MEMS Deformable Mirror Advancements for Space Telescopes

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Mirror Technology Days
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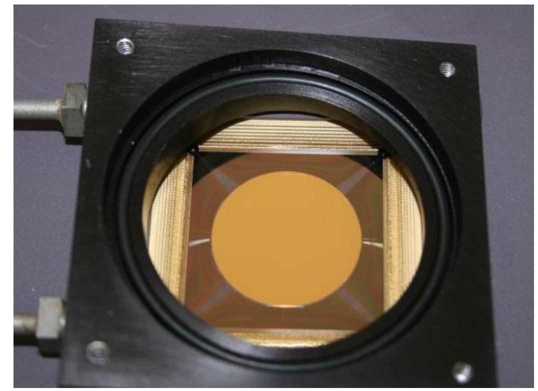
Redondo Beach, CA

NASA SBIR PHASE I/II
Approved for Public Release by NASA

Outline

- MEMS DM technology drivers and architecture overview
- Examples of MEMS DM in astronomical applications
- Current development program results
- Conclusions



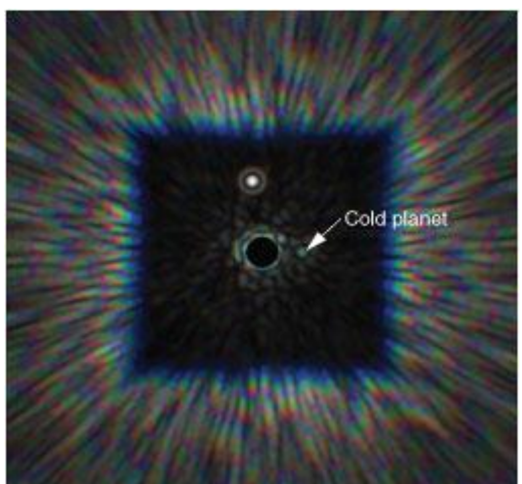
2040 Actuator (2K) Continuous Facesheet DM

High Actuator Count DM Technology Drivers

Ground & Space-Based Telescopes

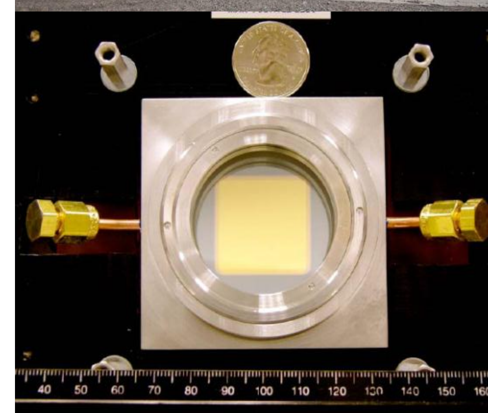
- Imaging and spectroscopic measurements of exoplanets
  - Gemini Planet Imager (GPI) first light scheduled for this year looking for Jupiter like planets.
  - High contrast coronagraphic imaging for discovery of new earth like planets.

Example coronagraph



IMAGING & CHARACTERIZING EXOPLANETS

gpi



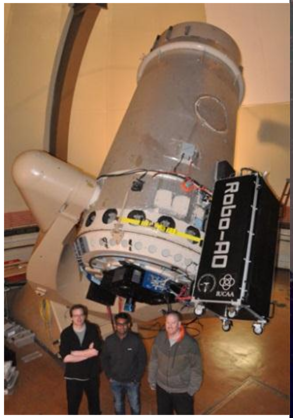
4096 Element Mirror

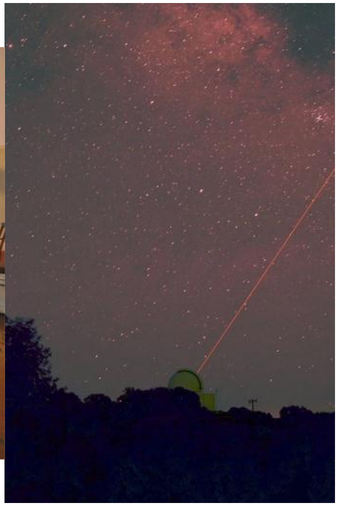
Ground based telescopes using BMC DMs

- Lick Observatory (VILLAGES):
  - 140DM used for visible AO on 1m telescope (2007)
  - Visible AO using Kilo DM on 3m telescope (on-sky 2013)
- Gemini (GPI): High contrast AO system using a 4k DM (on sky 2013)
- Subaru Telescope (SCExAO): Subaru Coronagraphic Imager with Extreme Adaptive Optics using our newly designed 2K
- Palomar Observatory (Robo-AO): Low-cost, autonomous, integrated laser adaptive optics system using 140 element DM (2011)

DMs in many other test beds around the world


Lick Observatory, Mt Hamilton, CA

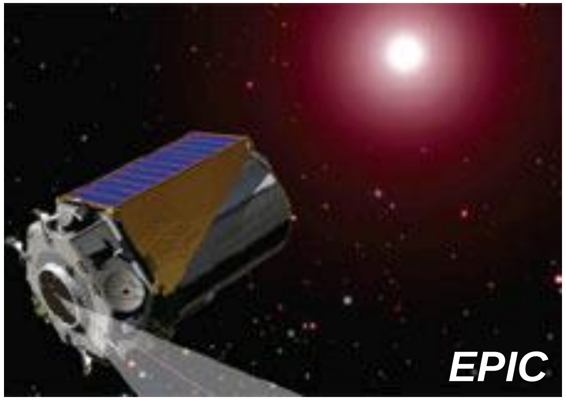




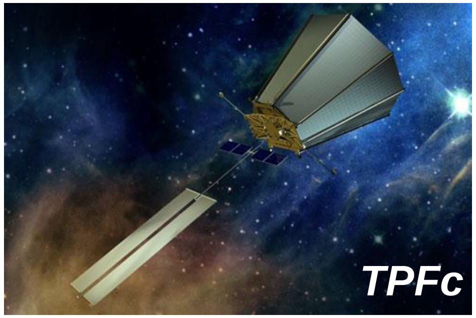
http://www.astro.caltech.edu/Robo-AO/

MEMS DMs for Space Telescopes

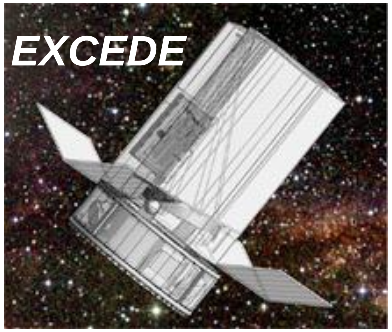
- Correction of static and slow moving (thermal) aberrations in space-based optical imaging systems
  - Astronomy – Direct Planet Detection
    - High Contrast Imaging



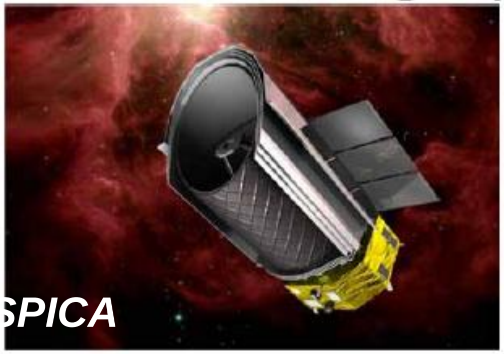
Extrasolar Planetary Imaging Coronagraph



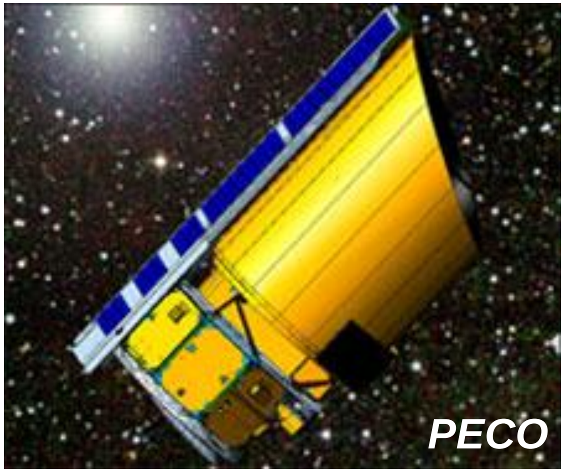
Terrestrial Planet Finder Coronagraph



The Exoplanetary Circumstellar Environment and Disk Explorer



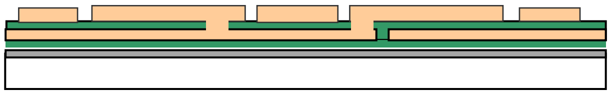
Space Infrared Telescope for Cosmology and Astrophysics



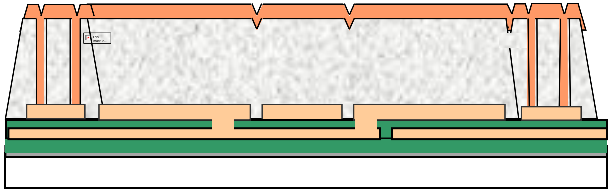
Pupil-mapping Exoplanet Coronagraphic Observer

MEMS DM Fabrication

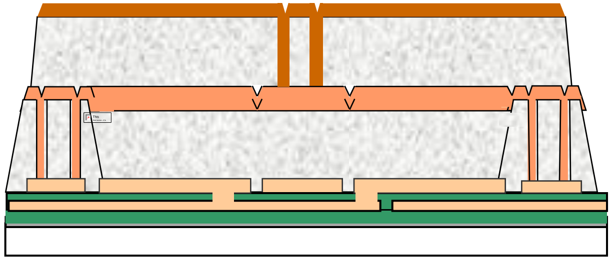
(deposit, pattern, etch, repeat)



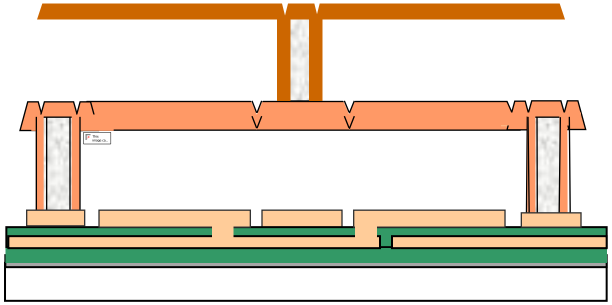
Electrodes & wire traces:
polysilicon (conductor) & silicon nitride (insulator)



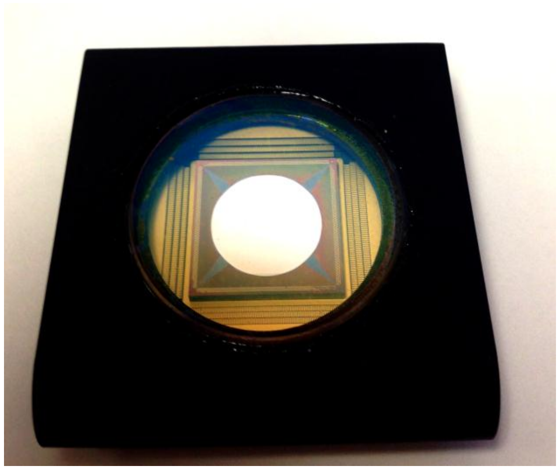
Actuator array:
oxide (sacrificial spacer) and polysilicon (actuator structure)



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

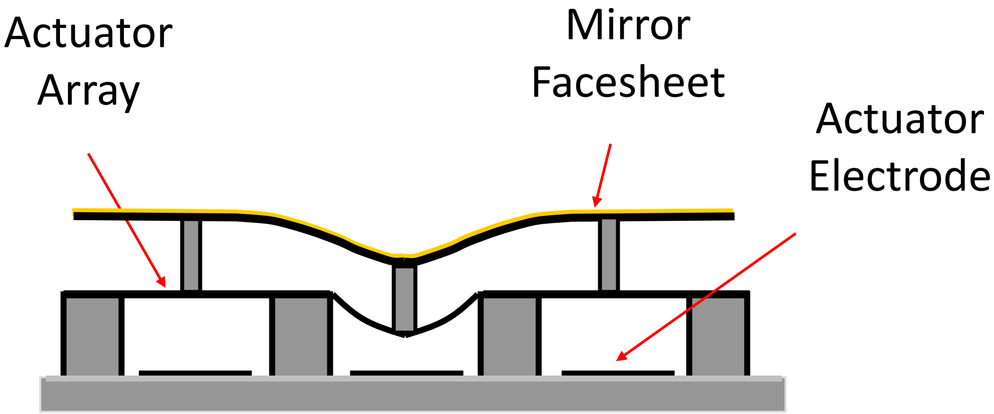


MEMS DM:
Etch away sacrificial oxides in HF, and deposit reflective coating

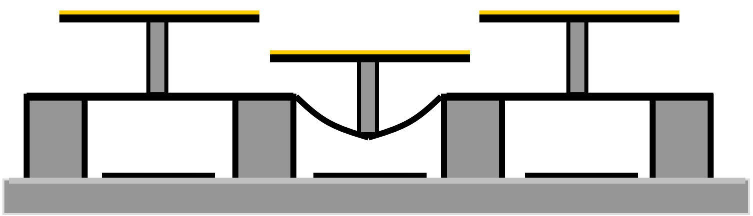


Attach die to a ceramic package and wirebond

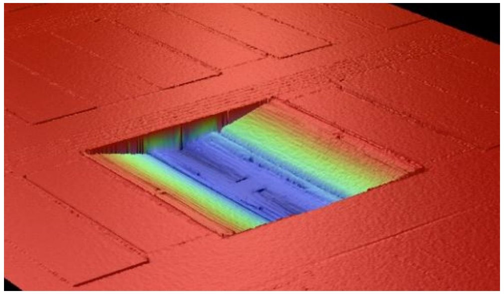
MEMS DM Architecture



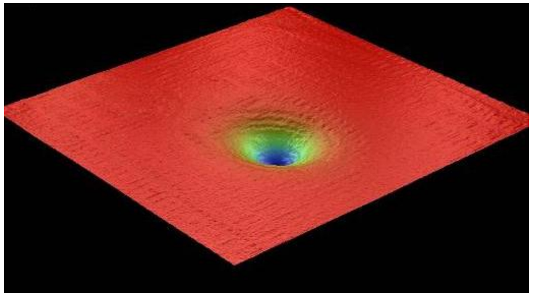
Continuous mirror
(smooth phase control)



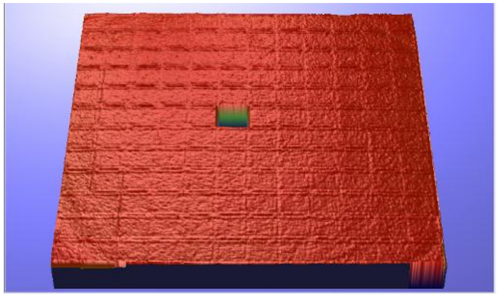
Segmented mirror
(uncoupled control)



Deflected Actuator



Deformed Mirror Membrane



Deformed Segmented Mirror

BMC Mirror Architecture

- **Mirror Properties**
  - Strokes up to 5.5µm
  - Current actuator spacing from 250 to 450µm
  - Surface figure <20nm RMS
  - Aluminum, Gold or Protected Silver coatings
- **Technology Advantages**
  - No hysteresis
  - Repeatable positioning
  - Low power operation
  - Fill factor (>99.8%)
    - Continuous devices
  - No polarization effects
  - Mechanical response time as low as 15µs
  - Drive electronics frame rates of up to 100kHz

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

MEMS development programs

Recently Closed:

SBIR Phase II Contract # NNX11CB23C

Enhanced Fabrication Processes Development for High Actuator Count Deformable Mirrors

Open Contracts:

SBIR Phase II Contract # NNX13CP03C

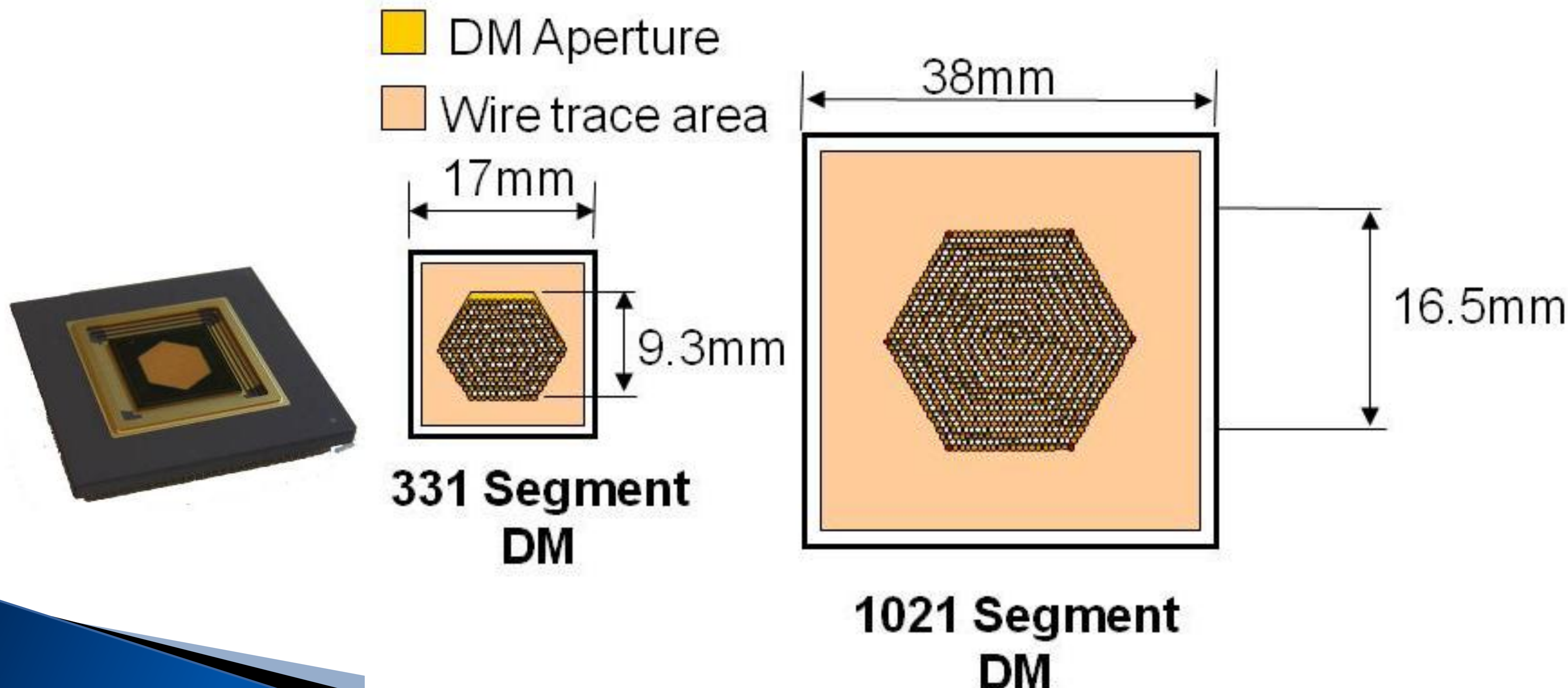
Topography Improvements in MEMS DMs for High-contrast, High-resolution Imaging

SBIR Phase II Contract # NNX12CA50C

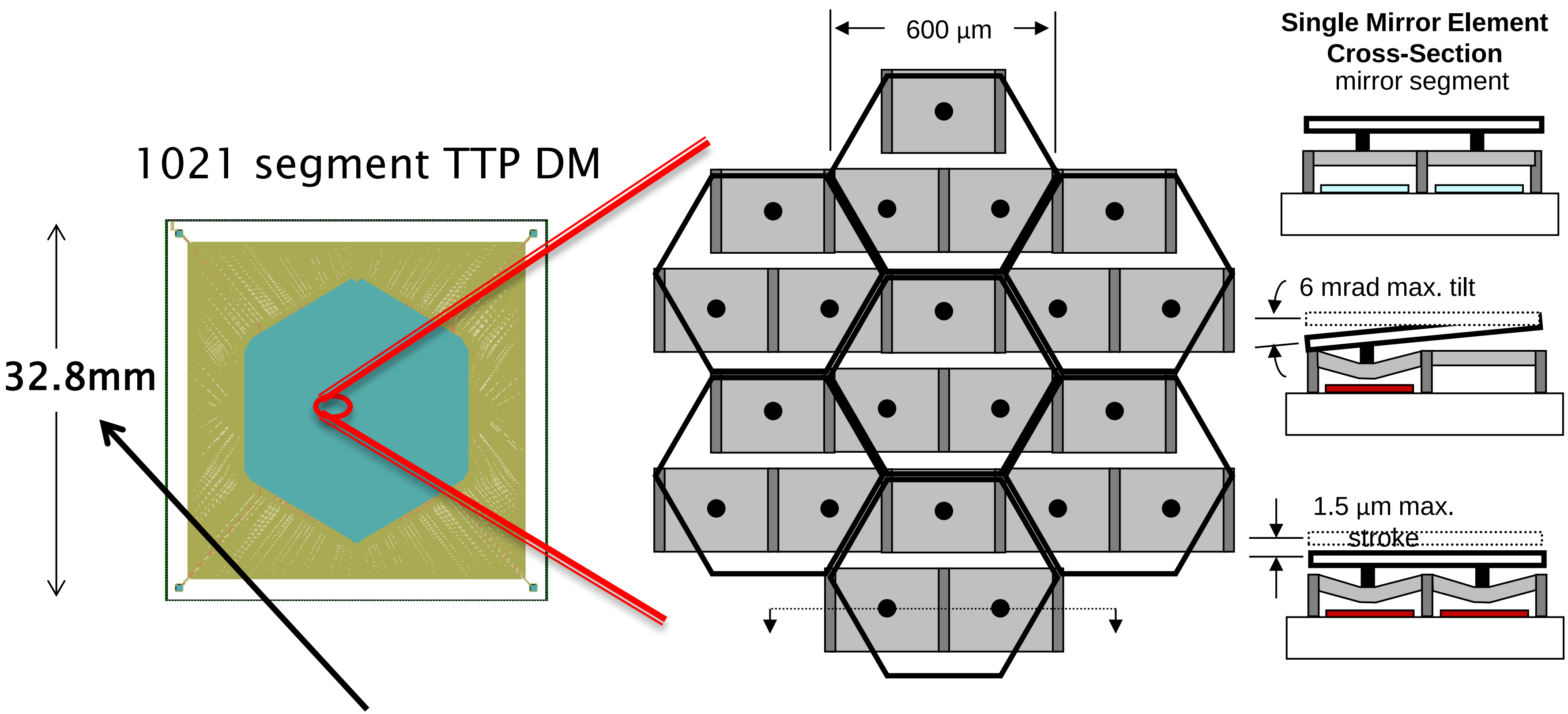
Enhanced Reliability MEMS Deformable Mirrors for Space Imaging Applications

Program Objectives

- Scale up a previous mirror design from 331/993 segments/actuators to 1021/3063
- Improve overall device yield

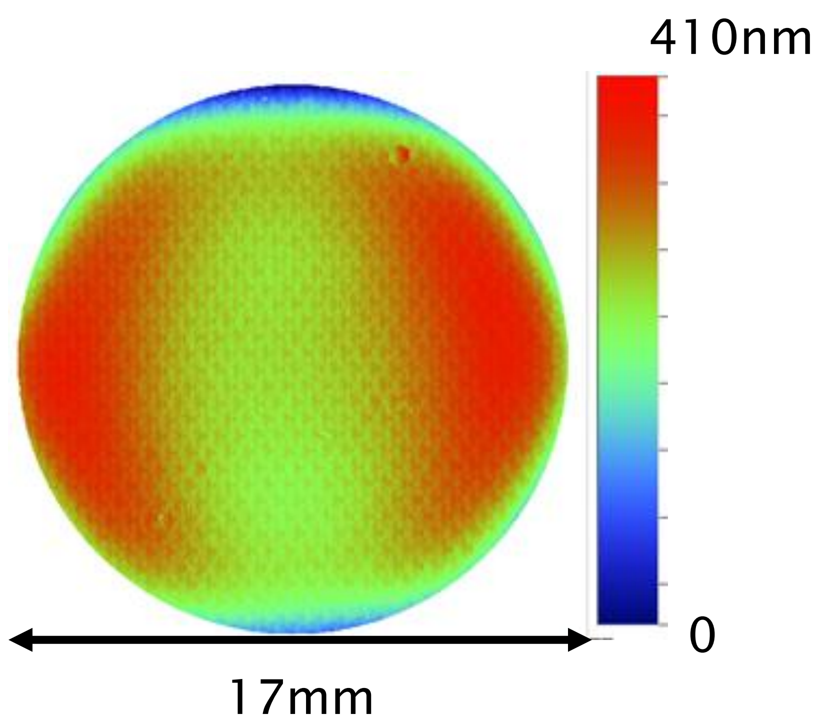


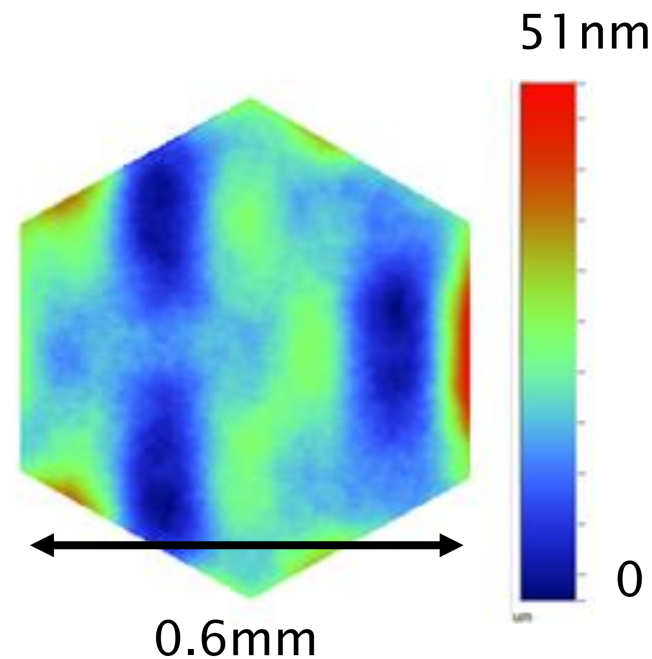
Tip/Tilt/Piston Mirror Architecture



Die size minimized through design optimization for Improved device yield

Tip/Tilt/Piston DM Development Results





Segment RMS 7nm

Active Aperture Unpowered Surface Figure

Tip/Tilt/Piston DM Electromechanical Results

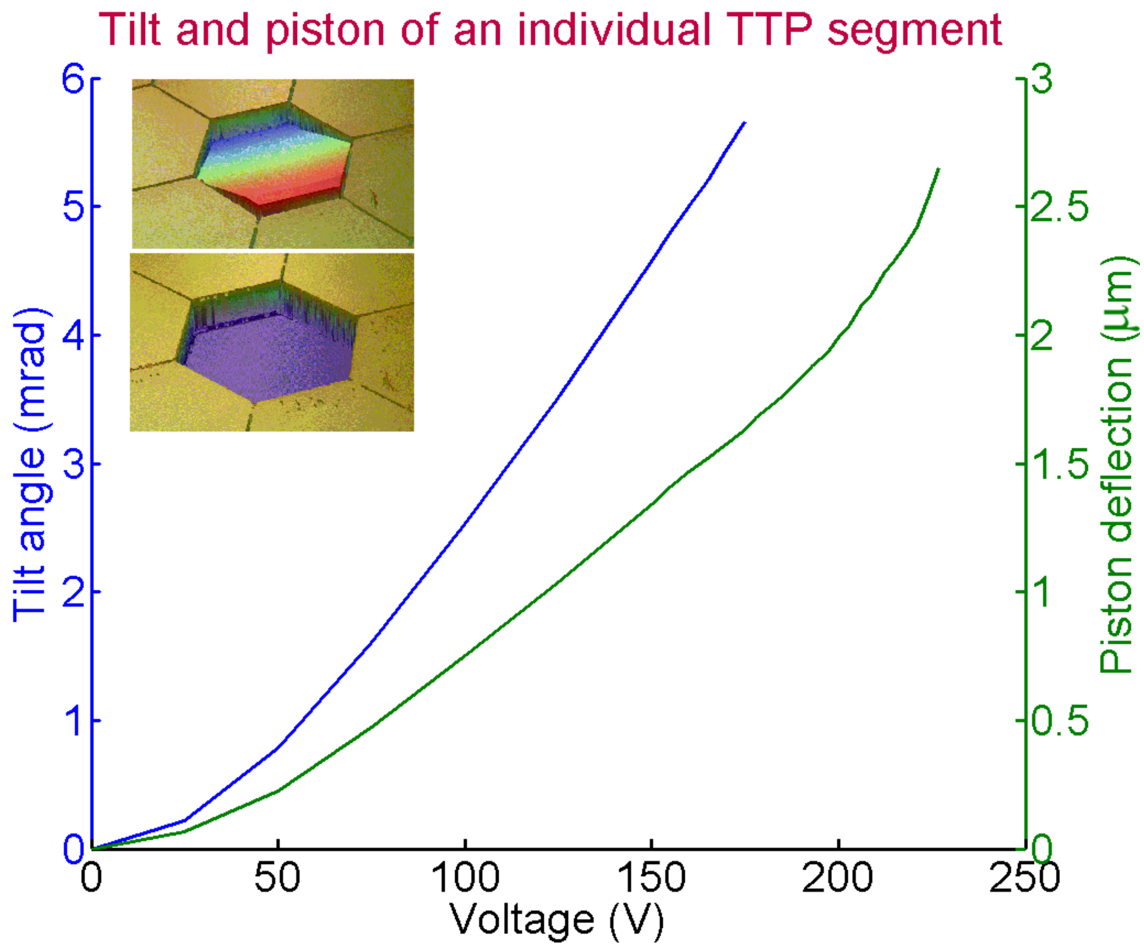
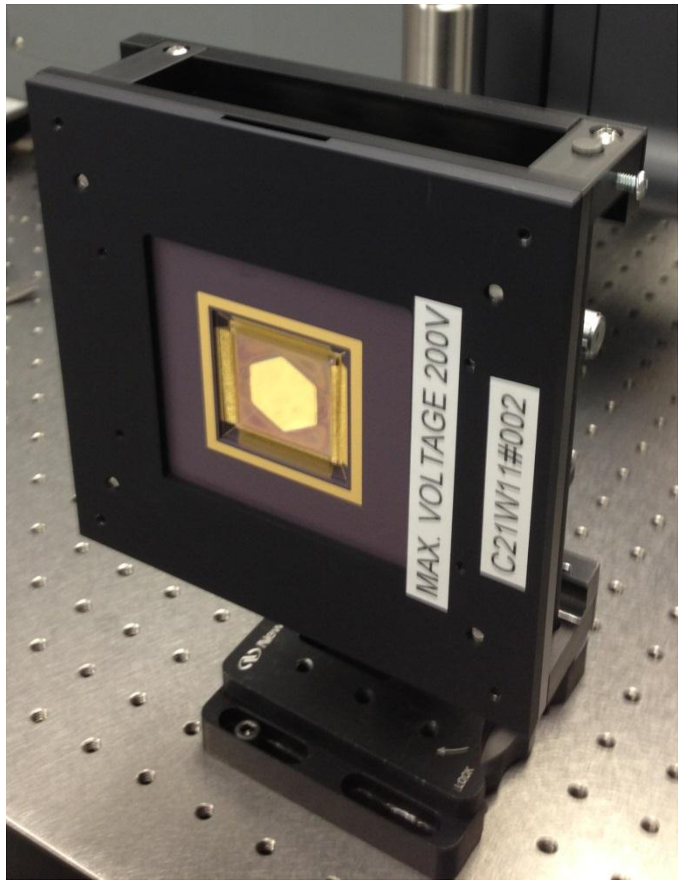


Figure 16. Tilt (blue) and piston (green) for an individual segment.

Tip/Tilt/Piston DM Development Results

Delivered to JPL June 2013

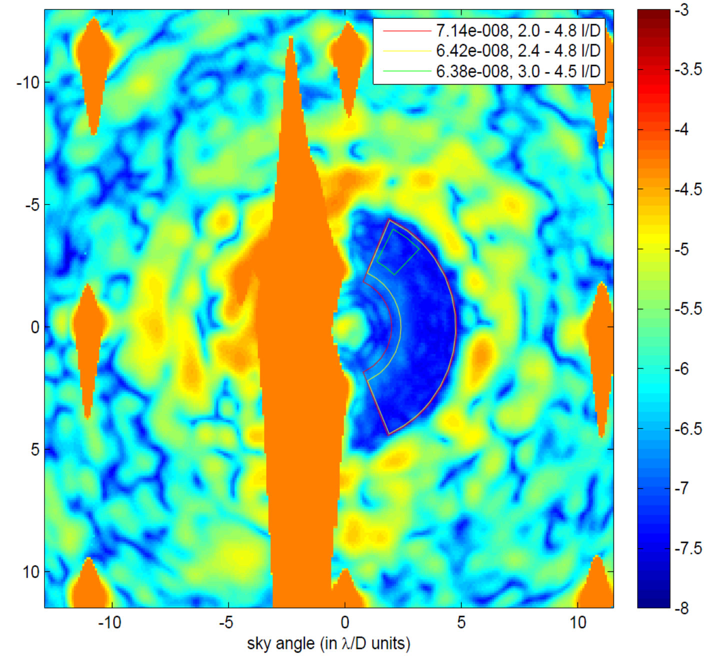


99% Actuator Yield

Topography Improvement

Program Objectives

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

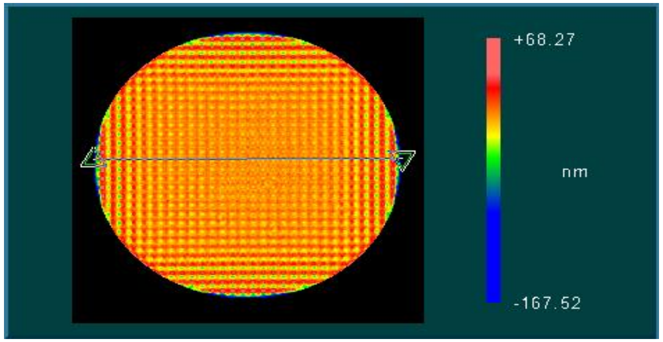


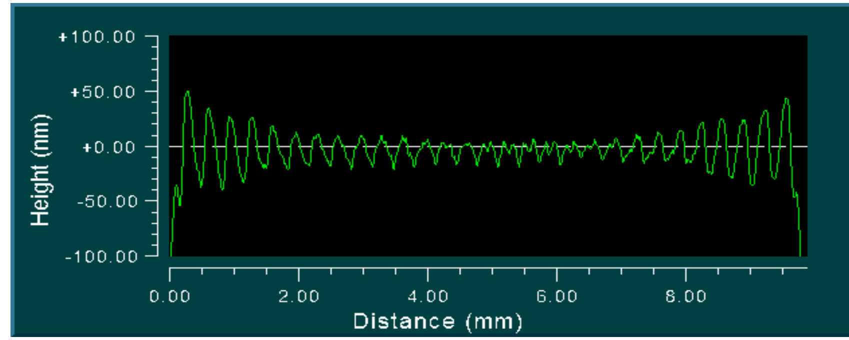
The presence of the diffraction peaks in the image plane creates optical problems:

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

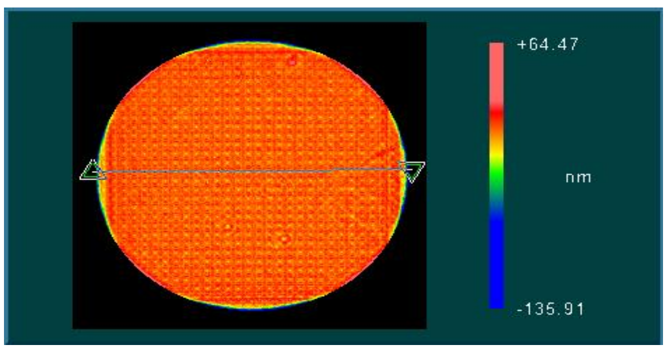
Topography Improvement Results

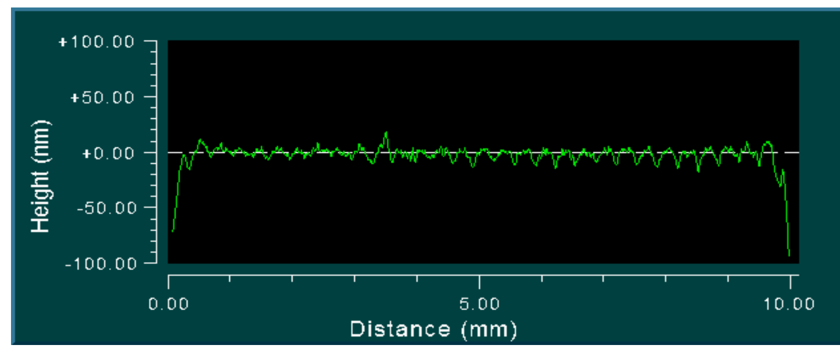
Scalloping Reduction





Kilo DM Before Film Treatment





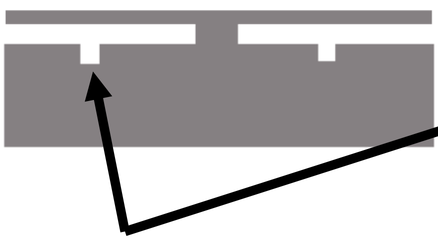
Kilo DM After Film Treatment

Topography Improvement Results

Print Through Reduction

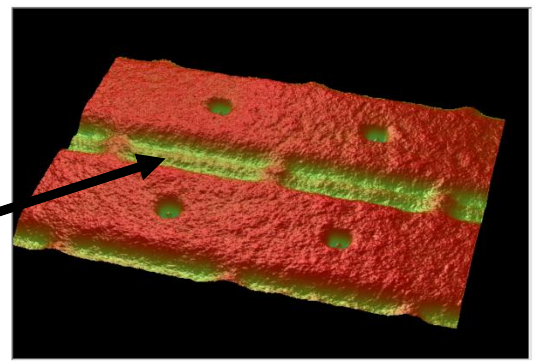
Process Development Experiments

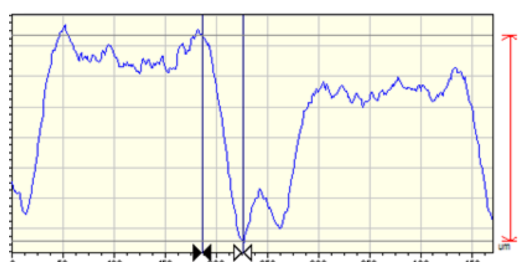
Side view of short loop structure



Substrate etch simulates actuator topography

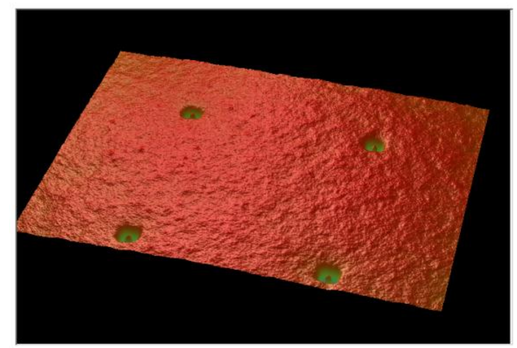
Heritage Anneal

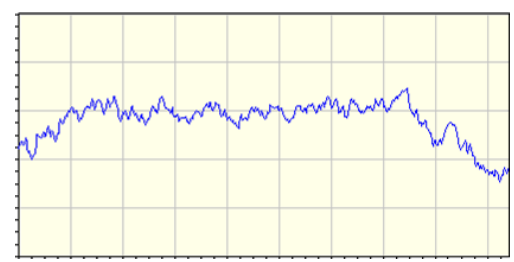




34nm P-V

Modified Annealing Process



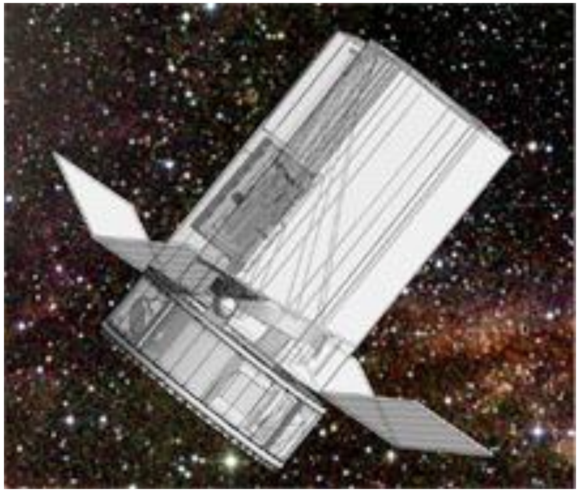


2nm P-V

Enhanced Reliability
Program Objectives

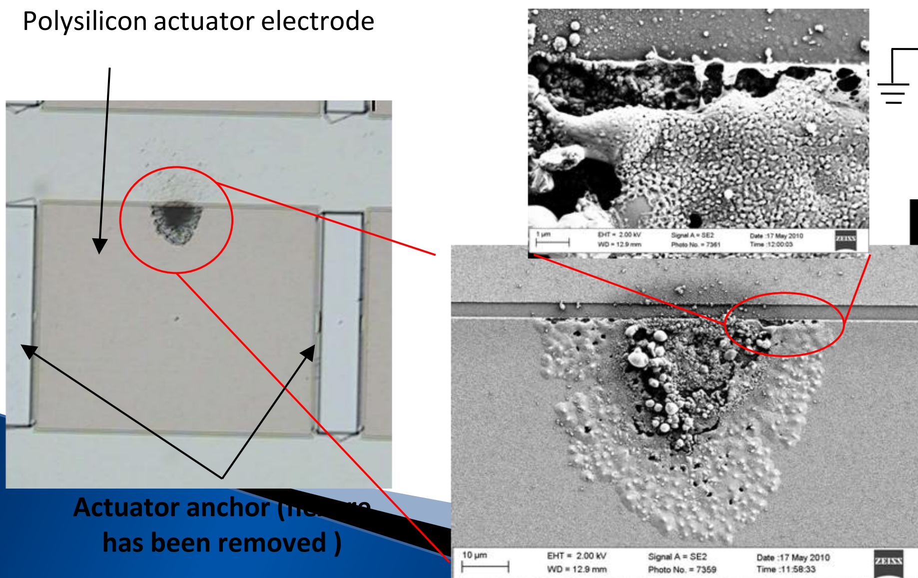
- Demonstrate the ability to prevent single point failures resulting from electrical overstress, that is caused by electronic or software faults that may occur during ground test or space-based operation

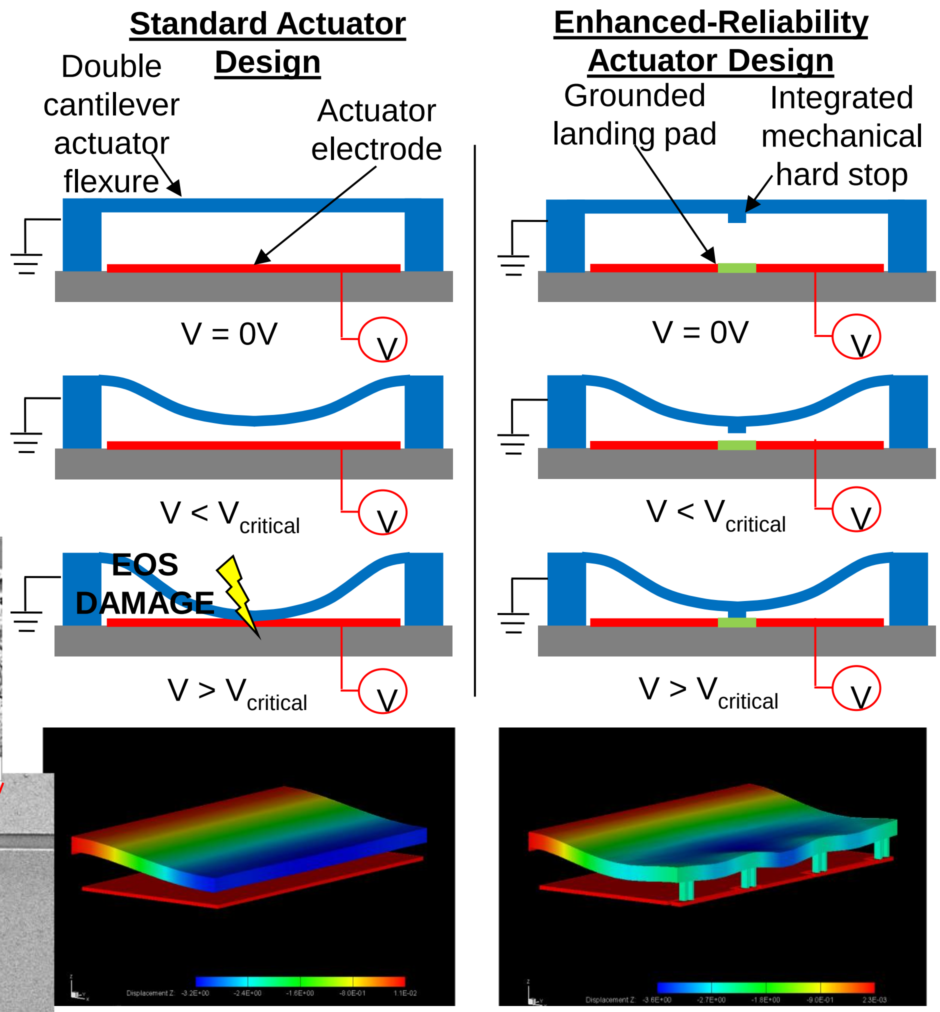
- Construct a 2048 actuator, continuous facesheet MEMS DM with enhanced reliability to advance the development of space-based high contrast imaging instruments



Enhanced Reliability DM Actuator Development

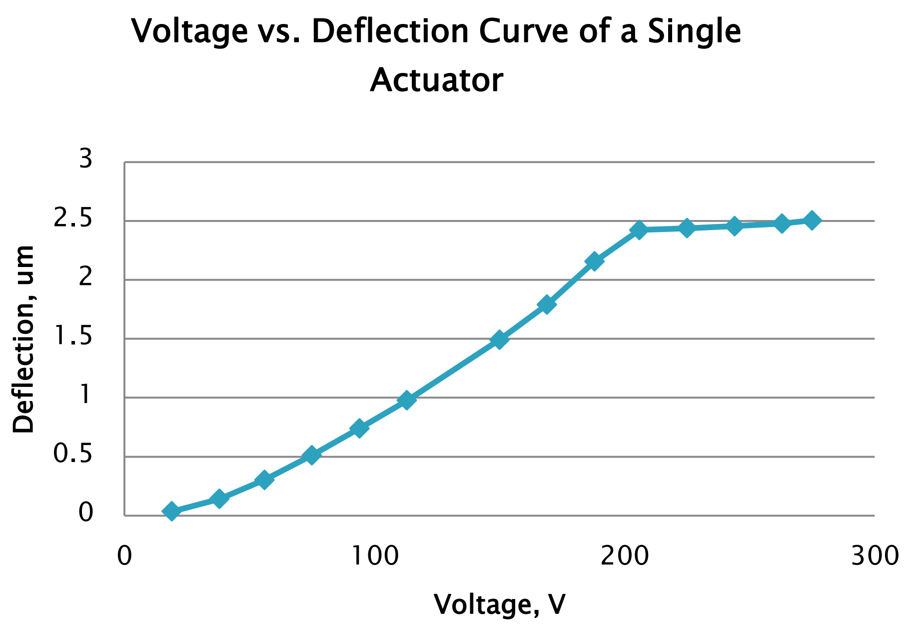
- In Phase I, mechanical hard stops were integrated in the actuator design to prevent EOS
- If EOS occurs, the hard stops touch down on a grounded landing pad which prevents the actuator flexure from touching the actuators electrode



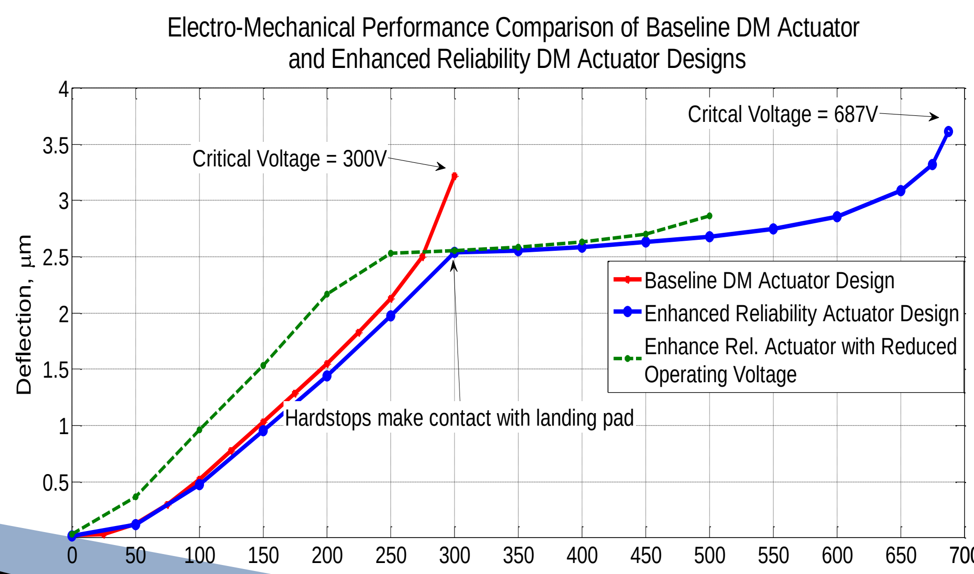


Actuator Array Performance

A voltage versus deflection curve of an actuator.

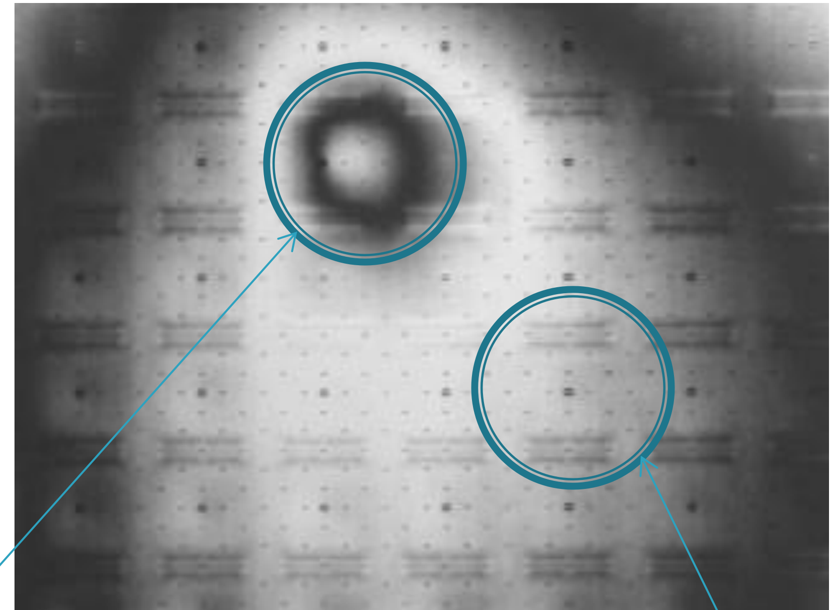


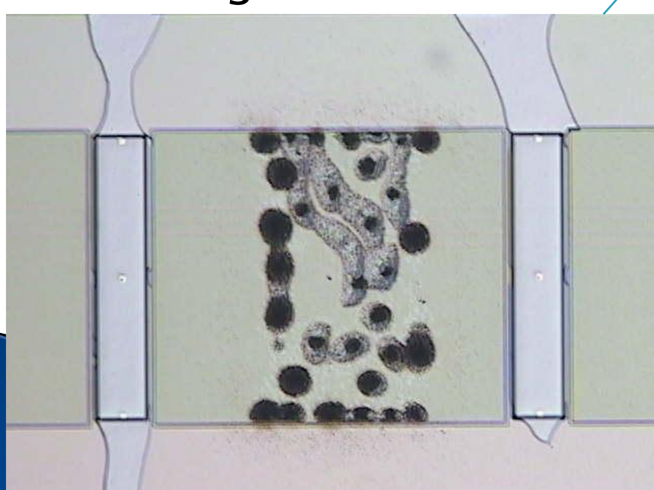
Voltage deflection results from Phase I



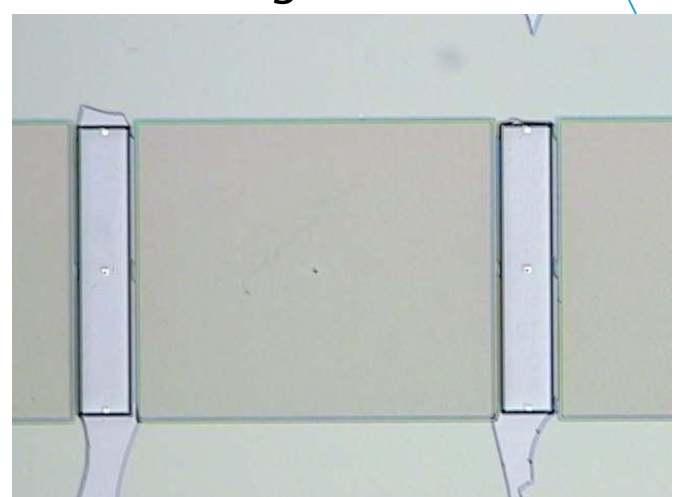
Reduction of Snap-Through Related Damage

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





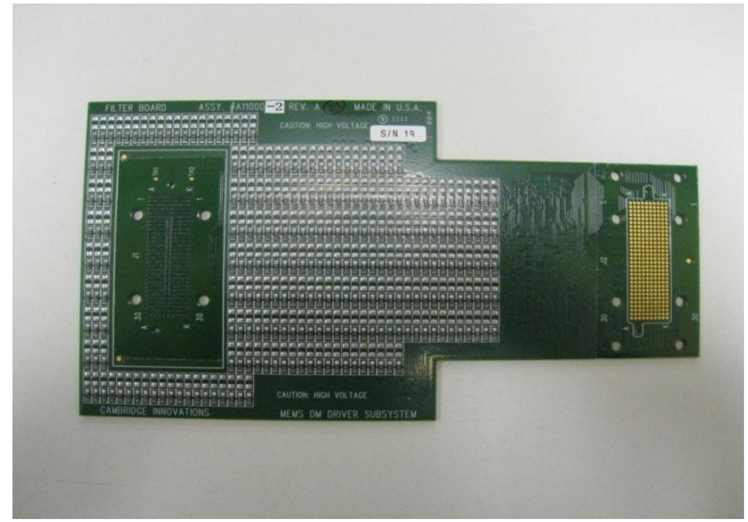
Electrode Without Current Limiting Electronics



Electrode with Current Limiting Electronics

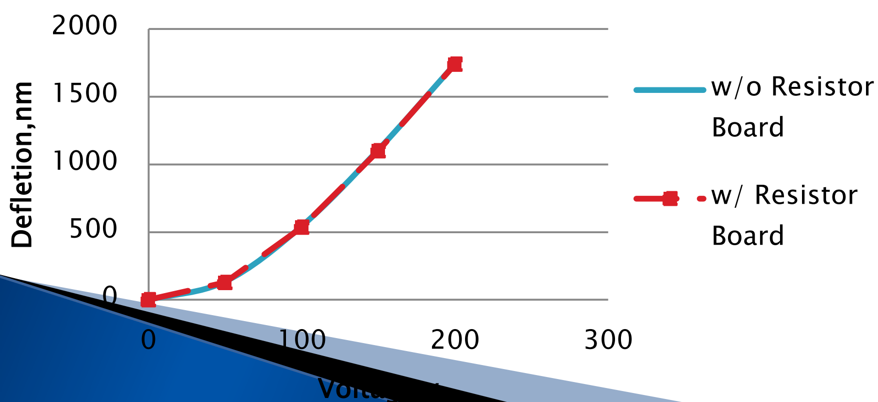
Current-limiting Resistor Boards

- 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

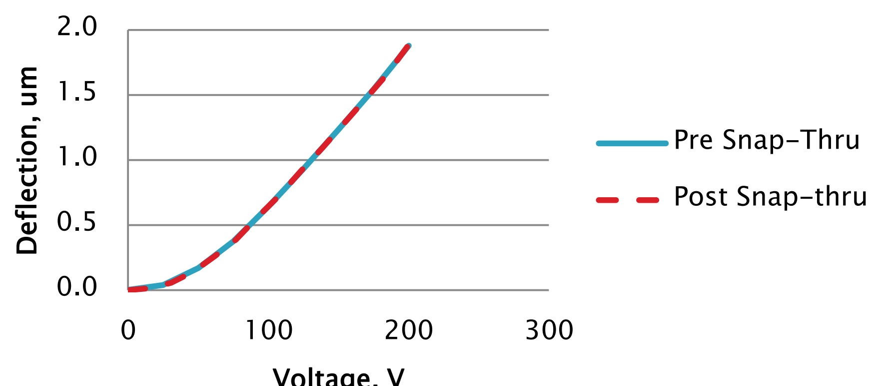


Comparison of Voltage vs. Deflection Curves of a 4x4 Actuator Array

With and Without Resistor Boards



Pre and Post Snap-Through

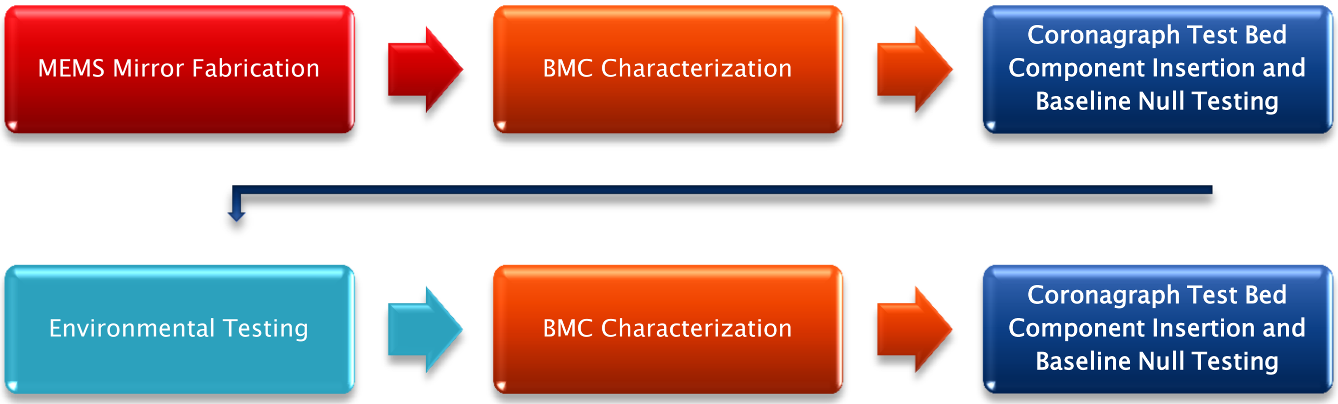


TDEM Project Overview

Project Name: MEMS Deformable Mirror Technology Development for Space-Based Exoplanet Detection

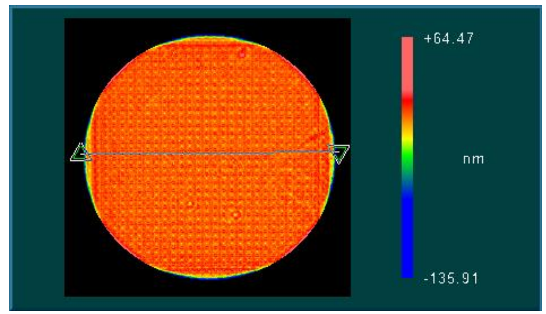
Project Objective:

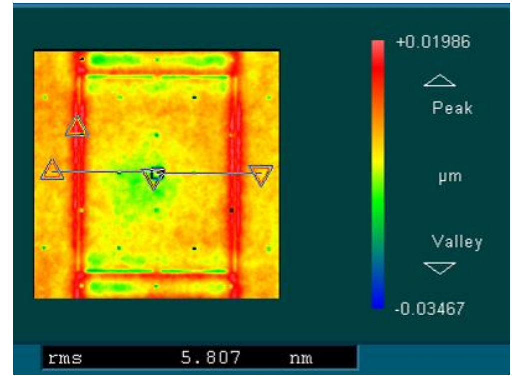
Demonstrate survivability of the BMC 952-actuator MEMS Continuous Surface Deformable Mirror (CDM) after exposure to dynamic mechanical environments close to those expected in coronagraph launch.

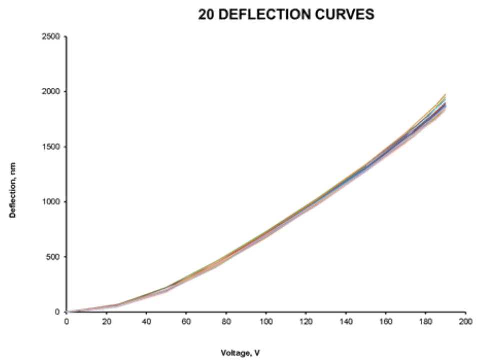


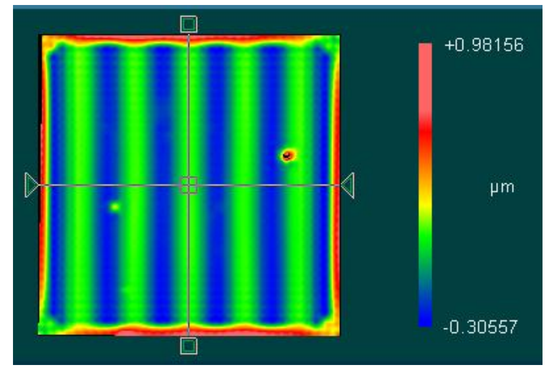
Before and After Testing Characterization

- 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.





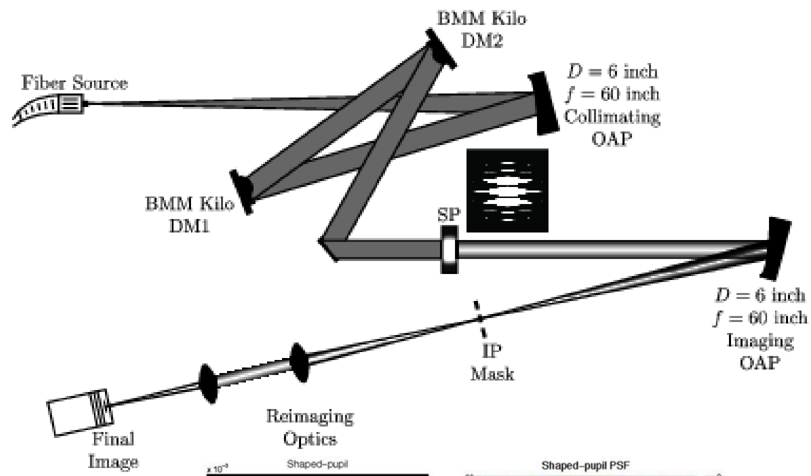


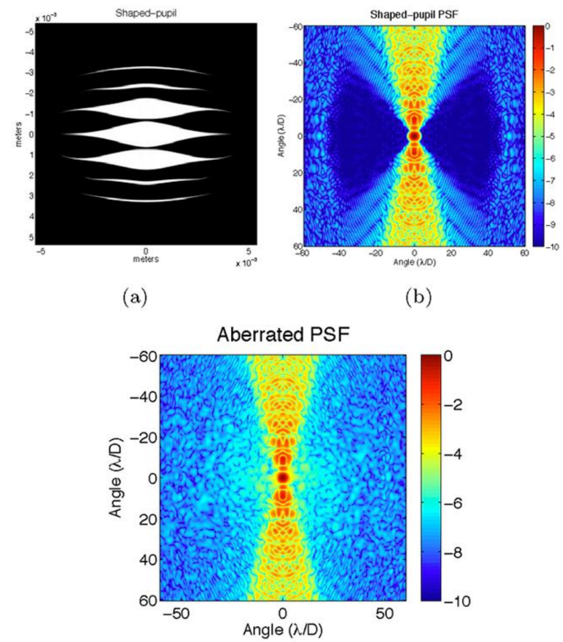


Test performed at BMC using Zygo Verifire laser Fizeau interferometer
Repeated at JPL Vacuum Surface Gauge for higher resolution measurements

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

Conclusion

- Delivered a 1021 Segment Tip-Tilt-Piston to JPL
- Promising topography improvement results
- Reliability has demonstrated prevention of failures from over voltage events.

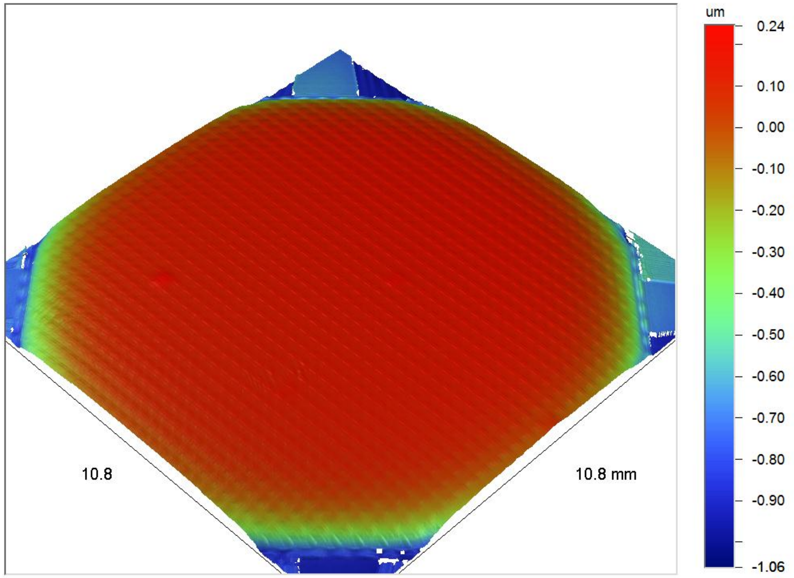
Acknowledgements

Funding from NASA

- SBIR Phase II # NNX11CB23C
- SBIR Phase II # NNX12CA50C
- SBIR Phase II # NNX13CP03C
- SBIR Phase II # NNH12CG27C

Thank You

Questions?

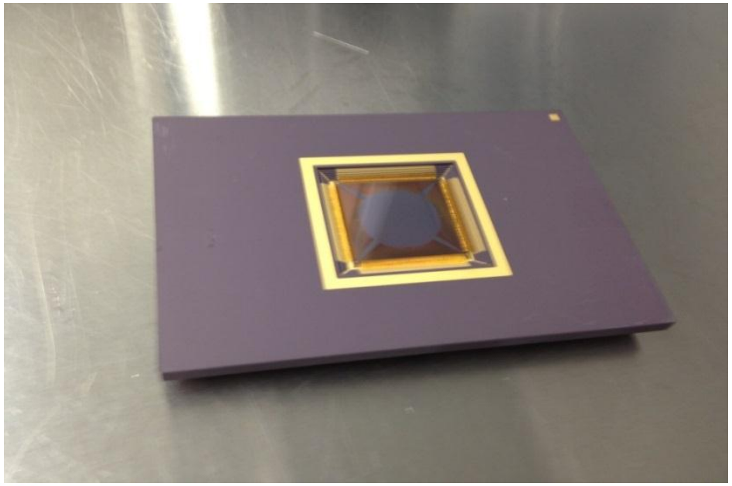


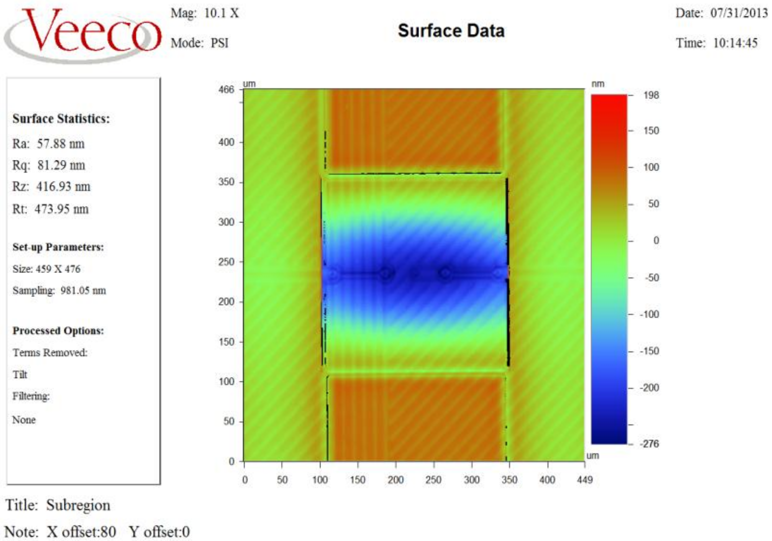
Peter Ryan, pjr@bostonmicromachines.com

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

Why MEMS for DMs?

Design

Easier to scale to larger arrays (**~4000**) needed for large telescope AO

Smaller size/weight/power needed for space-based AO

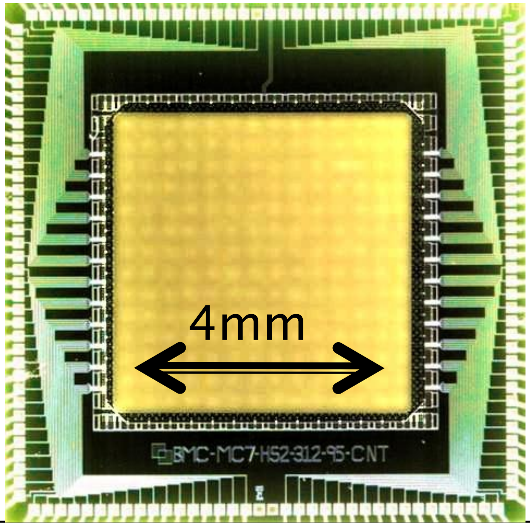
Manufacturability

10x Lower cost (**~$150/actuator**) than macroscale devices

Batch produced (vs. manual assembly)

Performance

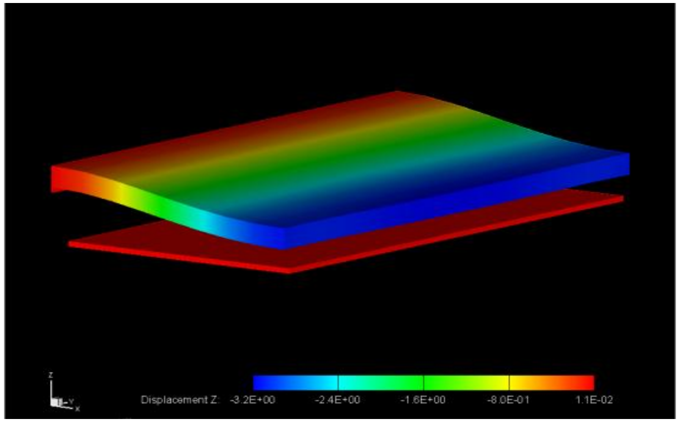
- No hysteresis
- Reliable
- Fast temporal response
- Predictable
- Compact
- Low Power
- Polarization and wavelength insensitive



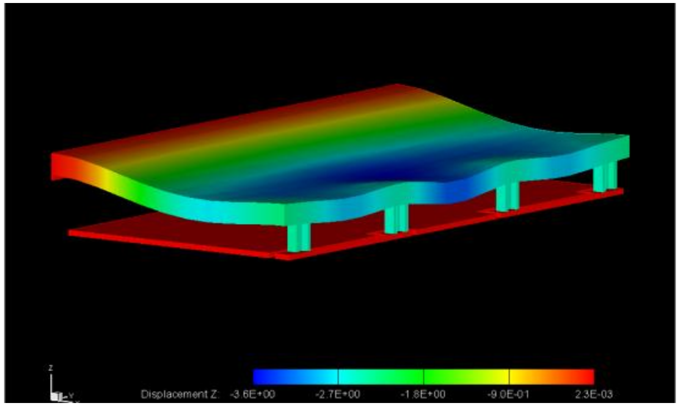
The advantages of these MEMS DMs have inspired a new generation of imaging instruments, and laser beam control systems

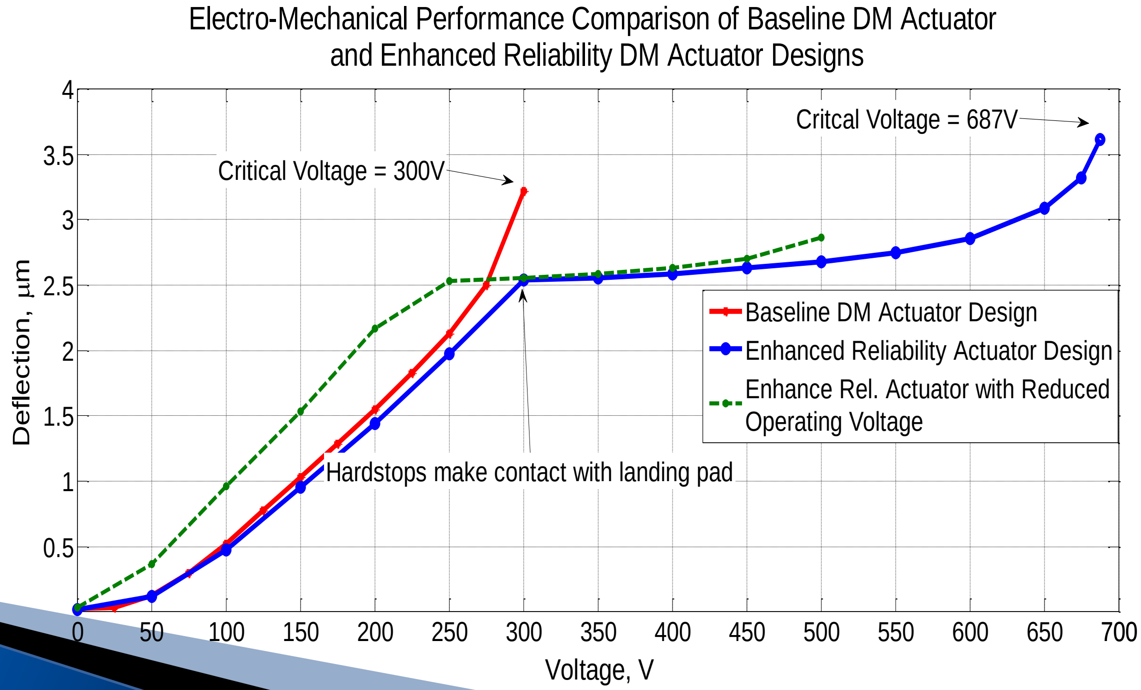
New Actuator Electromechanical Performance

Baseline Actuator Design



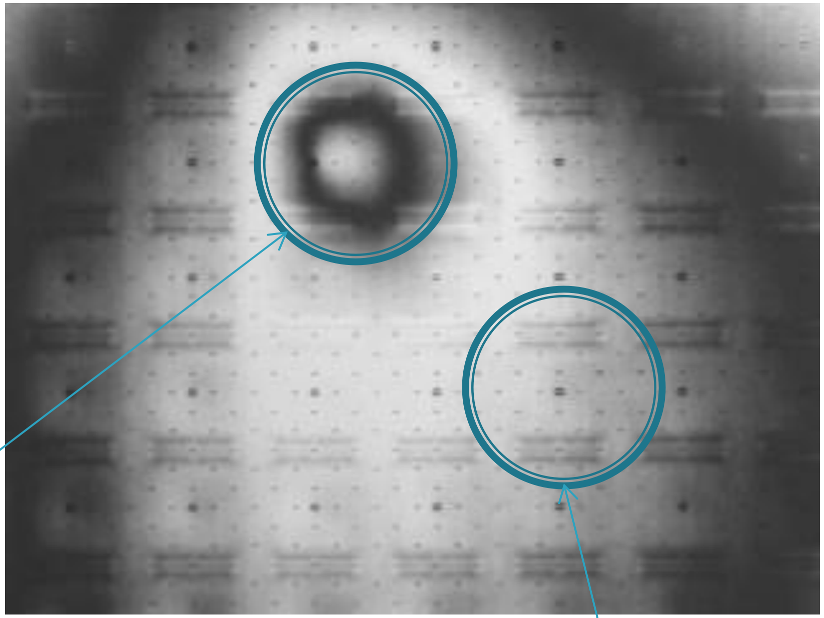
Enhanced Reliability Actuator Design



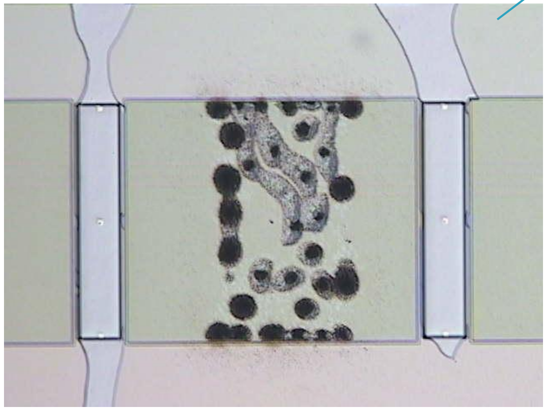


Prevention of Snap-Through Related Damage

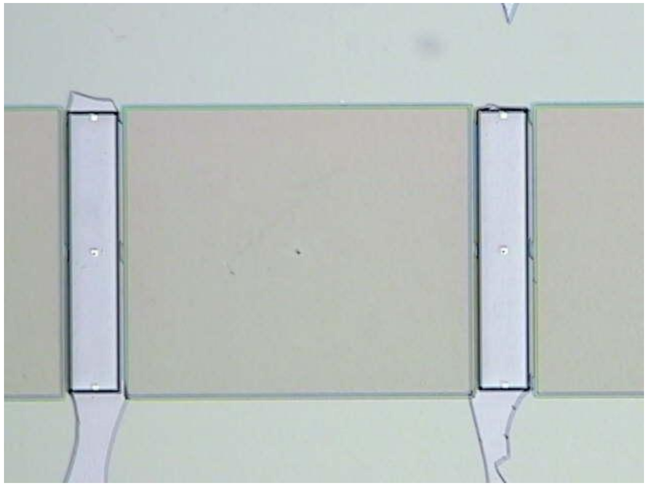
- Addition of current limiting elements further increases overall MEMS DM reliability
  - Eliminates high-current densities at snap-through



Without Current Limiting electronics

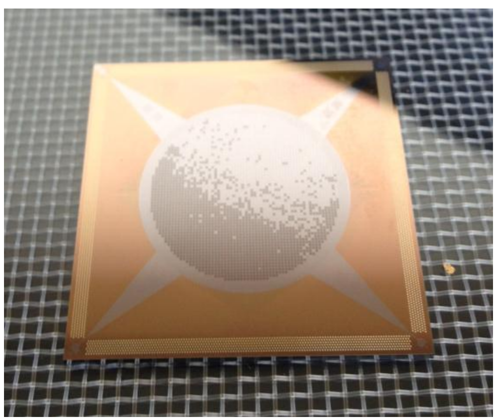


With Current Limiting electronics

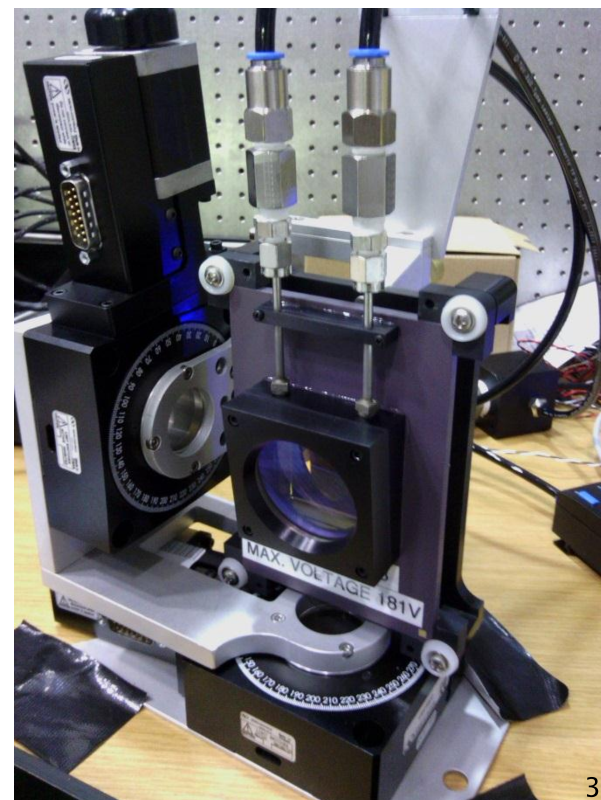


Topography Improvement Work Remaining

- 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

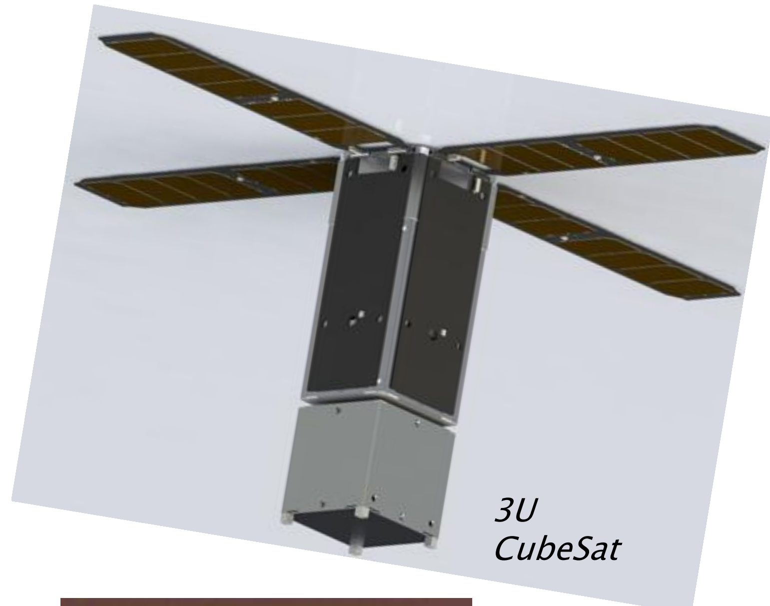


2K DM in it's optical mount

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

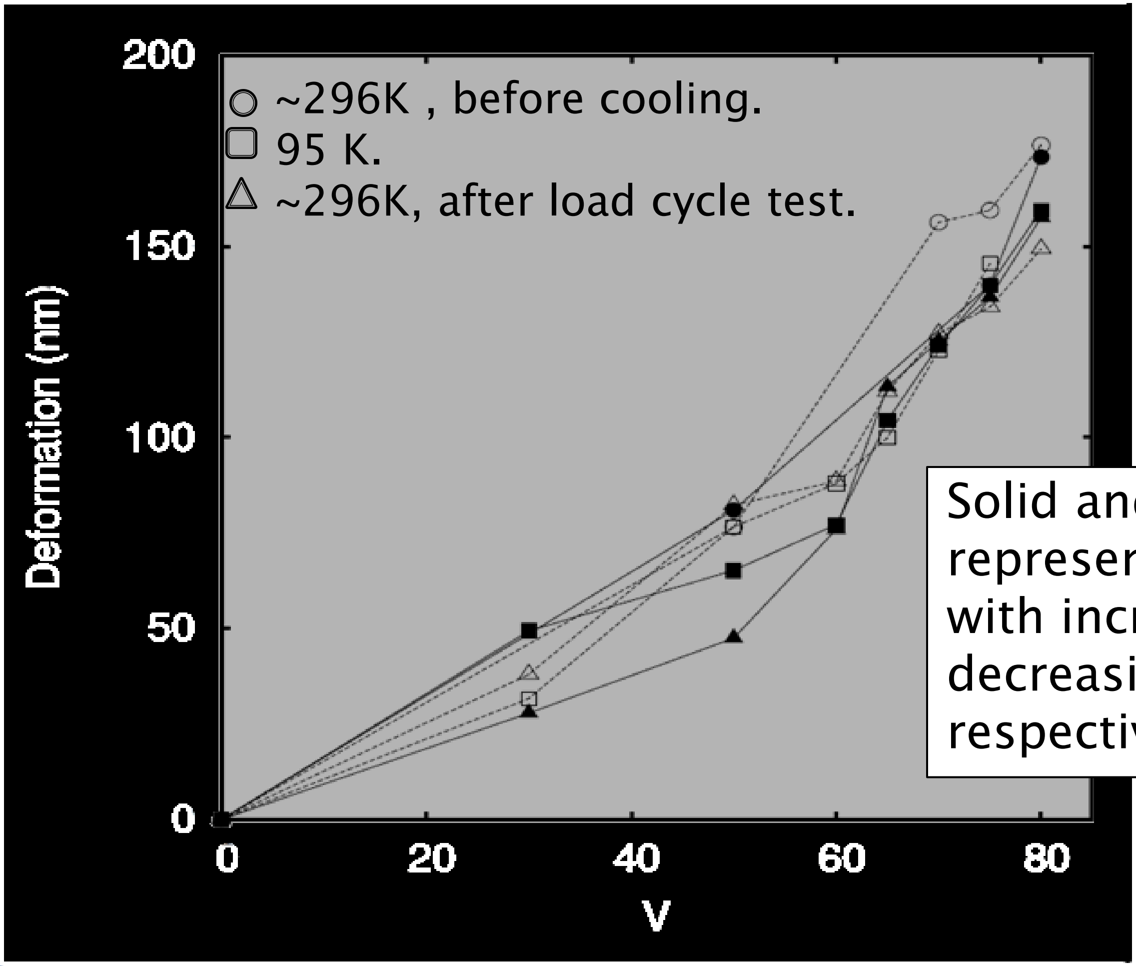
Thermal Testing

- 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

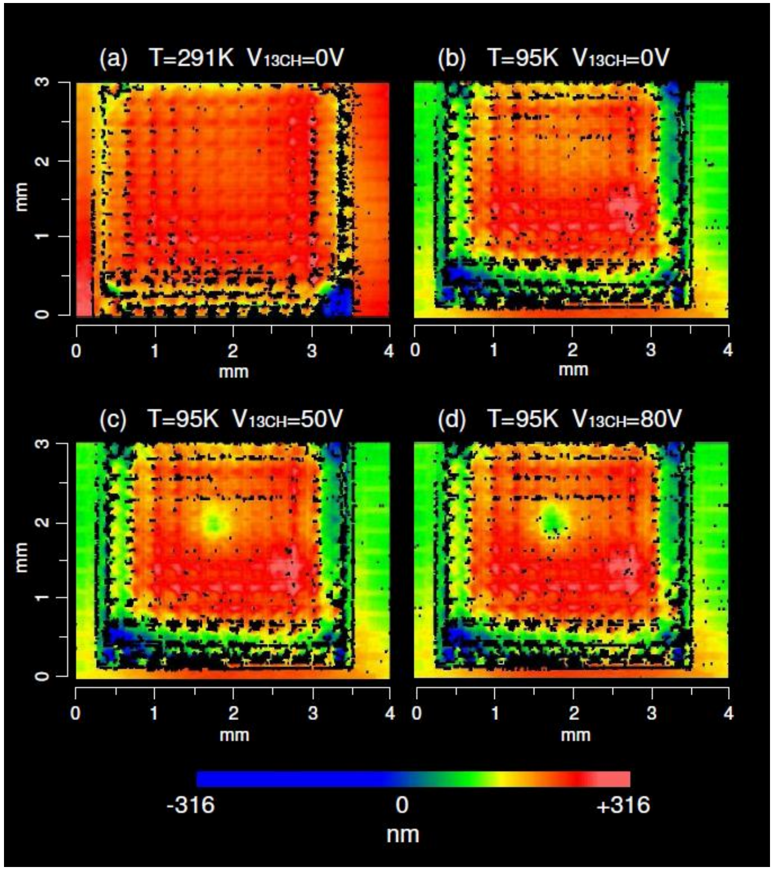
Voltage deflection measurements



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

Thermal Testing Results

Interferometric 3D surface data



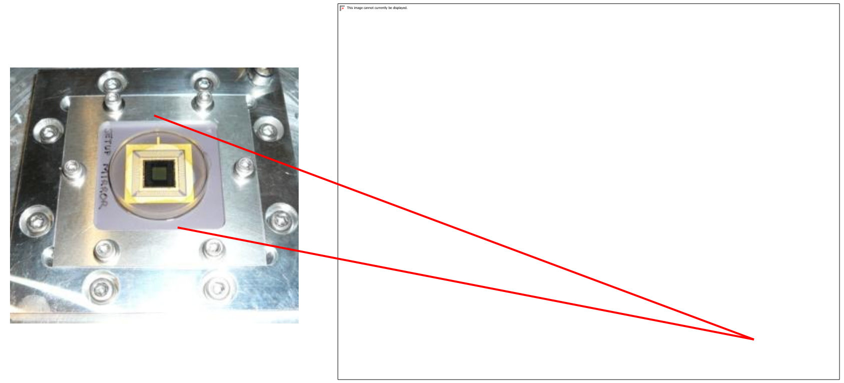
All data were obtained by measurements made through the window of the vacuum cryostat.

(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)

PICTURE project payload was shake tested with the DM in place

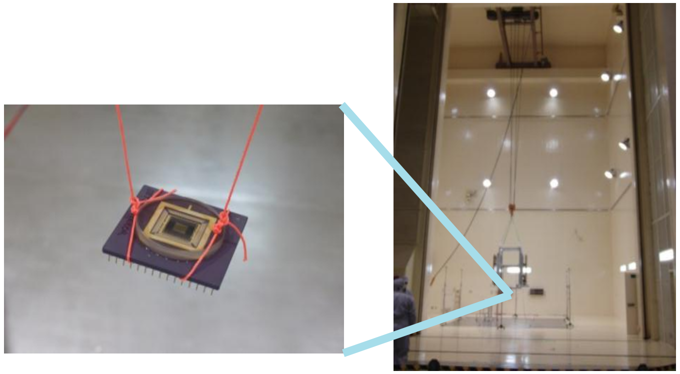
- DM: Kilo - DM
- Performed at: Wallops Flight Facility
- Test sequence: NASA Vehicle Level 2 levels
- Spectrum:

  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



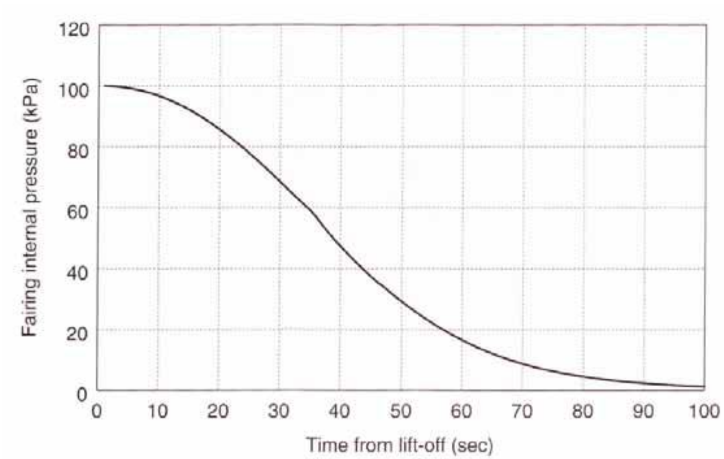
1/1oct center frequency	Acoustic pressure (dB)	Tolerance
31.5	128.0	+5/-10 dB
63	135.0	+- 3dB
125	139.6	+- 3dB
250	138.0	+- 3dB
500	135.0	+- 3dB
1000	132.0	+- 3dB
2000	129.0	+- 3dB
4000	124.0	+3- 10dB
8000	118.0	+- 6dB
Over all	144.0	+- 2dB

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

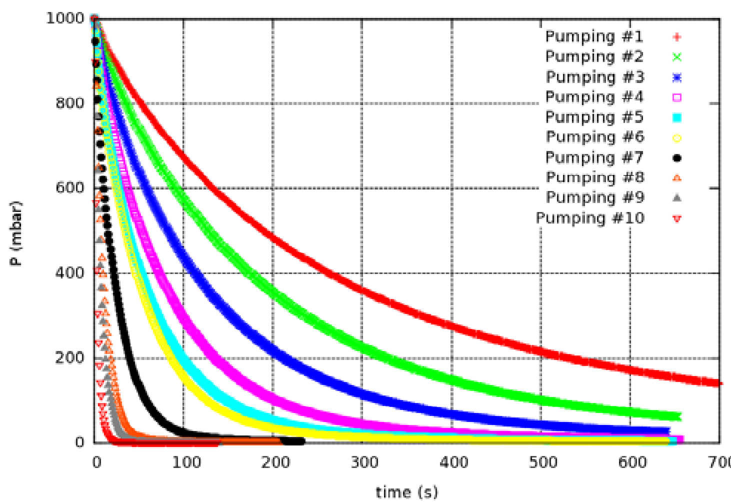
Rapid Pumping Testing

- 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



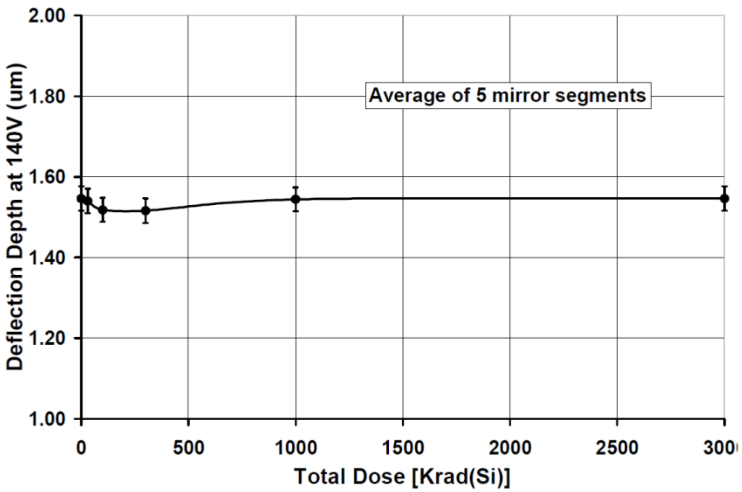
Testing results



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*