindrical, which is chiefly focus (Z4) and vertical astigmatism (Z6).
  - This means intentionally misaligning one of CGI's OAP pairs can introduce opposite-sign Z4 and Z6 to compensate.



*Slide c/o Brian Monacelli & Jordan Rupp (2/16/2023)

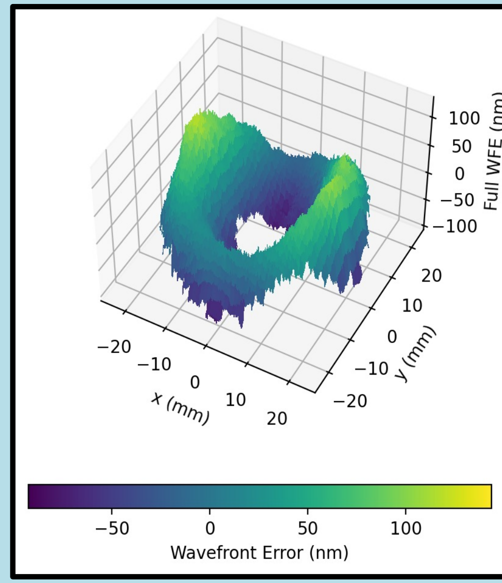
CGI Mitigations for Desiccation Drift

Prior to Correction



	WFE (nm RMS)
Z4	69.52 (+polarity)
Z6	151.02 (+polarity)
Total	**167.43**

After Correction



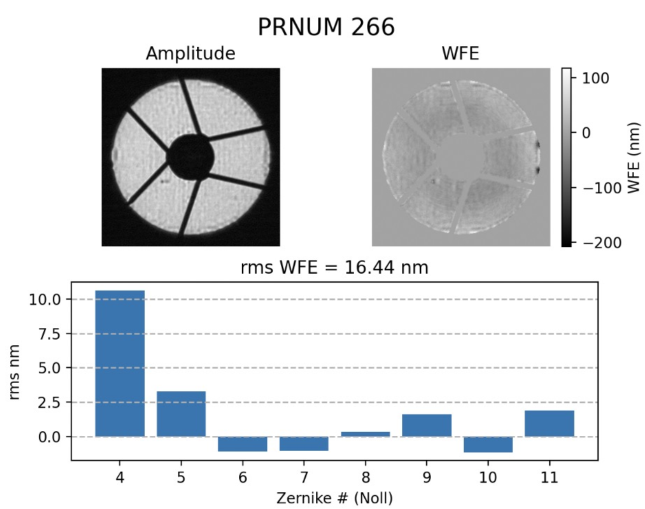
	WFE (nm RMS)
Z4	15.98 (+polarity)
Z6	19.96 (+polarity)
Total	**46.02**

This recovery in stroke budget took us from railing 30-40 actuators in HLC mode after flattening the DMs (potentially threatening to TTR5) to having ample margin against railing actuators and expecting 10^{-9} raw contrast levels.

CGI Mitigations for Desiccation Drift

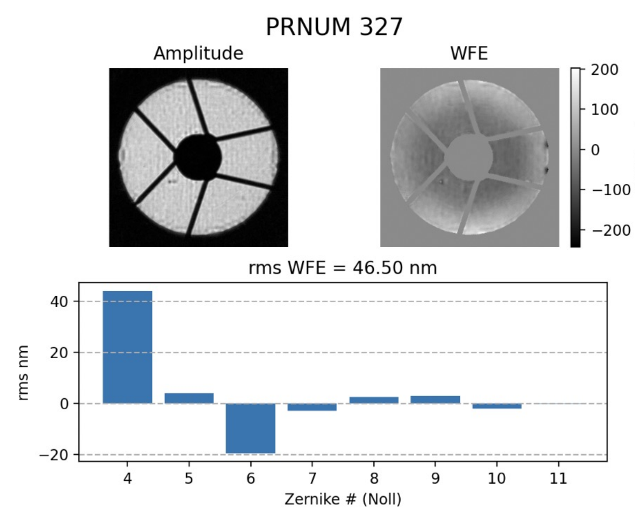
- Moisture drift also prompted a painstaking operational constraint during CGI FFT and TVAC.
  – DMs had to be maintained under constant nitrogen purge to prevent long wait times for stabilization during FFT and TVAC.
    - This significantly complicated logistics for CGI system environment testing (EMI/EMC and Random Vibration, specifically), as the purge needed to travel with the system to other JPL testing venues.

  – Residual dryout drift was still detected during system TVAC.



(Left) Phase Retrieval 266 (3/15/2024)

(Right) Phase Retrieval 327 (4/8/2024)



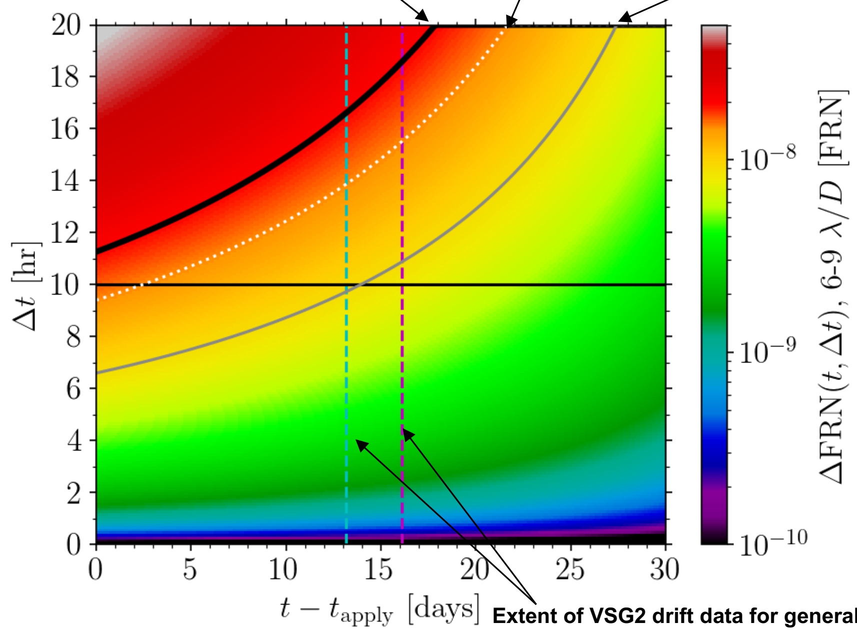
***Data c/o AJ Riggs & CGI PSE (7/19/2024)**

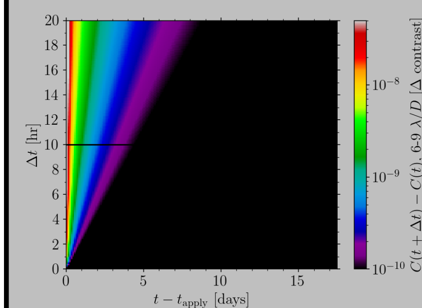
CGI Contrast Stability

- Contrast stability was deprecated from test to analysis for TVAC; a small window of contrast stability data was taken, but assessment is still pending.
  - However, we ***do*** have extrapolations from DM stand alone testing data using FRN budget analysis.

There ***are*** caveats here, per comment by Brian K.:

- FRN math is applied conservatively
- It is unknown if DM1 and DM2 have correlated drifts or not.
  - Correlated drifts would reduce effect by factor of ~2-4x
  - Non-correlated drifts could exacerbate effect by factor of ~7-15x
- Extrapolations past extent of VSG2 drift data (purple dashed line) are likely inaccurate.





Example plot (w/o FRN) from comparisons to log-drift expectations based on 0.48%/decade VSG1 measurements.

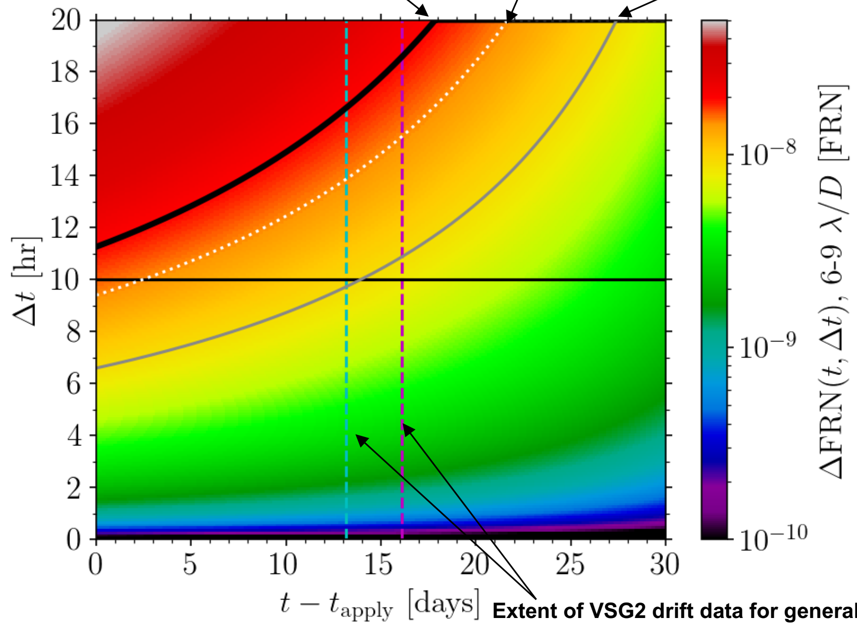
***Analysis data here c/o Brian Kern (9/20/2022)**

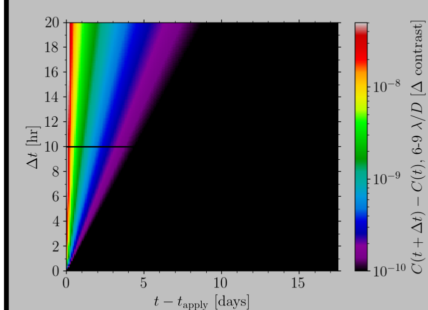
CGI Contrast Stability

- Contrast stability was deprecated from test to analysis for TVAC; a small window of contrast stability data was taken, but assessment is still pending.
  - However, we ***do*** have extrapolations from DM stand alone testing data using FRN budget analysis.

Even accounting for those caveats, though, this result rendered significant changes to CGI Con Ops:

- DM control maps applied prior to (and held through) WFI operations.
- Constraint introduced to set DMs at bias 5 days prior to observations, recommended holds of up to 15 days for best science data.
- CGI Fault Protection re-architected to avoid shutting DME off unless absolutely necessary.
- Testing stability immediately unfeasible in TVAC; CGI Contrast Stability deprecated from test to analysis





Example plot (w/o FRN) from comparisons to log-drift expectations based on 0.48%/decade VSG1 measurements.

*Analysis data here c/o Brian Kern (9/20/2022)