State of the Art in MEMS Deformable Mirrors

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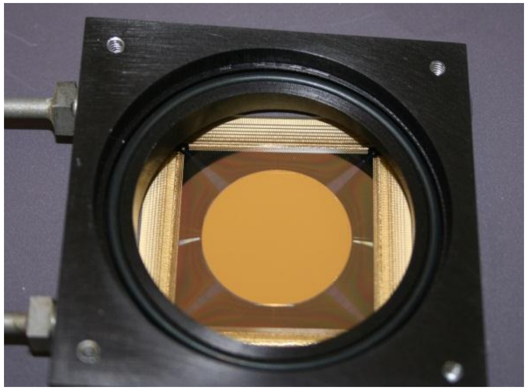
Mirror Technology Days
November 19, 2014
Albuquerque, NM

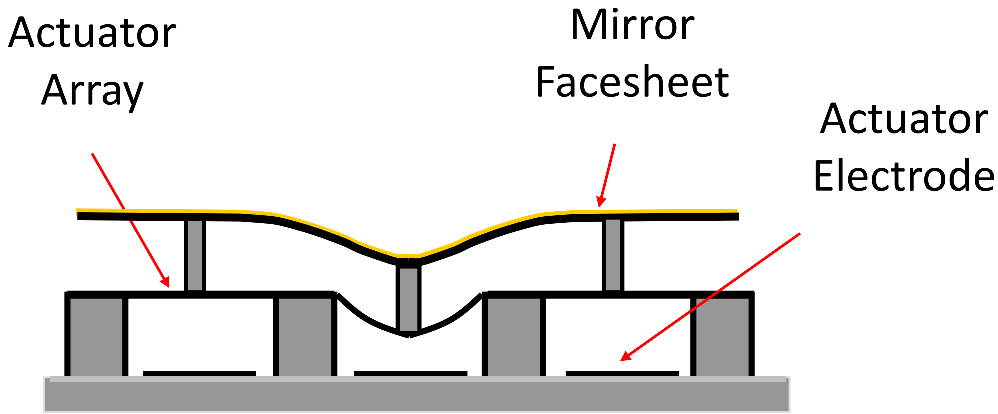
Outline

- Testing of current mirror technology for space applications
- Improving current mirror technology for high contrast imaging applications
- New advancements in MEMS mirrors
- BMC mirrors in the field

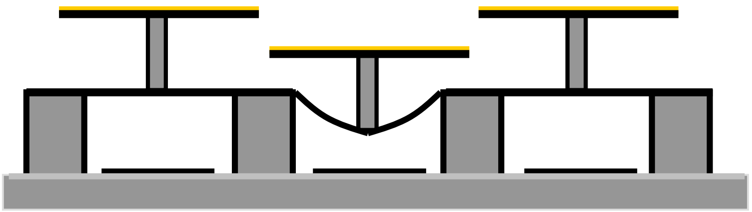


2040 Actuator (2K) Continuous Facesheet DM

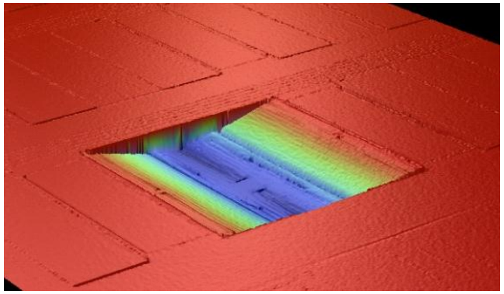
MEMS DM Architecture



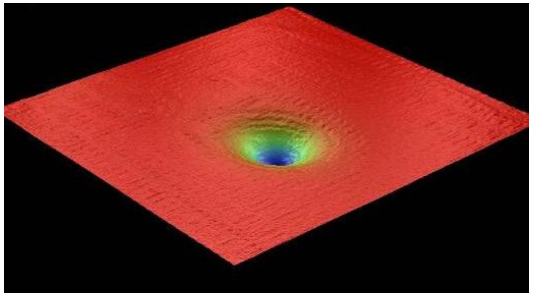
Continuous mirror
(smooth phase control)



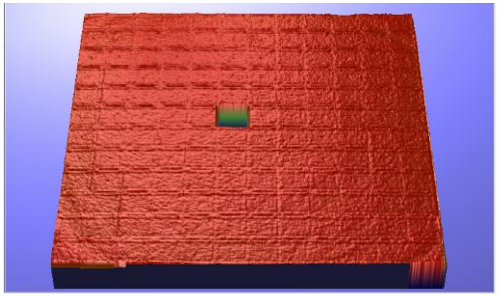
Segmented mirror
(uncoupled control)



Deflected Actuator



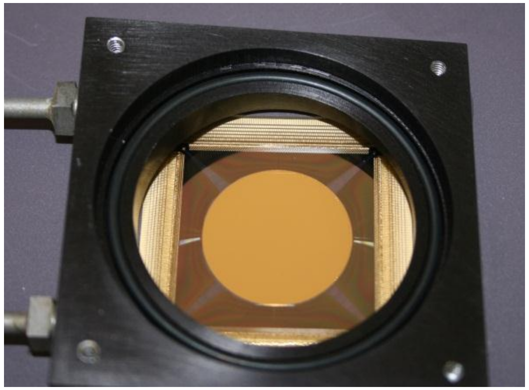
Deformed Mirror Membrane



Deformed Segmented Mirror

Outline

- Testing of current mirror technology for space applications



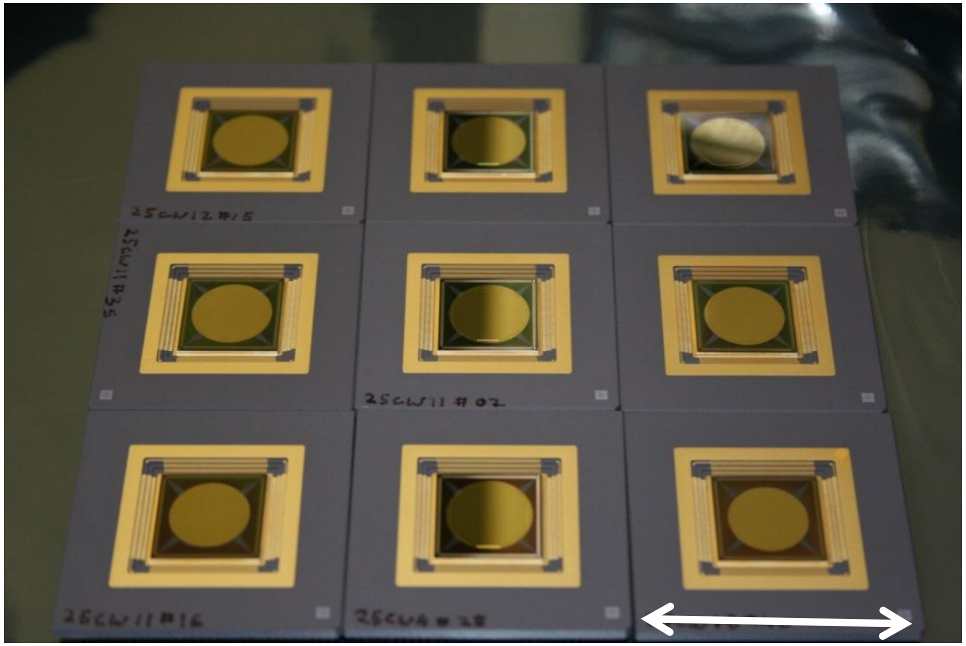
- Improving current mirror for high contrast imaging applications
- New advancements in MEMS mirrors
- BMC mirrors in the field

Testing current mirrors

Contract#: NNH12CQ27C
TDEM/ROSES
MEMS Deformable Mirror Technology Development for Space-Based Exoplanet Detection

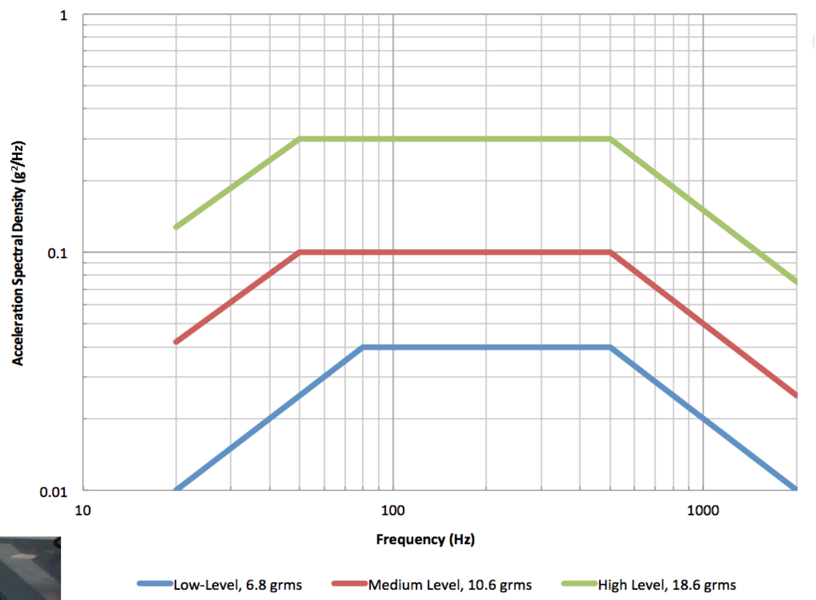
Objective: Demonstrate survivability of the BMC MEMS Deformable Mirror after exposure to dynamic mechanical environments close to those expected in space based coronagraph launch.

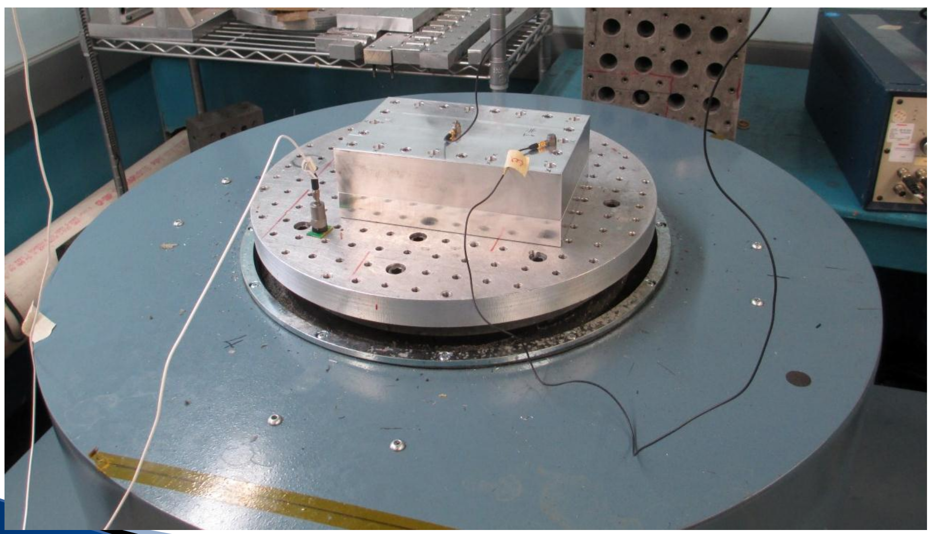
9 Mirrors ready for testing

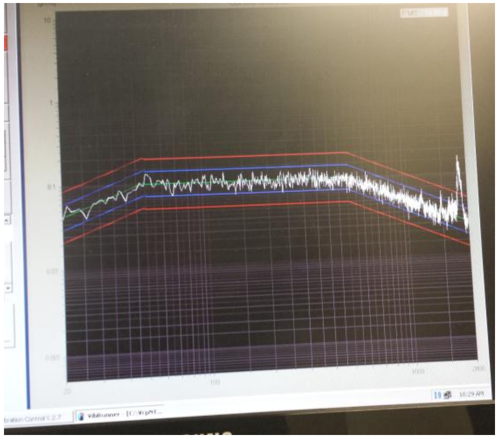


Exploratory Vibration Testing

Low, medium and high levels tested on test sample in X, Y, and Z





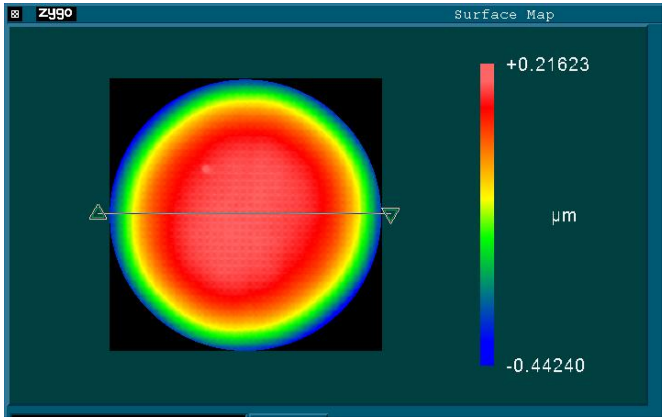


Exploratory Vibration Testing

- Visual testing after Low Level
- Visual and Functional testing after Medium and High level

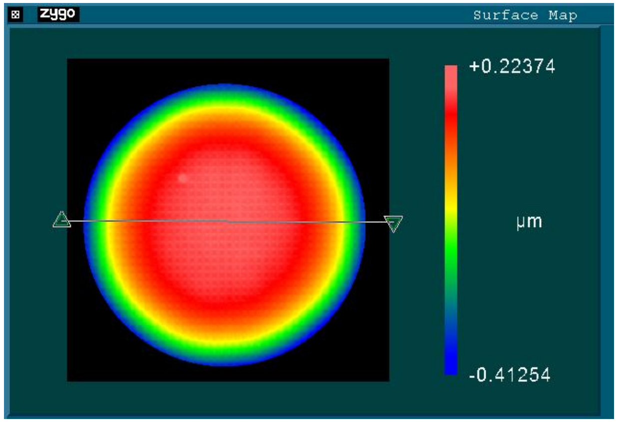
- All die attach and wirebonds held
- No change in unpowered and powered surface finish
- No change in electromechanical performance (yield and voltage v. deflection)

Before



PV = 0.659 µm
RMS = 0.163 µm

After



PV = 0.636 µm
RMS = 0.162 µm

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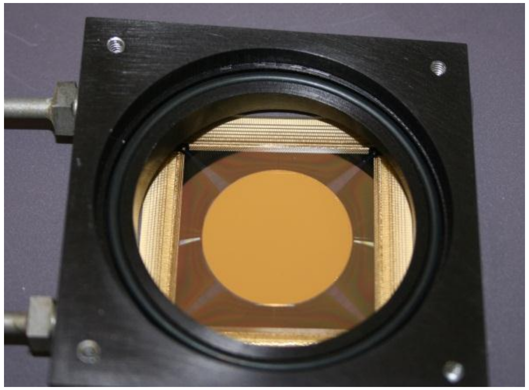
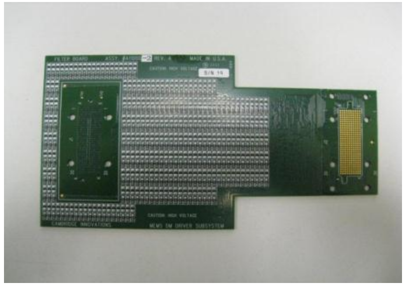


Enhanced Reliability

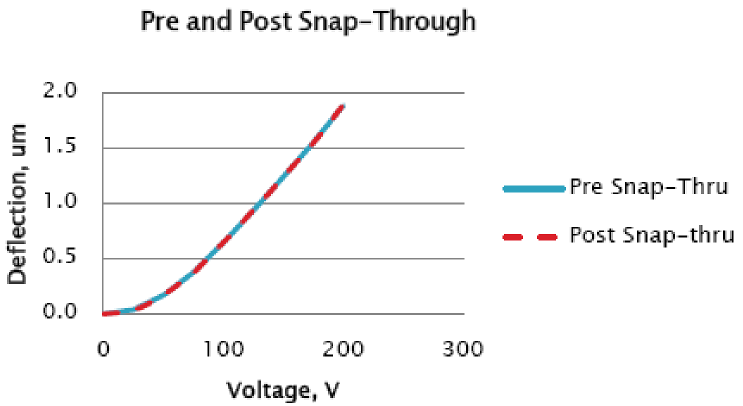
Contract #: NNX12CA50C

NASA Phase II SBIR

Enhanced Reliability MEMS Deformable Mirrors for Space Imaging Applications

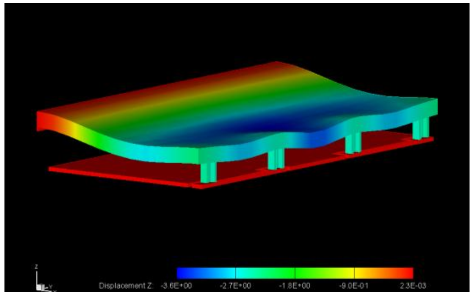


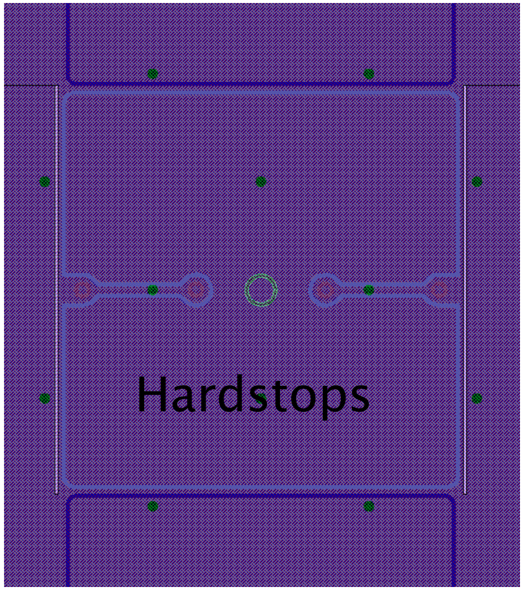
Objective: Demonstrate the ability to prevent single point failures resulting from electrical overstress caused by electronic or software faults that may occur during ground test or space-based operation

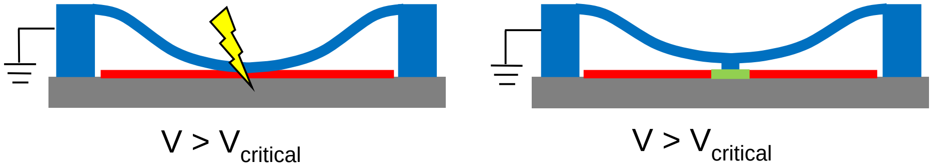


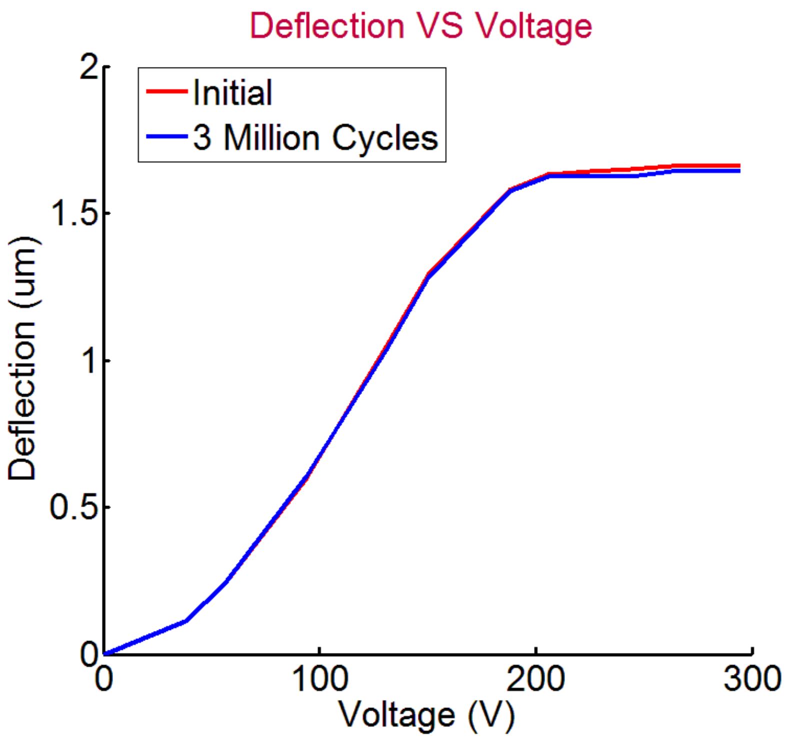
Reliability with Hard Stops

Enhanced Reliability
Actuator Design









Deflection versus voltage. Initial, after cycling 3 million times above critical voltage (295V).

Topography Improvements

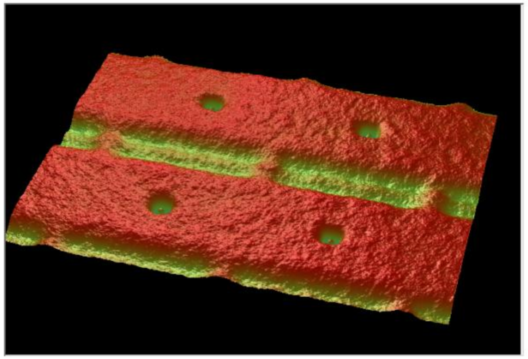
Contract#: NNX13CP03C

SBIR Phase II

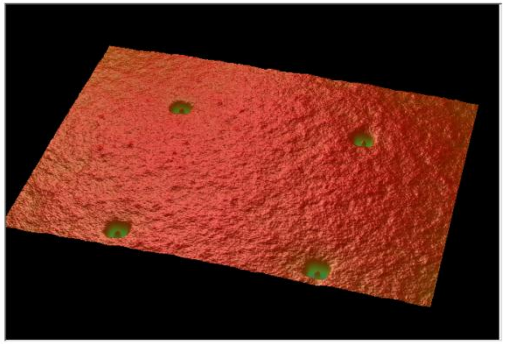
Topography Improvements in MEMS DMs for High-contrast, High-resolution Imaging

Objective: To develop a MEMS deformable mirror with reduce surface figure errors resulting from actuator "print-through" topography and stress-induced mirror scallop topography.

Heritage Anneal

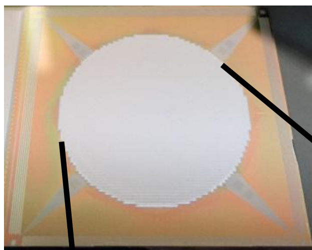


Modified Annealing Process



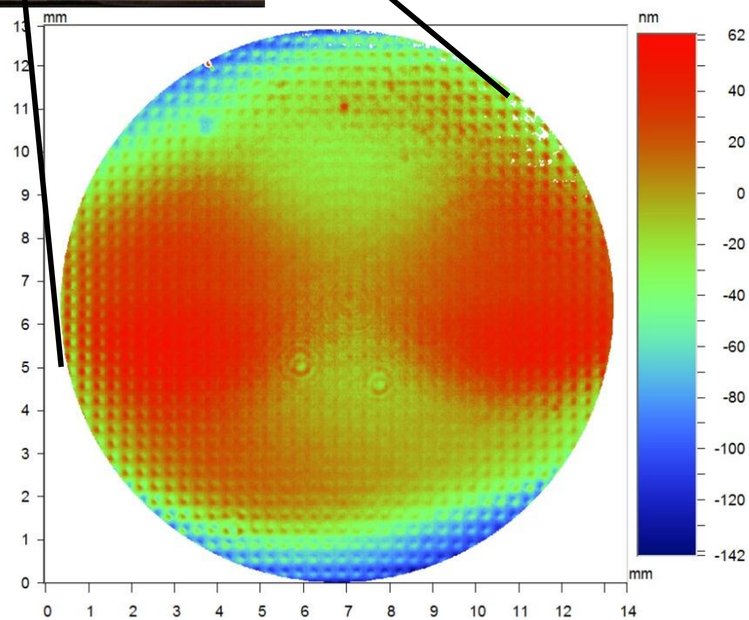
Topography Improvements

3064 Element Device



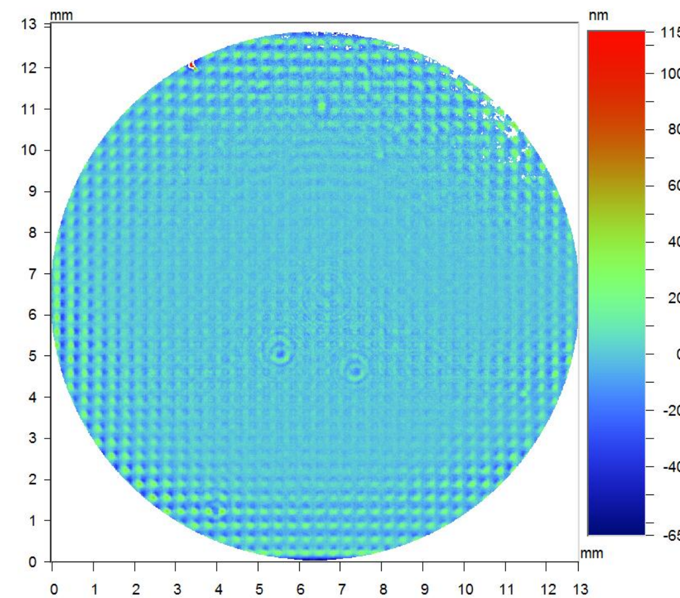
Modified annealing process results in unpowered full aperture surface figure λ/20

RMS = 30nm



Unpowered Surface

RMS = 6nm

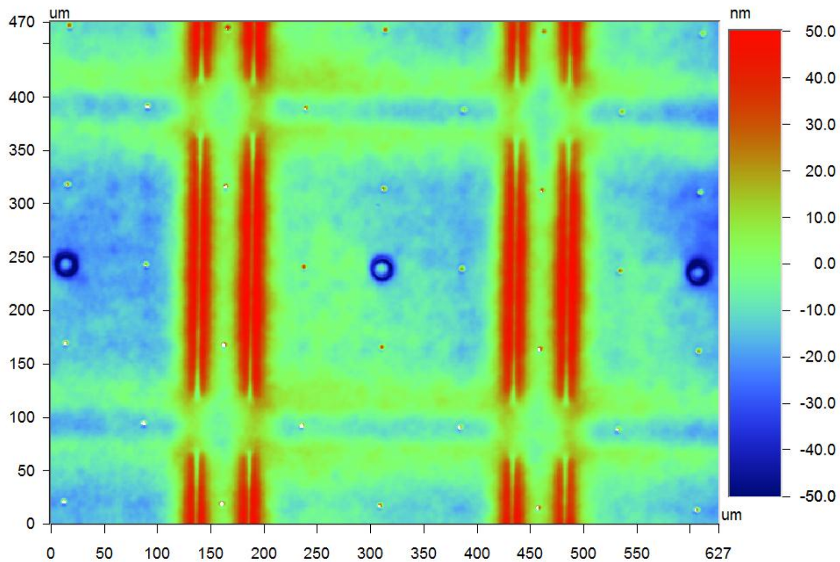


Flatness Outside Active Control Band

Topography Improvements

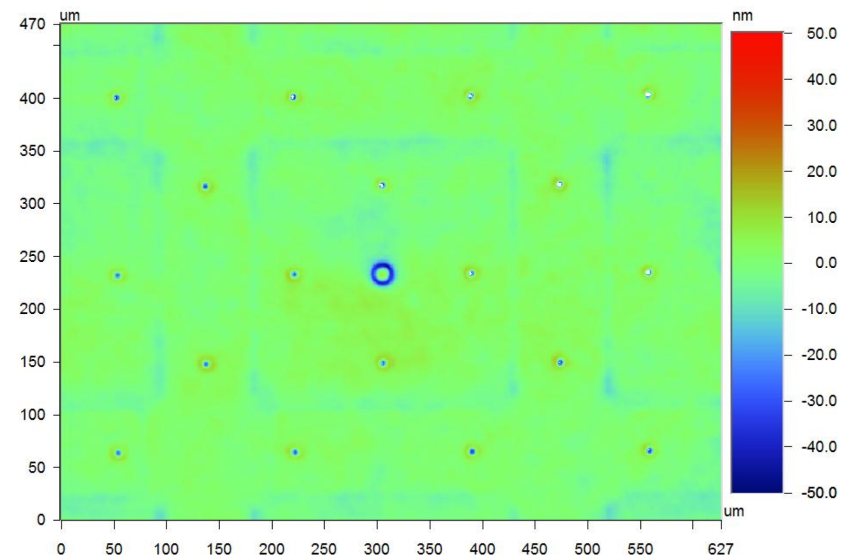
Single actuator surface figure improvement

RMS 13 nm



BMC's Heritage Anneal

RMS 2.5 nm



BMC's new modified Anneal

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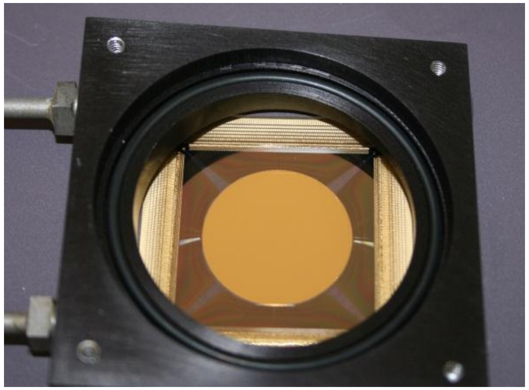


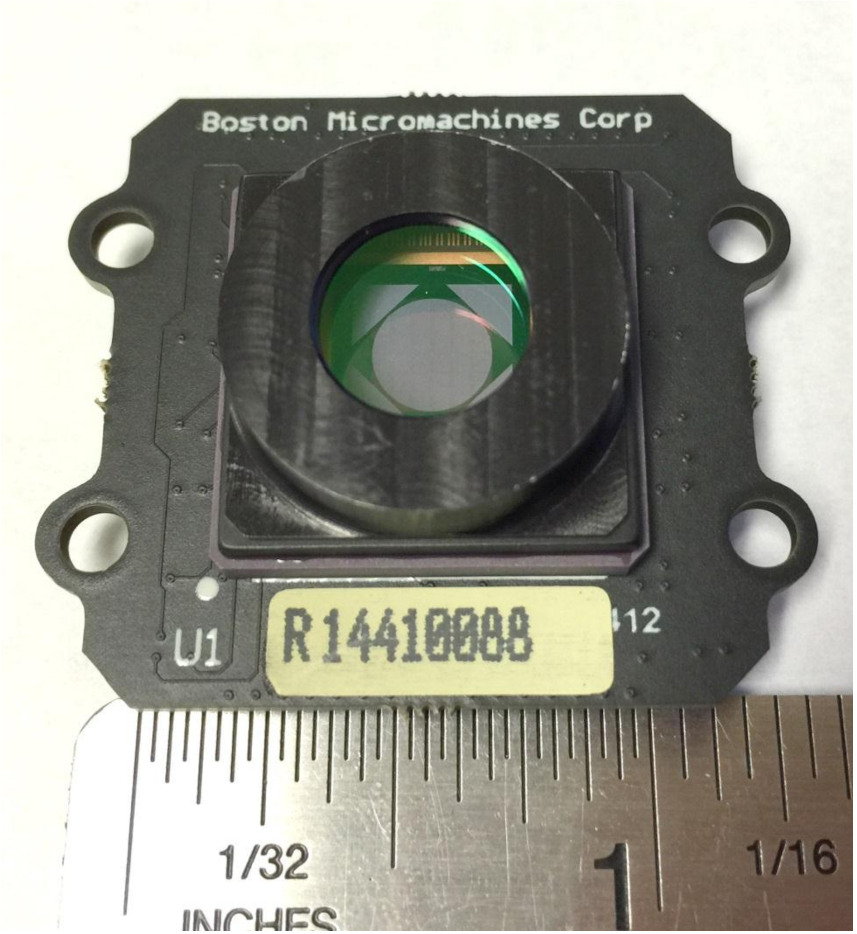
New Advancements in MEMS Mirrors

Contract#: NNH13CH37C

APRA/ROSES

Large Aperture DMs for Space-Based Observatories

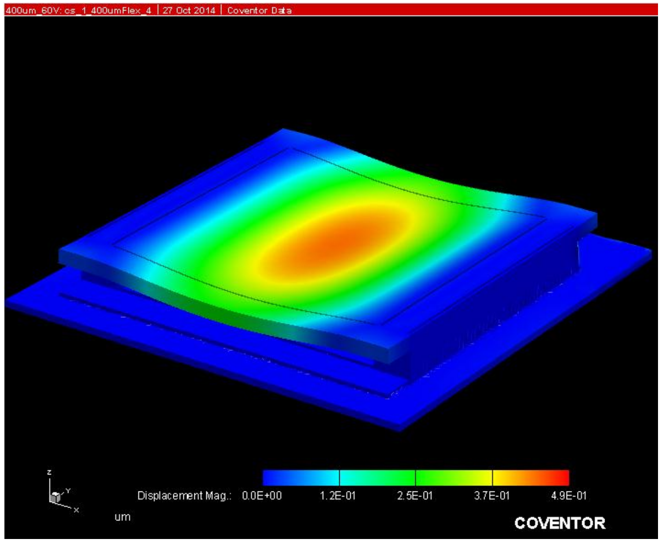
Objective: Demonstrate feasibility of manufacturing large actuator pitch MEMS DMs to improve optical performance in space-based telescopes



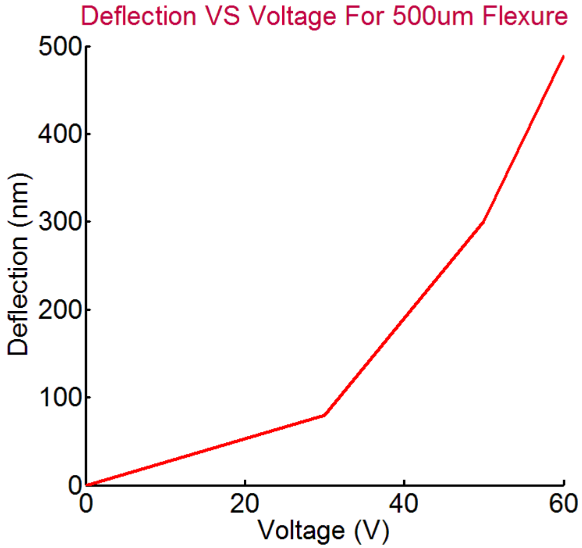
1mm pitch 6mm aperture mirror

New Advancements in MEMS Mirrors

Finite Element Modeling of New Actuator Design



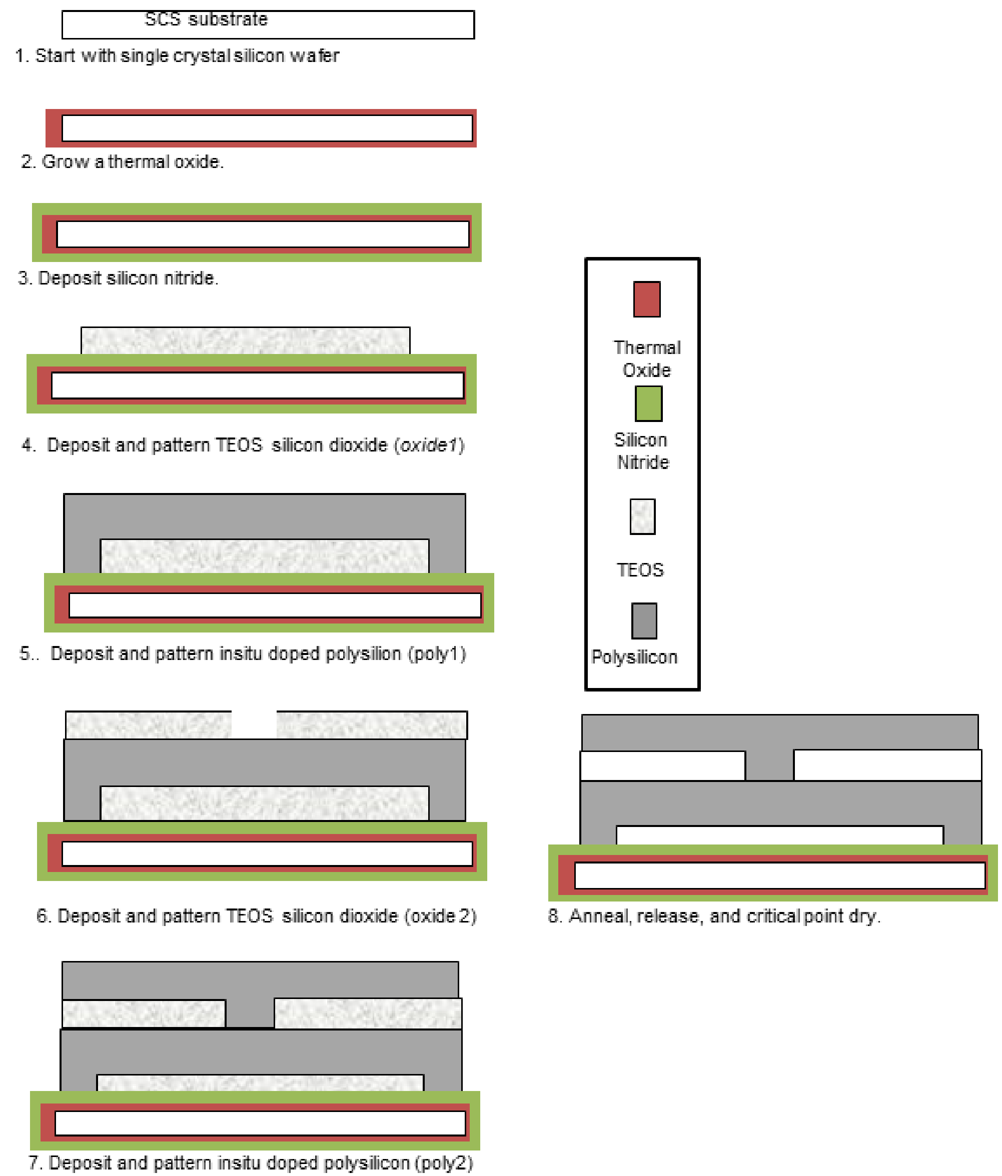
500 um Finite Element Analysis Model



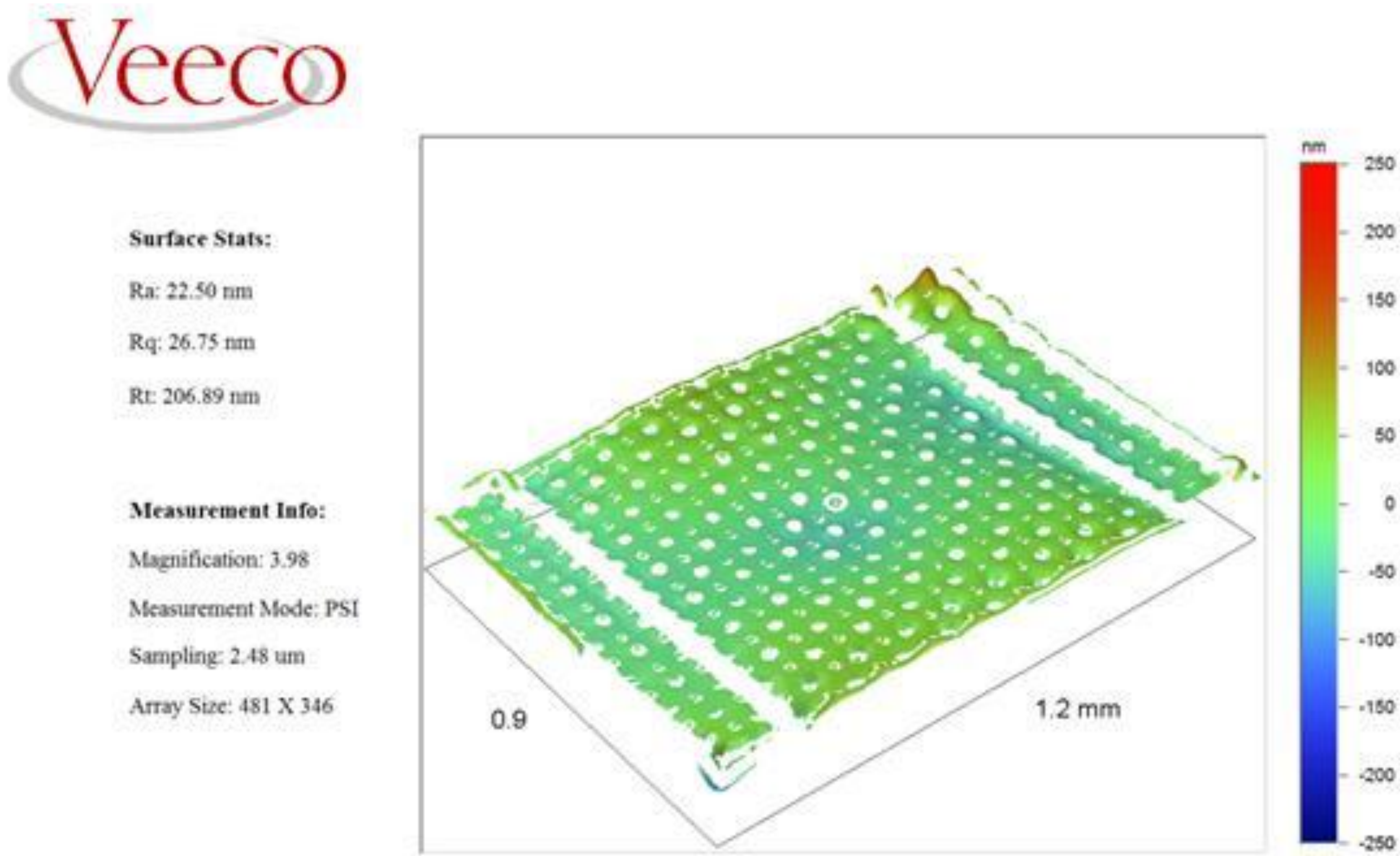
Voltage Deflection Results of the Model

New Advancements in MEMS Mirrors

New Fabrication Process

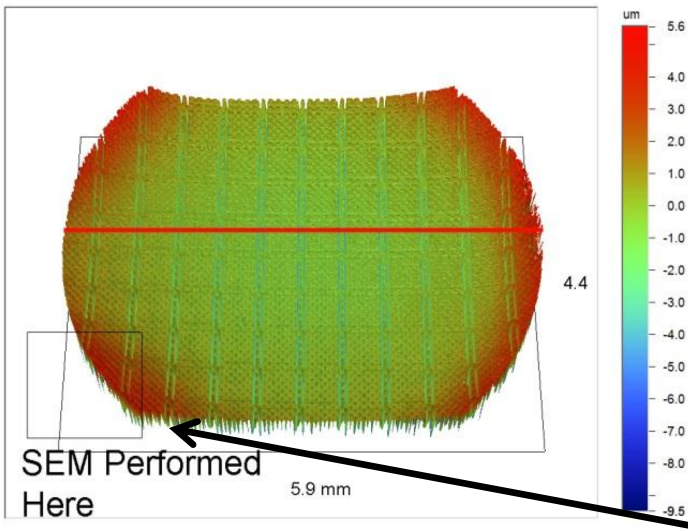


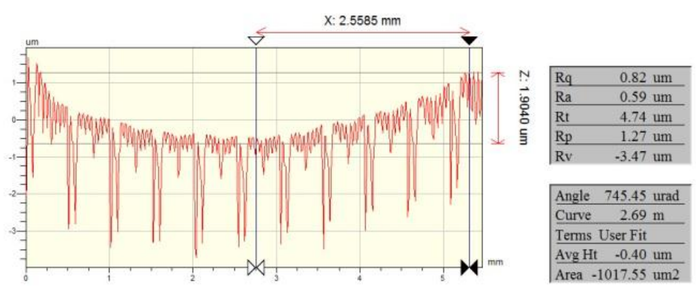
New Advancements in MEMS Mirrors



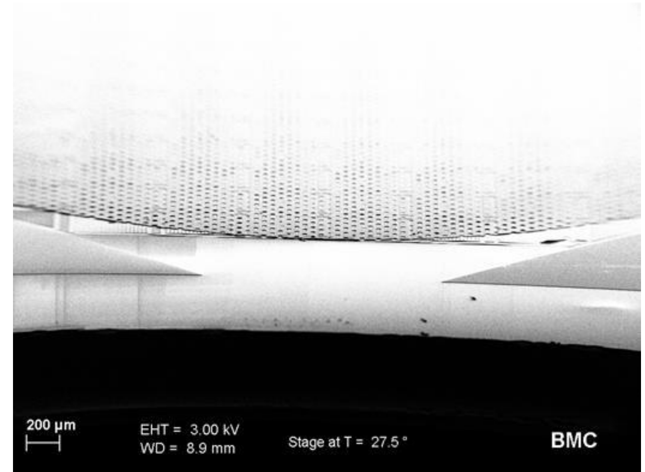
1mm Pitch MEMS Mirror Element

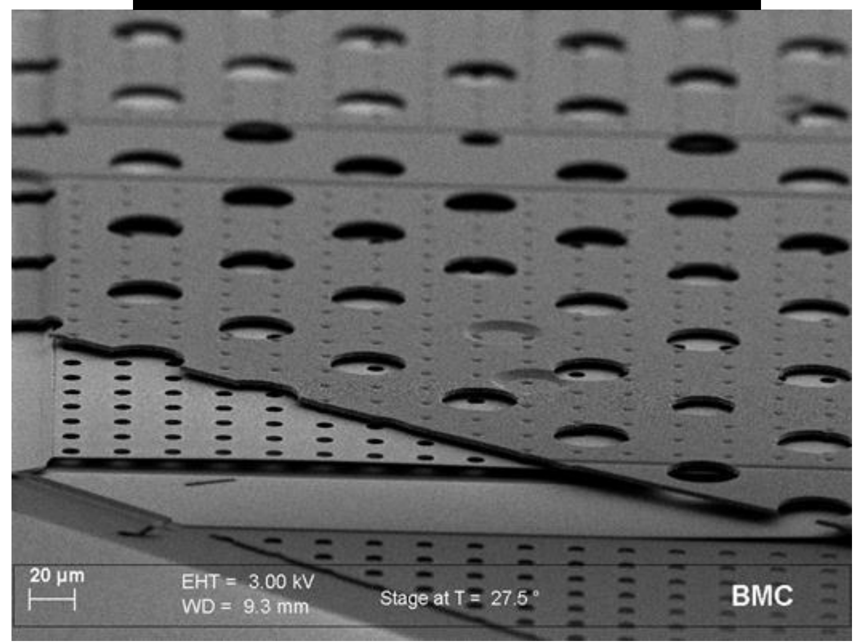
New Advancements in MEMS Mirrors





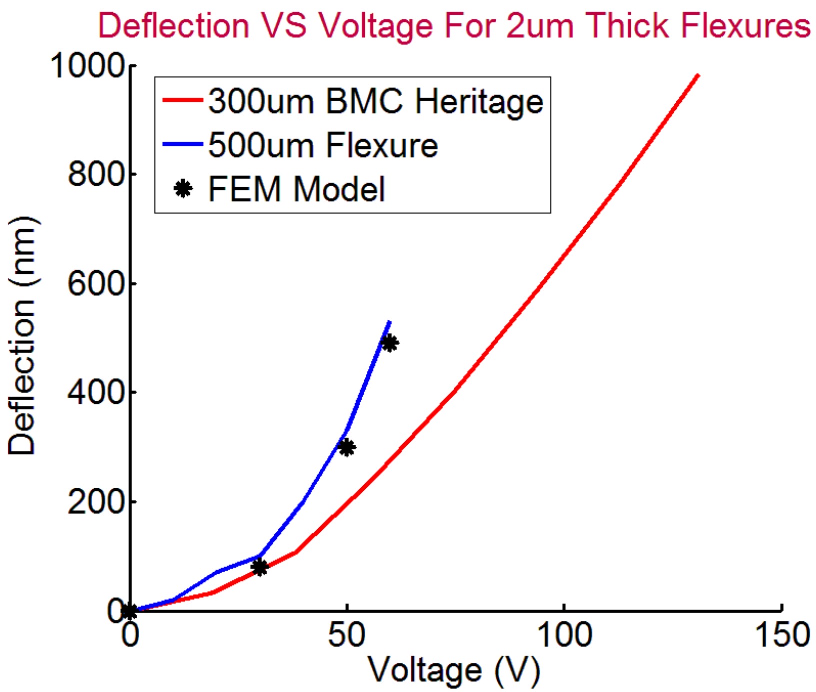
500um Pitch MEMS Mirror Facesheet



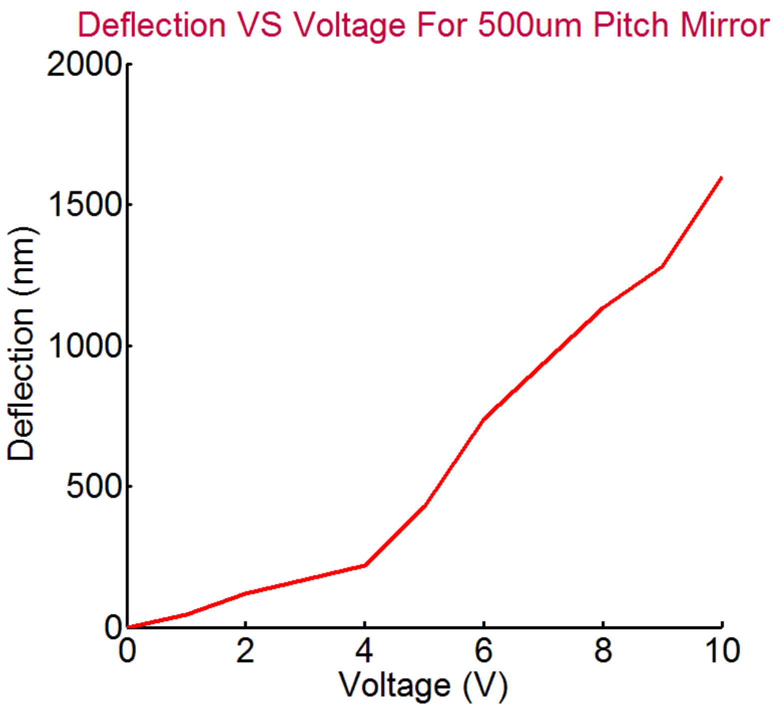


SEM taken at ~70 Degrees

New Advancements in MEMS Mirrors



Voltage Deflection Characteristics For 2 um Thick Flexures



Voltage Deflection Characteristics For 0.5 um Thick Flexures

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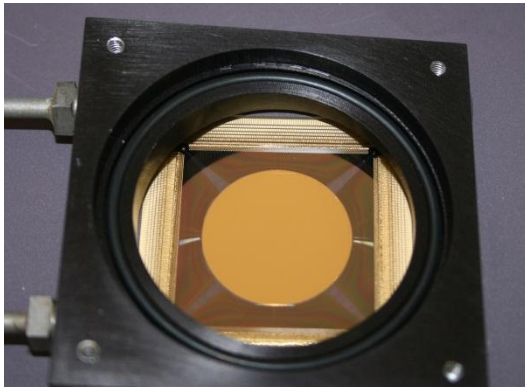
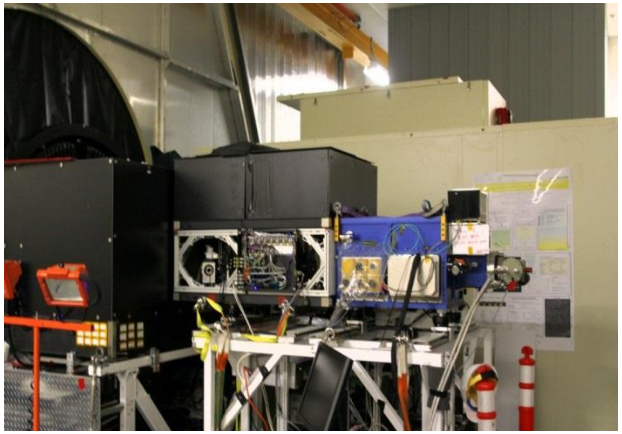
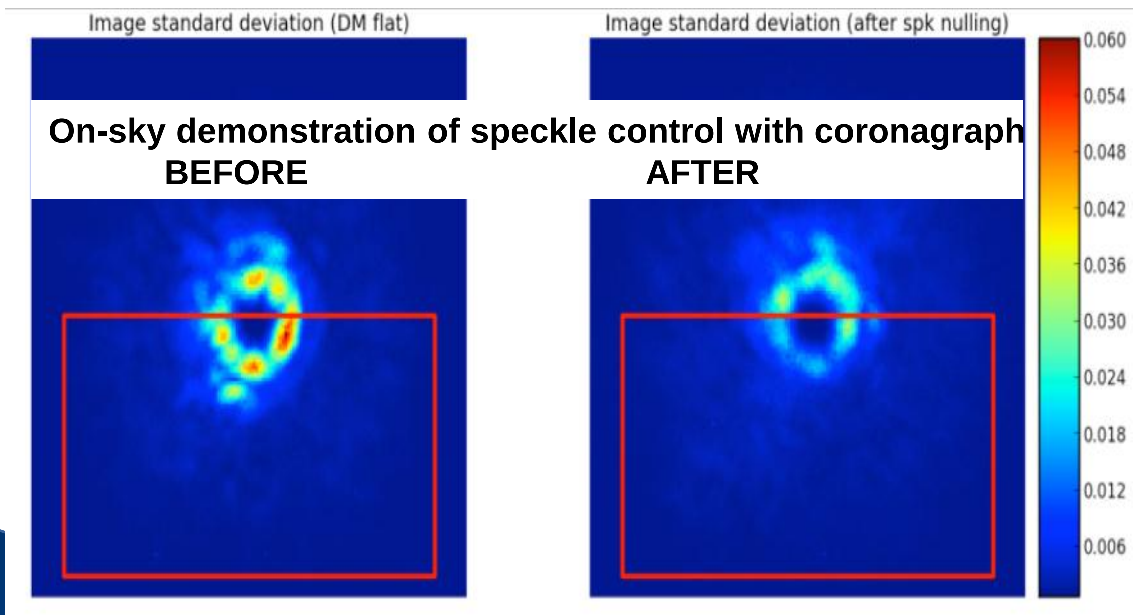


On-Sky Instruments using BMC Mirrors

Subaru Coronagraphic Extreme-AO (SCExAO)



Subaru Coronagraphic Extreme-AO (SCExAO)



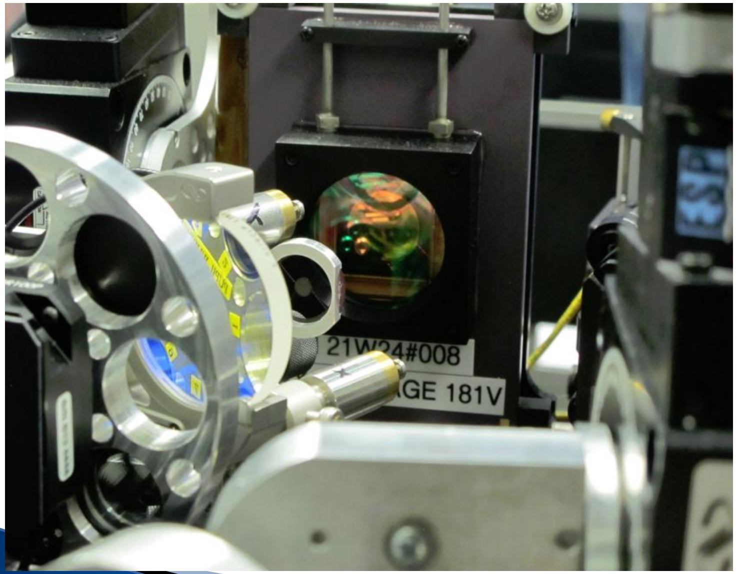
SCExAO used a kilo-DM (32x32)to modulate, control and cancel speckles to detect exoplanets

(Martinache 2012, 2013)

On-Sky Instruments using BMC Mirrors

2*k*-DM DM Validated in SCExAO Testbed

- The Subaru Coronographic Imager with Extreme Adaptive Optics is an upgrade of the high performance coronagraphic imager Hawaii Coronographic Imager with AO(HiCIAO)
- *2k-DM* Installed at the Subaru Telescope in 2012
- First light achieved 2013



Olivier Guyon, University of Arizona

4K DM for Gemini Planet Imager

The Gemini Planet Imager's main component is BMC's 4092 actuator DM with 3.5μm stroke, for Jovian exoplanet detection.

- Deployed on the 8-meter Gemini South Telescope
- first light image of the light scattered by a disk of dust orbiting November 2013

These near-infrared images (1.5-1.8 μm) show the planet glowing in infrared light from the heat released in its formation.

Beta Pictoris

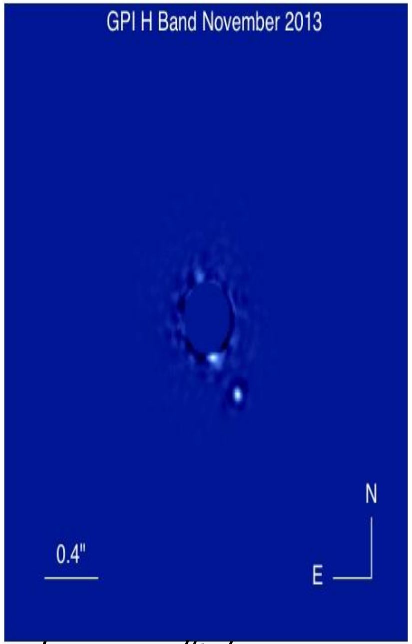


Image credit: Image processing by Christian Marois, NRC Canada

young star HR4796A

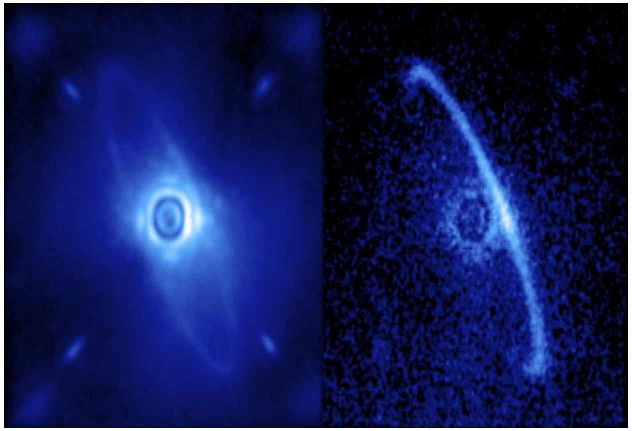
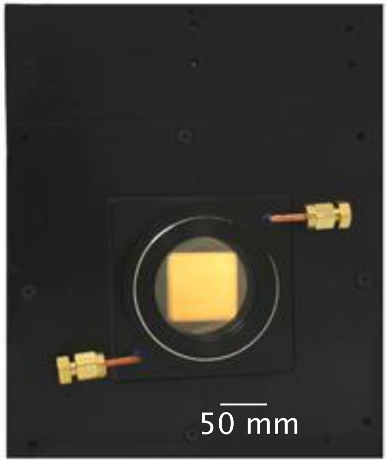


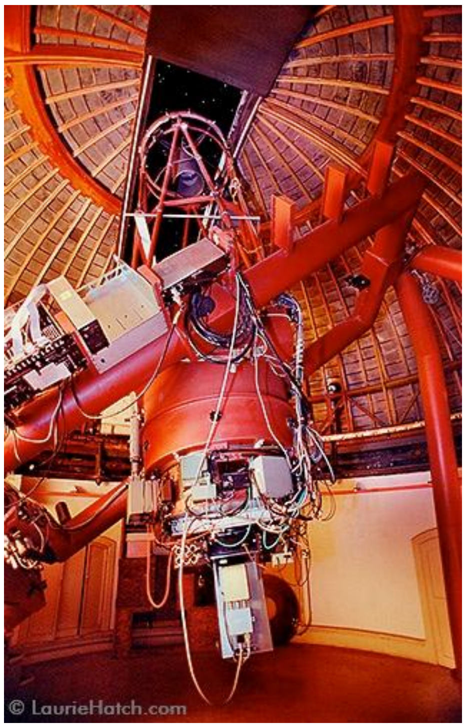
Image credit: Processing by Marshall Perrin, Space Telescope Science Institute



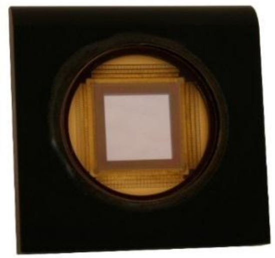
Application: ViLLaGEs* 1-m Telescope with Kilo-DM

A BMC MEMS DM has been used since 2007 at the 1m Nickel telescope at the Lick Observatory, in the MEMS-AO/Visible Light Laser Guidestar Experiments **(ViLLaGEs)**

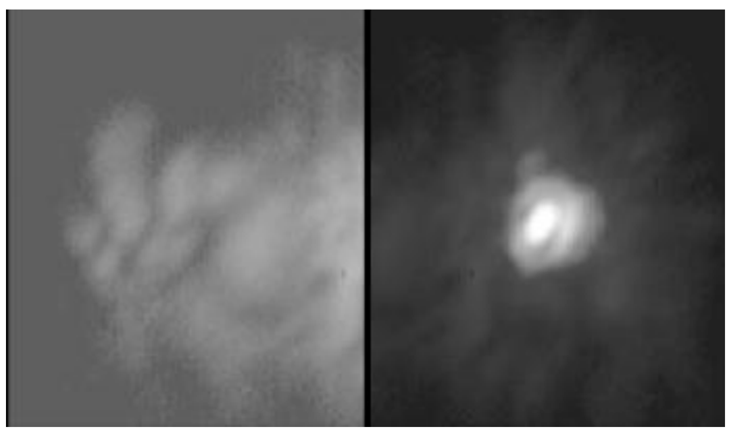
- **Diffraction limited imaging (I & R Band) demonstrated using both open and closed loop control**



Lick Observatory



1020 actuator MEMS DM installed on 3m Shane telescope AO system in 2013



Gavel D, et al. SPIE, 2008:688804-7.

Laboratory for Adaptive Optics

*ViLLaGEs: Visible Light Laser Guidestar Experiments

Conclusion

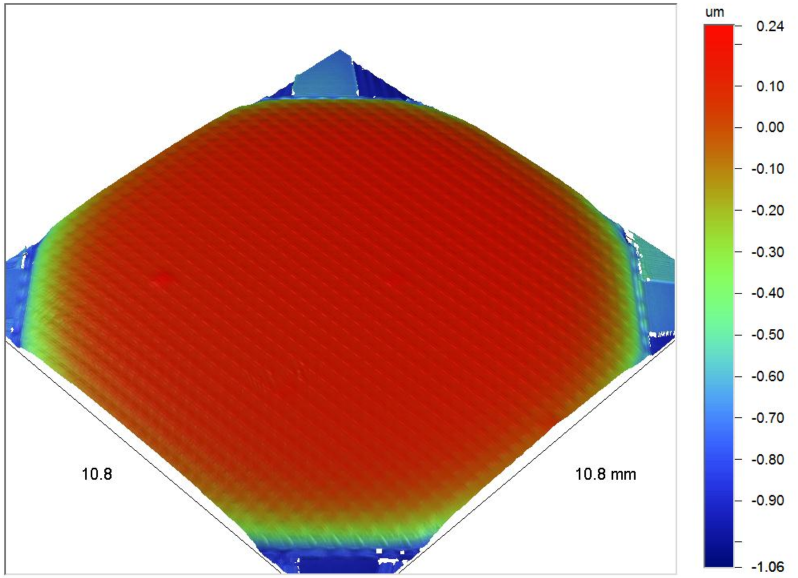
- Testing is ongoing with our TDEM program. Parts are finally about to ship to JPL, Princeton, and Goddard for testing.
- Improvements our current designs show good promise for built in redundant protection for space based imaging.
- Topographic improvements to our processes are currently being integrated into our heritage fabrication process.
- Demonstrated feasibility of up to 1mm pitch MEMS mirrors and showed lower actuation voltages are possible by using thinner films.

Acknowledgements

- Funding from NASA
  - Contract#: NNH12CQ27C TDEM/ROSES
  - Contract #: NNX12CA50C NASA Phase II SBIR
  - Contract#: NNX13CP03C NASA Phase II SBIR
  - Contract#: NNH13CH37C APRA/ROSES

Thank You

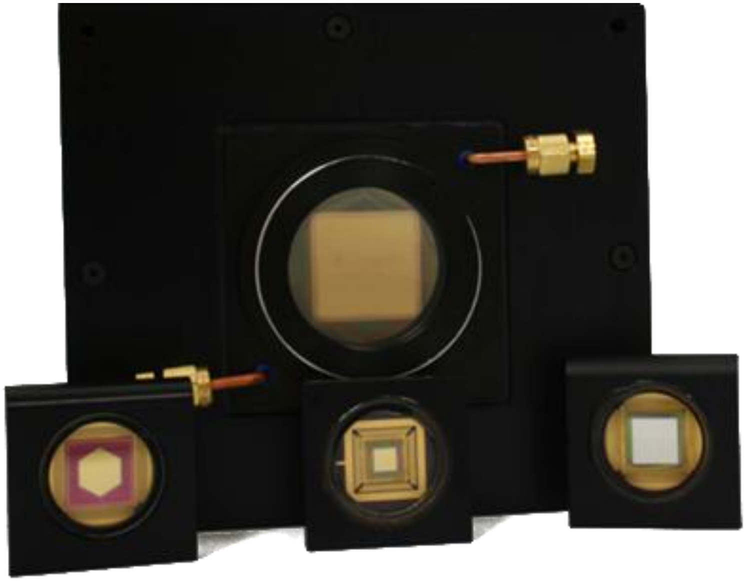
Questions?



Peter Ryan, pjr@bostonmicromachines.com

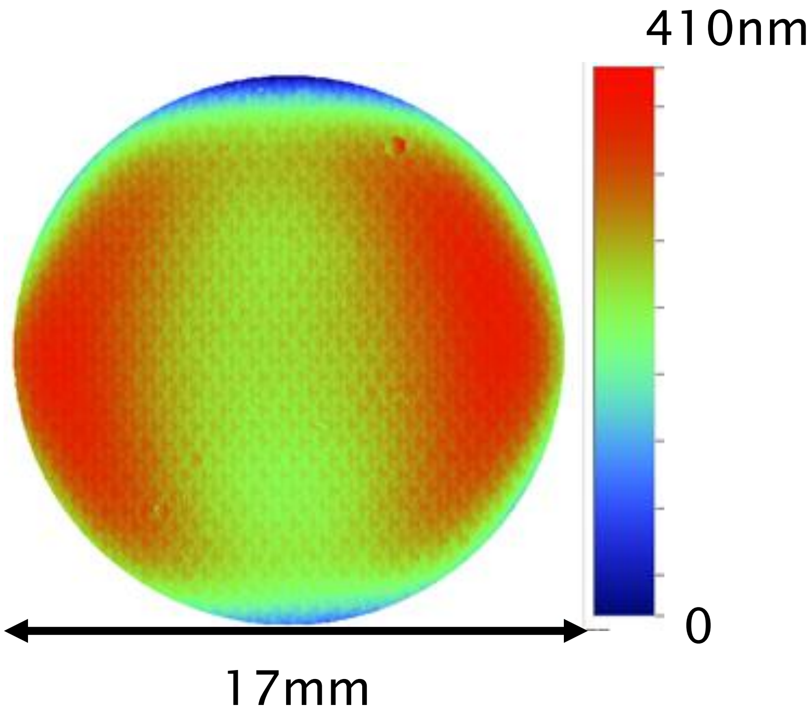
BMC Mirror Product Family

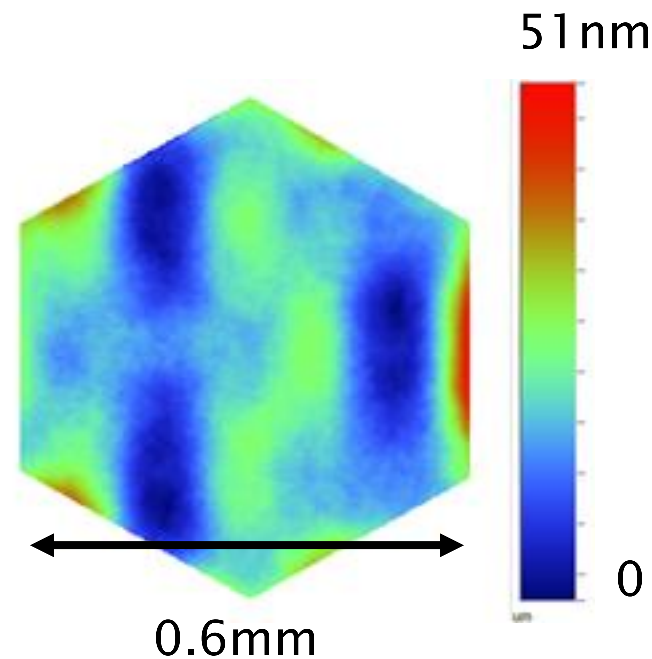
Product Name	Number of Actuators across aperture	Number of Actuators	Aperture Size (mm)
MINI	6	32	1.8
MULTI	12	140	3.6,4.8
C-MULTI	13	137	3.9,5.2
492	24	492	7.2
KILO	32	1020	9.6
C-KILO	34	952	10.2,11.5
2K	48	2040	19.2
3K	62	3064	18.6,21
331 TTP	Varies	993	9.3
1021 TTP	Varies	3063	16.5
Linear Array	140	140	



Heritage Continuous Facesheet Mirrors

Tip/Tilt/Piston DM Development Results





Segment RMS 7nm

Active Aperture Unpowered Surface Figure

Tip/Tilt/Piston DM Electromechanical Results

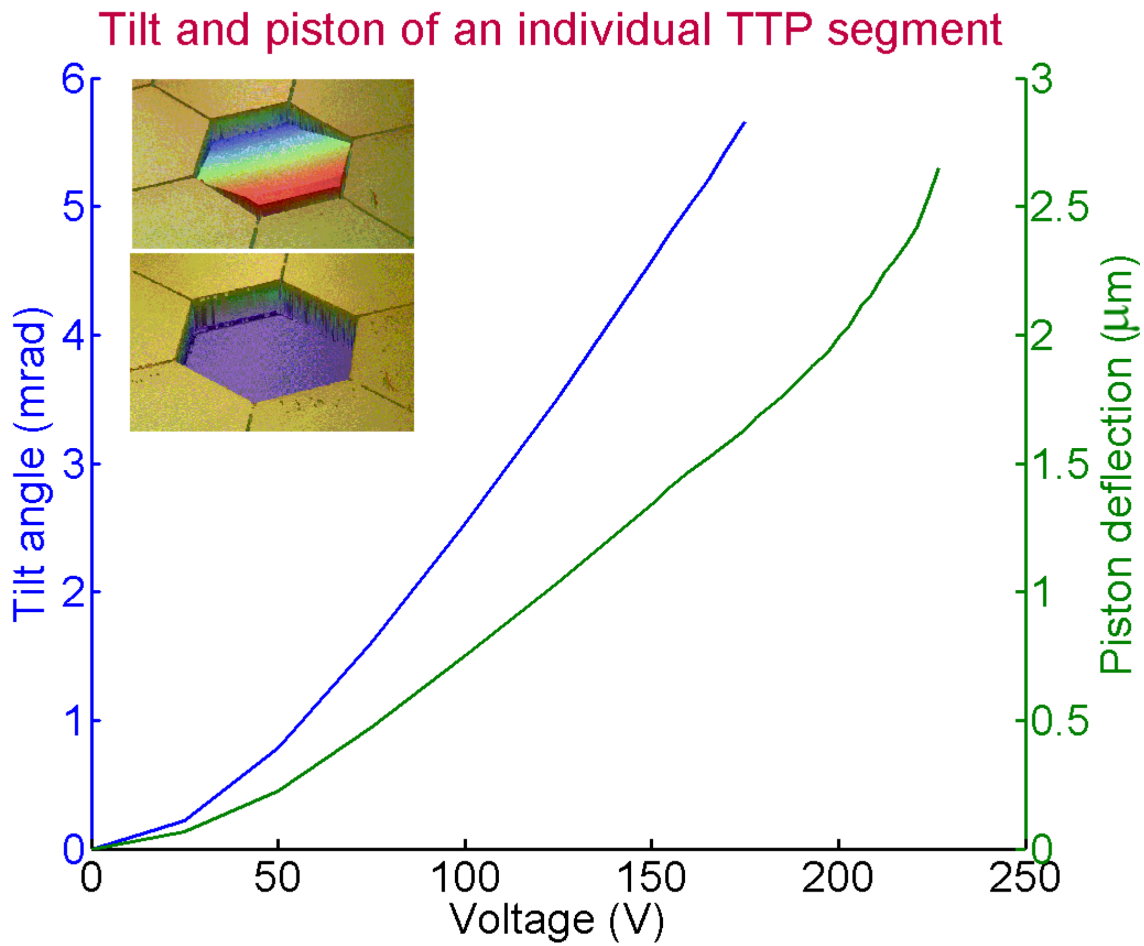
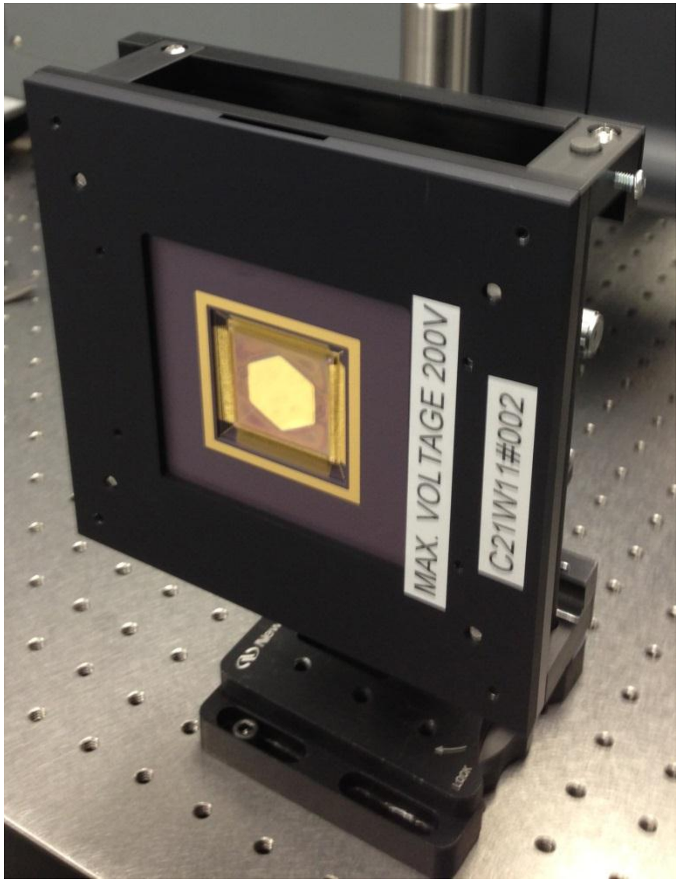


Figure 16. Tilt (blue) and piston (green) for an individual segment.

Tip/Tilt/Piston DM Development Results

Delivered to JPL June 2013

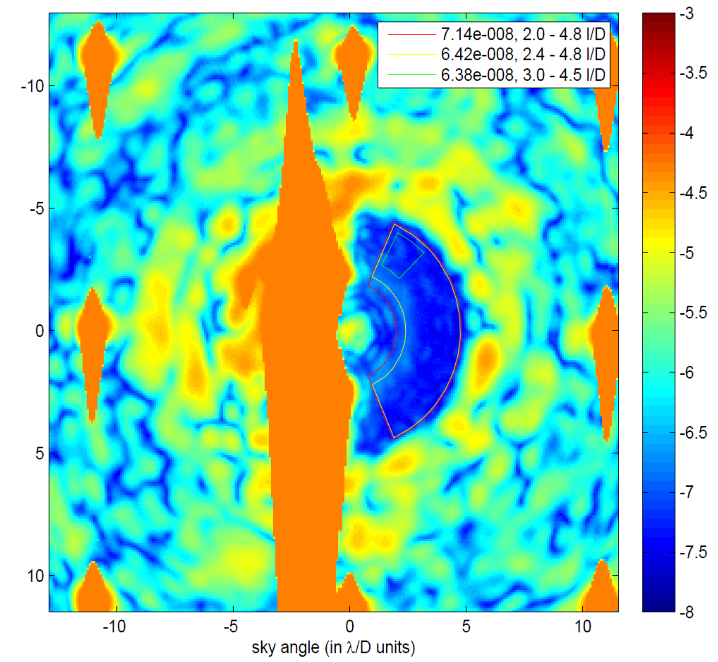


99% Actuator Yield

Topography Improvement

Program Objectives

- Reduce Scalloping
- Reduce Print Through
- Deliver a 3064 actuator continuous facesheet mirror

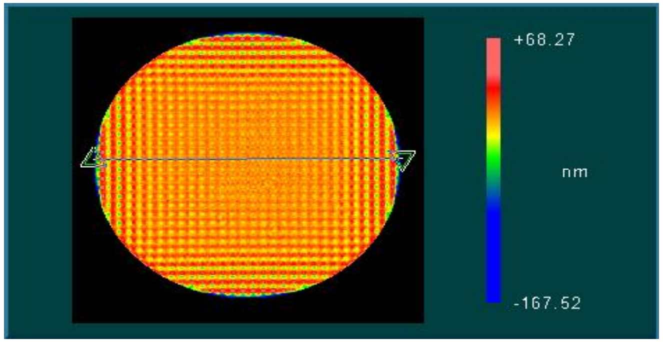


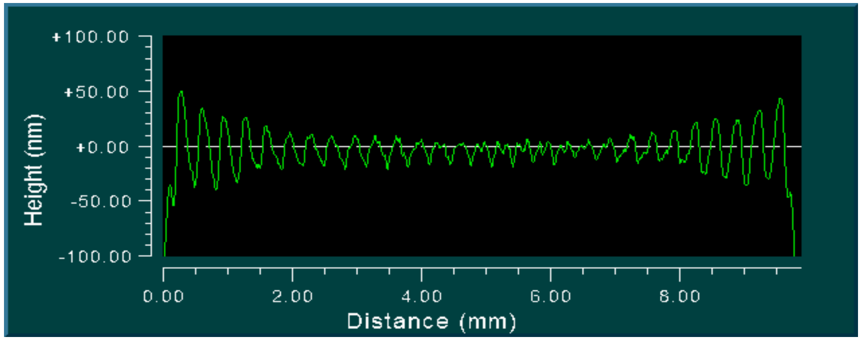
The presence of the diffraction peaks in the image plane creates optical problems:

- Local blind spots in the image plane
- Extended light leak from diffraction peaks across the image plane
- Chromaticity of the diffraction orders

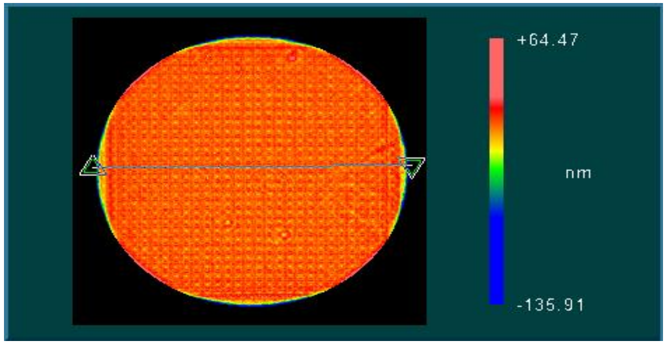
Topography Improvement Results

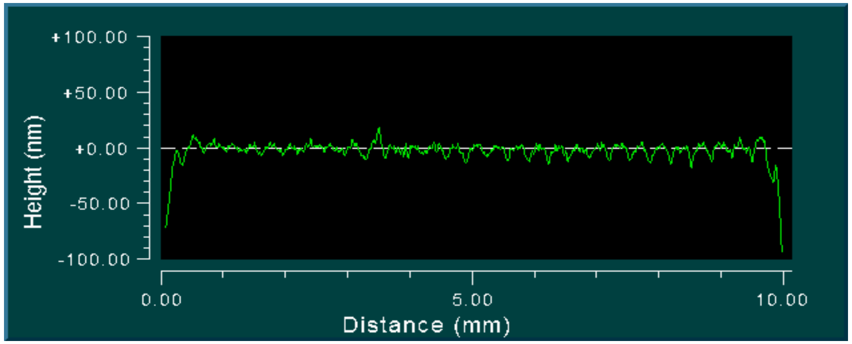
Scalloping Reduction





Kilo DM Before Film Treatment

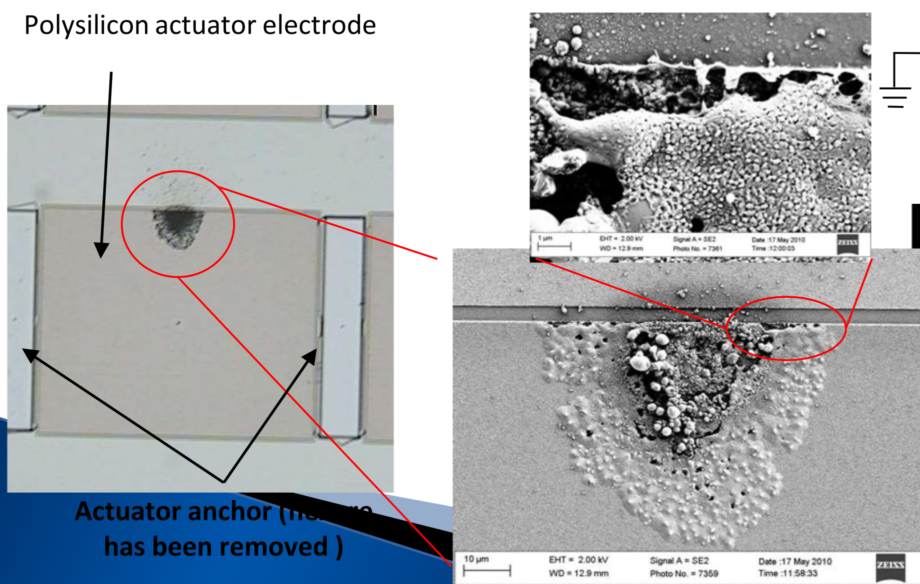


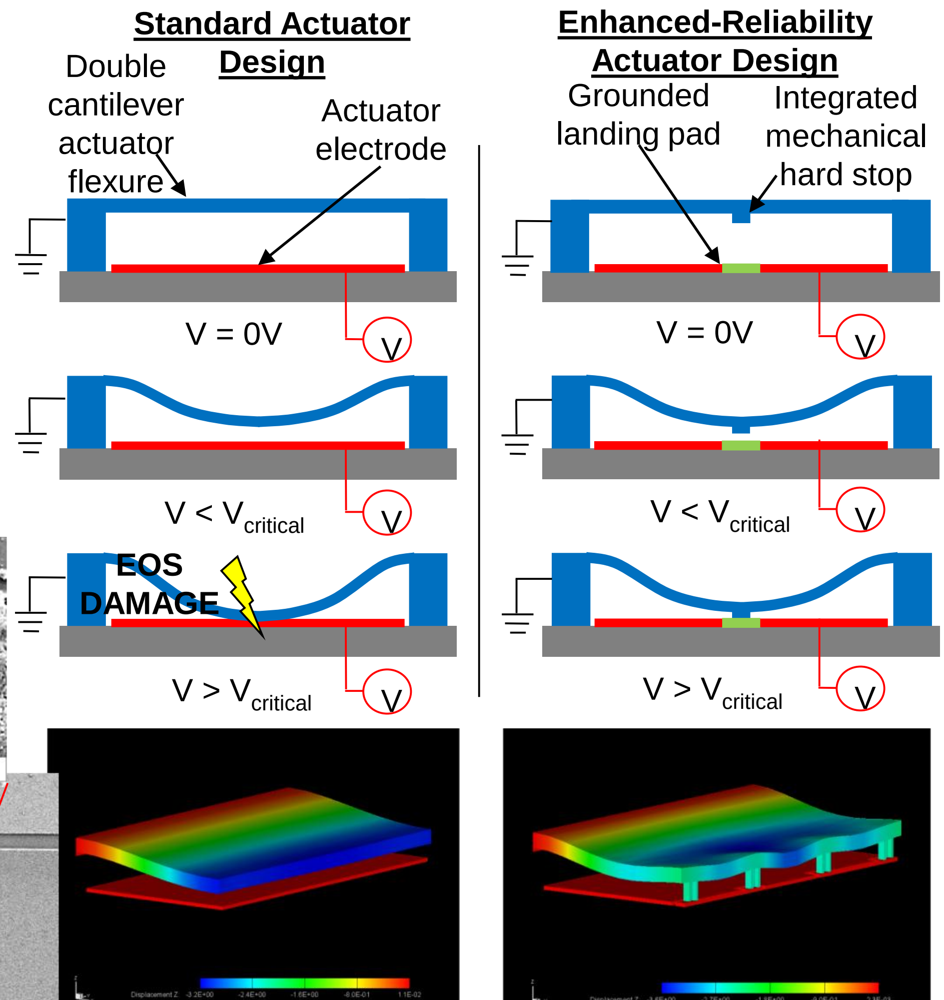


Kilo DM After Film Treatment

Enhanced Reliability DM Actuator Development

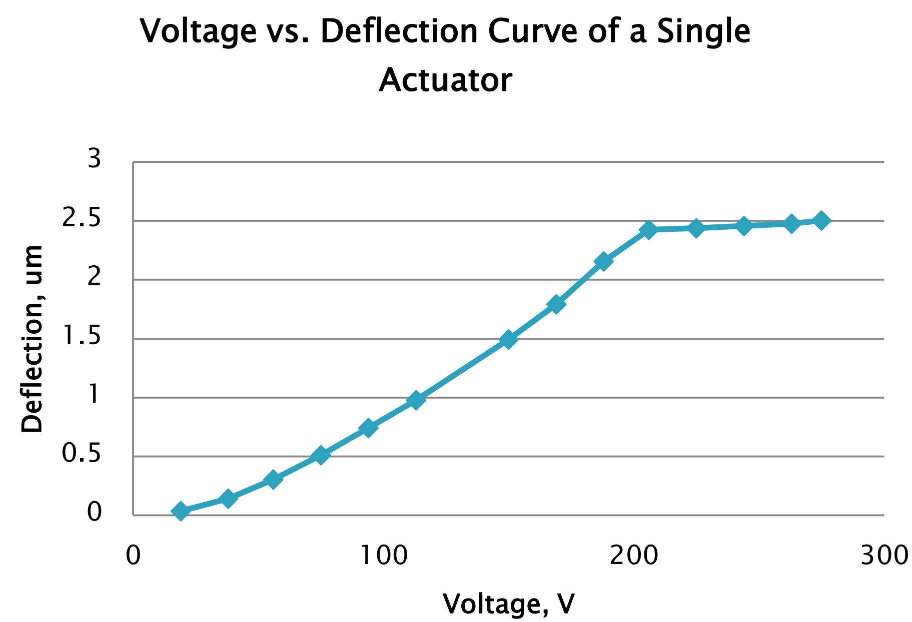
- In Phase I, mechanical hard stops were integrated in the actuator design to prevent EOS
- If EOS occurs, the hard stops touch down on a grounded landing pad which prevents the actuator flexure from touching the actuators electrode



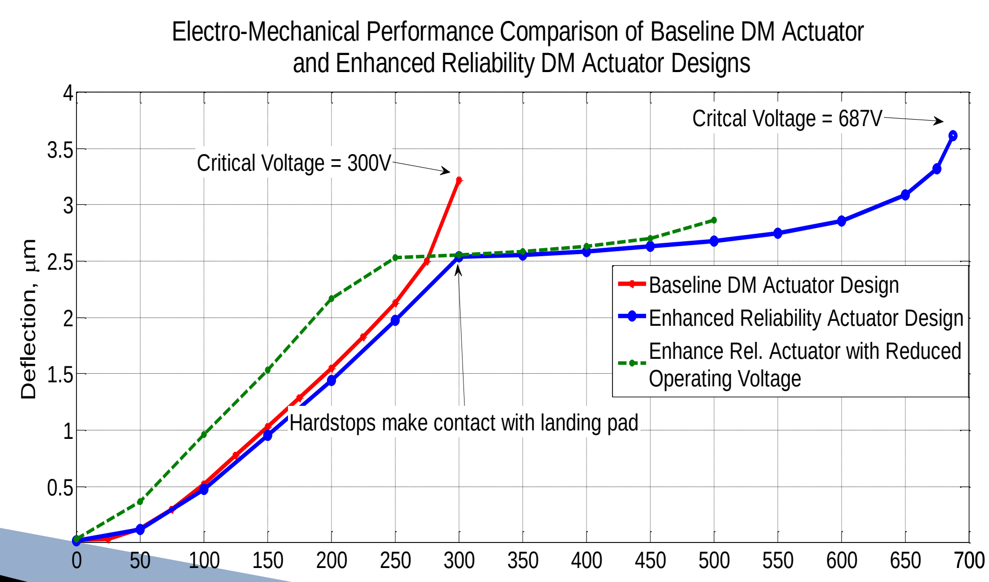


Actuator Array Performance

A voltage versus deflection curve of an actuator.

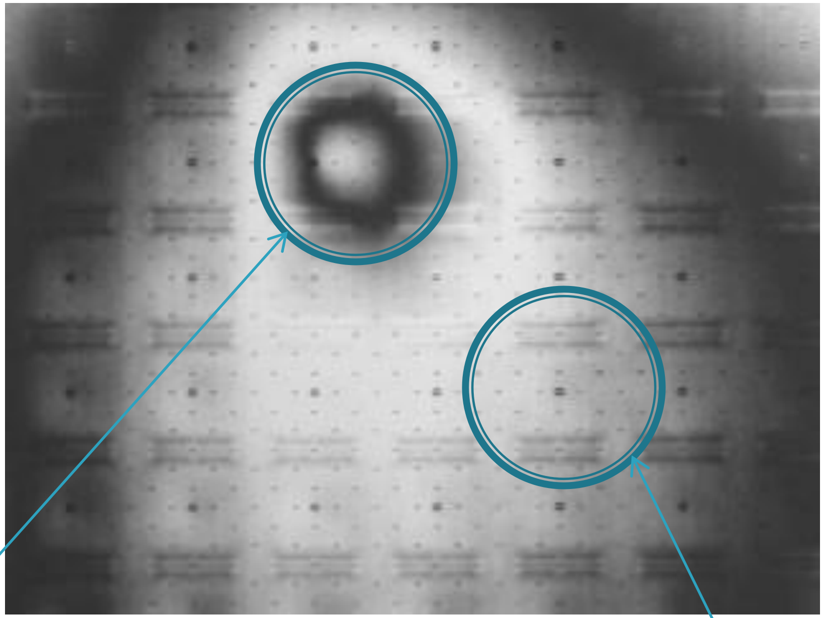


Voltage deflection results from Phase I

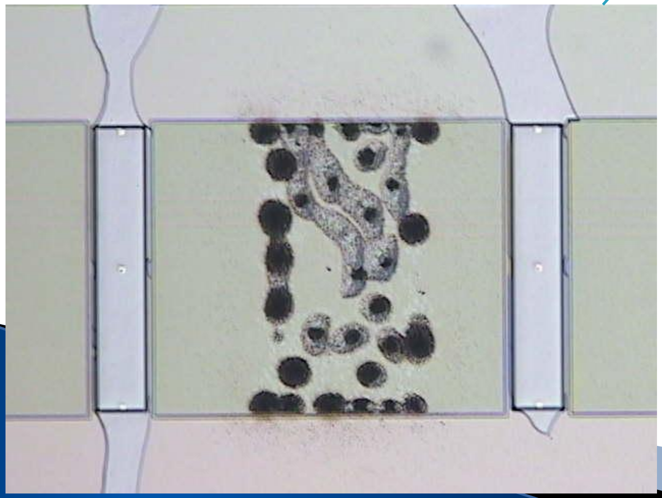


Reduction of Snap-Through Related Damage

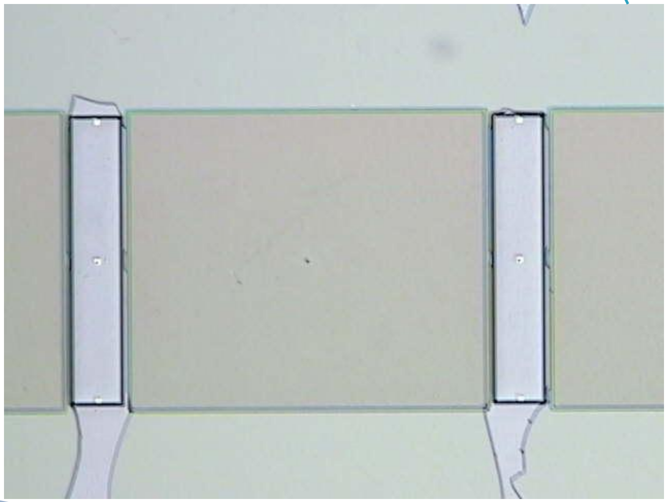
- In Phase I the addition of current limiting elements further increases overall MEMS DM reliability
- Reducing high-current densities at snap-through



Electrode Without Current Limiting Electronics

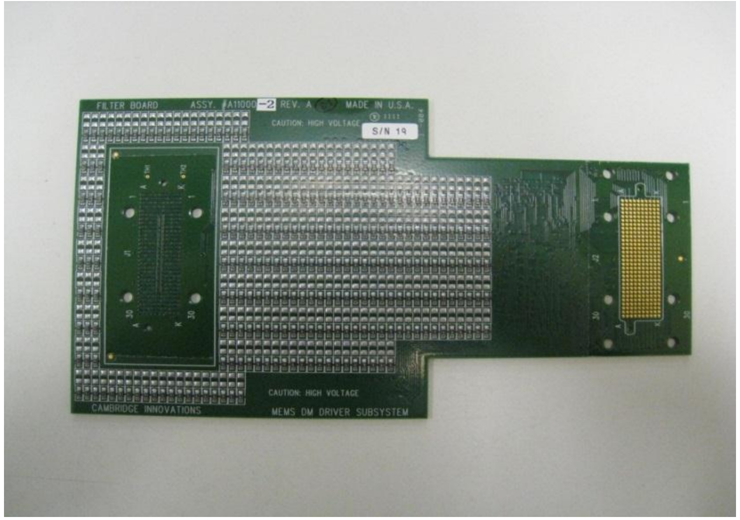


Electrode with Current Limiting Electronics



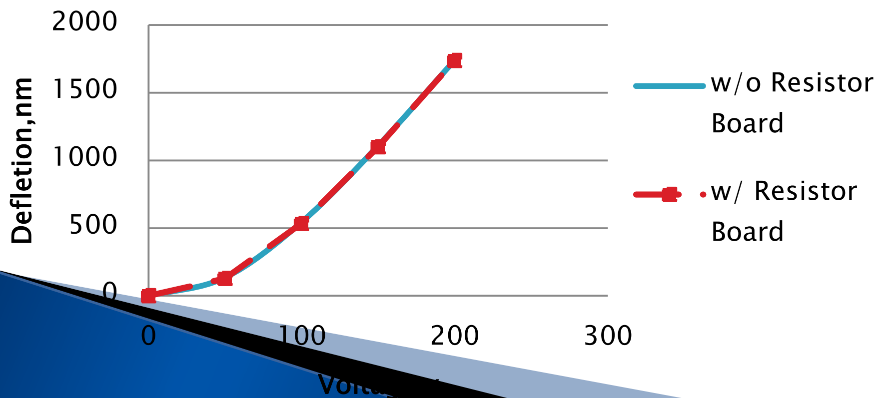
Current-limiting Resistor Boards

- Current-limiting resistor board with a 390 MOhm resistor inline for all channels has been fabricated and is being tested
- Trade off is reduced bandwidth

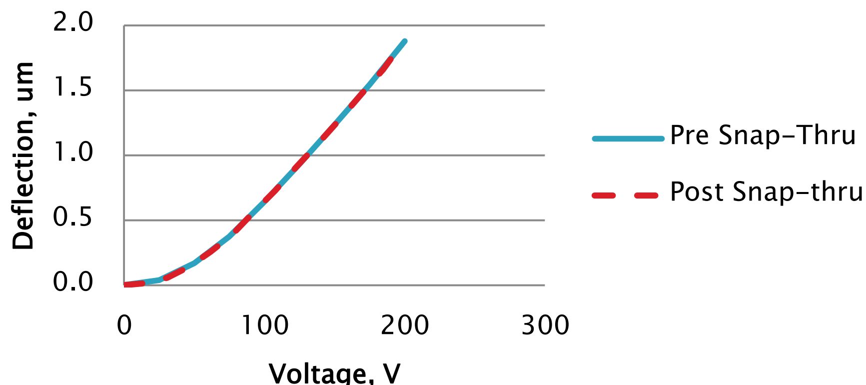


Comparison of Voltage vs. Deflection Curves of a 4x4 Actuator Array

With and Without Resistor Boards

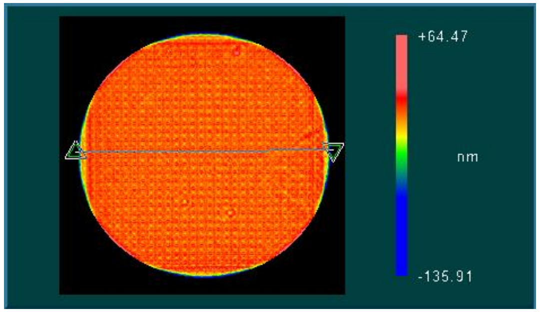


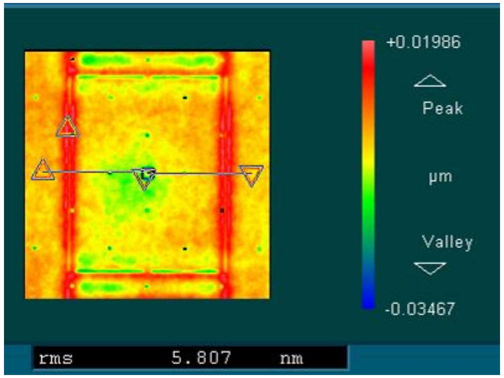
Pre and Post Snap-Through

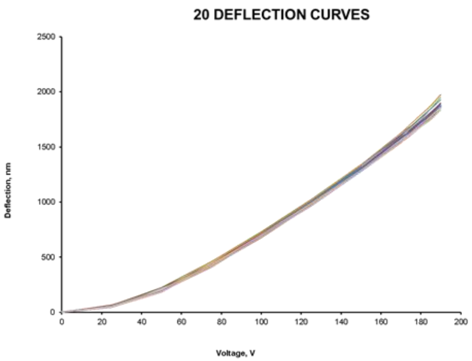


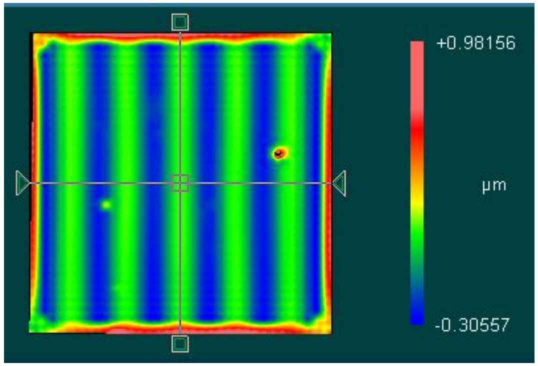
Before and After Testing Characterization

- Topographic surface maps of aperture
- Topographic surface maps over 600μm subapertures
- Voltage v. Deflection and influence function
- Stability
- Repeatability
- Imposing known surfaces on the mirror surface at multiple offsets.





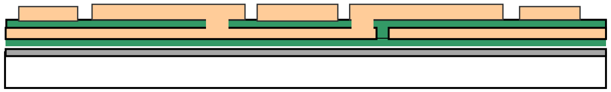




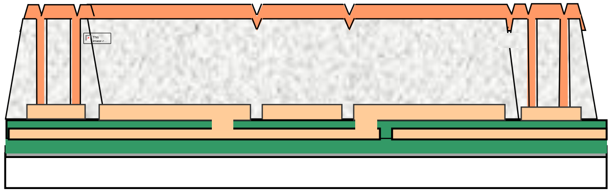
Test performed at BMC using Zygo Verifire laser Fizeau interferometer
Repeated at JPL Vacuum Surface Gauge for higher resolution measurements

MEMS DM Fabrication

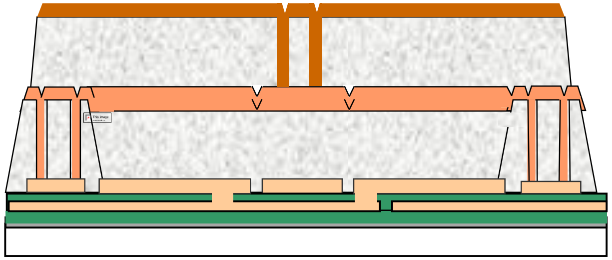
(deposit, pattern, etch, repeat)



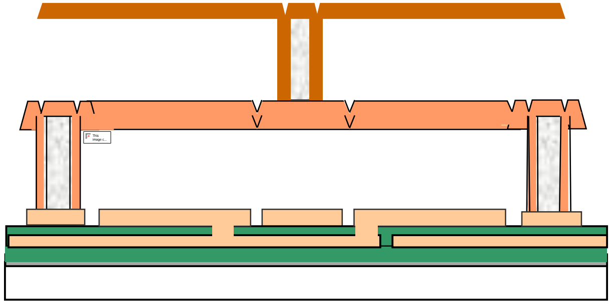
Electrodes & wire traces:
polysilicon (conductor) & silicon nitride (insulator)



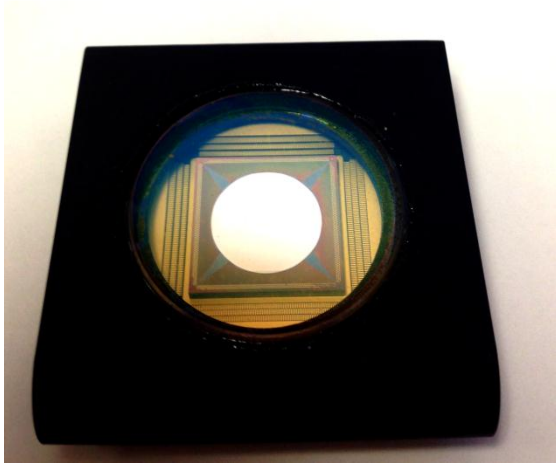
Actuator array:
oxide (sacrificial spacer) and polysilicon (actuator structure)



Mirror membrane:
oxide (spacer) and polysilicon (mirror)



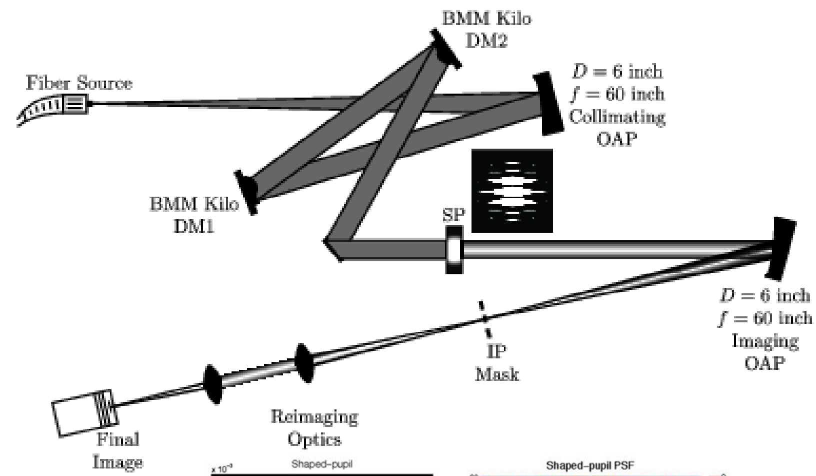
MEMS DM:
Etch away sacrificial oxides in HF, and deposit reflective coating

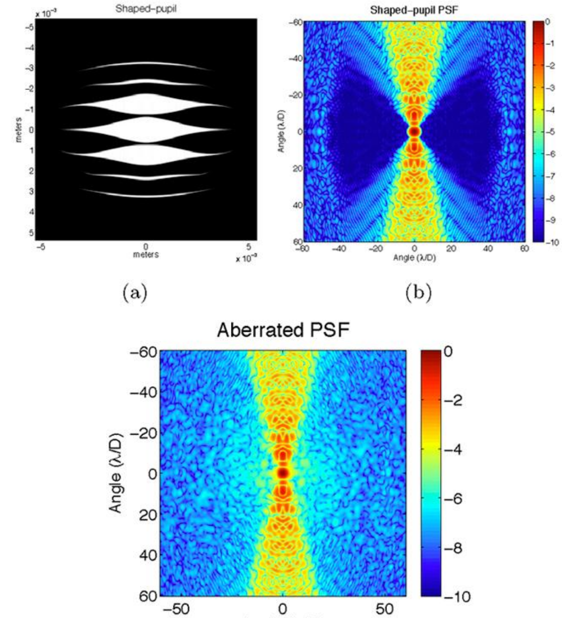


Attach die to a ceramic package and wirebond

High Contrast Imaging Laboratory (HCIL) at Princeton University

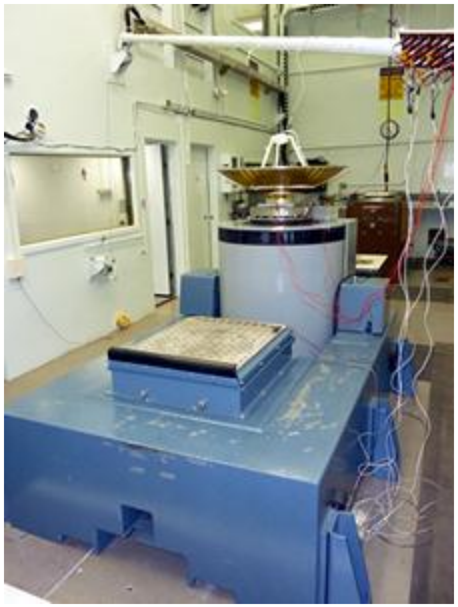
- Test the performance of two DMs in series with a shaped pupil coronagraph in both monochromatic and broadband (10% and 20%) light
- For each test the resulting voltage map on the DM will be recorded and used as a base line for future testing.





(a) (b) (c)

Environmental Testing at GSFC



Vibration
Random and Sinusoidal

Acoustic

Shock

Previous environmental testing (Thermal, acoustic, and vibration) performed at JAXA

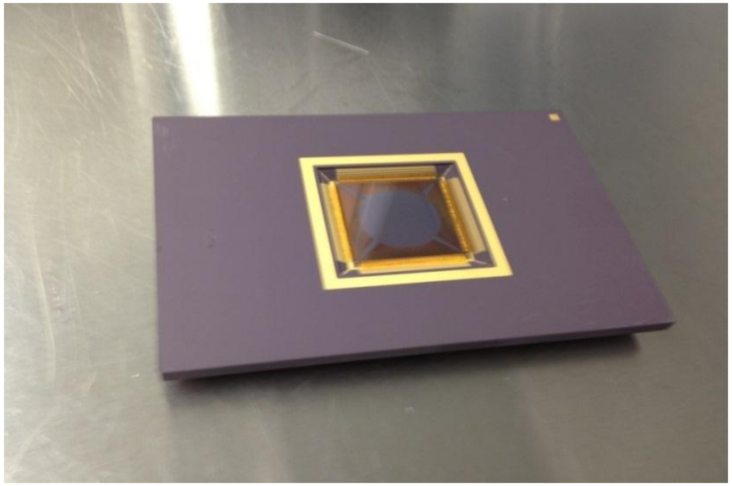
Current Project Status

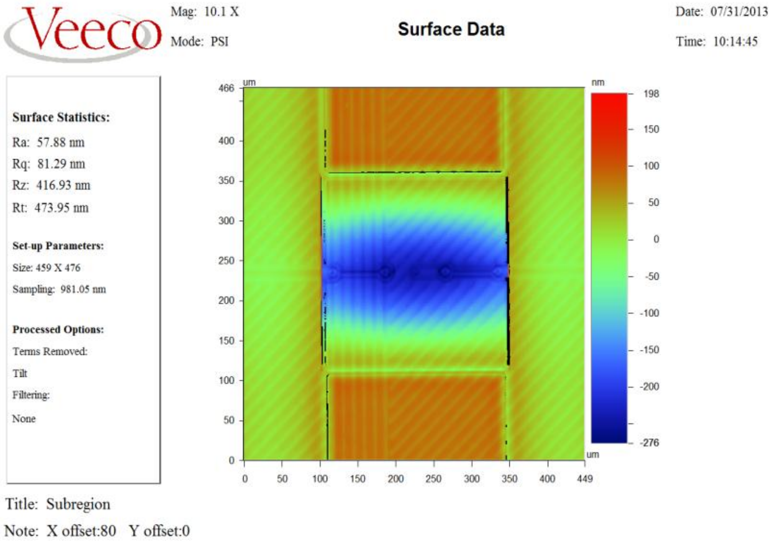
- Fabrication of MEMS Mirrors ongoing
- Automated testing procedure completed
  - Many measurements taken automatically
  - Long duration (over night)
- Coordination with JPL on testing
  - Test procedures
  - Drive electronics
  - Mirror Mount

DM Fabrication Run

- One 2048 poly 1 send-ahead actuator array device was packaged and wirebond with X-wire, insulated Au wire.
- Electromechanical performance has been verified by performing voltage versus deflection on a single actuator
- Snap-through tolerance testing will be performed by cycling actuators from 0V to maximum voltage of the driver

Packaged Send-Ahead device

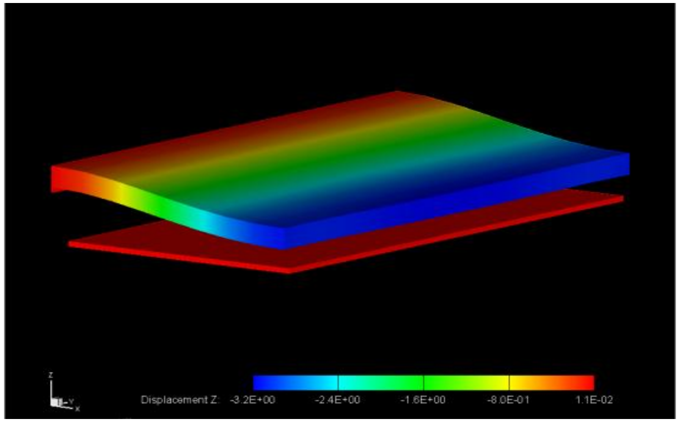




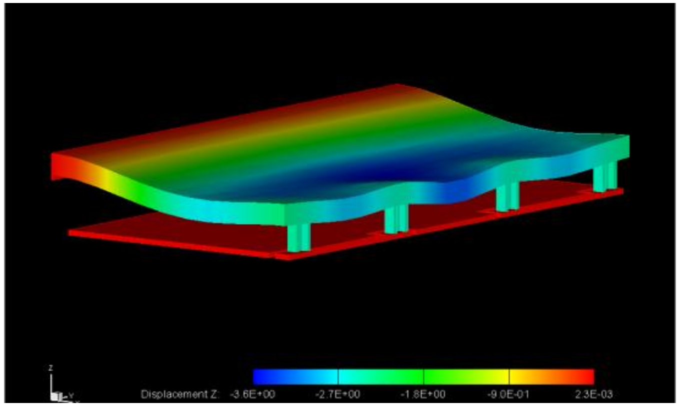
Surface Figure Image of a Single Actuator

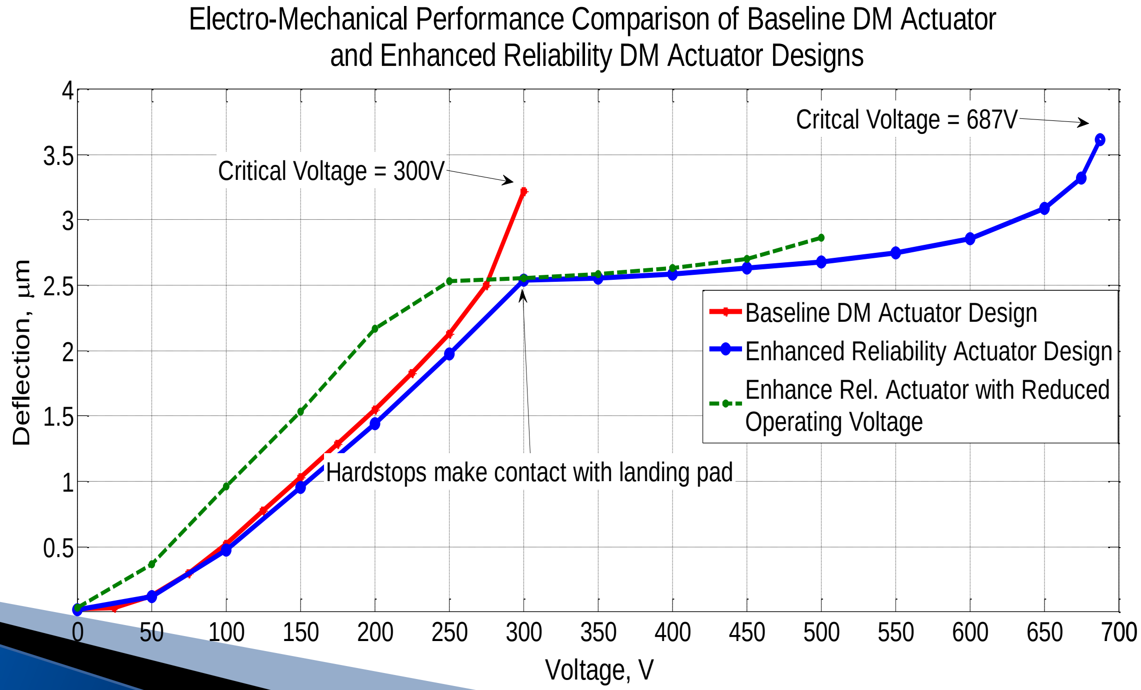
New Actuator Electromechanical Performance

Baseline Actuator Design



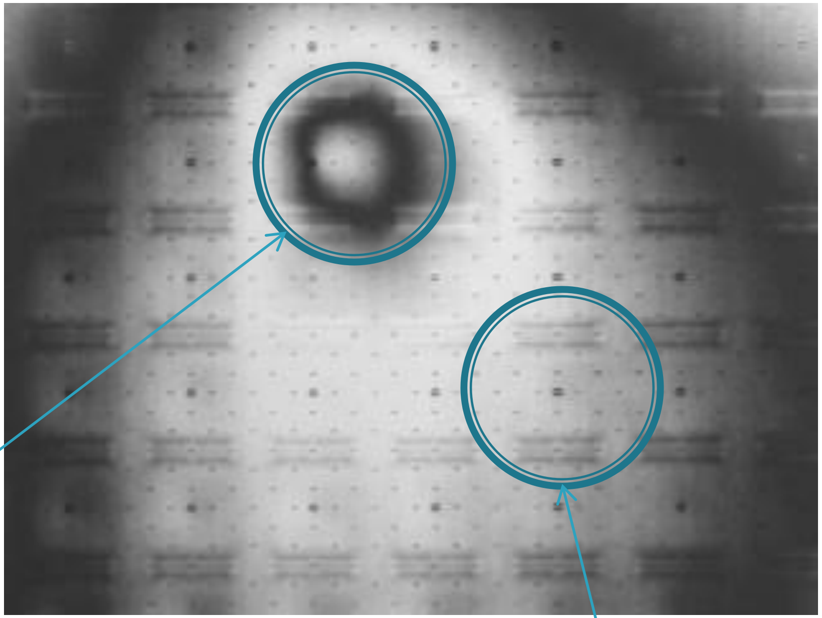
Enhanced Reliability Actuator Design



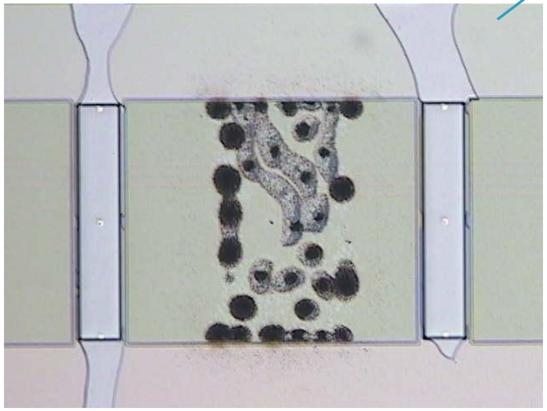


Prevention of Snap-Through Related Damage

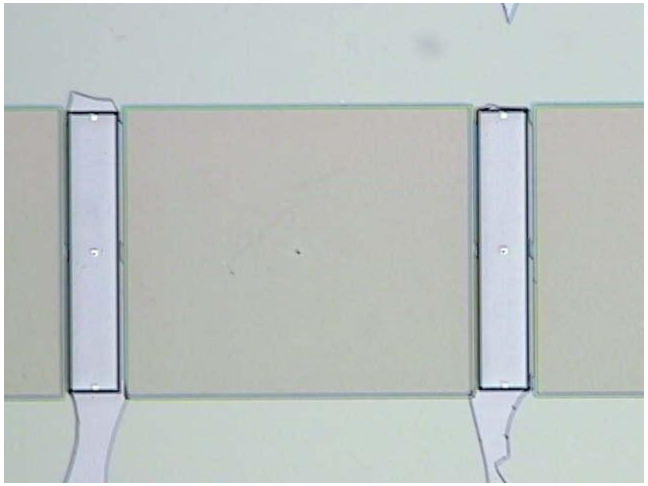
- Addition of current limiting elements further increases overall MEMS DM reliability
  - Eliminates high-current densities at snap-through



Without Current Limiting electronics

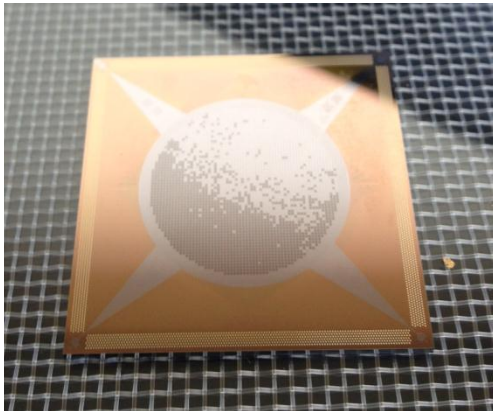


With Current Limiting electronics

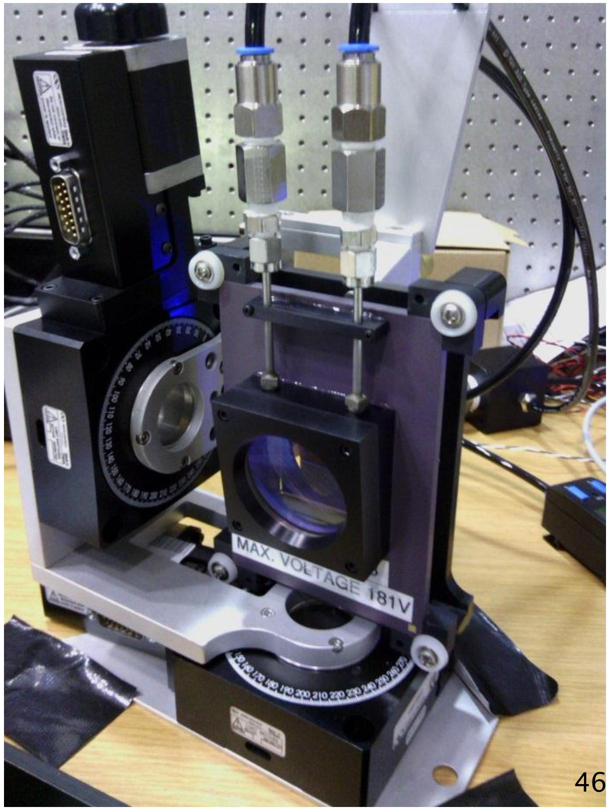


Topography Improvement Work Remaining

- Complete fabrication process
- mount the DM in a ceramic carrier, make the electrical interconnections using high density gold wire bonding techniques
- Assemble the component into an optical mount.
- Characterize optical quality and electromechanical DM performance.



3K Send Ahead Die 62 across 3064 total

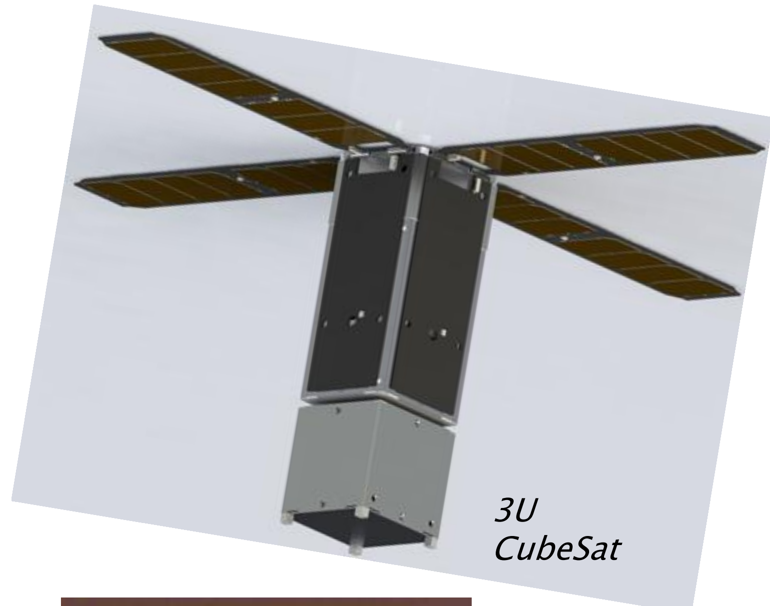


2K DM in it's optical mount

CubeSat MEMS Deformable Mirror Demonstration

Characterization of a Wavefront Control system on-orbit

Long duration operation in space environment, software and microcontroller, operations, data management



3U CubeSat

- Dr. Keri Cahoy, MIT
- Boeing Assistant Professor Department of Aeronautics and Astronautics

BMC Mini MEMS DM

Back up slides for Environmental Testing

Environmental Testing Performed on BMC's Deformable mirrors

Prepared for:
DM Environmental Testing
2nd Teleconference
September 11, 2012
By:

Paul Bierden
Steven Cornelissen

Outline

- Testing Performed
  - Thermal
  - Vibration
  - Acoustic
  - Rapid Pump
  - Radiation
- Future Work

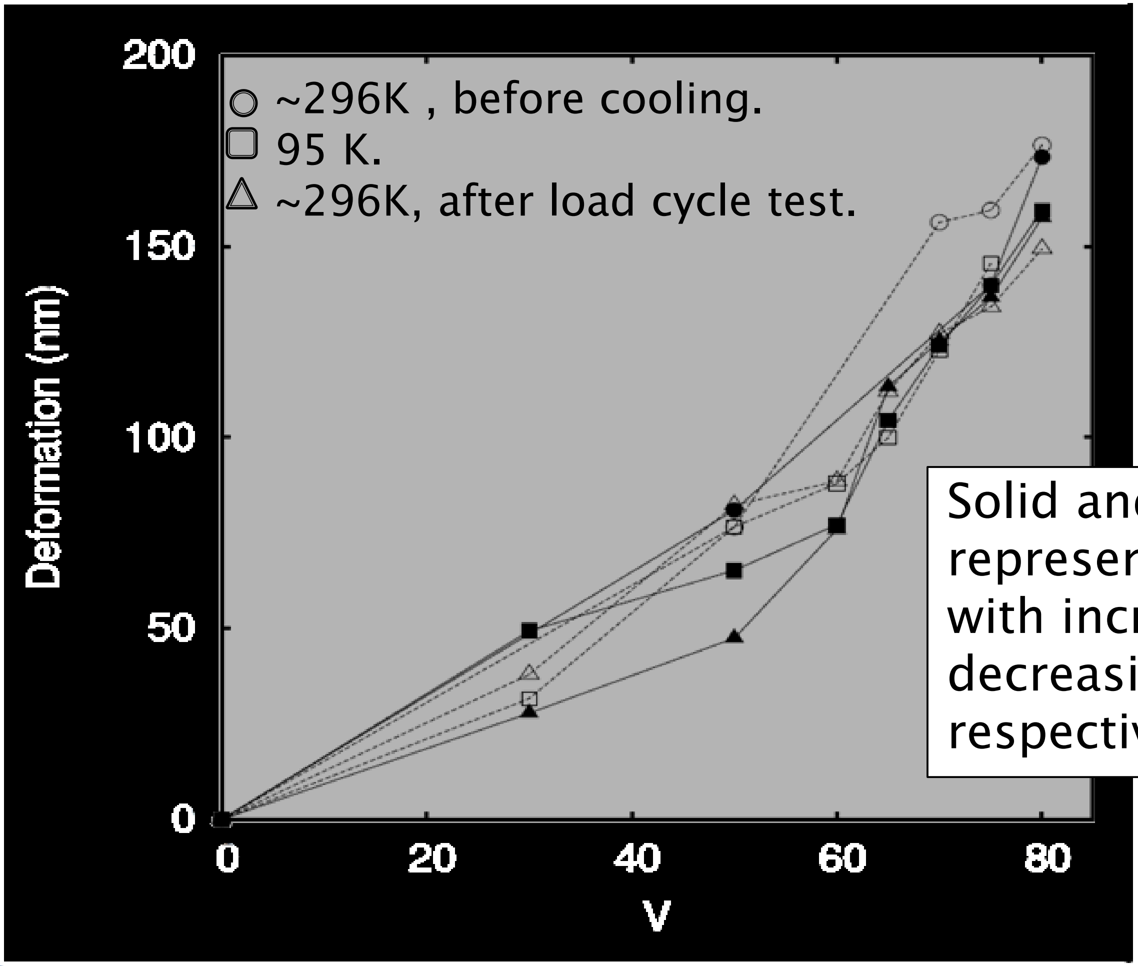
Thermal Testing

- DM: Multi-DM with custom package
- Date: 2008
- Location: JAXA
- Pressure: ~10^{-6} torr
- Test:
  - 95K exposure and operation
- See publication:

  "A Micro Electrical Mechanical Systems (MEMS)-based Cryogenic Deformable Mirror," Enya, K.; Kataza, H.; Bierden, P., Publications of the Astronomical Society of the Pacific, Volume 121, issue 877, pp.260-265

Thermal Testing Results

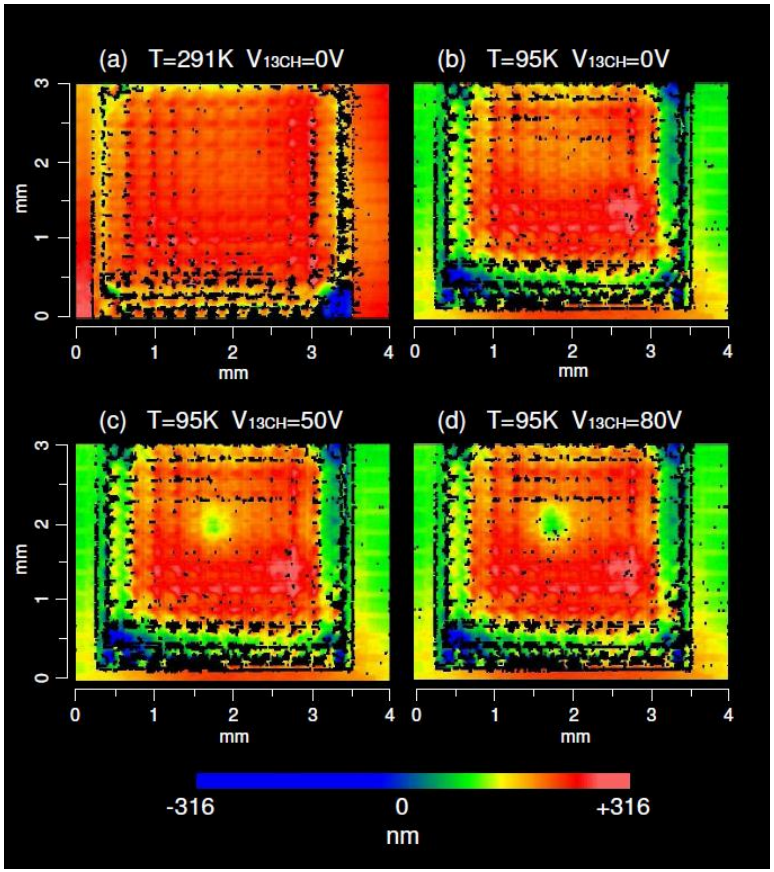
Voltage deflection measurements



Solid and empty symbols represent data obtained with increasing and decreasing voltages, respectively.

Thermal Testing Results

Interferometric 3D surface data



All data were obtained by measurements made through the window of the vacuum cryostat.

(a) Surface without voltage applied at room temperature.

(b) Surface without voltage applied at 95 K.

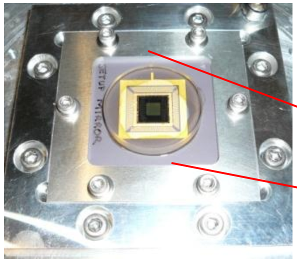
(c) Surface with 50V on the 13th CH at 95 K.

(d) Surface with 80V on the 13th CH at 95 K.

The difference between (a) and (b) is much smaller than the deformation caused by the voltage applied.

Vibration Testing

- DM: Mini-DM with window
- Temperature: ambient
- Pressure: 1atm
- Date: Feb. 14th, 2011
- Performed by: ISAS/JAXA
- Test sequence:
  - Zygo inspection
  - Vibration sequence ->Zygo inspection
  - Heavier vibration sequence ->Zygo inspection
- Vibration levels: -12dB, -6dB, -3dB, 0dB, +3dB
- Direction of the vibration: Vertical direction from DM surface.
- Time of each vibration load: 60 sec.
- Conclusion:
  - No significant changes found during inspection



0dB Vibration Profiles

Frequency (Hz)	PSD (G^2/Hz)
20	4.3
80	67.3
270	67.3
413	28.9
800	28.9
2000	2.5
Over all	21.1 Grms

Vibration Testing (2)

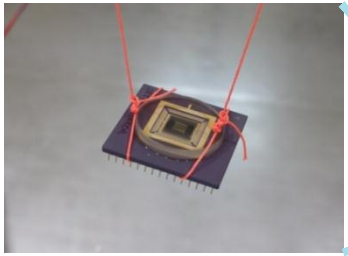
<u>PICTURE project payload was shake tested with the DM in place</u>

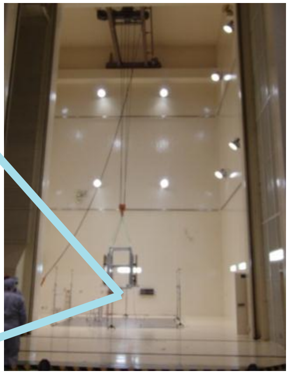
- DM: Kilo - DM
- Performed at: Wallops Flight Facility
- Test sequence: NASA Vehicle Level 2 levels
- Spectrum:

  12.7gms
  0.01g2/Hz 20Hz
  0.10g2/Hz 1000Hz
  (on 1.8bd/oct slope)
  0.10g2/Hz 1000-2000Hz
- Direction of the vibration: 3 axes
- Time of each vibration load: 10 sec/axes
- Conclusion: The DM was tested successfully after being shaken within the full payload

Acoustic Testing

- DM: Mini-DM w/ window
- Temperature: ambient
- Pressure: 1atm
- Date: Feb. 3th, 2011
- Performed by: Tsukuba Space Center/JAXA
- Acoustic level: See table
- Time of acoustic load:
  - 60(+2-0) second
- Test sequence:
  - Zygo inspection (actuator yield inspection)
  - Acoustic load in TSC
  - Zygo inspection
- Conclusion:
  - No significant changes found during inspection





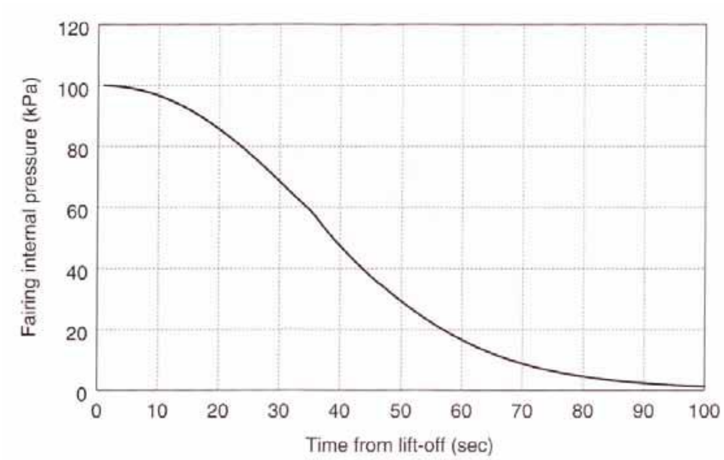
1/1oct center frequency	Acoustic pressure (dB)	Tolerance
31.5	128.0	+5/-10 dB
63	135.0	+- 3dB
125	139.6	+- 3dB
250	138.0	+- 3dB
500	135.0	+- 3dB
1000	132.0	+- 3dB
2000	129.0	+- 3dB
4000	124.0	+3- 10dB
8000	118.0	+- 6dB
Over all	144.0	+- 2dB

* $0dB=2x10^{-5}$[Pa]

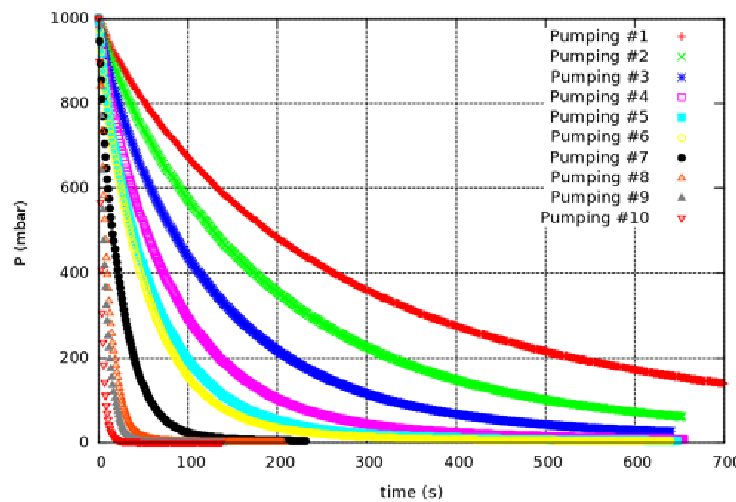
Rapid Pumping Testing

- DM: Mini-DM, no window
- Temperature: ambient
- Date: June 7th , 2011
- Performed by: ISAS/JAXA
- Test sequence:
  - Pumping sequence
  - Deformability check
  - Repeat
- Pumping profile #10 is more rapid than the expected pressure profile of H IIA rocket fairing at any pressure.
- Conclusion:
  - No significant changes found during inspection

H IIA rocket fairing internal pressure



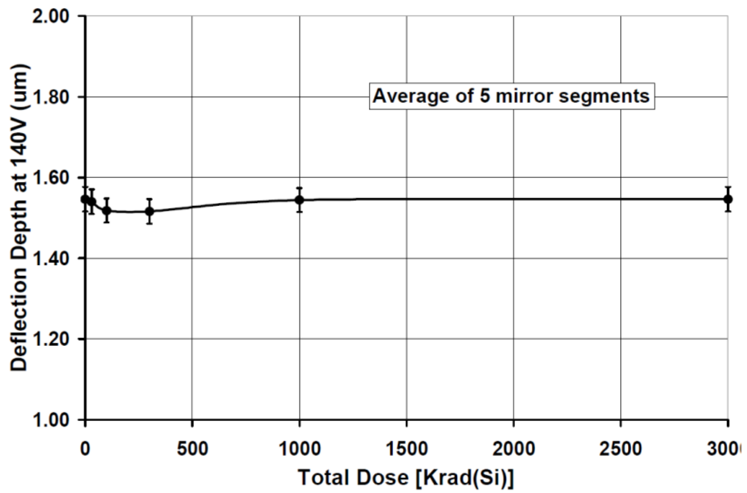
Testing results



Radiation Exposure Testing

- DM: 1.5um stroke DM
- Temperature: ambient
- Date: 2003
- Performed by: JPL High Dose Rate (HDR) facility
- Test sequence:
  - Used cobalt-60 gamma rays up to 3Mrad.
  - Two groups with five mirror actuators each, all located on a single device.
  - One group of segments irradiated without bias (electrodes at ground),
  - One group irradiated with a deflection voltage of 140 volts.
  - Device removed after each exposure, run temporarily removing bias from the segments that were biased, and measured with a Wyko model RST Plus Optical Profiler.
- Conclusion:
  - Deflection data for both of the test groups indicated no significant effects due to radiation

Testing results



Change in mirror deflection due to radiation for biased segments.

Ref:

T. F. Miyahira, H. D. Becker, S. S. McClure, L. D. Edmonds and A. H. Johnston, “Total Dose Degradation of Optical MEMS Mirrors,”Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

FutureTesting

- Testing of MEMS DMs
  - Surface finish (unpowered and actively flattened)
  - Actuator yield
  - Voltage v. Deflection
  - Influence function
  - Frequency response
- Characterize at BMC and test beds
  - JPL APEP test bed/HCIT
  - GSFC VNT
  - Princeton University HCIL
- Environmental testing at GSFC's Environmental Test and Integration Facilities (ETIF)
  - Vibration
  - Acoustic
  - Thermal
- *TDEM program not started*