Recent Progress in MEMS Deformable Mirrors

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BOSTON MICROMACHINES CORPORATION
SHAPING LIGHT

Mirror Technology/SBIR/STTR Workshop
Northrop-Grumman Aerospace Systems Presentation Center
Redondo Beach, California, United States
16 November 2017

SPIE.
CONNECTING MINDS. ADVANCING LIGHT.

Outline

- BMC DM Technology
- NASA funded mirror technology programs
- Space astronomy operations
- Ground astronomy operation

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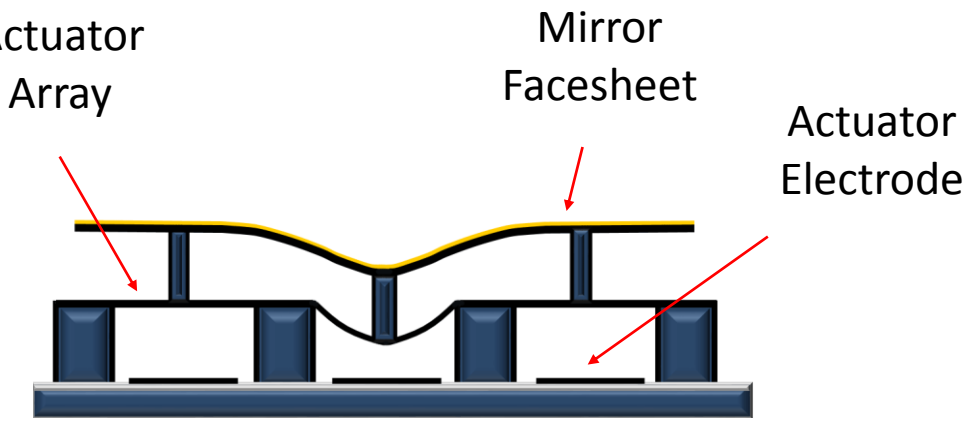
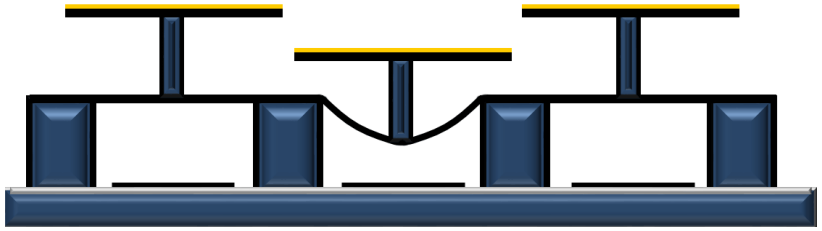
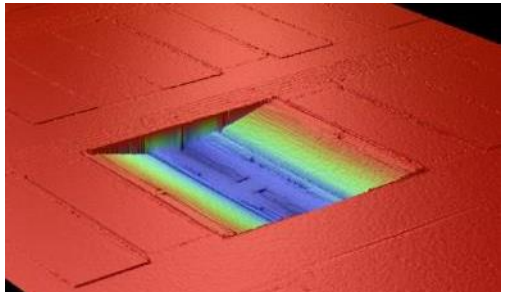
MEMS DM Architecture



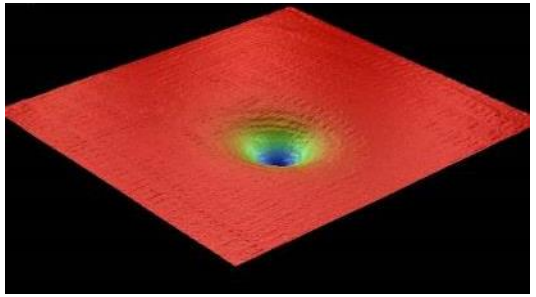
Continuous mirror
(smooth phase control)



Segmented mirror
(uncoupled control)



Deflected Actuator



Deformed Mirror Membrane

Deformed Segmented Mirror

BMC Mirror Family

Small Cartesian Arrays

- Square arrays from 32 to 140 actuators
- Strokes: 1.5µm, 3.5µm or 5.5µm

Medium Cartesian Arrays

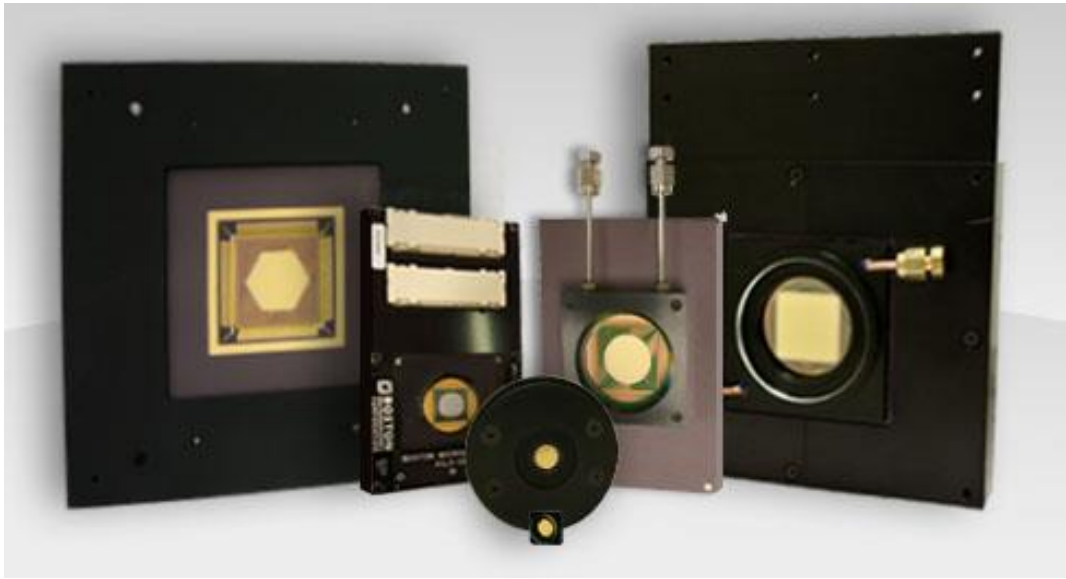
- Square and circular arrays from 492 to **1020**
- 1.5µm & 3.5µm stroke

Large Cartesian Arrays

- Square and circular arrays from **2040** to 4092
- 1.5µm and 3.5µm stroke

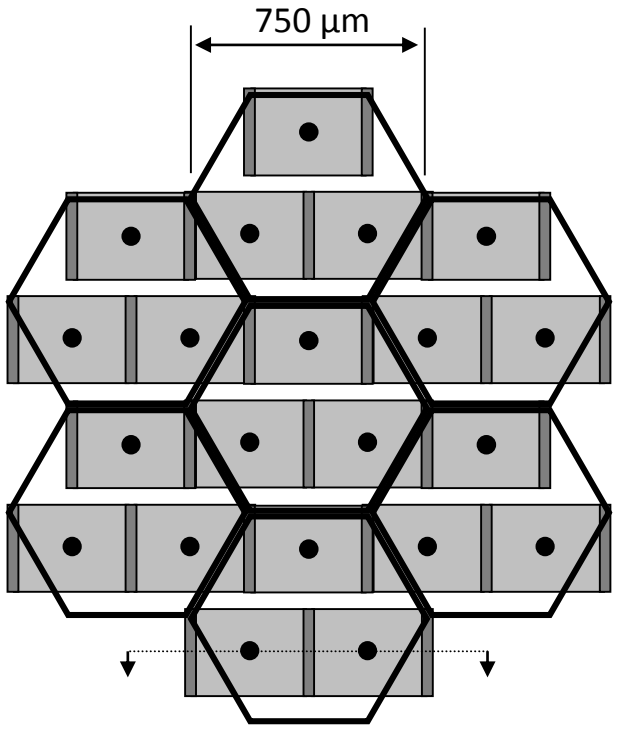
Hex Tip-Tilt-Piston

- 37, **331- and 1021-Segment Devices**

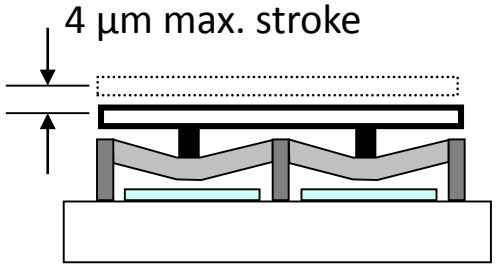


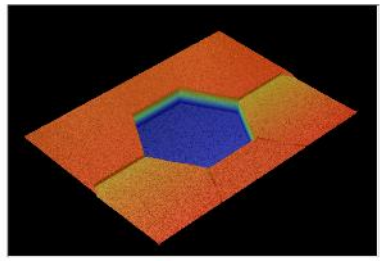
Developed through NASA funding

Hex-Close Pack Deformable Mirror
Tip-Tilt-Piston

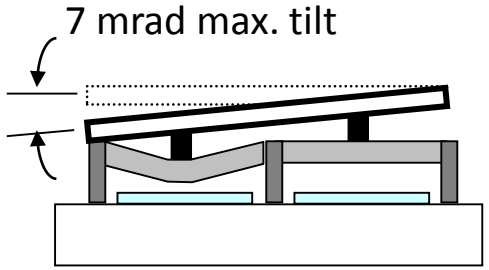


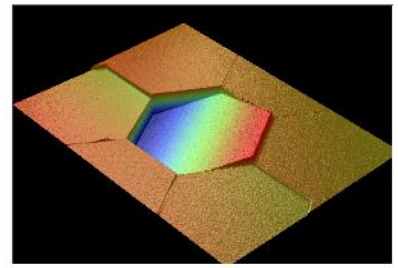
- Up to 3063 actuators
- Independent hexagonal segments
  - 3 actuators per segment



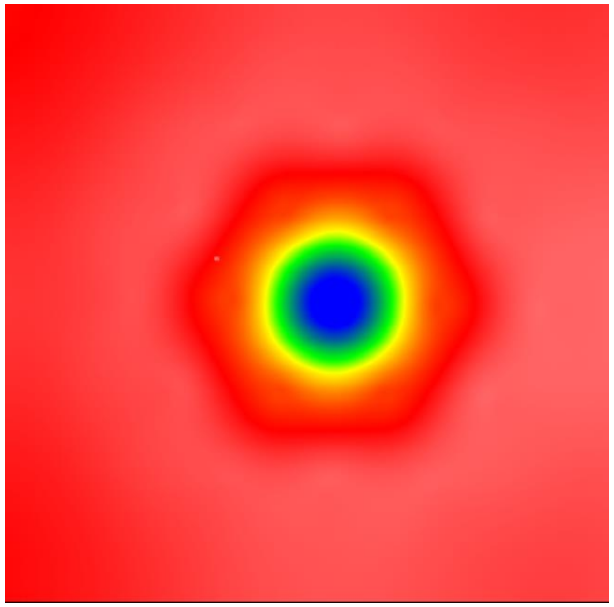


- 4 µm max. stroke
- 7 mrad max. tilt angle

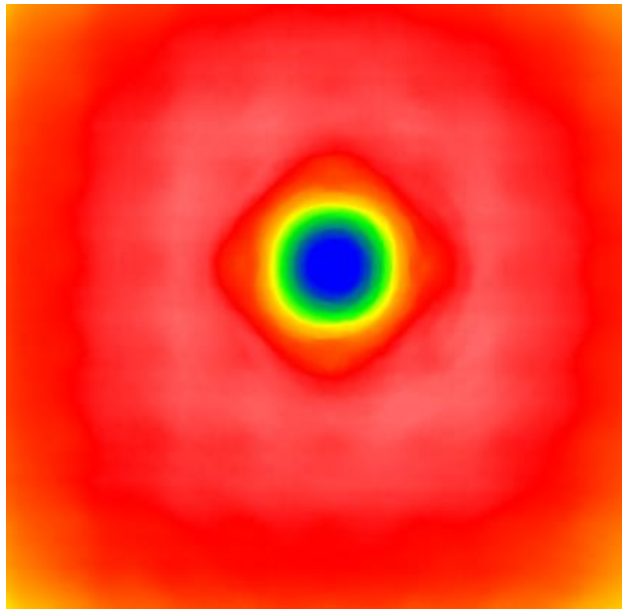




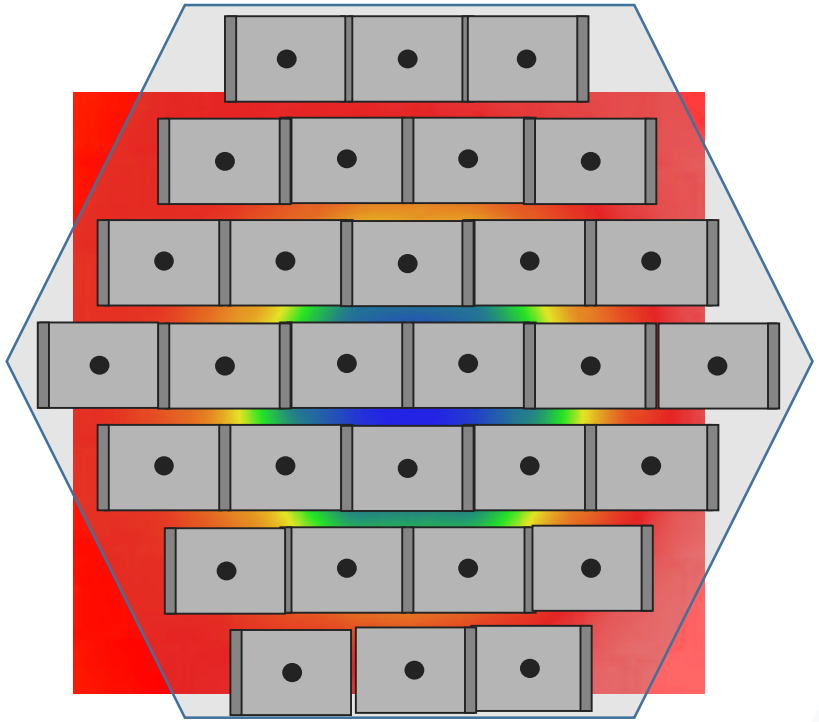
Continuous Hex-Close Pack DM



Hex



Cartesian



7 actuator “circle”

Same actuator design, 3.5µm stroke device

Outline

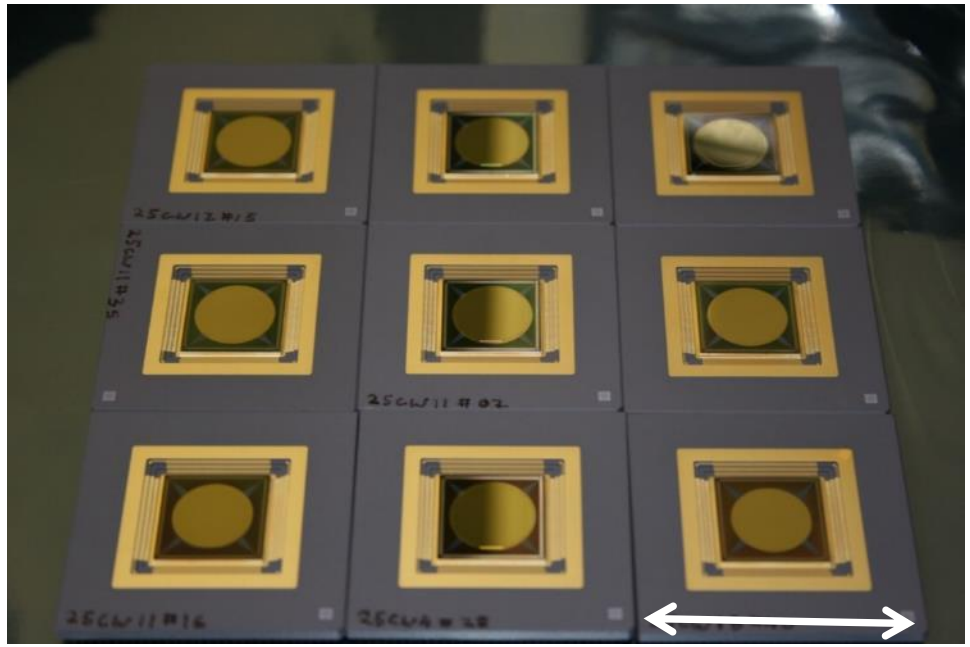
- BMC DM Technology
- NASA funded mirror technology programs
- Space astronomy operations
- Ground astronomy operation

MEMS Deformable Mirror Technology Development for Space-Based Exoplanet Detection

Contract#: NNH12CQ27CSAT/TDEM

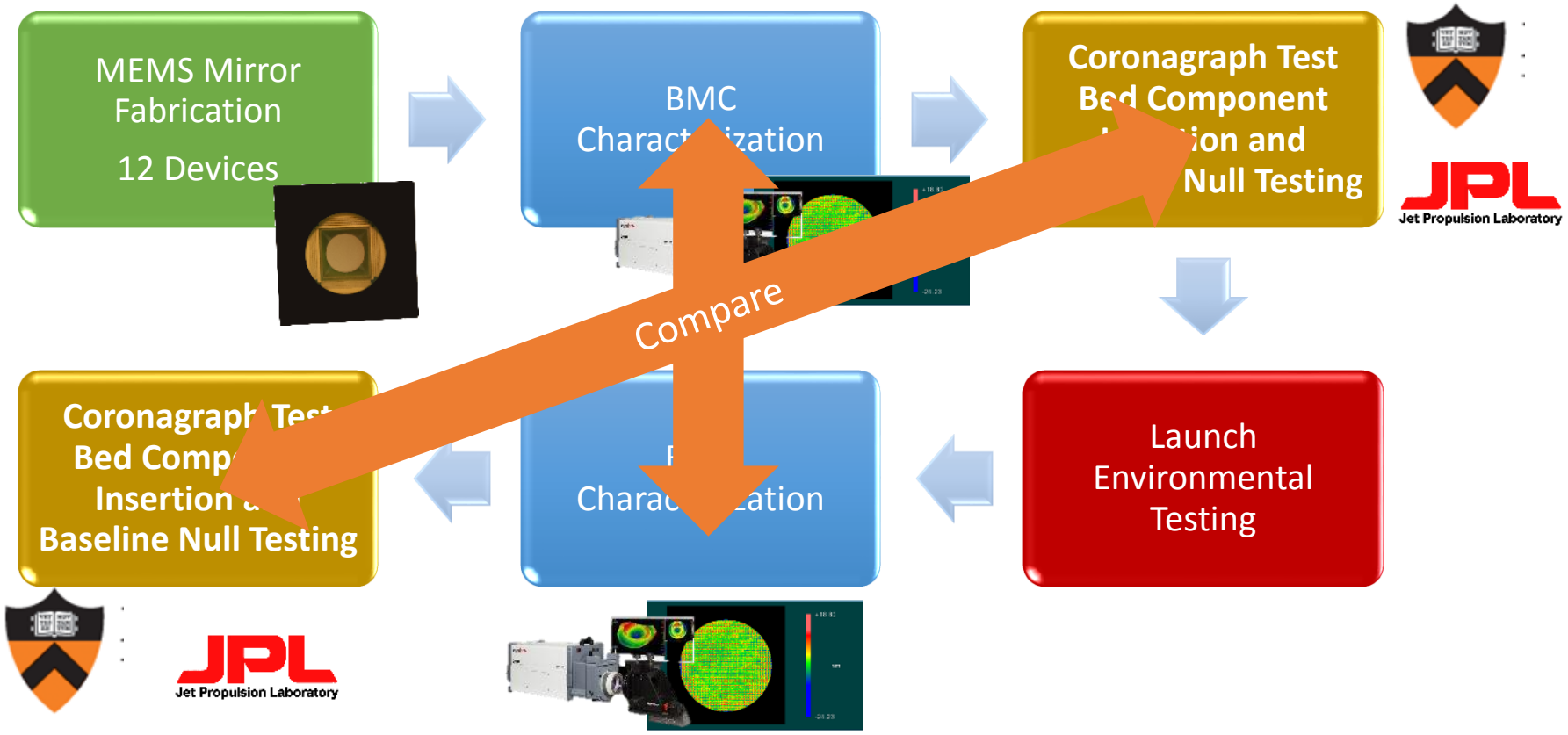
Objective: Demonstrate survivability of the BMC MEMS Deformable Mirror after exposure to dynamic mechanical environments close to those expected in space based coronagraph launch.

9 Mirrors ready for testing



5cm

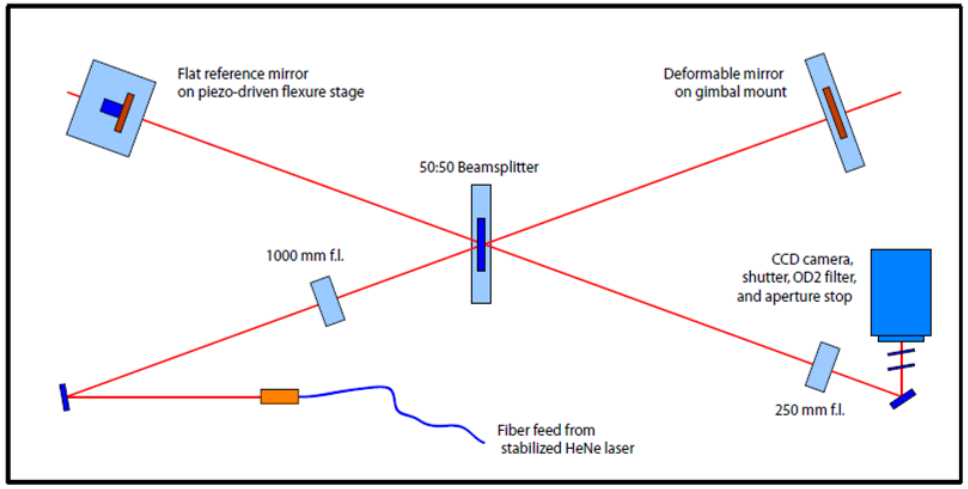
Project Flow



Vacuum Surface Gauge (VSG) Measurements

Two 952 actuator MEMS DMs (tested separately)

- Surface figure of DM at zero bias
- Surface figure of DM for flat surface
- Actuator gains for all 952 actuators for small up/down pokes about the flat surface condition
- Drift in surface for “flat” condition for 48 hour period
- Repeatability from “flat” and BMC/JPL solution for 10 repeats



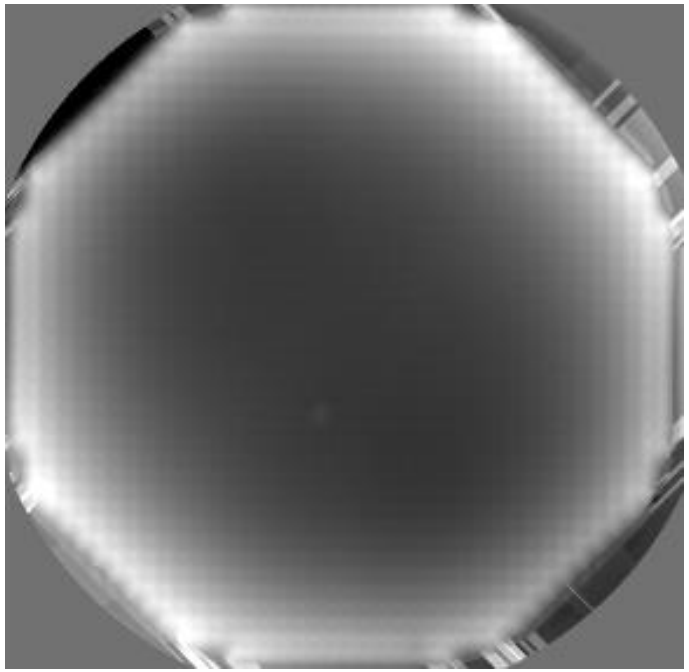
VSG is mounted on a 36 x 72 inch optical table. End-points of axes are the threaded holes 4.5 x 6.5 inches from table corners. Beam height = 4.405 inches.

- VSG is a Michelson interferometer mounted in a vibration isolated vacuum chamber
- Light source is 632.8 nm frequency HeNe laser
- Reference mirror is mounted on a piezo-driven flexure translation stage
- Deformable mirror under test is on a gimbal mount with a temperature controlled stage

Work performed by: Frank Greer, Cory Hill, Brian Gordon, John Trauger

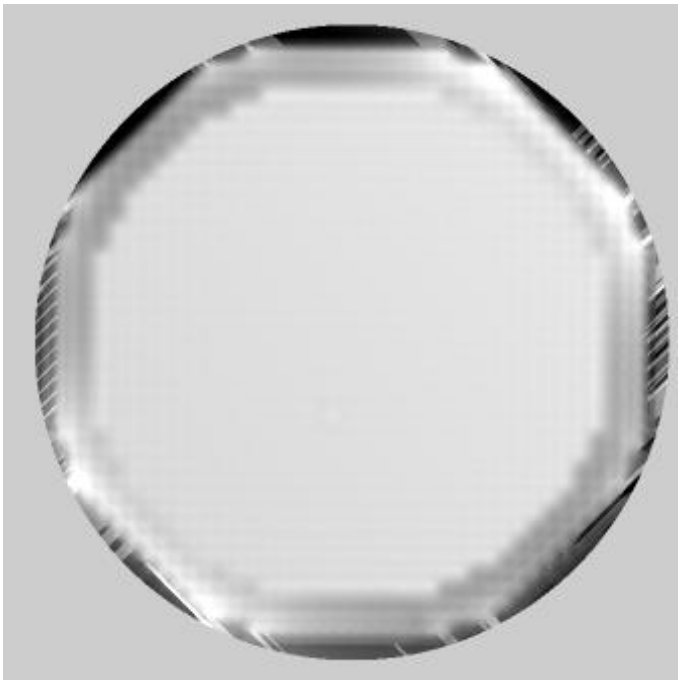
Flattened DM

Unpowered mirror



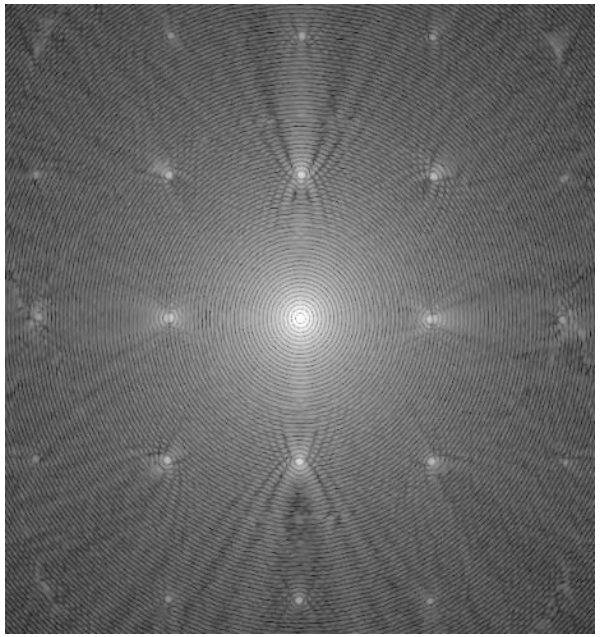
PV Focus 1428 nm, PV 45° astig 360 nm,
PV 90° astig 3 nm, RMS in higher 110 nm

Flattened DM



6.6nm PV focus,
2.9nm PV 45 deg astig,
0.3nm PV 90 deg astig,
7.6nm RMS higher order terms

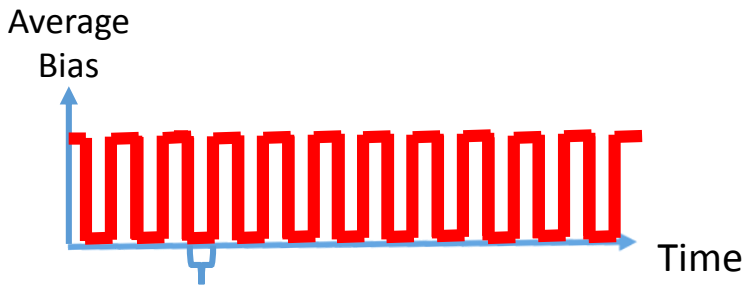
Point Spread Function Flattened DM



PSF with best flat BMC
RMS= 7.6 nm RMS)

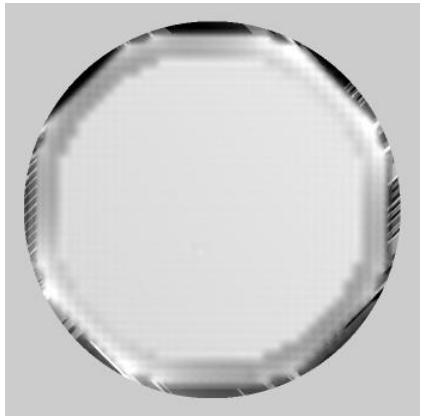
Strehl at λ = 633 nm : 0.96

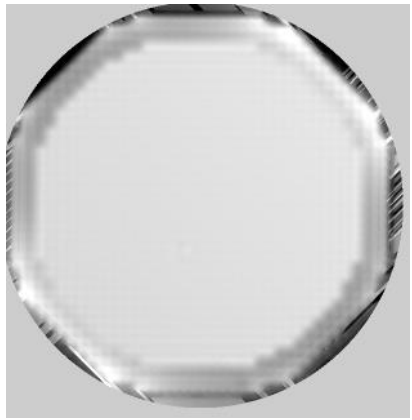
Repeatability Test Results

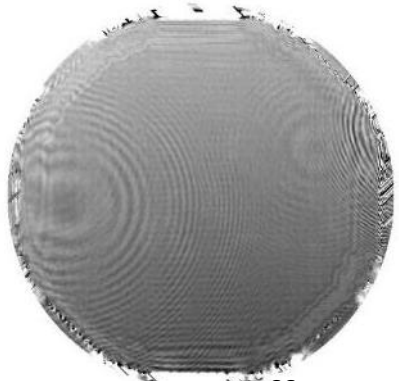


20 min

DM1

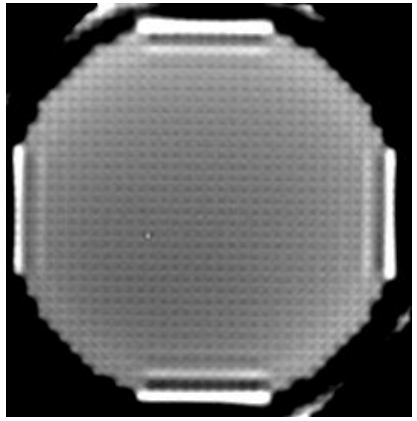


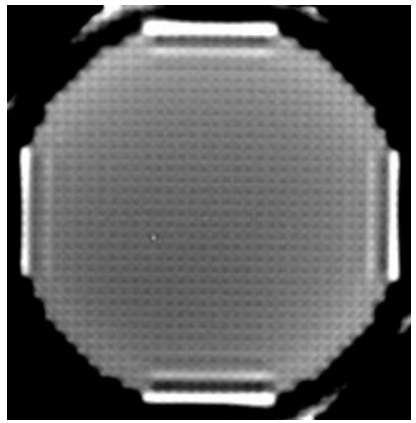


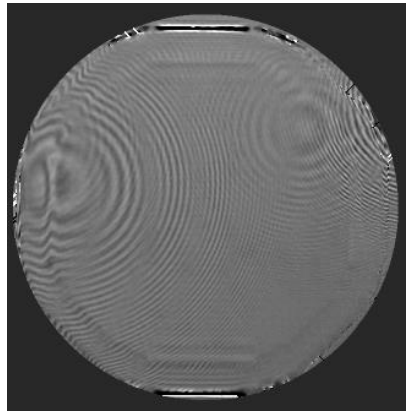


1.4nm RMS difference

DM2







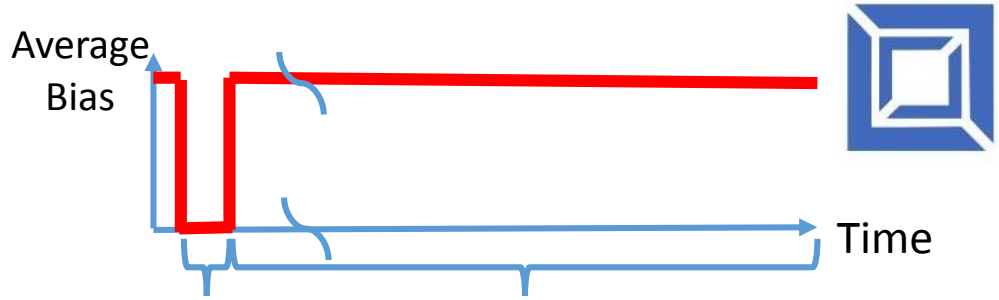
1.4nm RMS difference

Initial “Flat” solution

“Flat” solution 10 iterations of zero volts to “flat”

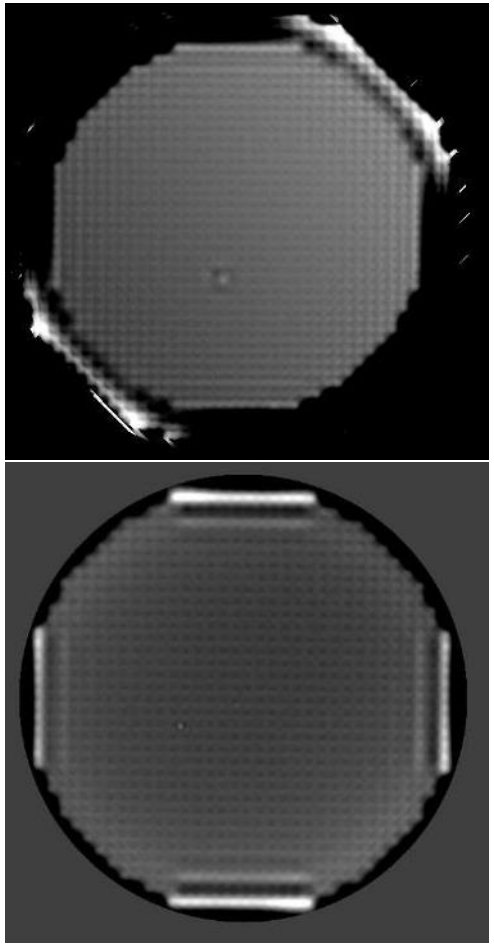
No obvious differences between maps.

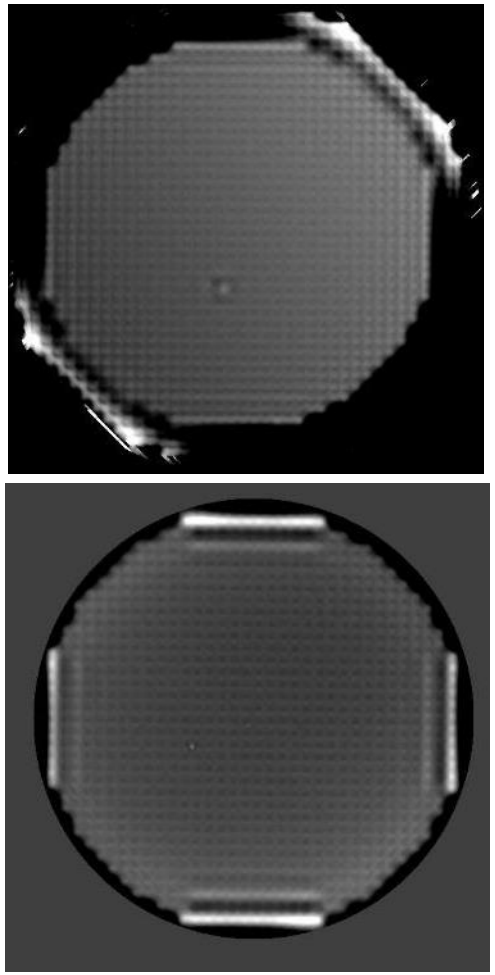
Comparison of flats from settling test

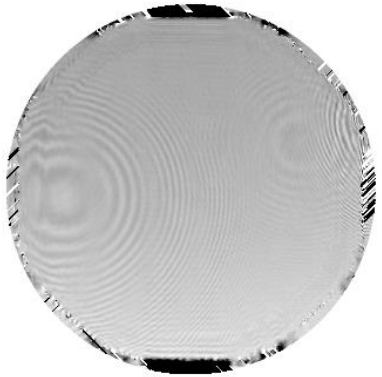


DM1

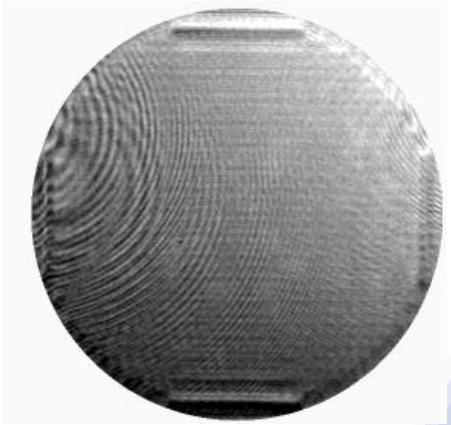
DM2







2.1nm RMS difference



0.9nm RMS difference

First map

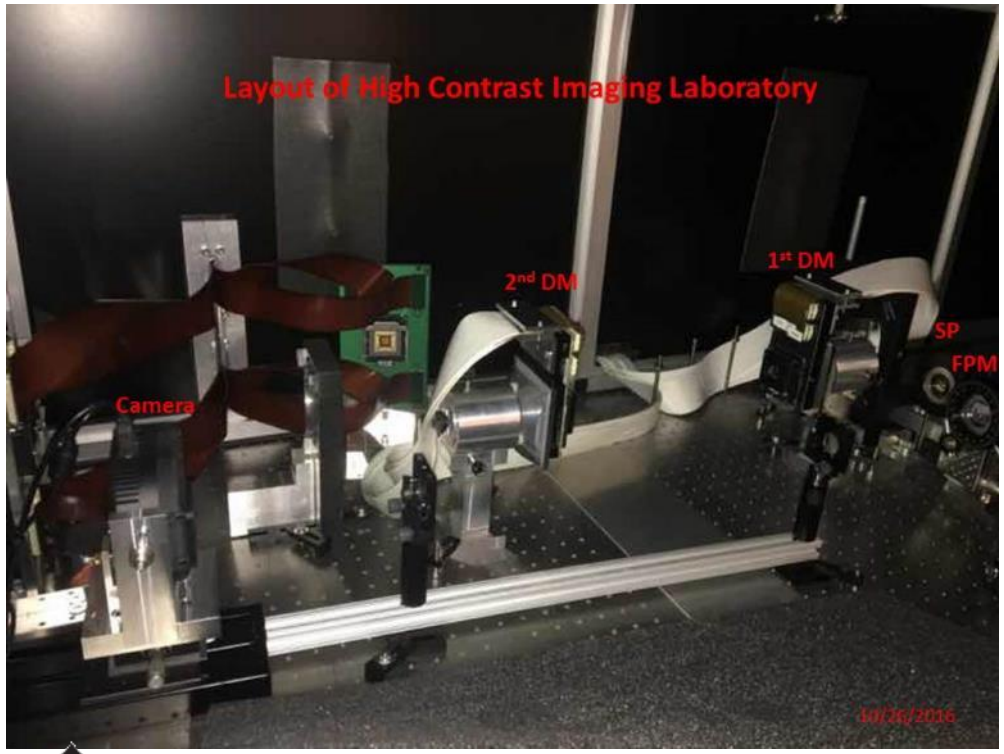
Last map

No significant changes observed in the settling time test (48hrs)

High Contrast Imaging Laboratory(HCIL)

Kasdin Lab, Princeton University

Focal Plane Wavefront Correction (FPWC) for Exoplanet Coronagraph Imaging



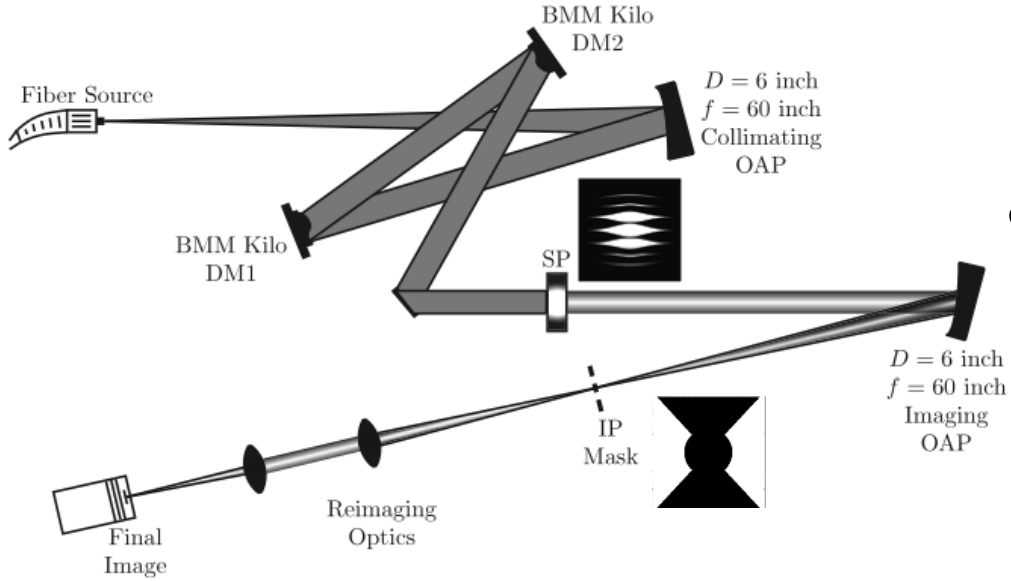


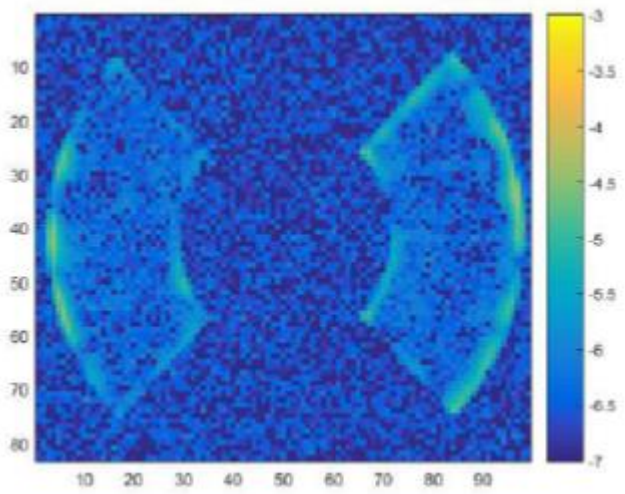
Image Credit:
Groff & Kasdin 2013

- **Shaped pupil coronagraph** technique is used to achieve high contrast for exoplanet direct imaging.
- 2 BMC **deformable mirrors** are included to compensate optical aberrations in the system.

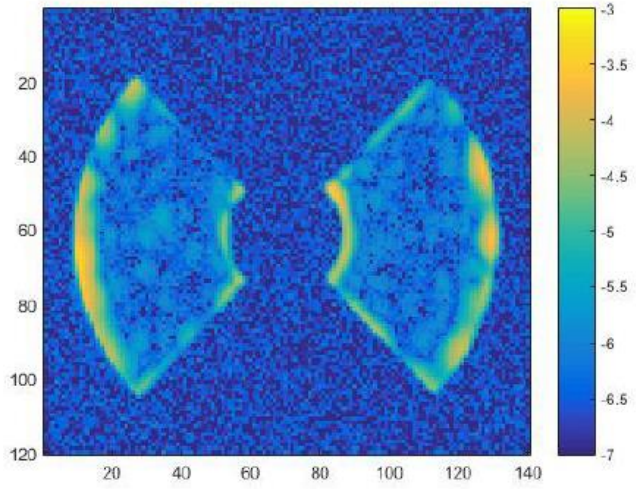
PRINCETON
UNIVERSITY

Lab Results

- Batch process estimator with two pairs of probes
- Stroke minimization controller
- Two BMC DMs with 952 actuators on each
- Achieved 2 x 10^{-7} contrast within 6-11 λ/D and 9 x 10^{-7} contrast 5-14 λ/D



6-11 λ/D



5-14 λ/D

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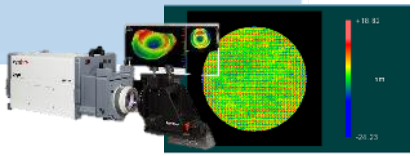
Project Flow

MEMS Mirror Fabrication

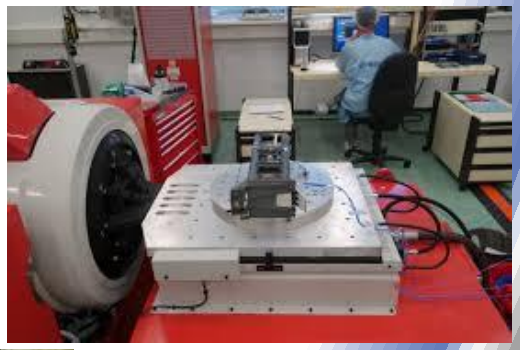
12 Devices

BMC Characterization

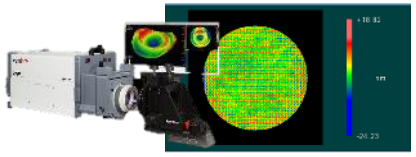


Coronagraph Test Bed Component Insertion and Baseline Null Testing

Launch Environmental Testing



BMC Characterization

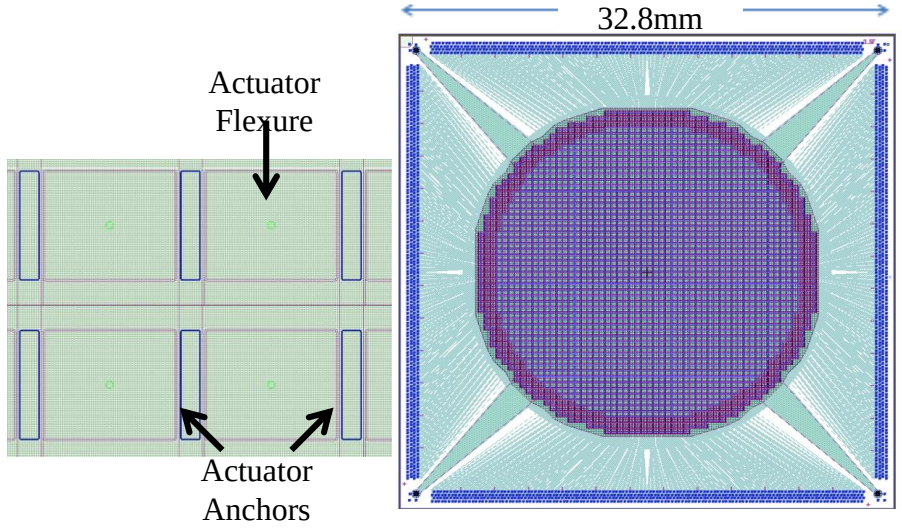


Coronagraph Test Bed Component Insertion and Baseline Null Testing

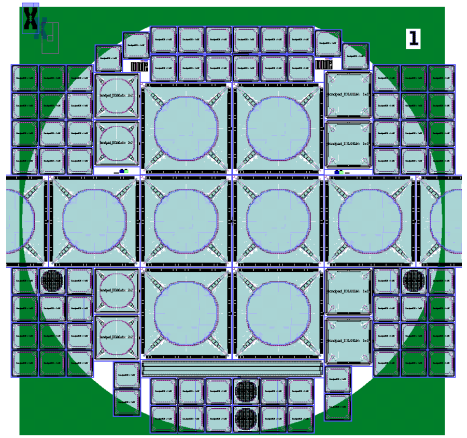
Improved Yield, Performance and Reliability of High-Actuator-Count Deformable Mirrors

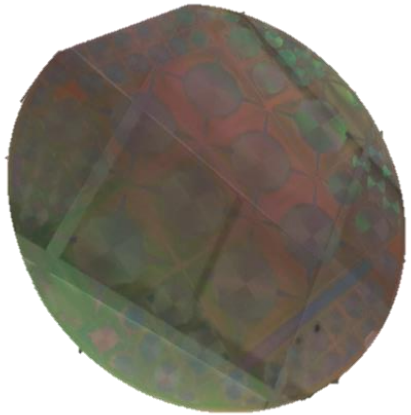
Contract Number: NNX16CP14C Phase II SBIR

Mirror architecture	2040 actuators
Active Aperture Diameter	19.6mm
# Actuators across active diameter	50
Actuator Pitch	400µm
Actuator Stroke	1.5µm
Operating Voltage	0-100V
Mirror Surface Figure	<5nm RMS

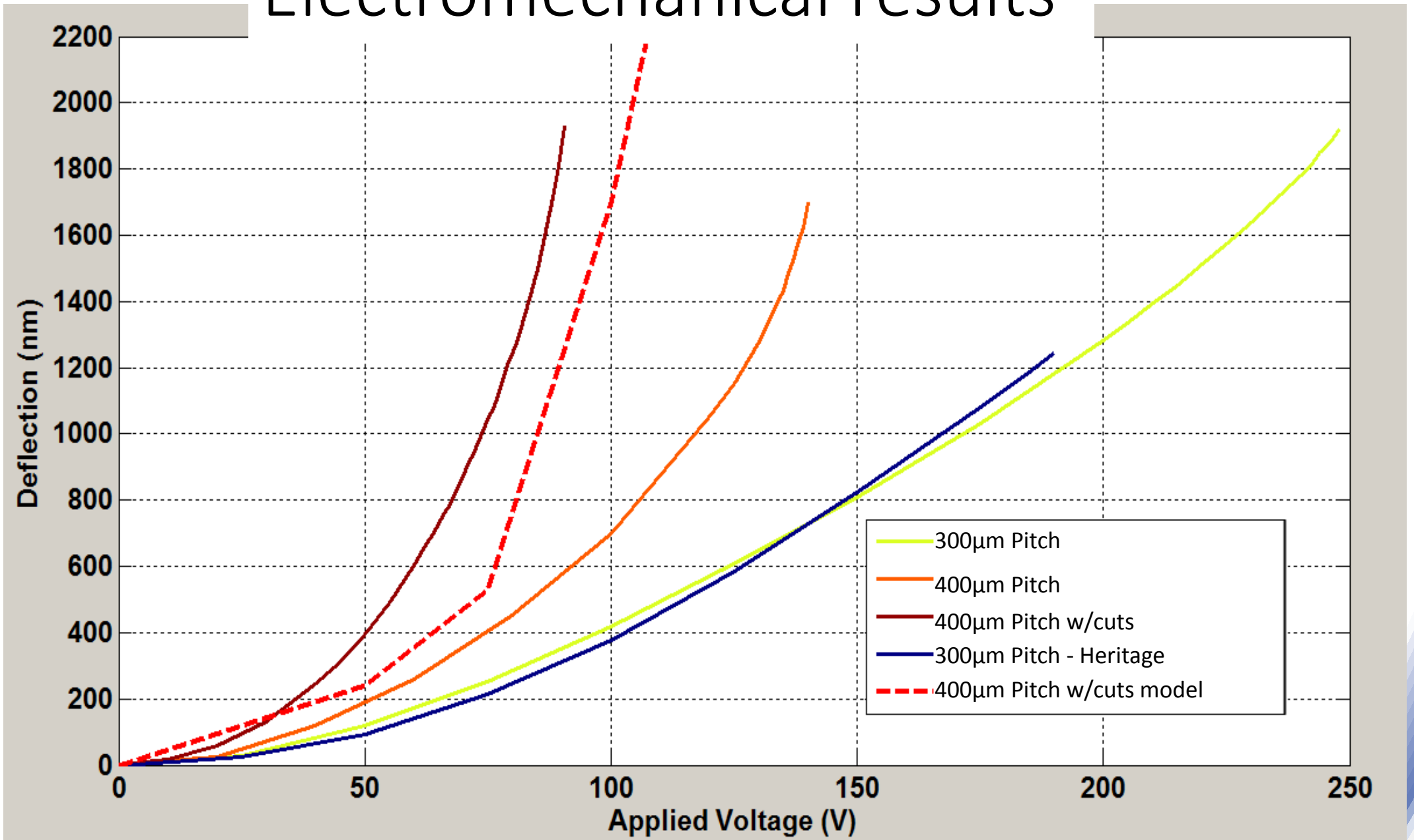


Design of actuators for lower voltage operation

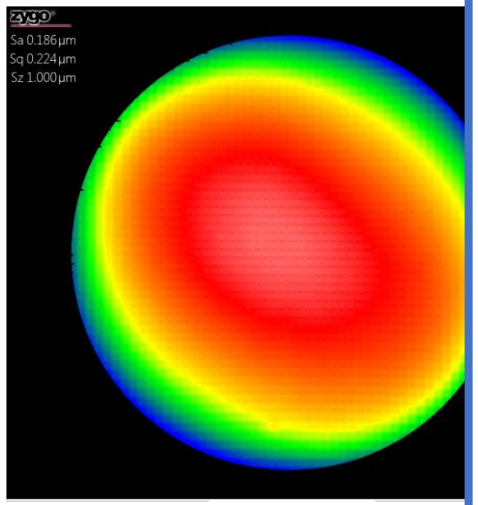




Electromechanical results



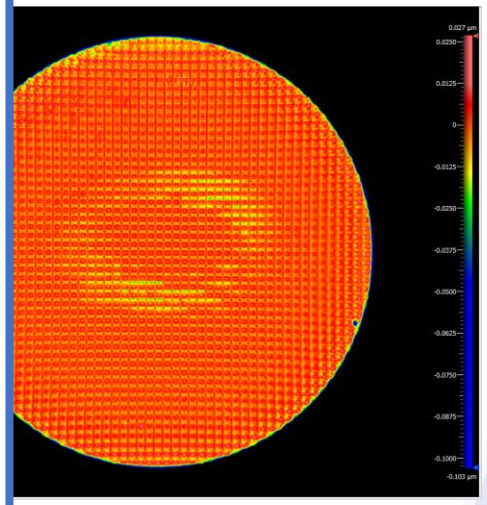
Initial Die Inspection



20mm

Unpowered
P-V 900nm
RMS 200nm

RMS 84nm

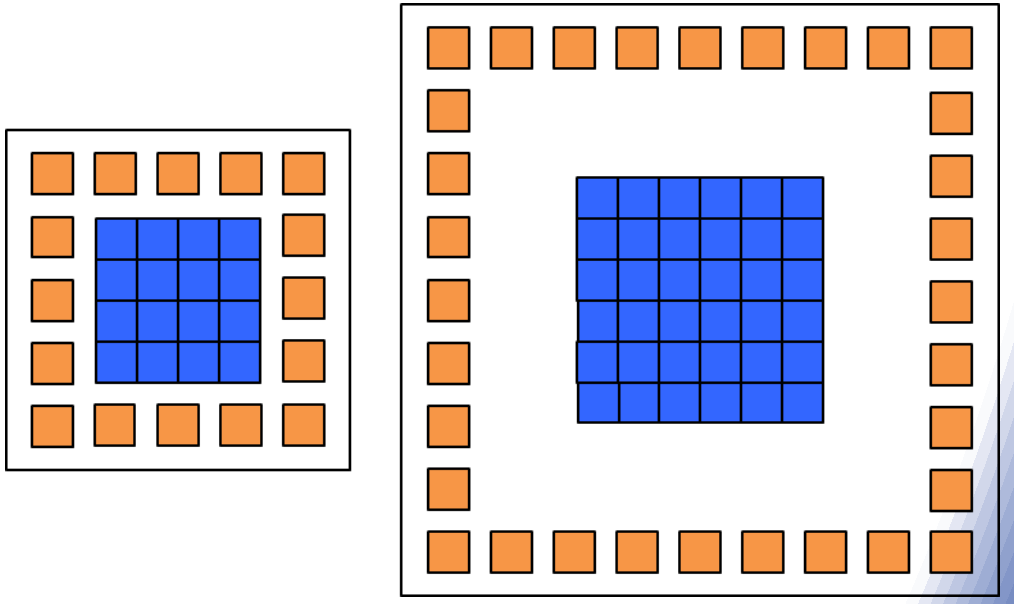


Pass Filter (λ = 2.5/mm)
133nm
7nm

Currently coating and packaging die.
Project completion April 2018.
Delivery – 2k DM.

Need for Even Higher Actuator Count DM (10k +)

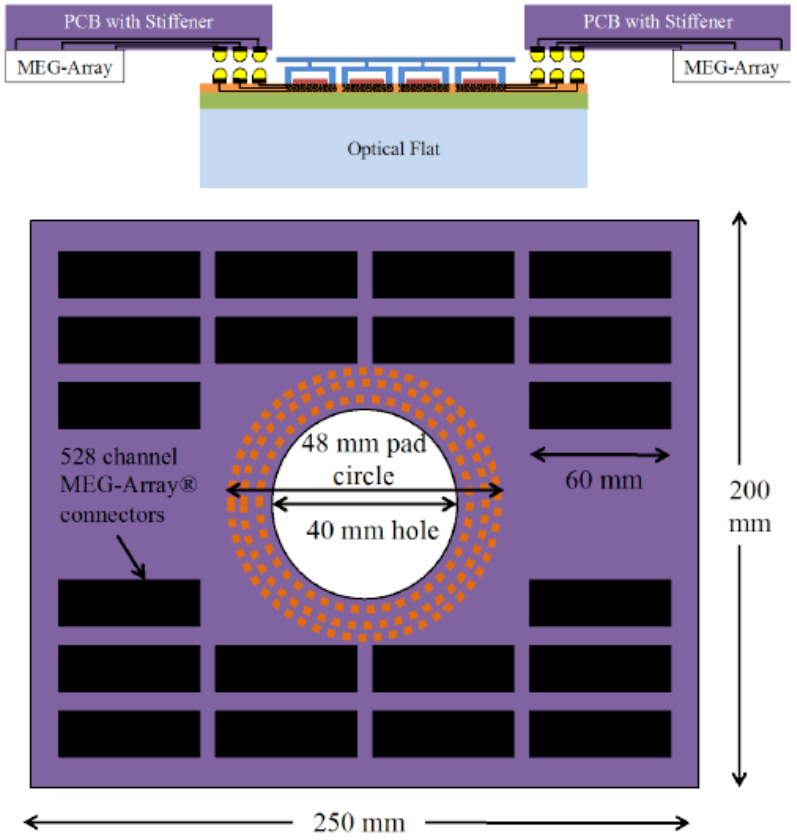
- For many next generation instruments(ground and space based), more actuators are needed
- Limited by electrical interconnects
  - Wirebond for each actuator
  - Span of active optical surface scales with N
  - Span of the chip scales with N^2
  - Limits number of die on a wafer
  - Increases the likely hood of a single point defect causing short/failure

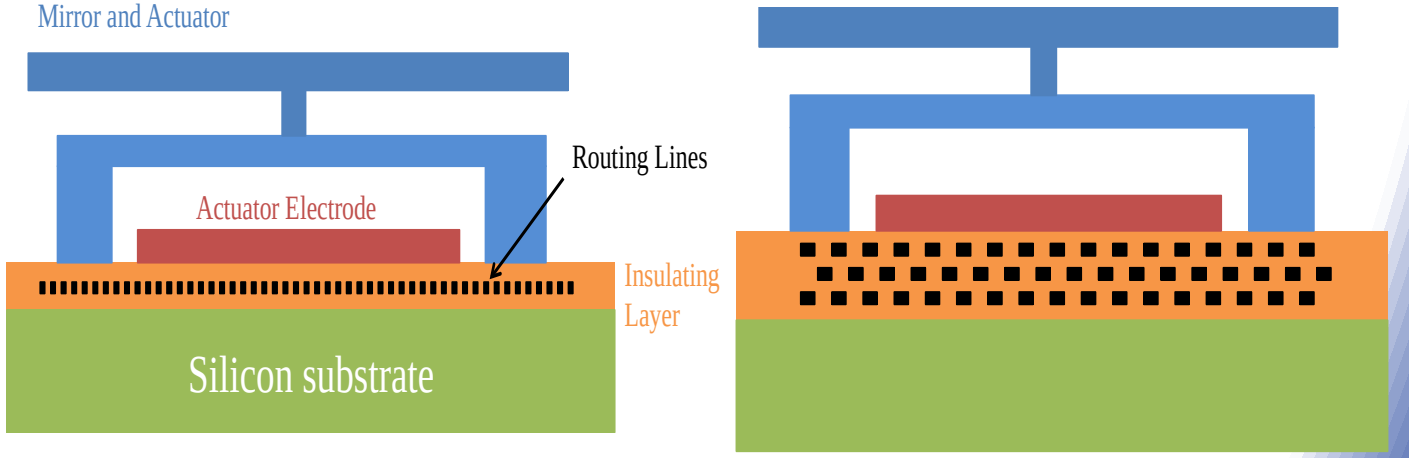


By adding 2 more actuators across the aperture, the die size increased by ~3x

Technology Development for High-Actuator-Count MEMS DM Systems

- NASA Contract #NNX17CP76P Phase I SBIR



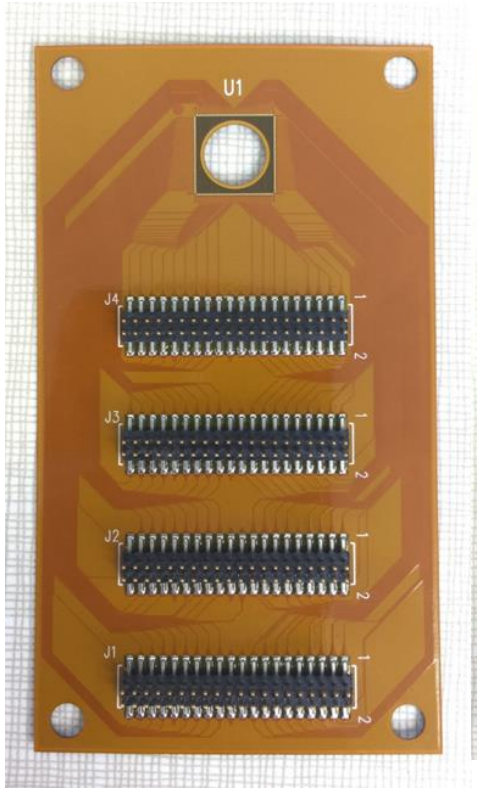


Goals:

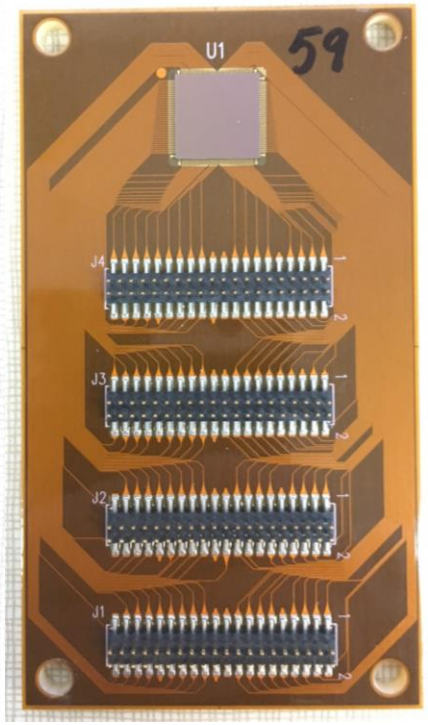
- Demonstrate flip-chip bonding approach on smaller actuator count devices
- Layout 100 Actuator-Across –Aperture DM with multiple routing lines

Demonstration of Bonding

- Flex circuit PCB for high density bond pads
- Used heritage 140- actuator DM
- Central hole provides optical access for active aperture



Backside
No Die attached



Backside
Die attached

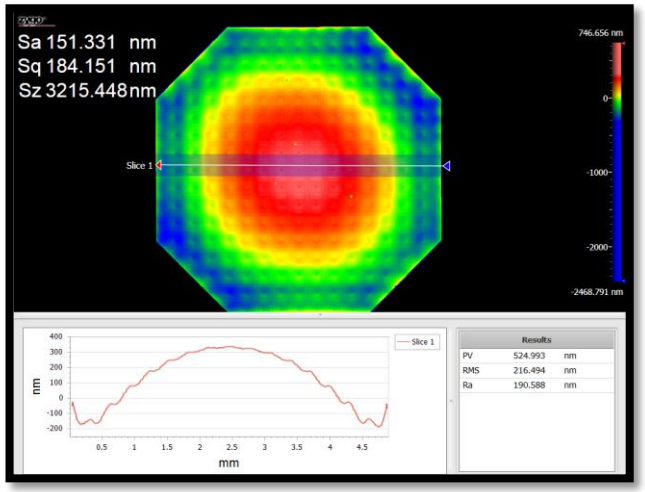
Frontside
Die attached

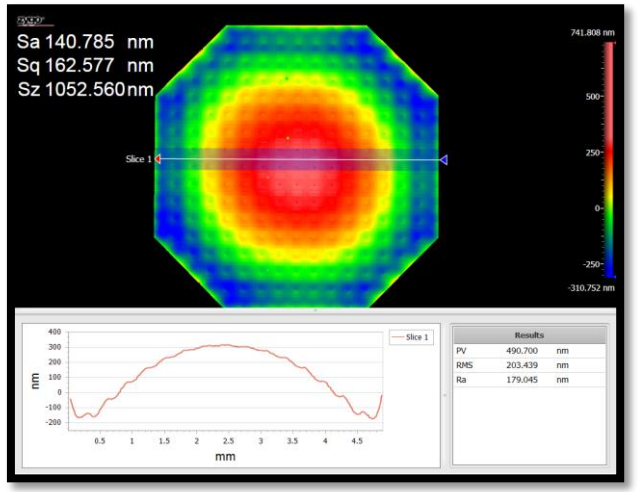
Compliant Stencil Epoxy Bond Surface figure

Before Bond

After Bond

Unpowered

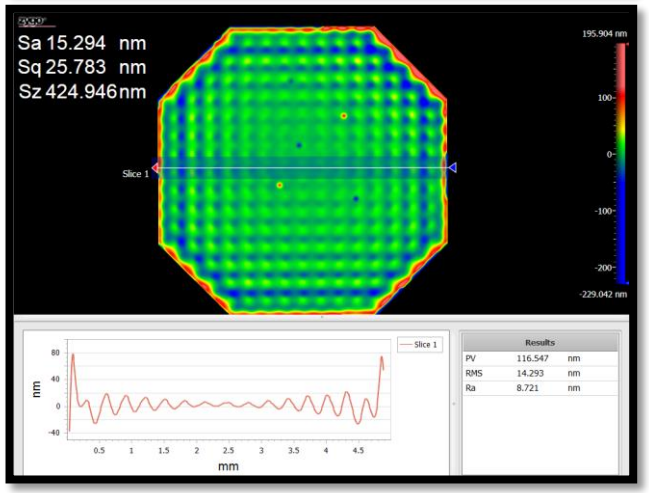


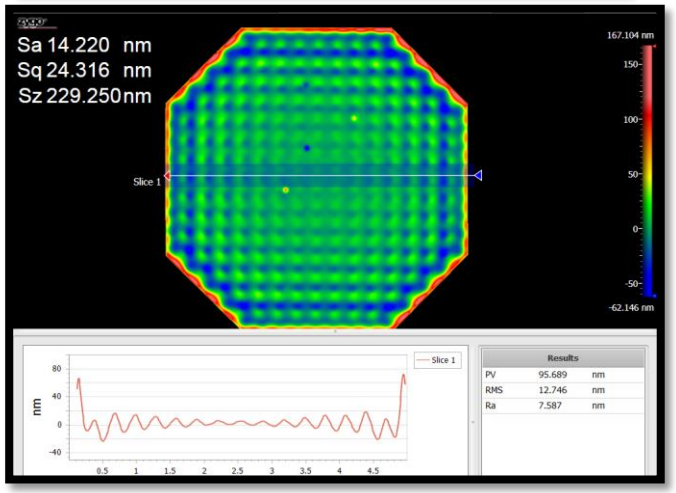


Vertical scale

-200 to 400nm

Unpowered, filtered





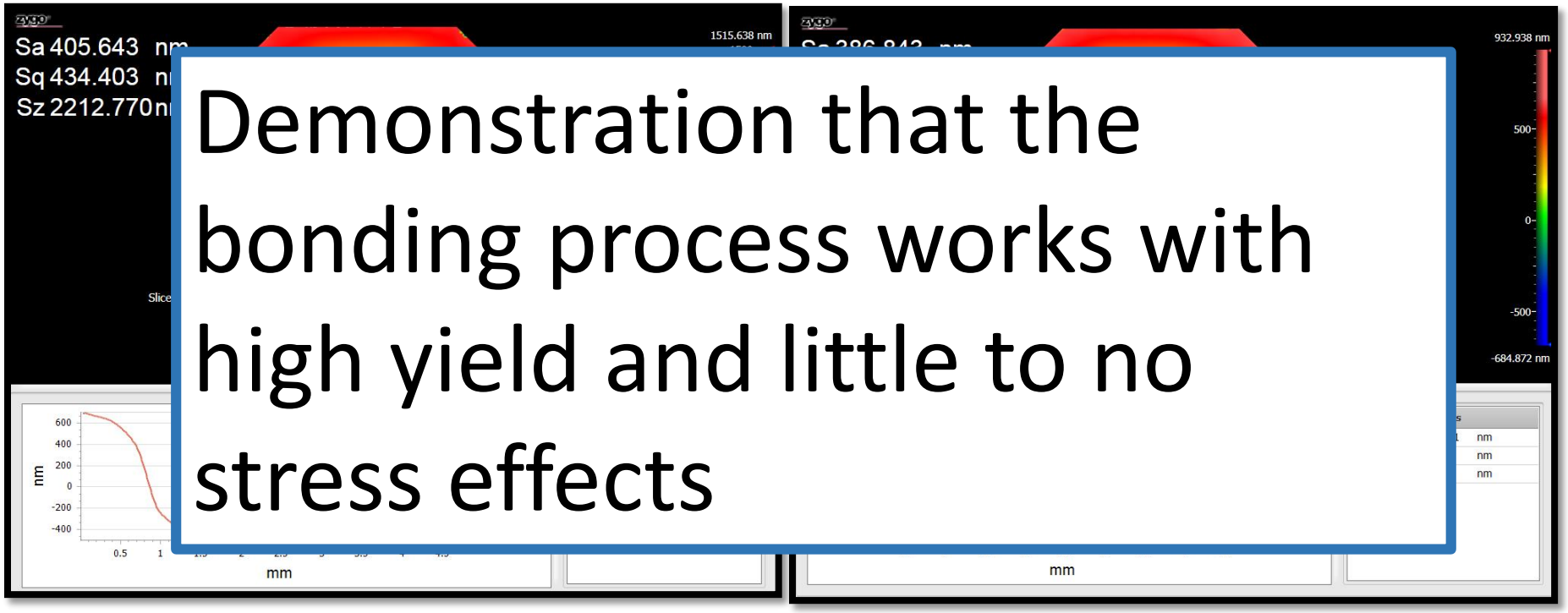
-40 to 80nm

Compliant Stencil Epoxy

150V Piston Subtracted From Unpowered

Before Bond

After Bond



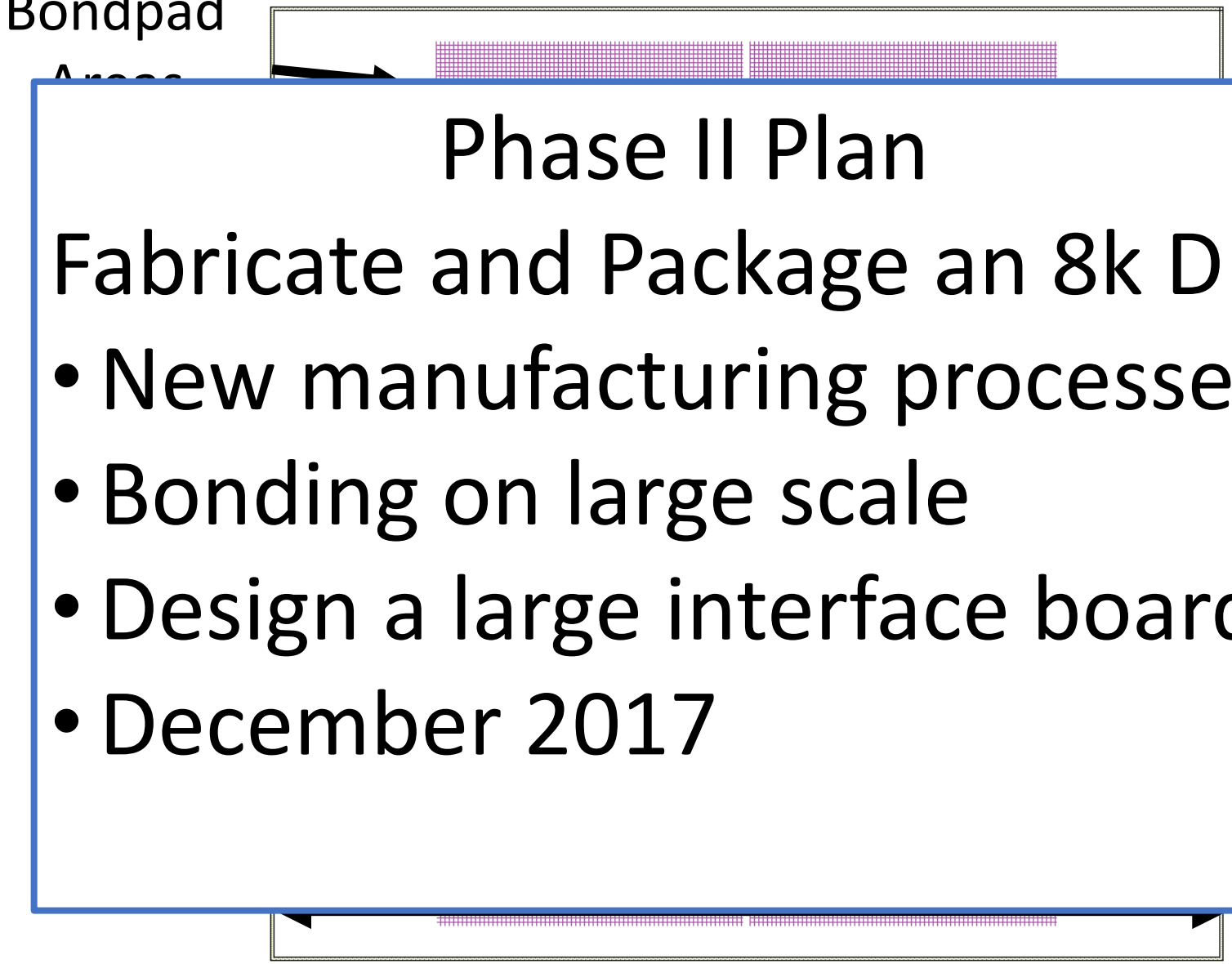
Demonstration that the bonding process works with high yield and little to no stress effects

Vertical scale

-500 to 700nm

All the actuators that were working prior to the bond work after

Layout for 7860 Actuator MEMS DM, 100 across



Phase II Plan

Fabricate and Package an 8k DM

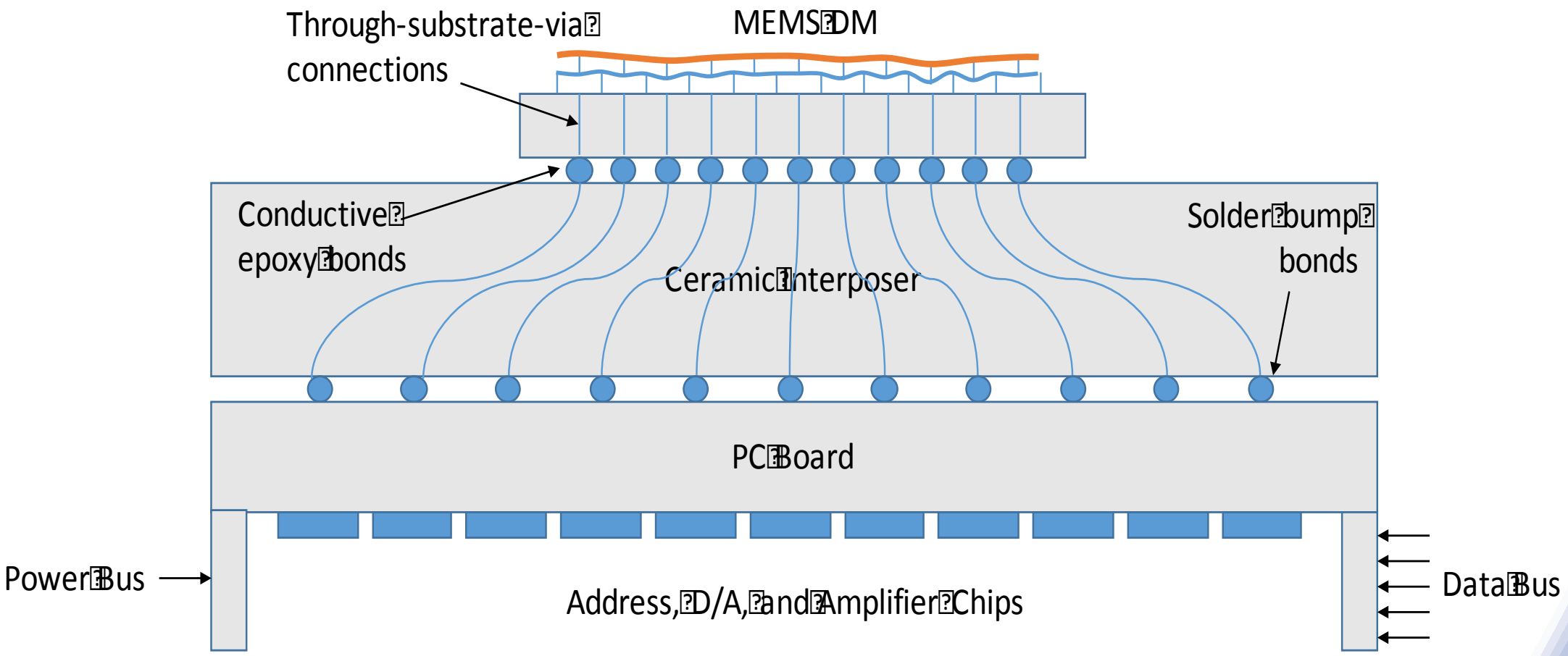
- New manufacturing processes
- Bonding on large scale
- Design a large interface board
- December 2017

Compact, scalable deformable mirror systems for space-based imaging of exo-earths

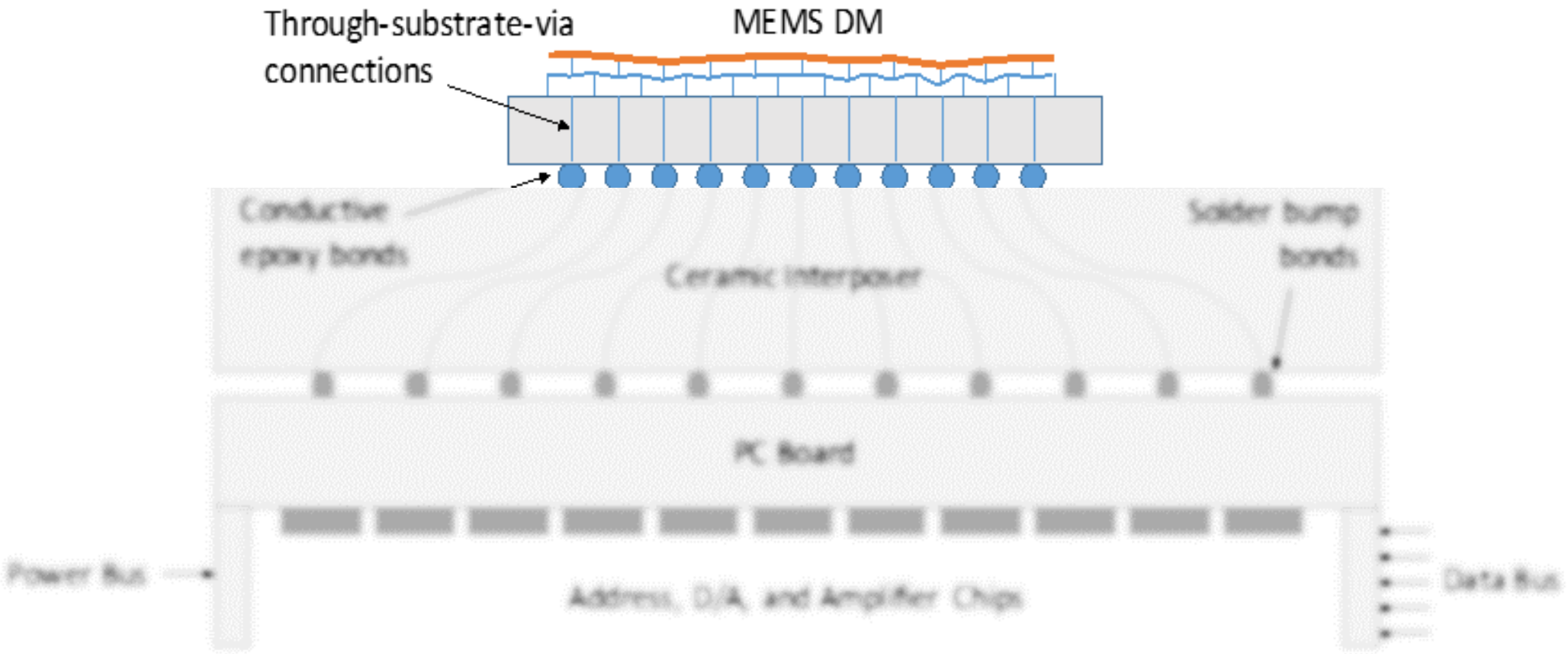
NASA Contract: NNX17AI66G APRA Program

- Goals:
  - Demonstrate a **new architecture and integration approach** for compact, robust large-format deformable mirror systems, and
  - Show **a feasible path for scaling up** that demonstration platform and manufacturing integration approach to larger formats with up to 10,000 actuators

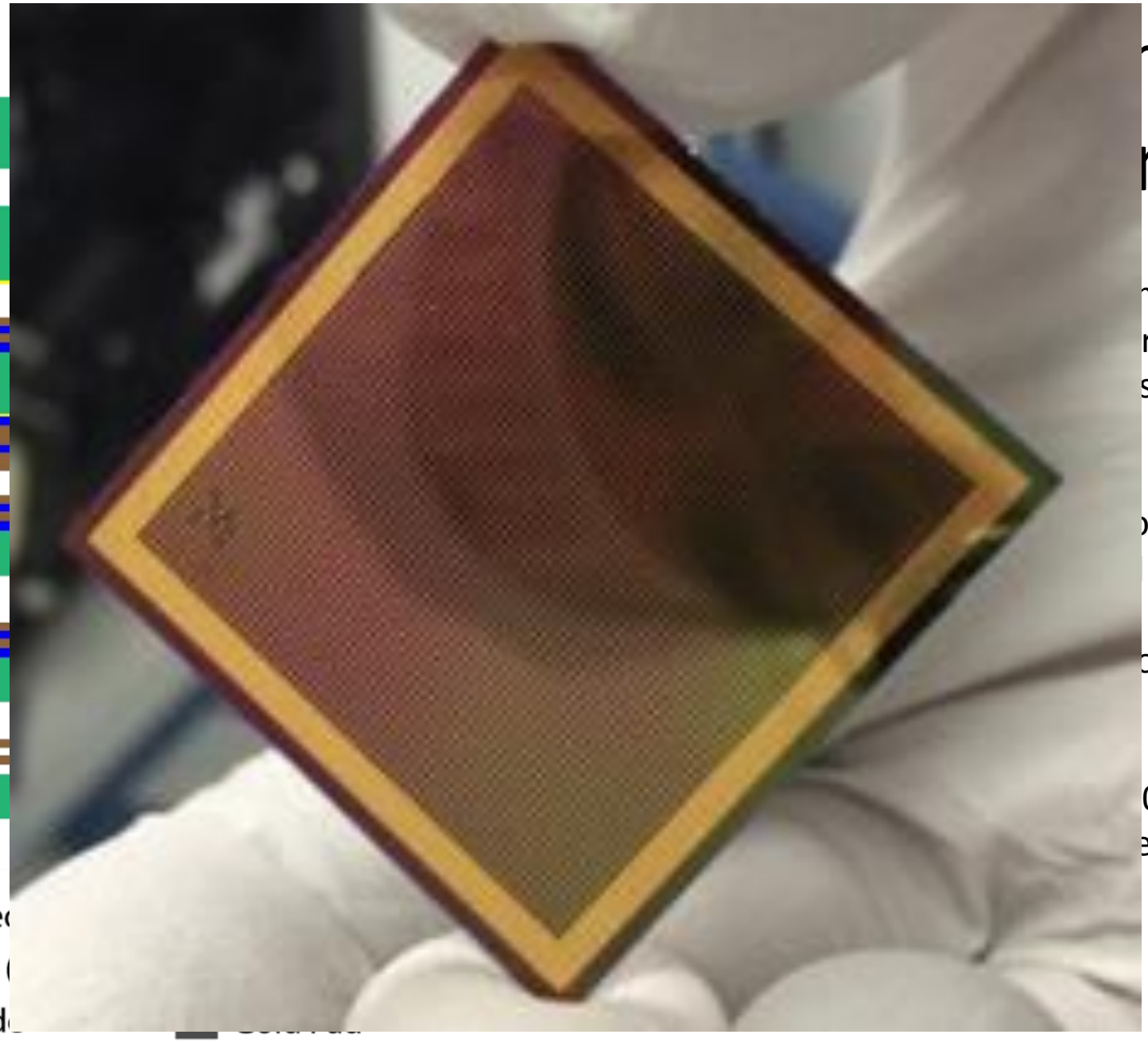
Proposed Architecture

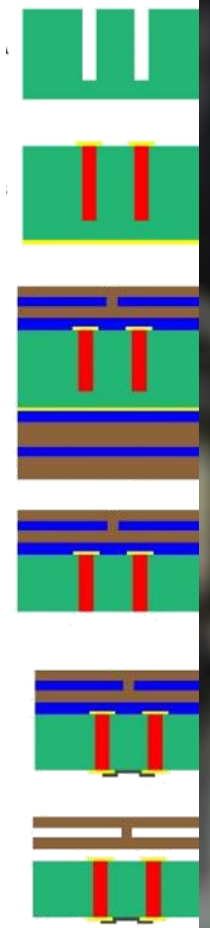


Proposed Architecture



r-Via DM rototype





Highly Doped
Via Isolation
Silicon Nitrid

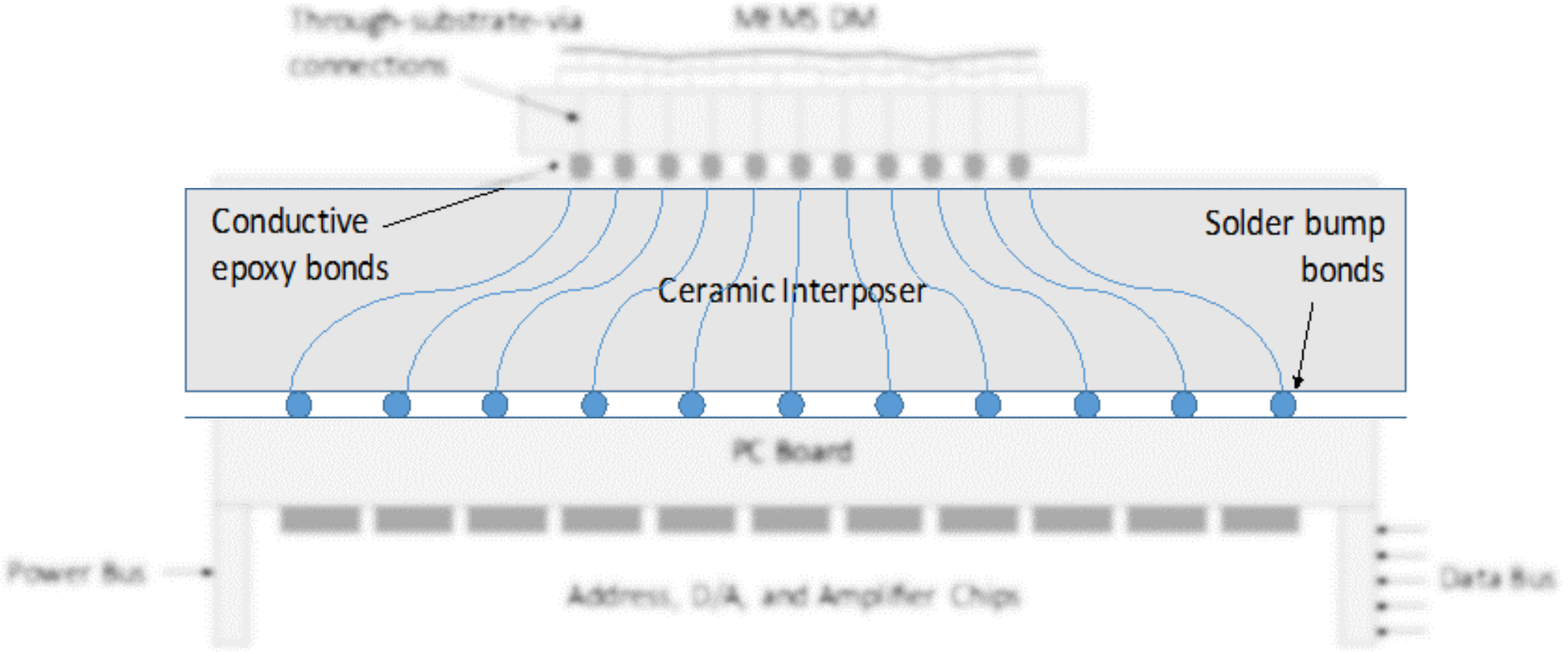
nanufacturing) relies
r design, but
ses through-wafer-via

nally low defect level
and reliability

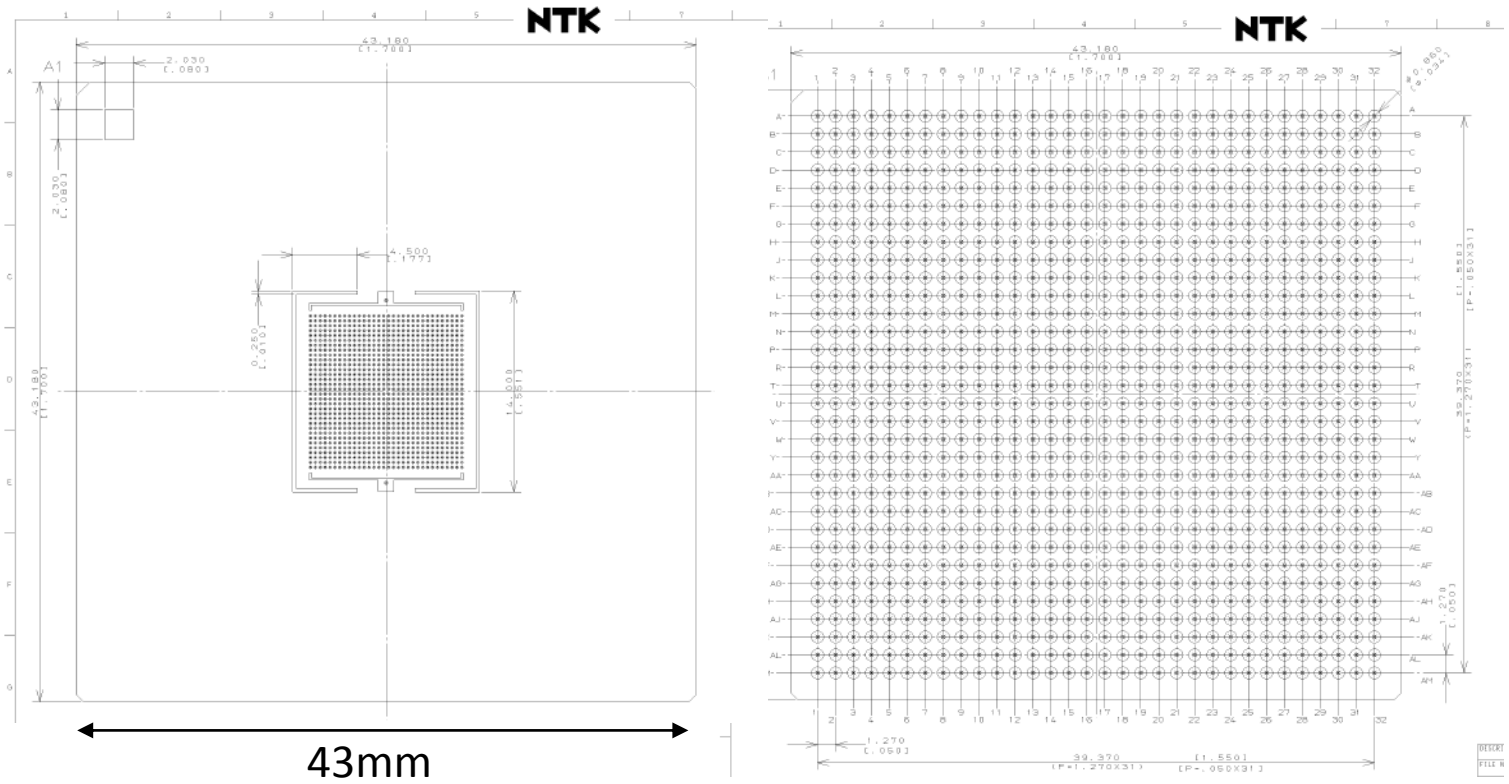
o packaging of TWV

020 actuator, and
ed and tested

Proposed Architecture



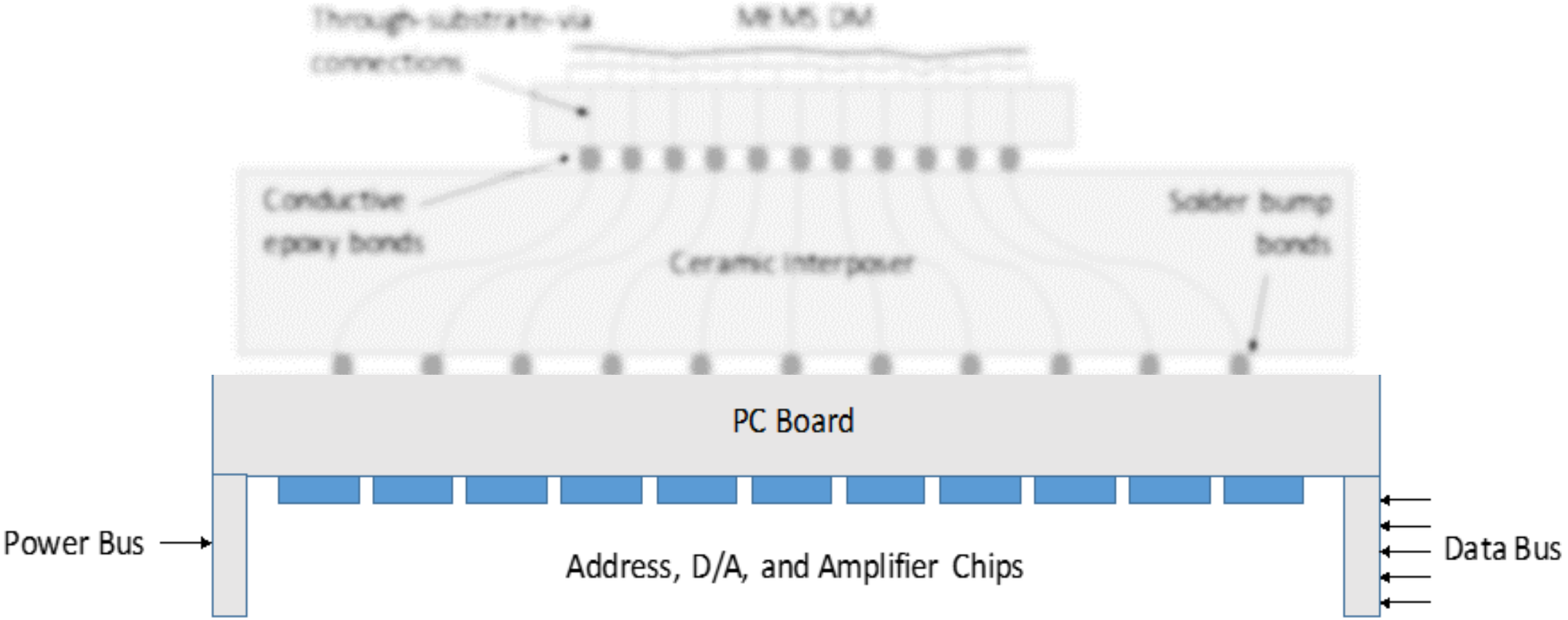
Ceramic Interposer



- Material: aluminum oxide with gold traces
- Top Surface: 1024 LGA Pads electroless gold, (32x32 on 340um pitch)
- Bottom Surface: 1024 BGA pads Electroless gold (32x32 on 1mm pitch)

Currently being fabricated

Proposed Architecture (Concept)

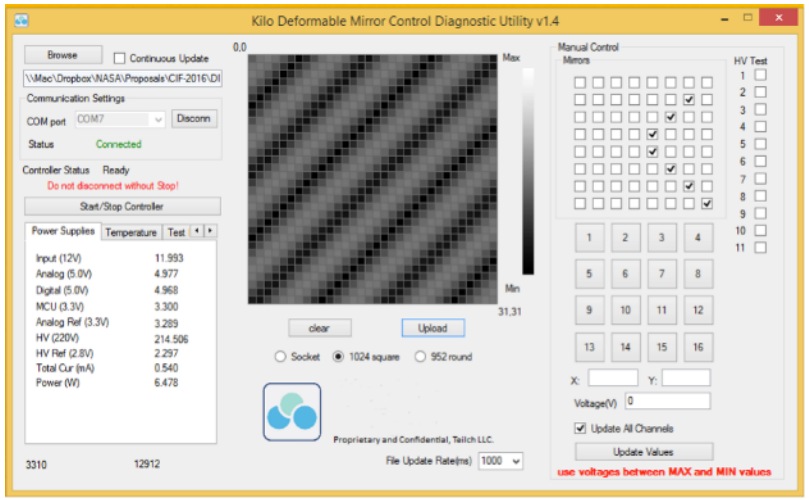


Electronics Design

TEILCH

AMES RESEARCH CENTER

NASA



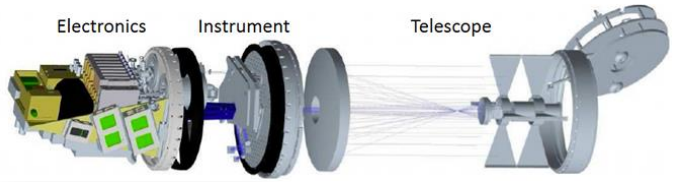
- The controller has a volume of 90mm (w) x 90mm (l) x 54.6mm (h), w/o mirror and socket.
- It only requires a 12V power supply and consumes 6W.
- USB interface for data
- 0-215V, 16 bits
- Scalable technology for greater channel count

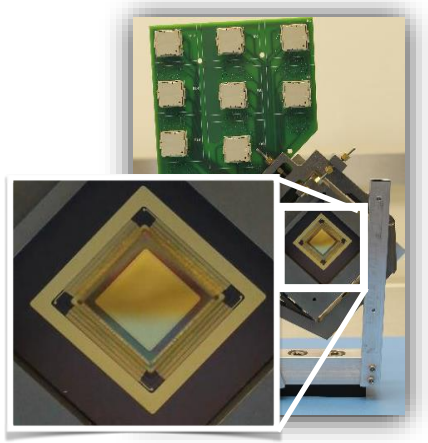
Outline

- BMC DM Technology
- NASA funded mirror technology programs
- Space astronomy operations
- Ground astronomy operation

PICTURE-B PROGRAM

PI: Supriya Chakrabarti, UMASS Lowell





Launched 2015

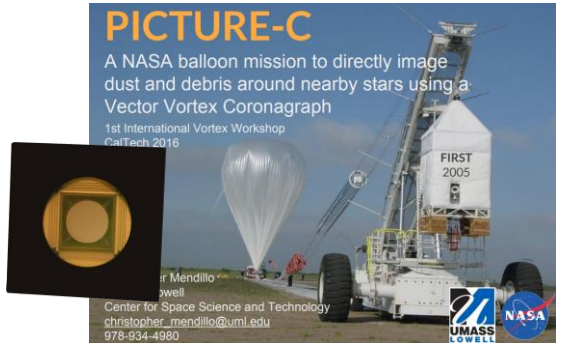
DOUGLAS 2016, COURTESY UML

CUBESAT: DEFORMABLE MIRROR DEMONSTRATION MISSION (DEMI)

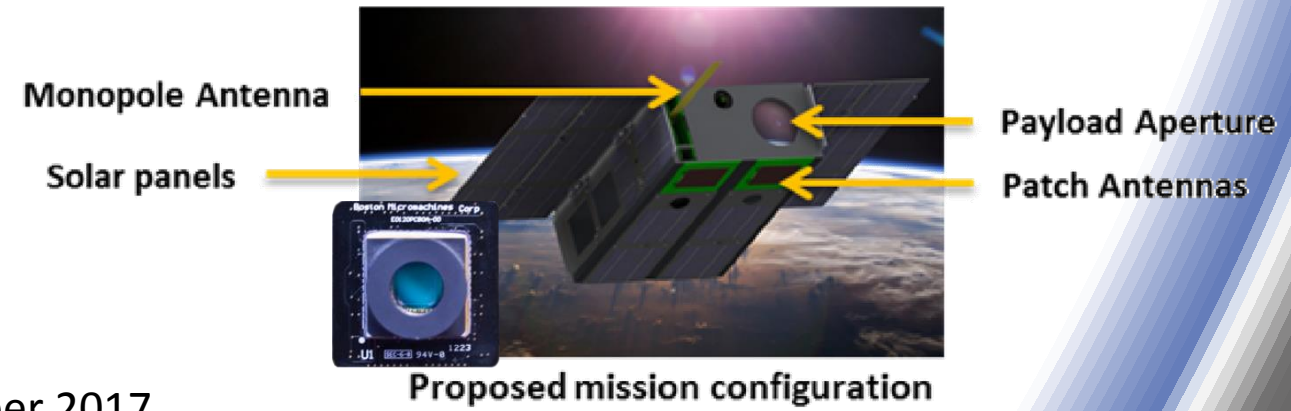
PI: John Merk, Aurora Flight Systems, Keri Kahoy, MIT

PICTURE-C PROGRAM

PI: Supriya Chakrabarti, UMASS Lowell



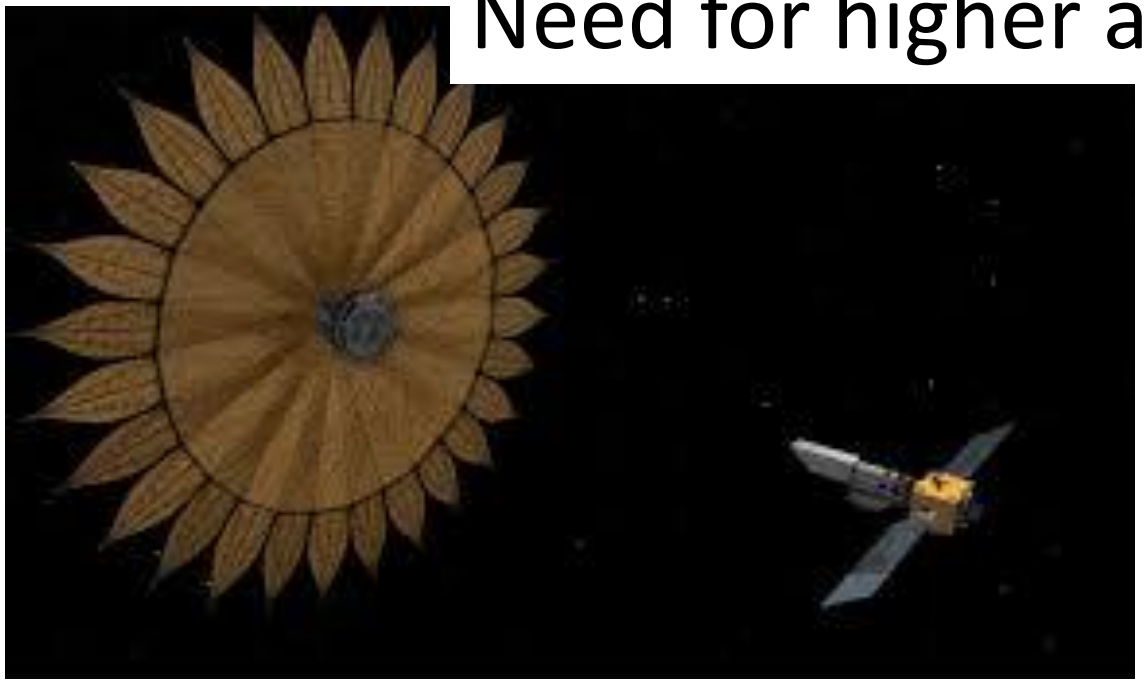
DM Delivered November 2017
First Flight 2018



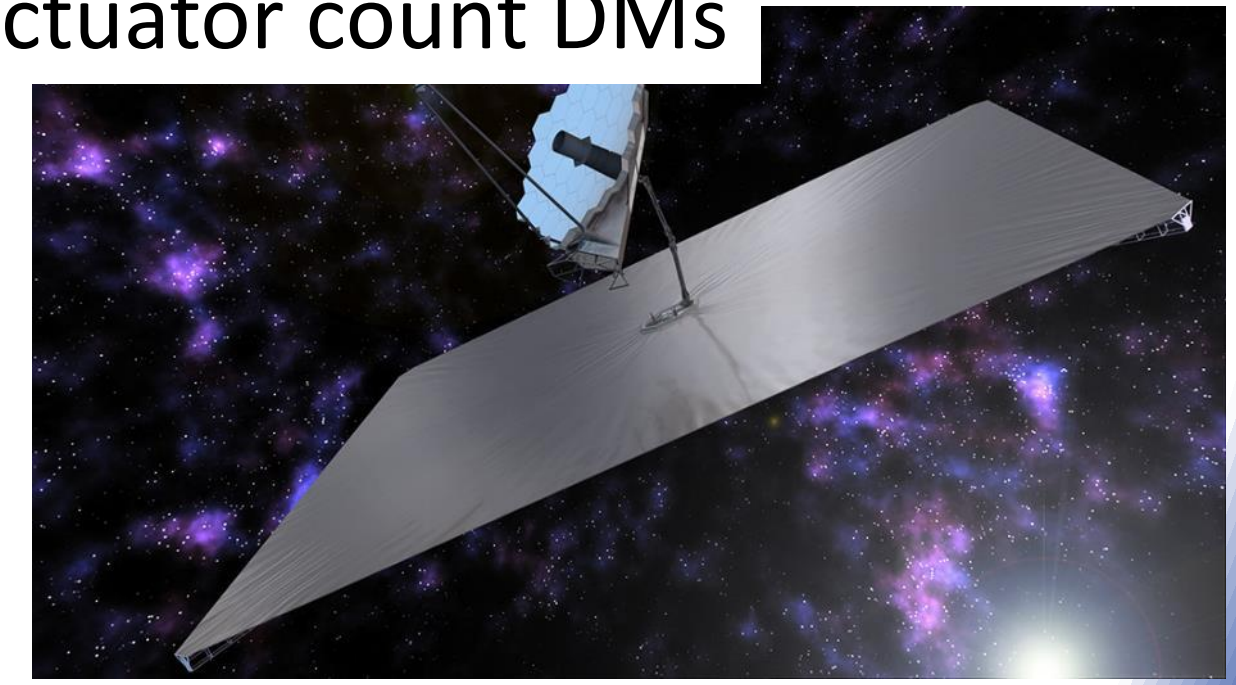
Proposed mission configuration

Future Space Missions

Need for higher actuator count DMs



Habitable Exoplanet Imaging Mission (HabEx)



Large UV/Optical/IR Surveyor (LUVOIR)

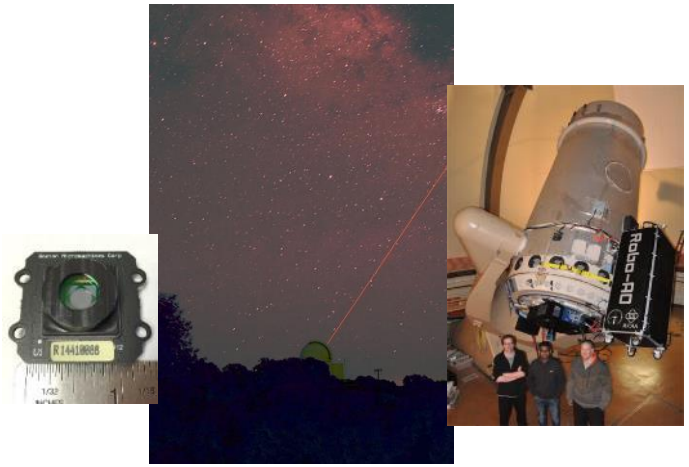
Outline

- BMC DM Technology
- NASA funded mirror technology programs
- Space astronomy operations
- Ground astronomy operation

On-Sky Instruments using BMC Mirrors

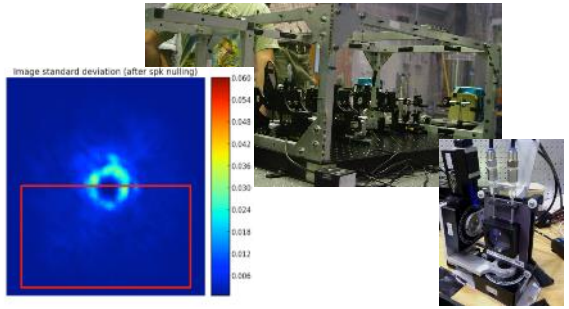
ROBO-AO

- Multi-DM Installed Palomar 2011/ Moved to Kitt Peak 2015



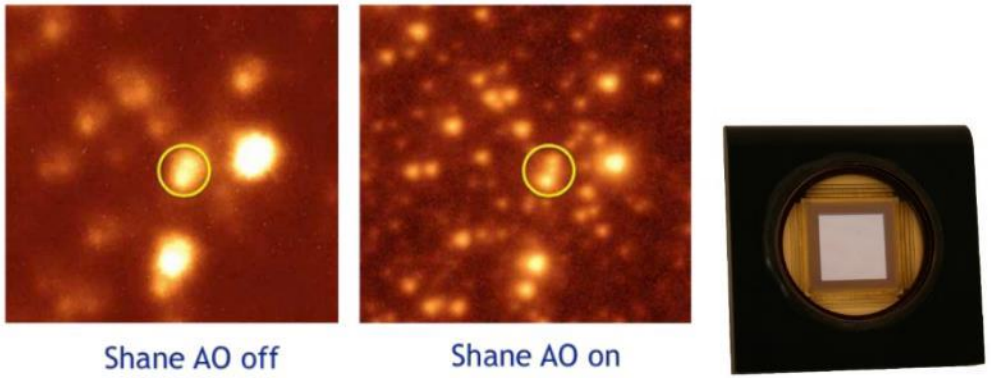
SCExAO, Subaru telescope

- 2040 installed 2013



Shane-AO, Lick Observatory

- Kilo-DM installed 2013
- Visible Light Laser Guidestar Experiments

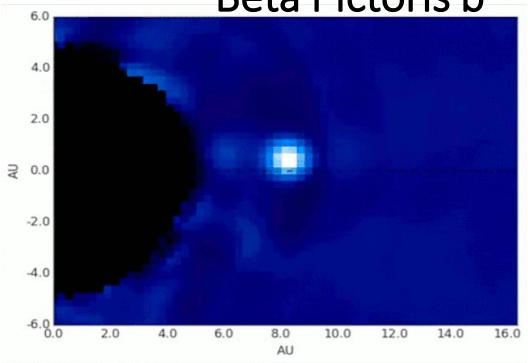


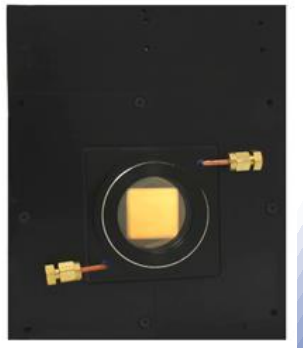
Portion of the M92 globular cluster taken in H band.

Gemini Planet Imager, Gemini South

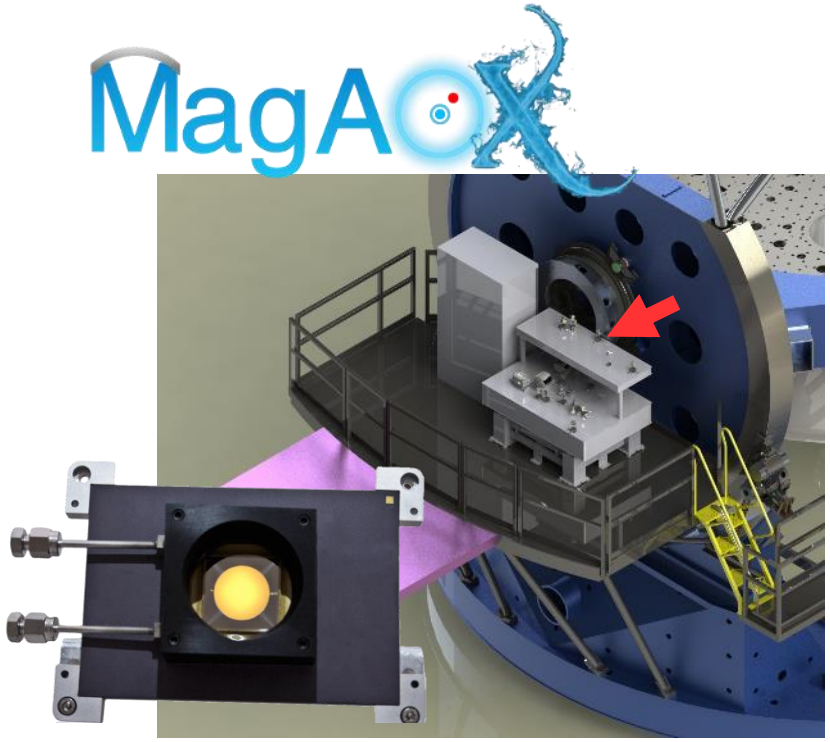
- 4092 installed 2013

Beta Pictoris b



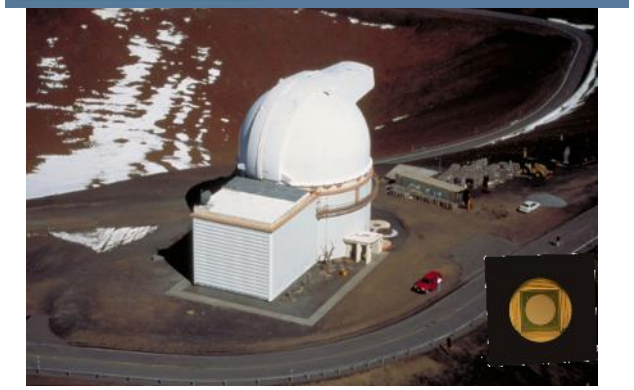


Next Instruments

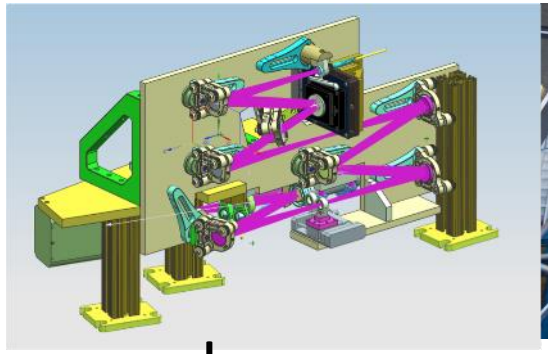


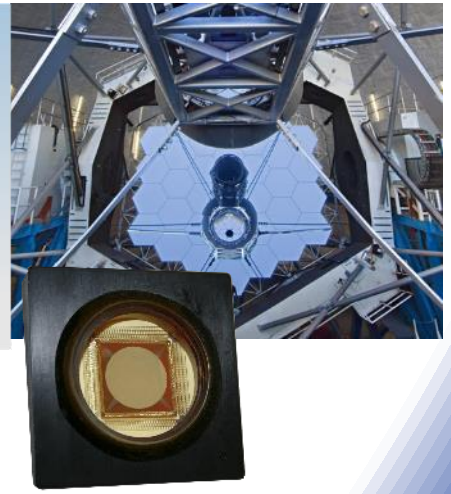
MagAO-X on the Clay Nasmyth platform.
Arrow shows location of BMC 2K.

University of Hawaii Institute for Astronomy



Rapid Transit Surveyor
492 DM
Successor of Robo-AO





Keck Planet Imager and Characterizer (KPIC)

3.5 um Stroke 952

Conclusion

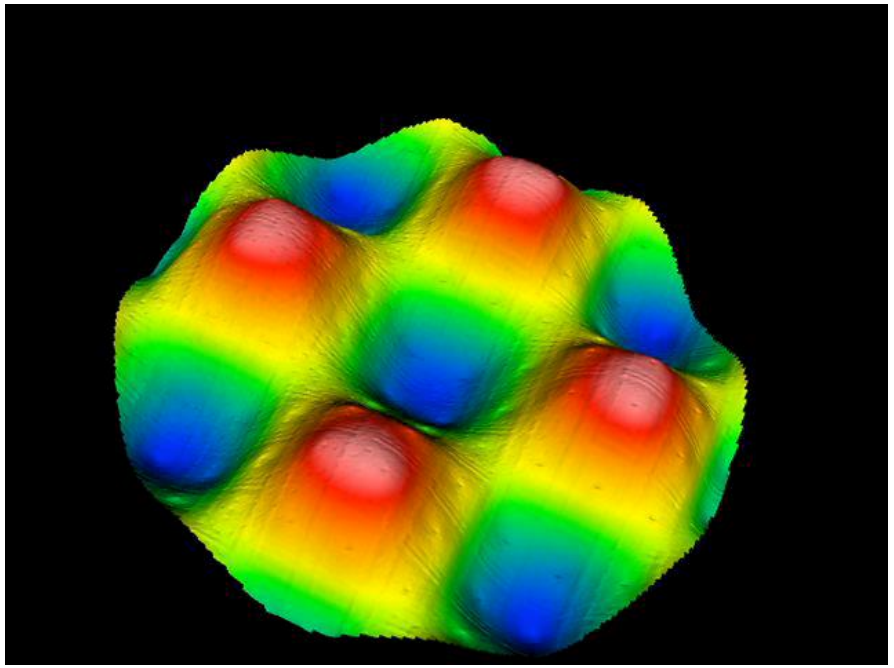
- Results from our Phase I and II program show good promise for next generation MEMS DMs.
- Testing is ongoing with our TDEM program. Parts are ready for environmental testing.
- APRA program setting new path for high actuator count system

Acknowledgements

- Funding from NASA
  - **Contract#: NNH12CQ27C SAT/TDEM**
  - **Contract #: NNX16CP14C NASA Phase II SBIR**
  - **Contract#: NNX17CP76P NASA Phase I SBIR**
  - **Contract#: NNX17AI66G/80NSSC18K0082 APRA**

Thank You

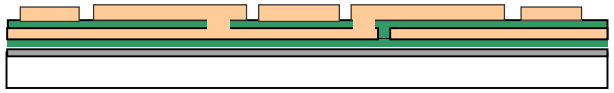
Questions?



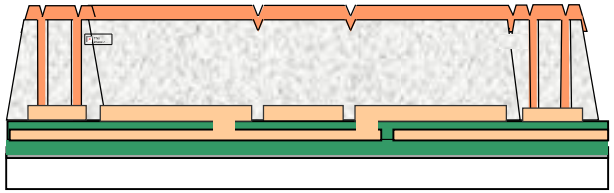
Paul Bierden, pab@bostonmicromachines.com

MEMS DM Fabrication

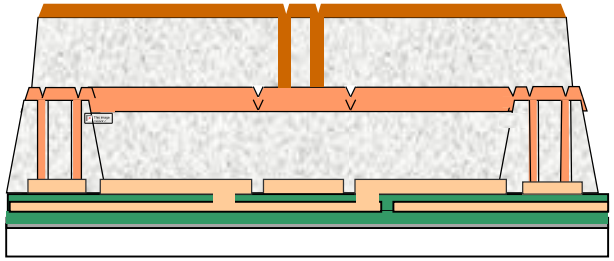
(deposit, pattern, etch, repeat)



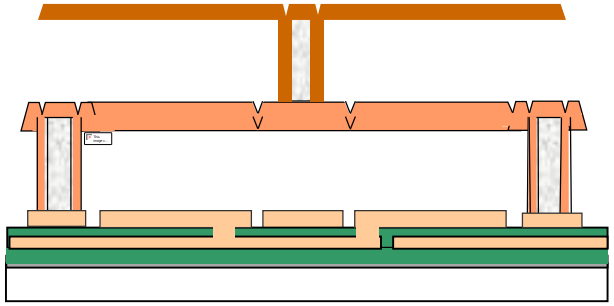
Electrodes & wire traces:
polysilicon (conductor) & silicon nitride (insulator)



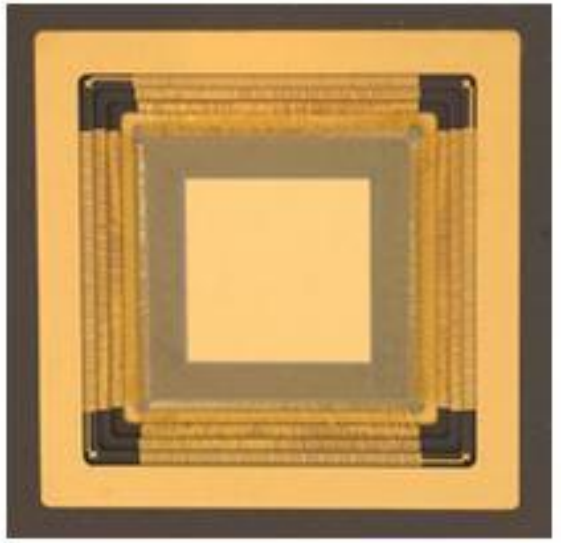
Actuator array:
oxide (sacrificial spacer) and polysilicon (actuator structure)



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



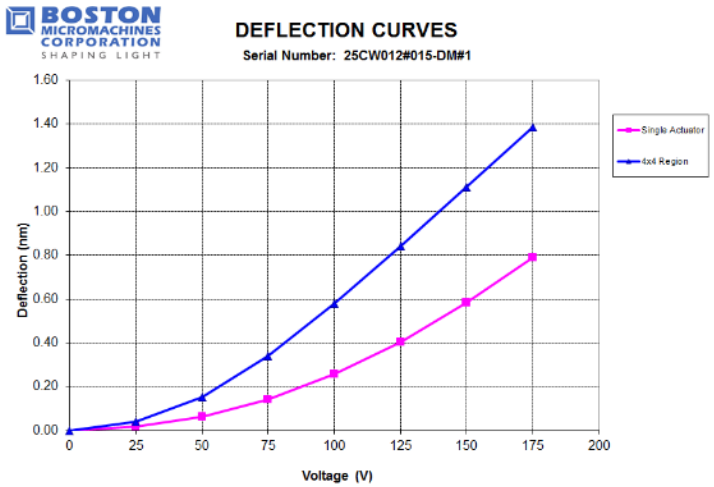
MEMS DM:
Etch away sacrificial oxides in HF, and deposit reflective coating



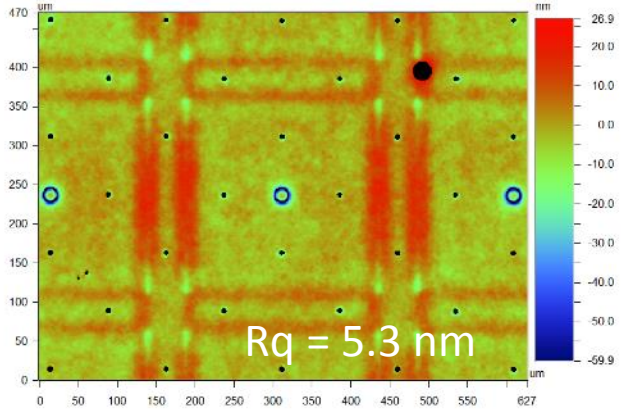
Attach die to a ceramic package and wirebond

12 DMs Fabricated and Characterized

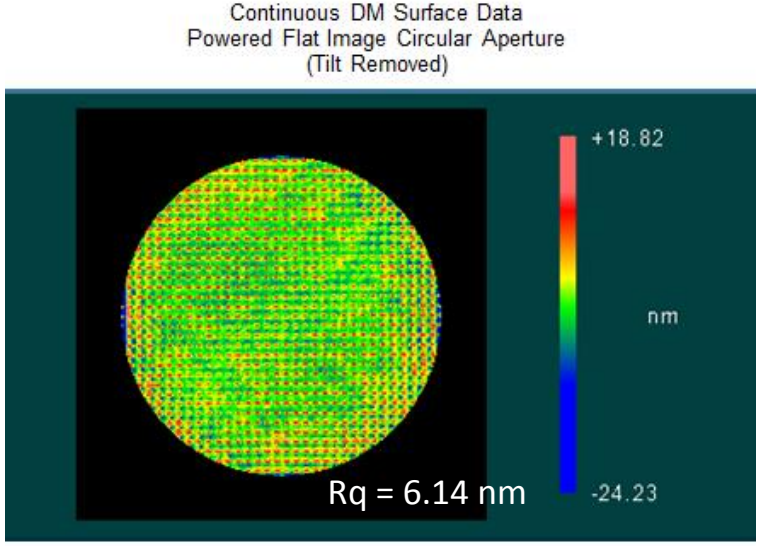
Voltage v. Deflection



Single Actuator Surface Figure

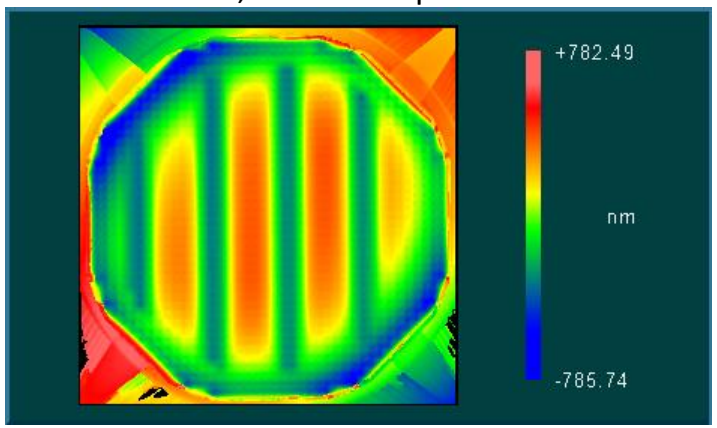


Active Flattening of DM Surface



Sinusoid Shape

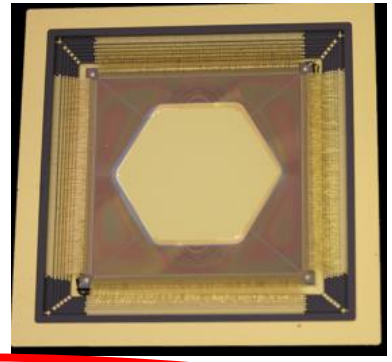
4 Period, 400nm Amplitude



Delivered to JPL (2) and Princeton (2)

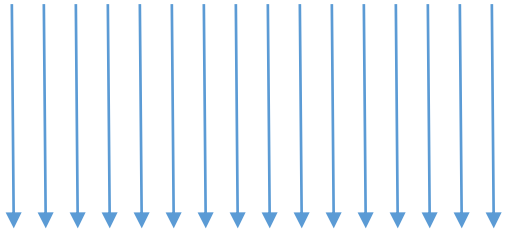
High Spatial Frequency DM: ELTs and Space Astronomy

DM



Ground 3-4um stroke, 200 across aperture
Space 1-2 um stroke, 100 across aperture

Interconnection



Ground and Space same

Electronics

Ground 10kHz, 12-14 bit
Space 100 Hz, 16+ bit, SWAP important