MEMS Deformable Mirrors for Astronomical Adaptive Optics

Paul Bierden

President, Boston Micromachines Corp.

May 11, 2017

ExEP Technology Colloquium Series

BOSTON MICROMACHINES CORPORATION
SHAPING LIGHT

NASA EXOPLANET PROGRAM

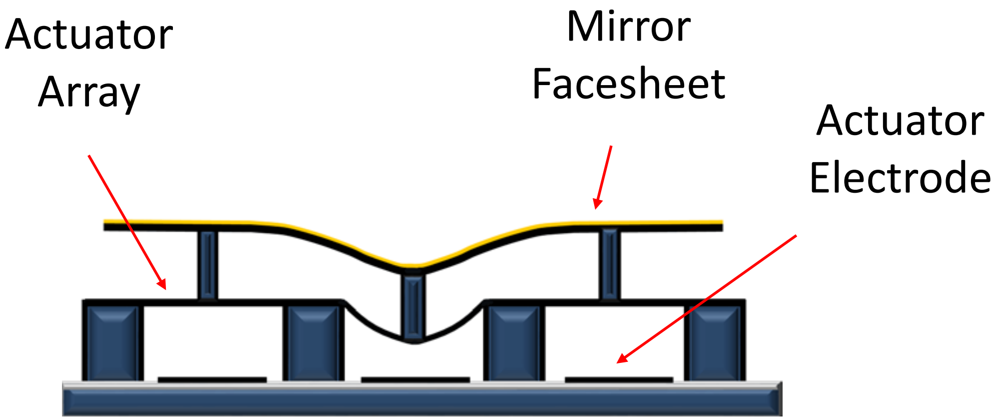
Outline

- BMC DM Technology
- DM Technology Development and Advancement
- Space astronomy operations
- Ground astronomy operation
- Conclusion

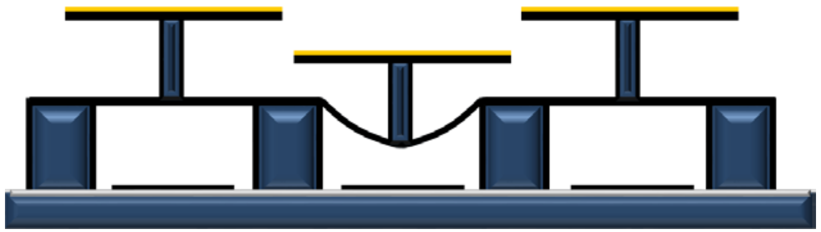
Outline

- BMC DM Technology
- DM Technology Development and Advancement
- Space astronomy operations
- Ground astronomy operation
- Conclusion

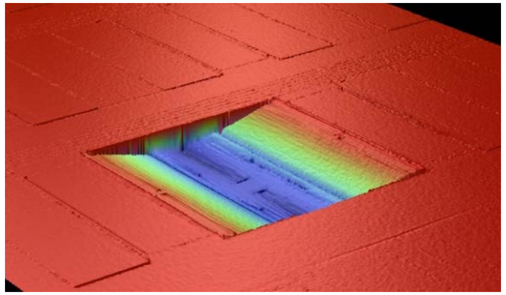
MEMS DM Architecture



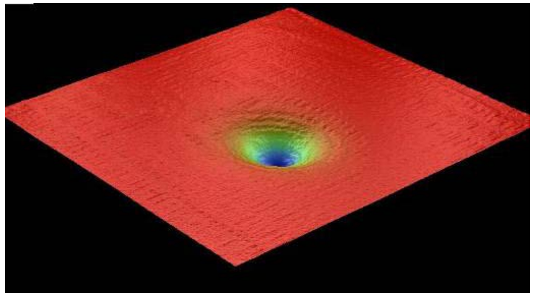
Continuous mirror (smooth phase control)



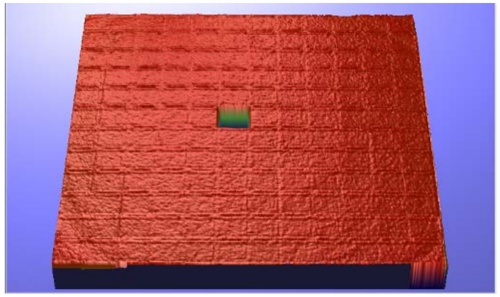
Segmented mirror (uncoupled control)



Deflected Actuator

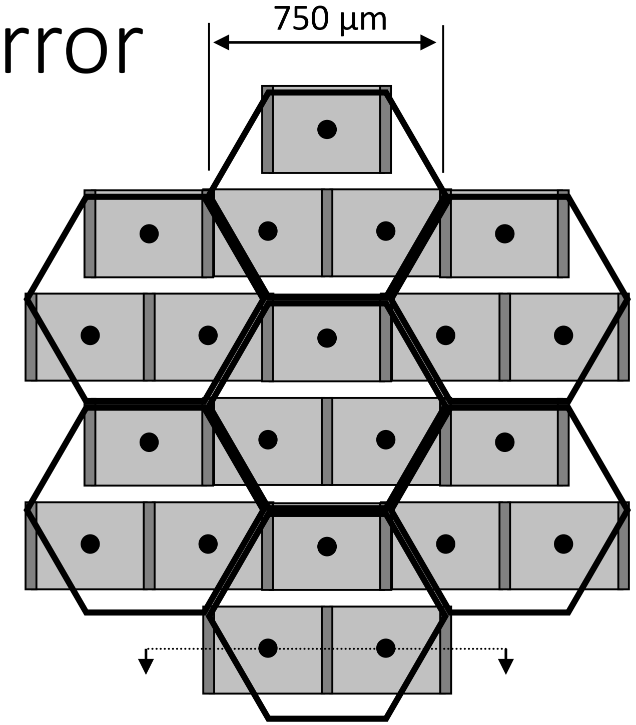


Deformed Mirror Membrane

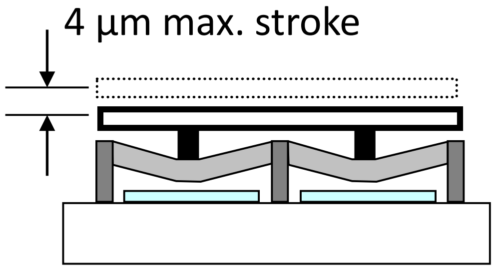


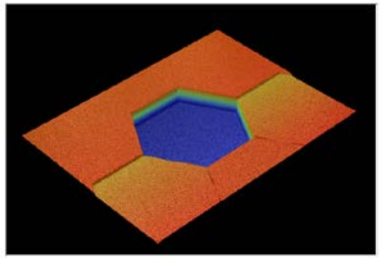
Deformed Segmented Mirror

Hex Tip-Tilt-Piston Deformable Mirror

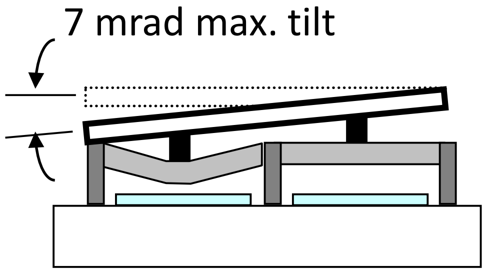


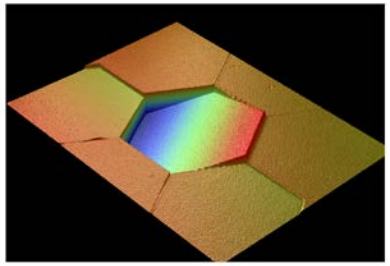
- Up to 3063 actuators
- Independent hexagonal segments
  - 3 actuators per segment





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





BMC Mirror Family

Small Cartesian Arrays

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

Medium Cartesian Arrays

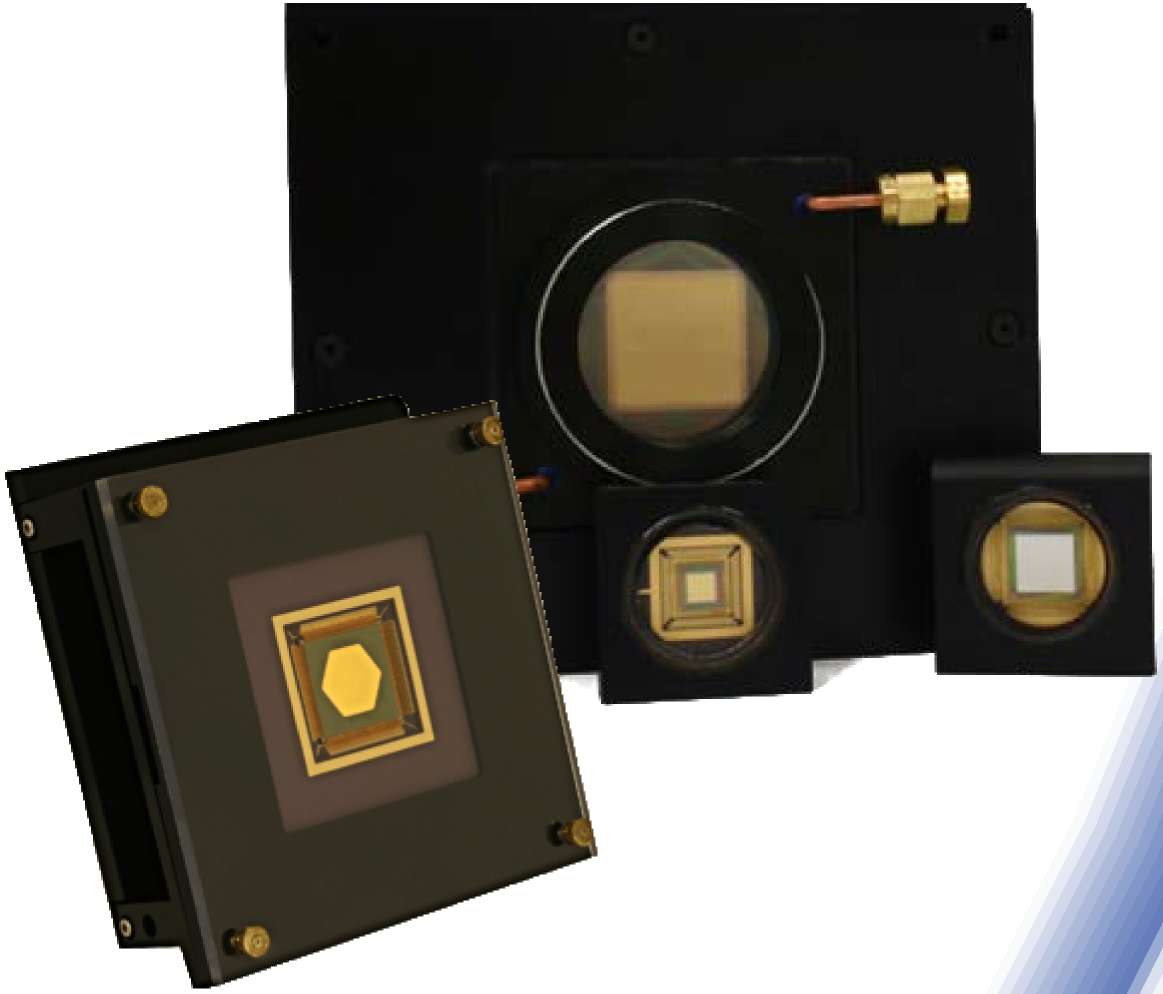
- Square and circular arrays from 492 to 1020
- 1.5µm & 3.5µm stroke

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



BMC Mirror Family

Small Cartesian Arrays

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

Medium Cartesian Arrays

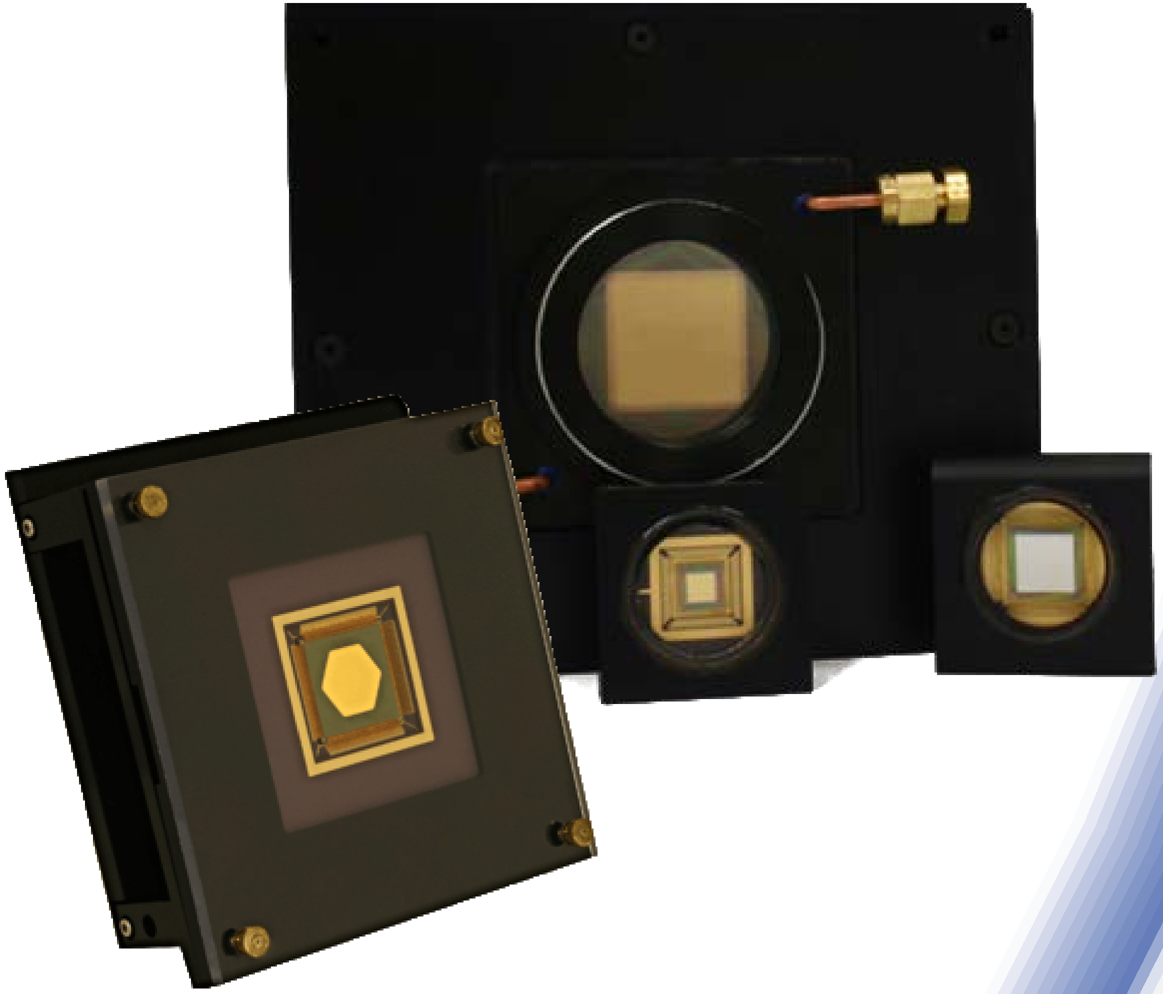
- Square and circular arrays from 492 to **1020**
- 1.5µm & 3.5µm stroke

Large Cartesian Arrays

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

Hex Tip-Tilt-Piston

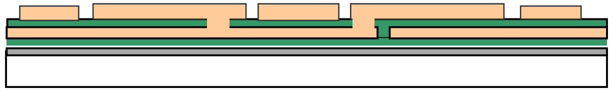
- 37, **331- and 1021-Segment Devices**



Developed through NASA funding

MEMS DM Fabrication

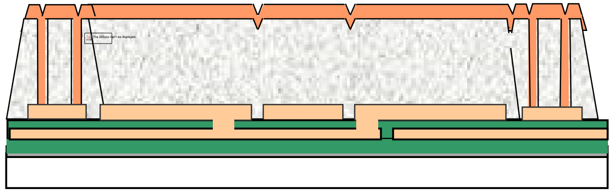
(deposit, pattern, etch, repeat)



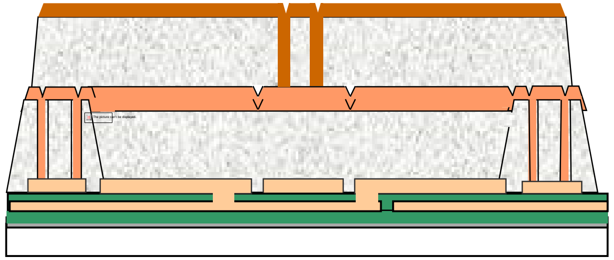
Electrodes & wire traces:
polysilicon (conductor) & silicon nitride (insulator)

Ground 8µm

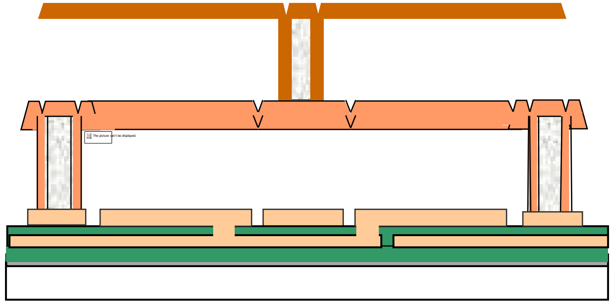
Space 5µm



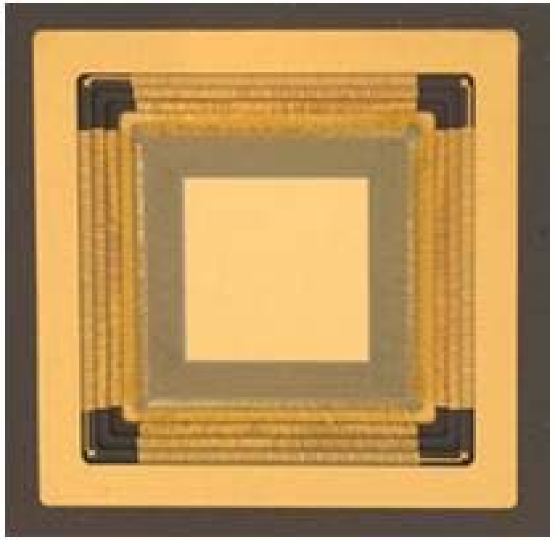
Actuator array:
oxide (sacrificial spacer) and polysilicon (actuator structure)



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



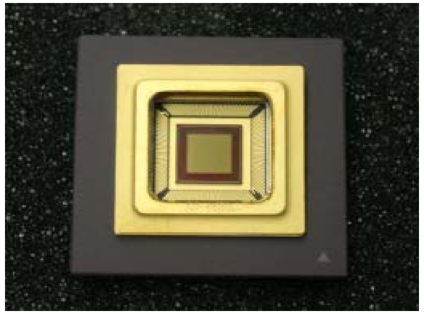
MEMS DM:
Etch away sacrificial oxides in HF, and deposit reflective coating

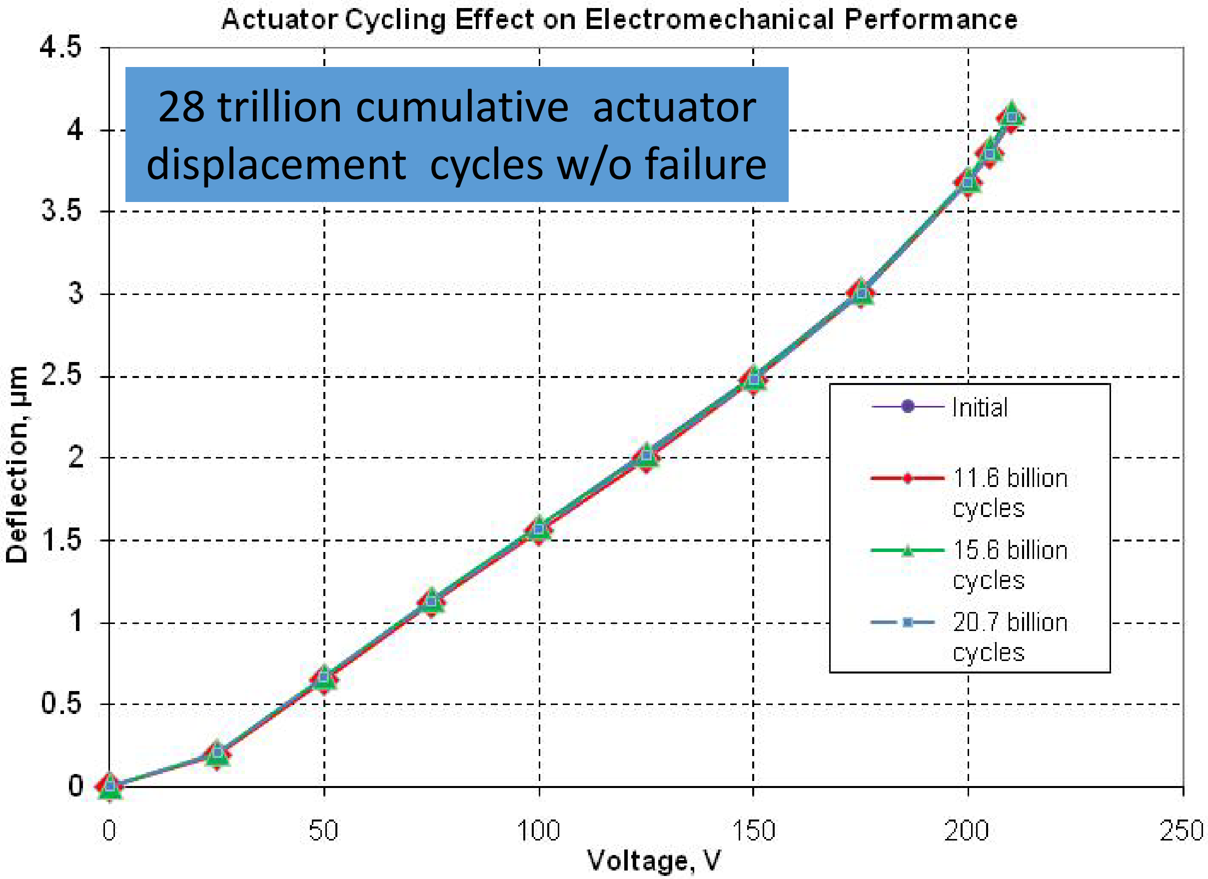


Attach die to a ceramic package and wirebond

MEMS DMs Characteristics

Reliable

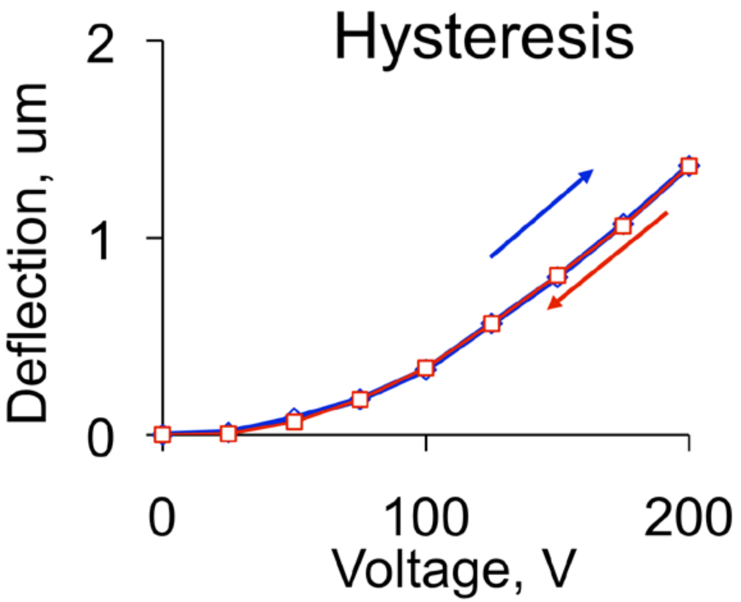




MEMS DMs Characteristics
Repeatable and Stable

- Repeatability:
  - 97% of the actuators returned to a commanded shape to under 1.0 nm phase
  - 73% of the actuators returned to a commanded shape to under 0.4 nm phase
- Stability:

	1.33 min	8 min	38 min
MEMS MIRROR	0.088nm	0.106nm	0.150nm
Reference Flat	0.042nm	0.116nm	0.122nm



Morzinski et al, *Characterizing the potential of MEMS deformable mirrors for astronomical adaptive optics* 2016SPIE.9909E..01M

Outline

- BMC DM Technology
- DM Technology Development and Advancement
- Space astronomy operations
- Ground astronomy operation
- Conclusion

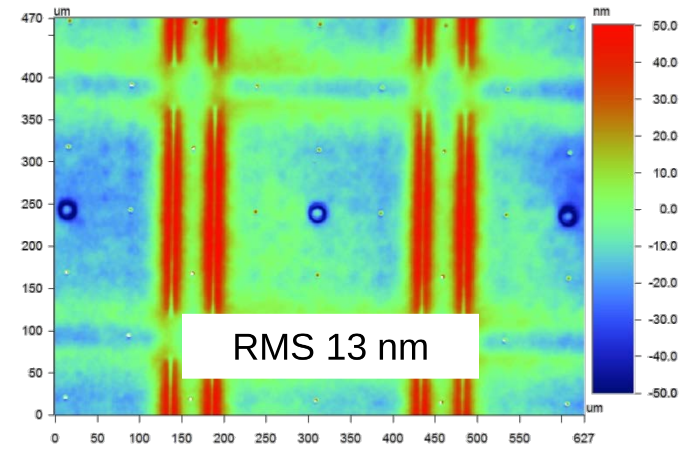
Technology Research

Over the past years BMC has performed research and development for the improvement of MEMS DM for space applications

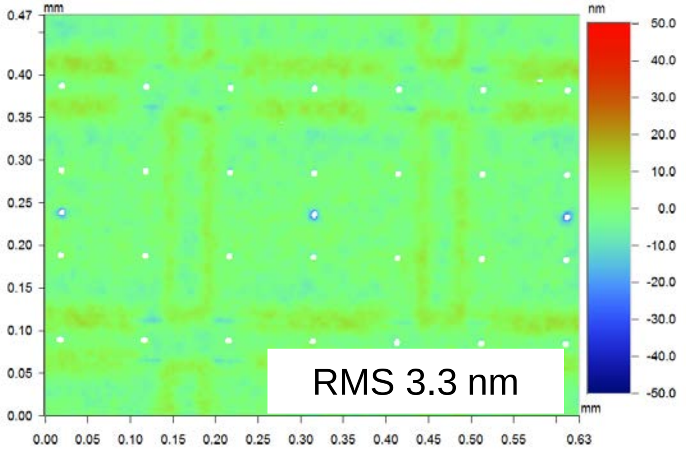
- Topography
- Yield
- Reliability
- Reduced operating voltage
- Hex TTP development
- Technology development

Topography Improvements

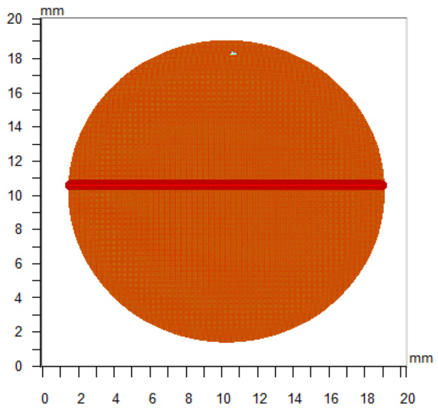
Heritage Process

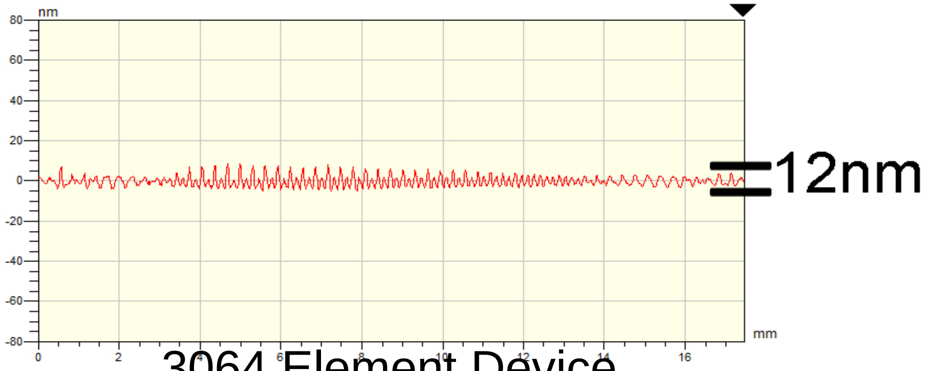


Modified Process

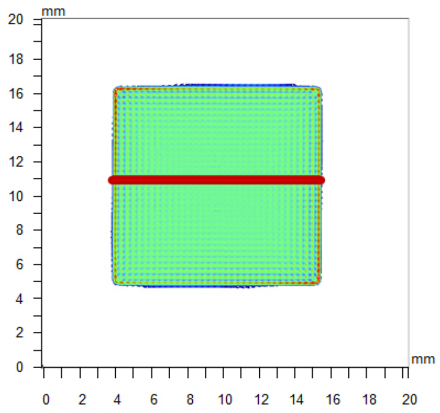


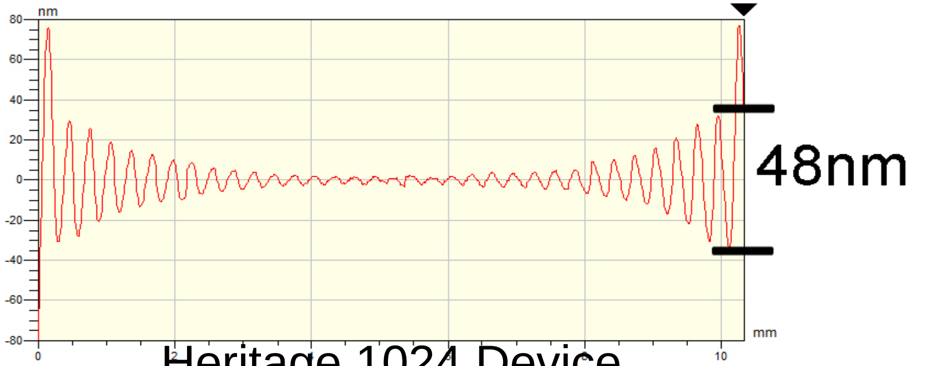
Scalloping across mirror compared to heritage devices





3064 Element Device

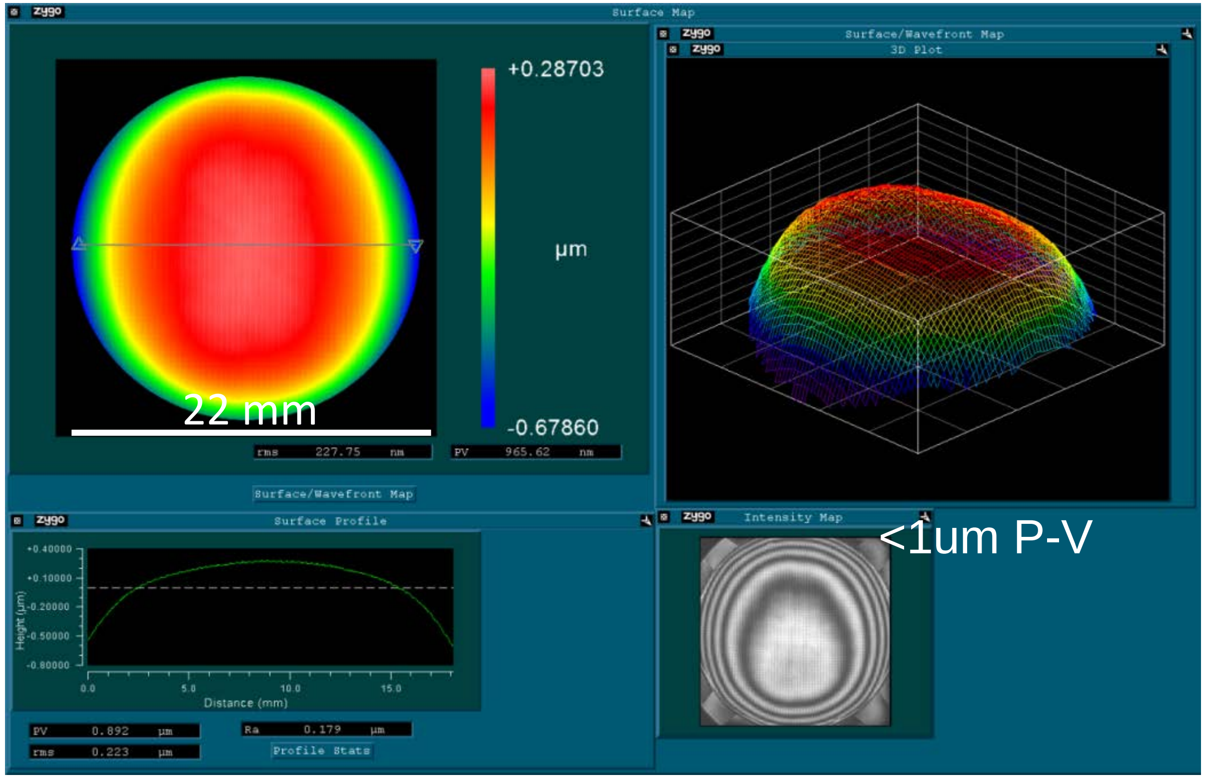




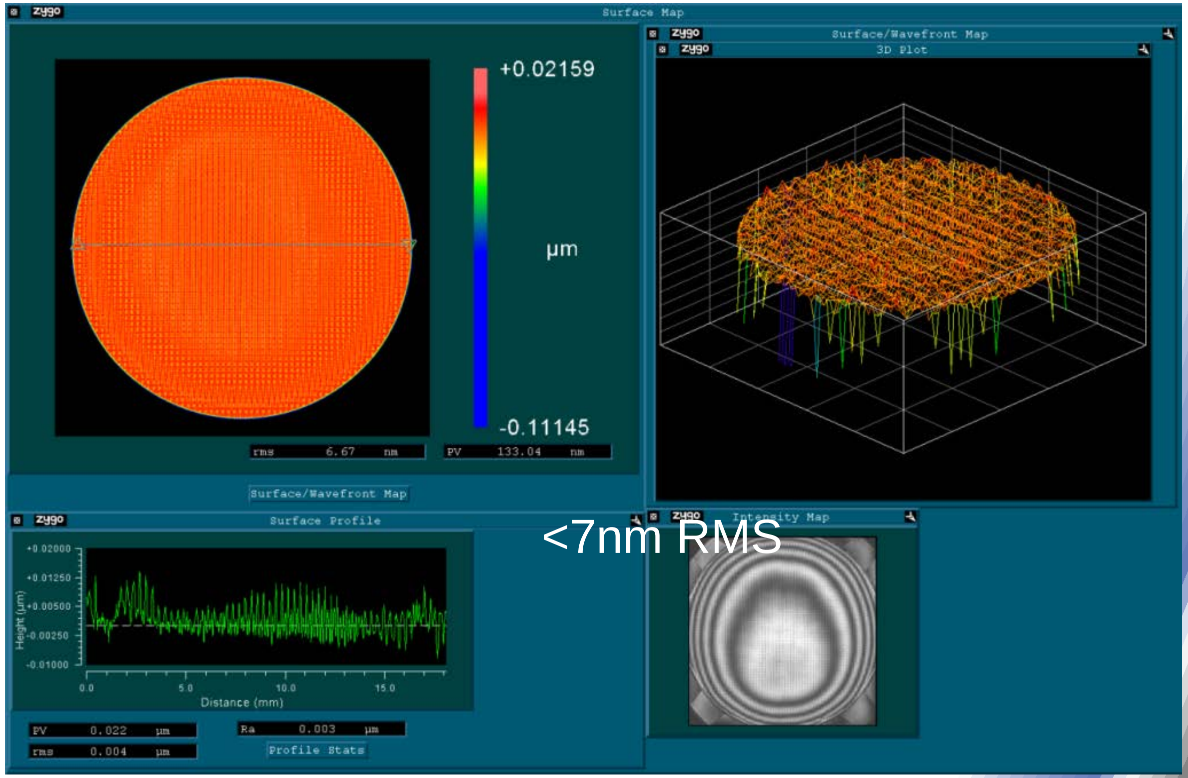
Heritage 1024 Device

Note 3064 aperture is 17mm while heritage is 10mm

Topography Improvements

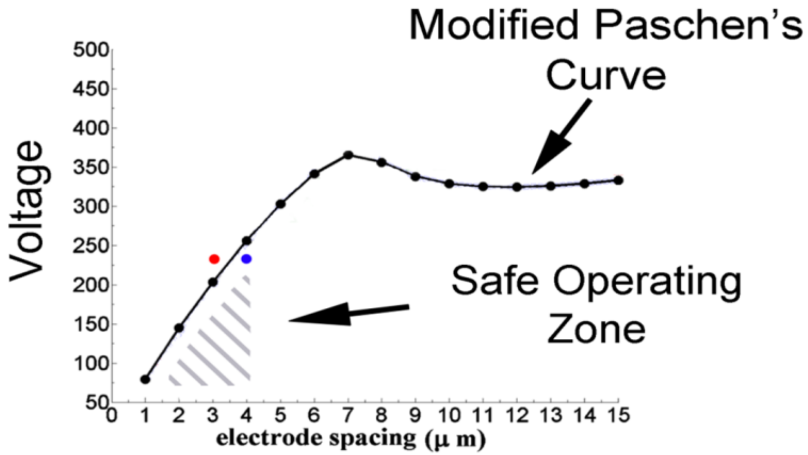


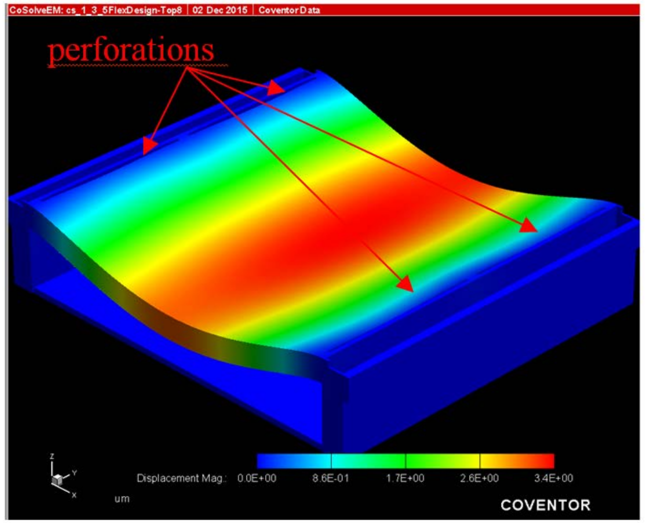
Unpowered Surface



With low order filtered
(control bandwidth)

Reduction in Operating Voltage (Ongoing)

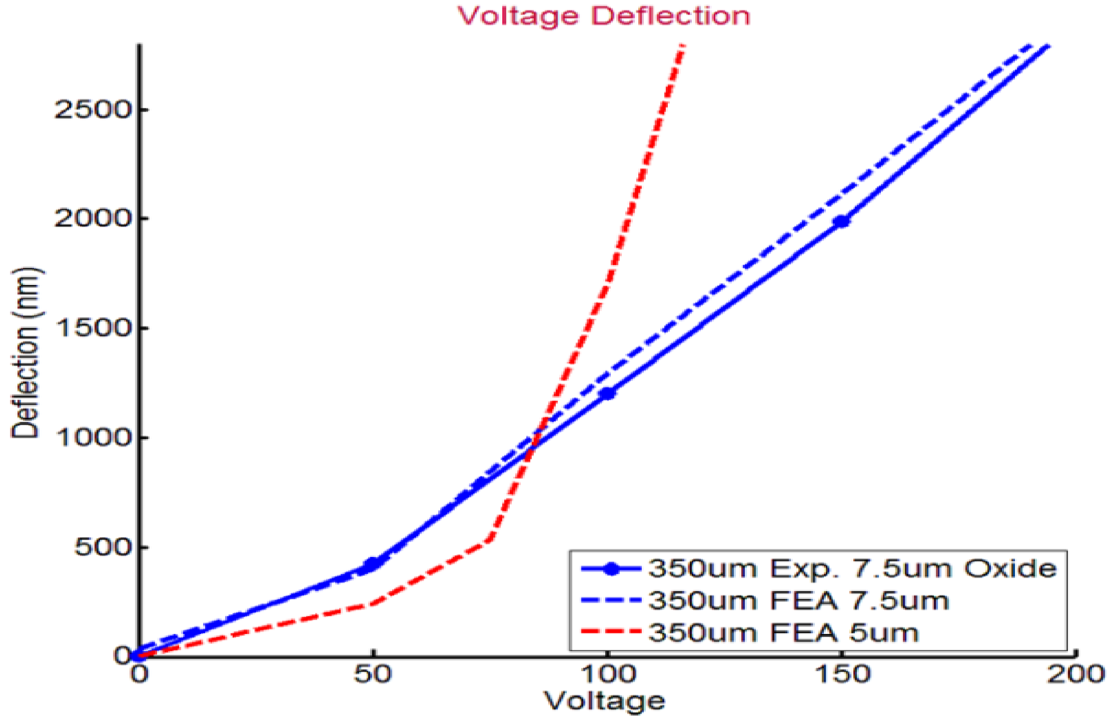




Modified design allows full actuation at lower voltage

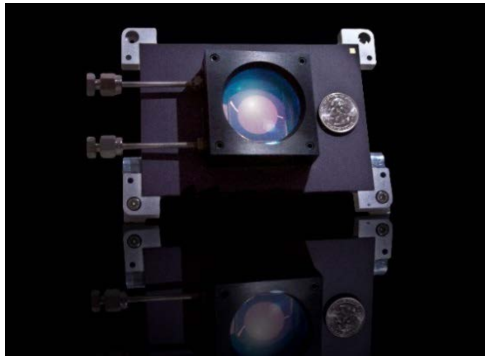
Reduced Operating Voltage

- Lower power usage
- Easier electronics
- Safer operation

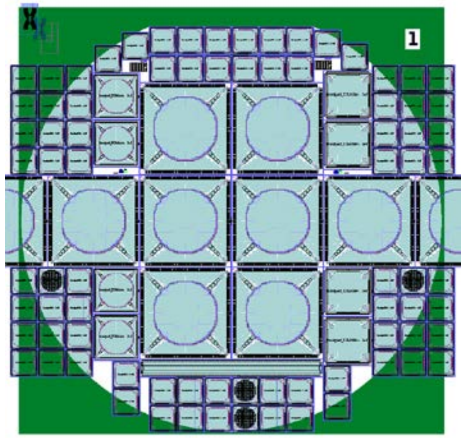


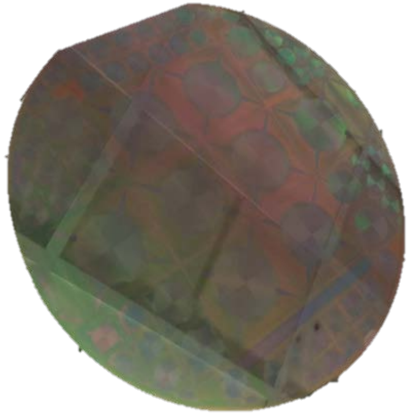
Improved Yield, Performance and Reliability of High-Actuator-Count Deformable Mirrors

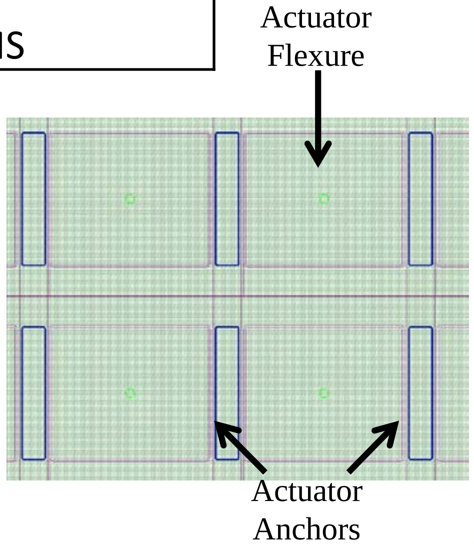
Contract Number: NNX16CP14C (Start 4/2016)

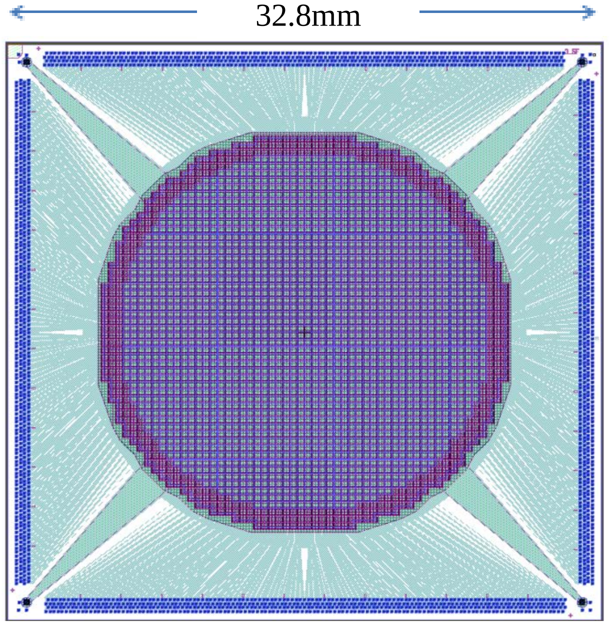


Mirror architecture	2040 actuators
Active Aperture Diameter	19.6mm
# Actuators across active diameter	50
Actuator Pitch	400µm
Actuator Stroke	1.5µm
Operating Voltage	0-100V
Mirror Surface Figure	<5nm RMS









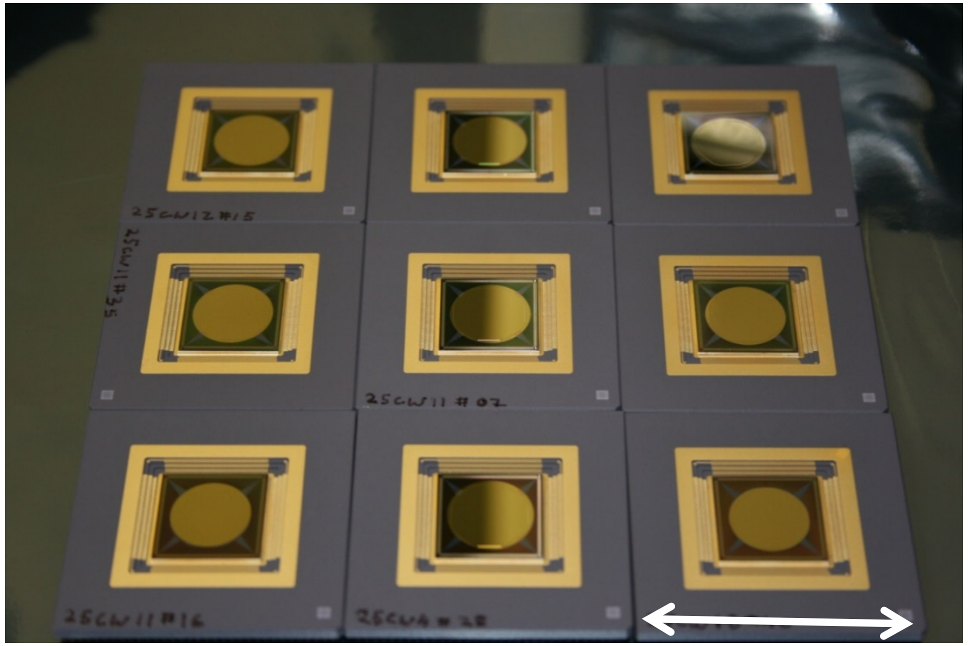
Layout of a 2040-actuator device design (Right), showing all nine mask layers required to form the MEMS deformable mirror.

TDEM Program

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

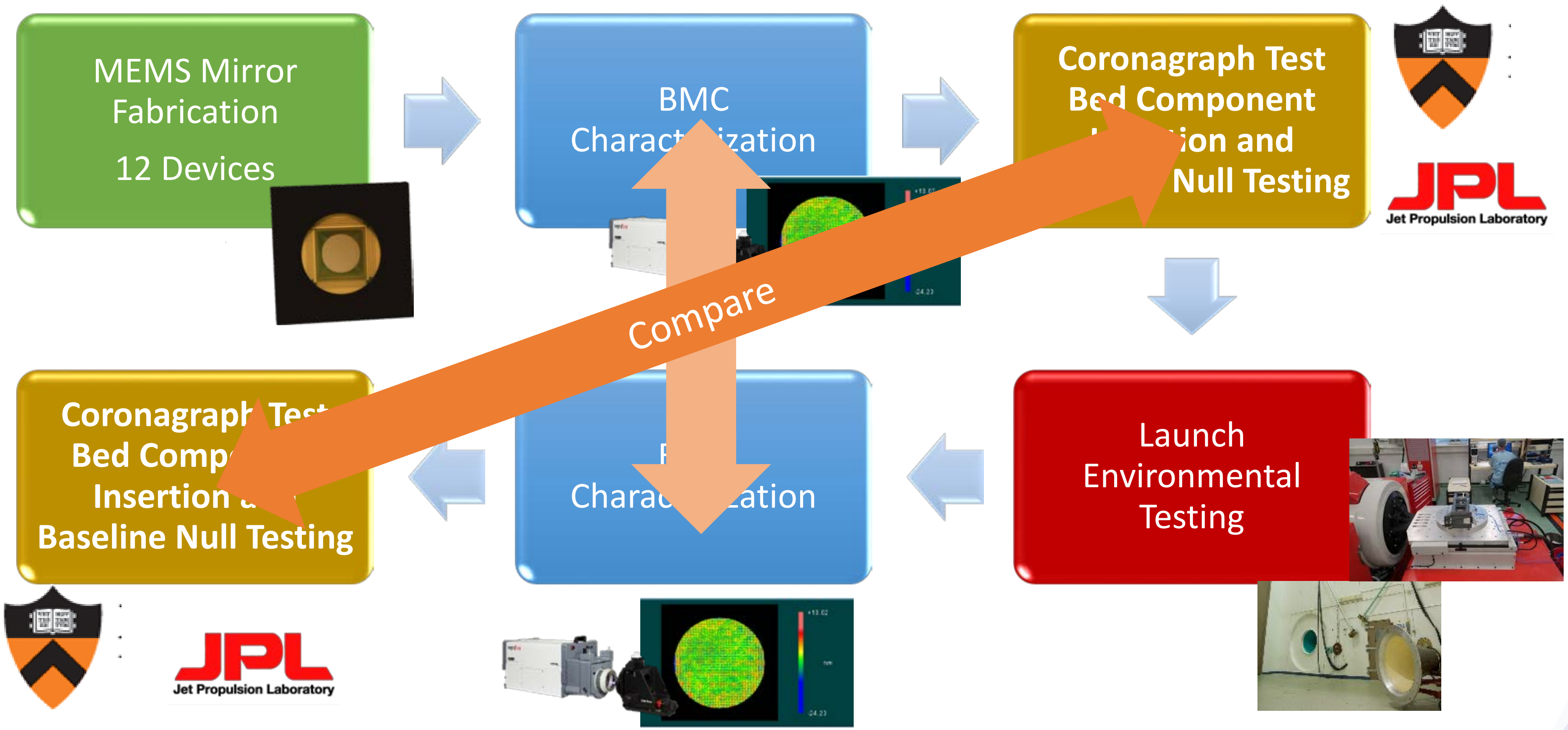
Objective: Demonstrate survivability of the BMC MEMS Deformable Mirror after exposure to dynamic mechanical environments close to those expected in space based coronagraph launch.

9 Mirrors ready for testing



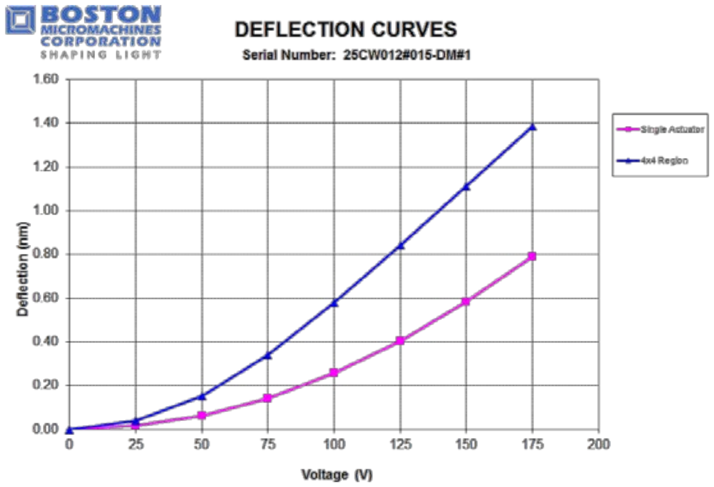
5cm

Project Flow



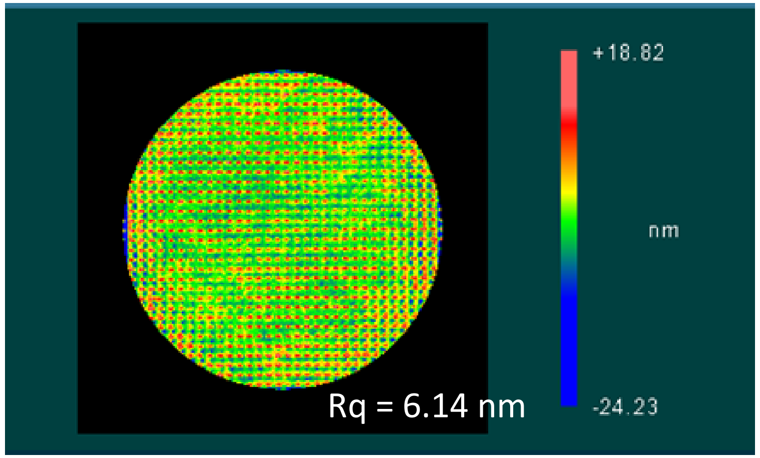
12 DMs Fabricated and Characterized

Voltage v. Deflection

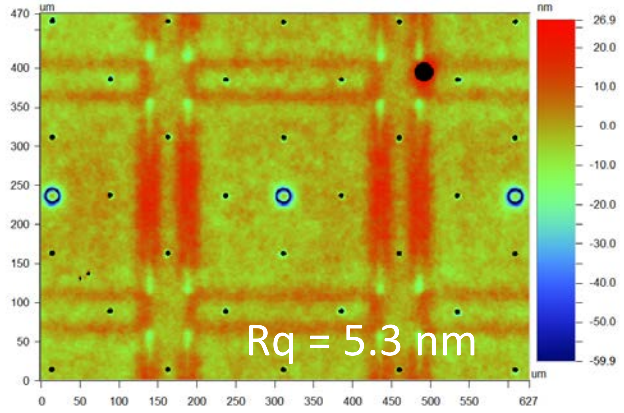


Active Flattening of DM Surface

Continuous DM Surface Data
Powered Flat Image Circular Aperture
(Tilt Removed)

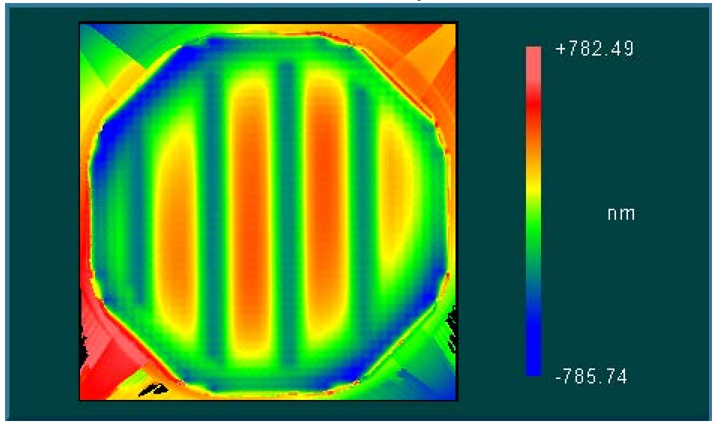


Single Actuator Surface Figure



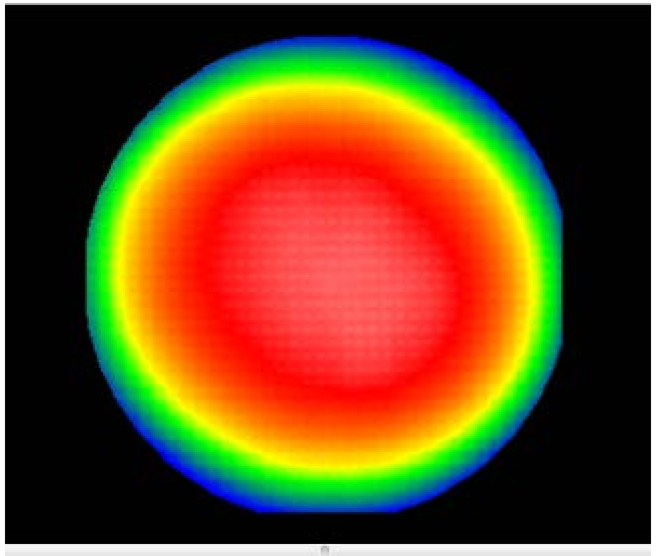
Sinusoid Shape

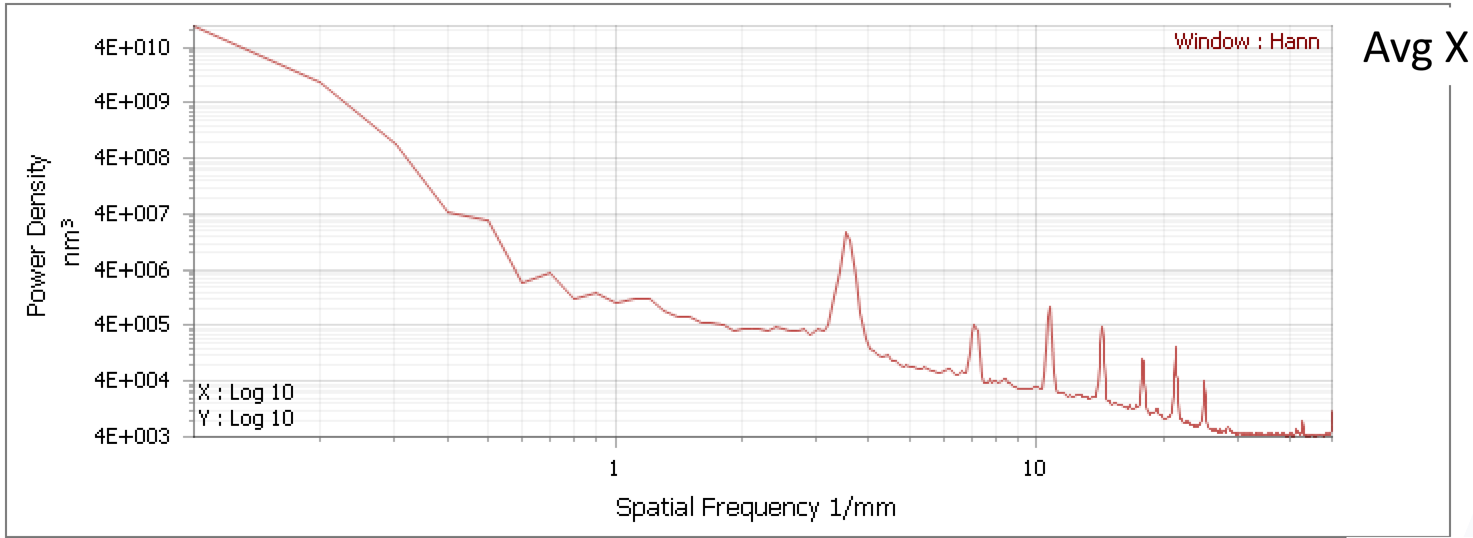
4 Period, 400nm Amplitude



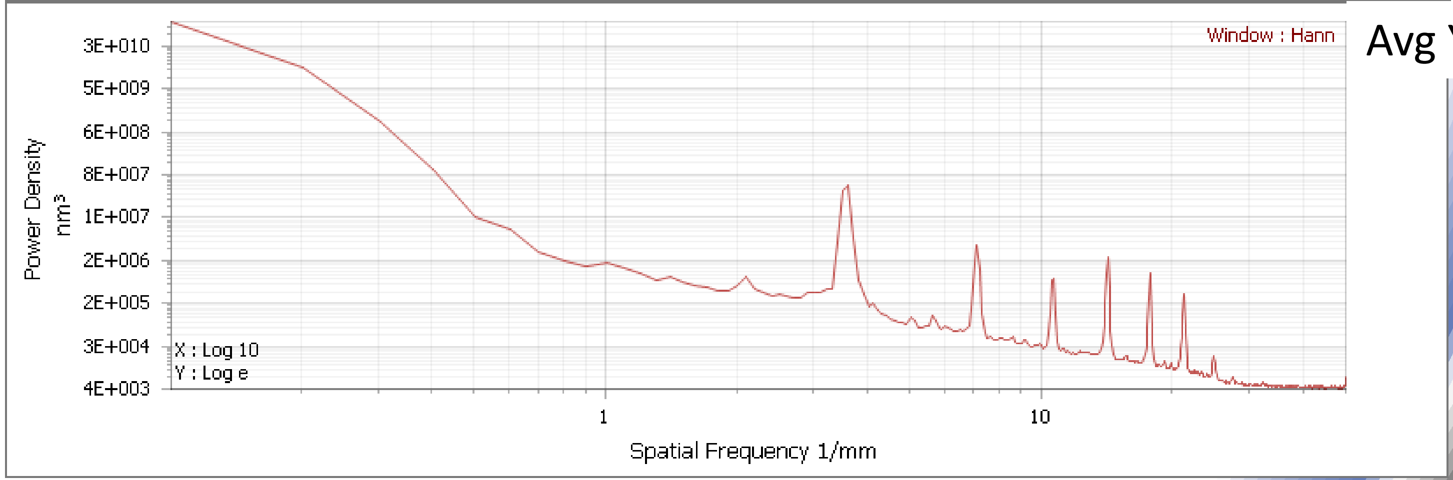
Delivered to JPL (2) and Princeton (2)

Power Spectral Density



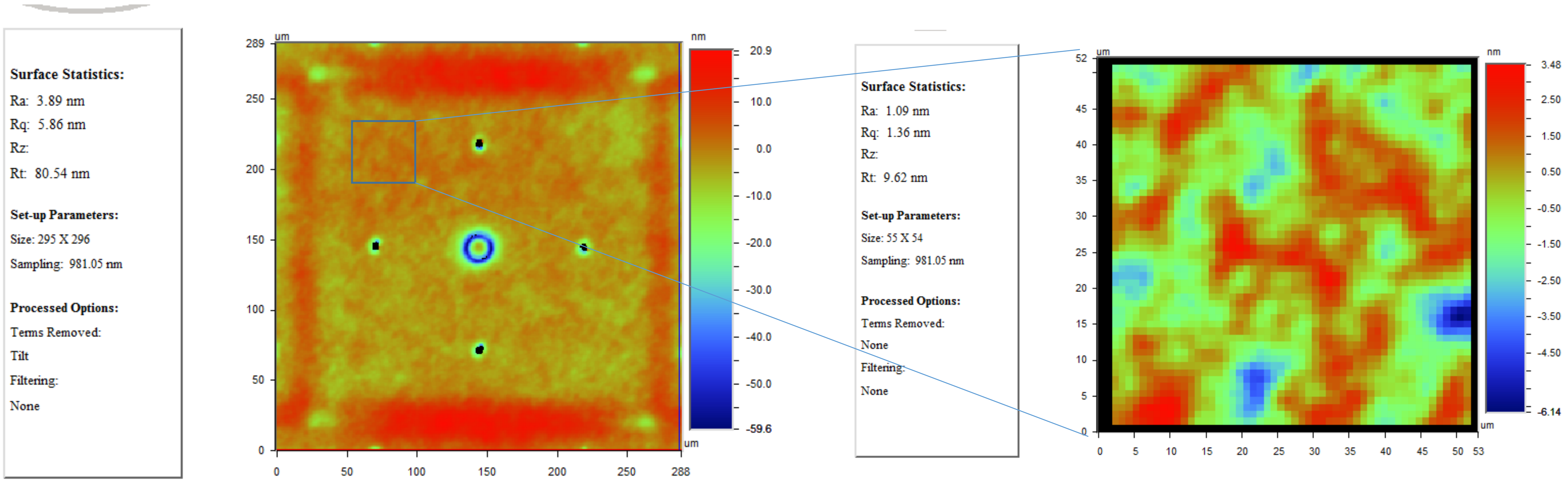


Avg X



Avg Y

Surface Finish and Figure of MEMS DMs



Single Actuator (300µm x 300µm)
RMS – 5.9 nm

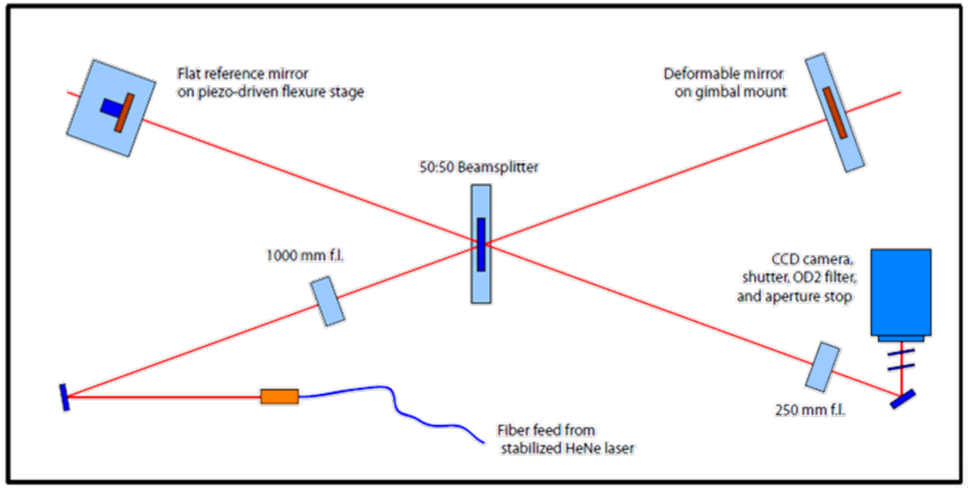
Micro-roughness (50µm x 50µm)
RMS – 1.4 nm

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

<u>*Work performed by: Frank Greer, Cory Hill, Brian Gordon, John Trauger*</u>

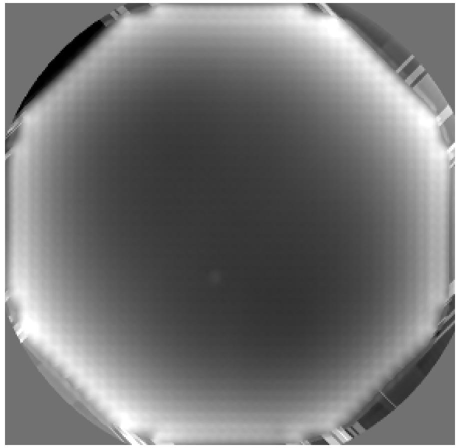


VSG is mounted on a 36 x 72 inch optical table. End-points of axes are the threaded holes 4.5 x 6.5 inches from table corners. Beam height = 4.405 inches.

- 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

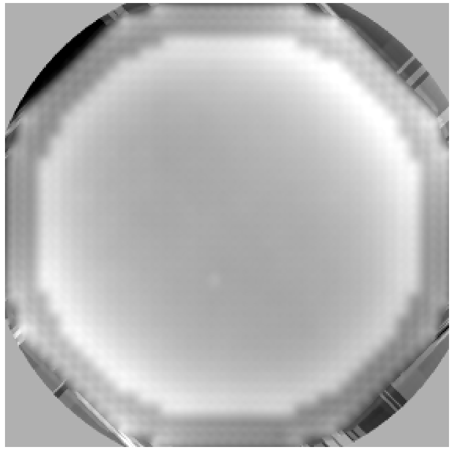
Flattening Protocol

Unpowered mirror



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

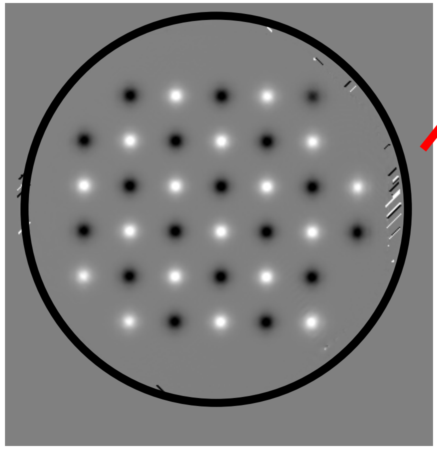
Mirror with 100V bias



PV Focus 667.3 nm, PV 45° astig 257 nm, PV 90° astig 17.3 nm, RMS in higher 48 nm

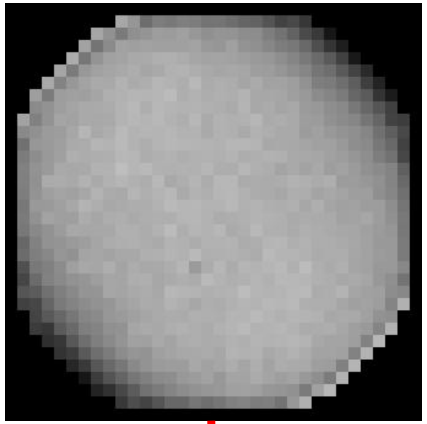
5 x5 array of +/- 10 V pokes

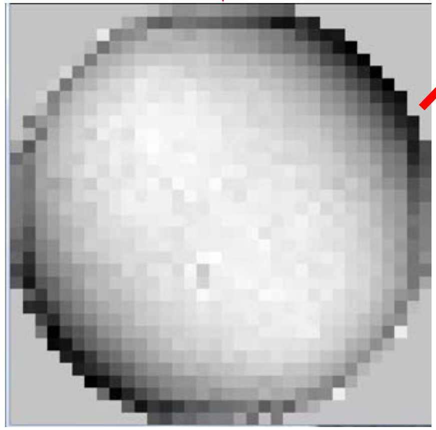
(difference of two images, circle drawn for clarity)



Pokes used to measure gains and calculate voltage map for flat surface figure

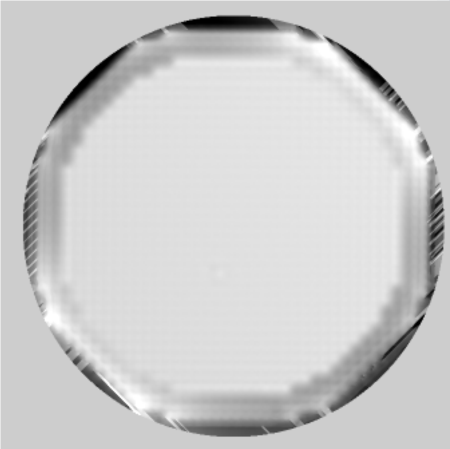
Actuator gain map measured about "flat" condition (5-10nm/V range)





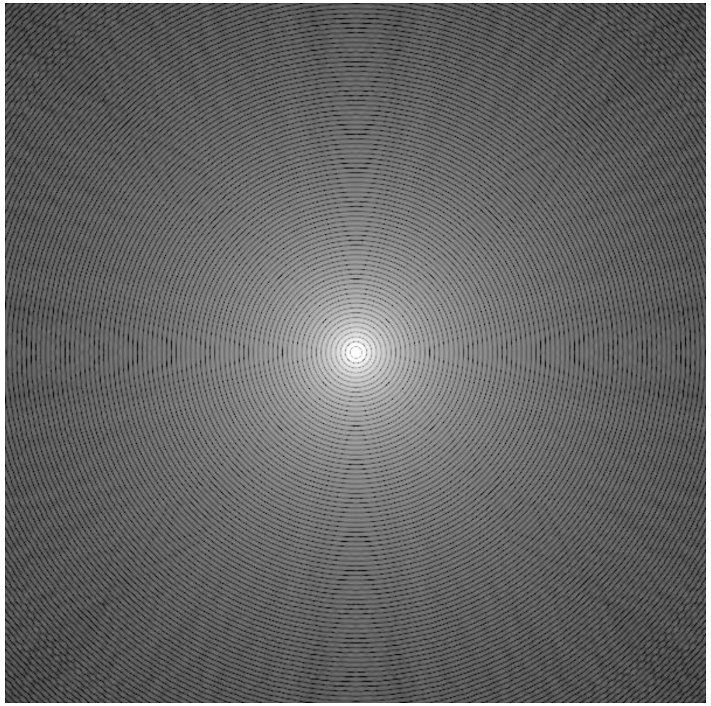
Voltage map for flat surface figure centered about 100V (55 – 112V range)

Flattened DM

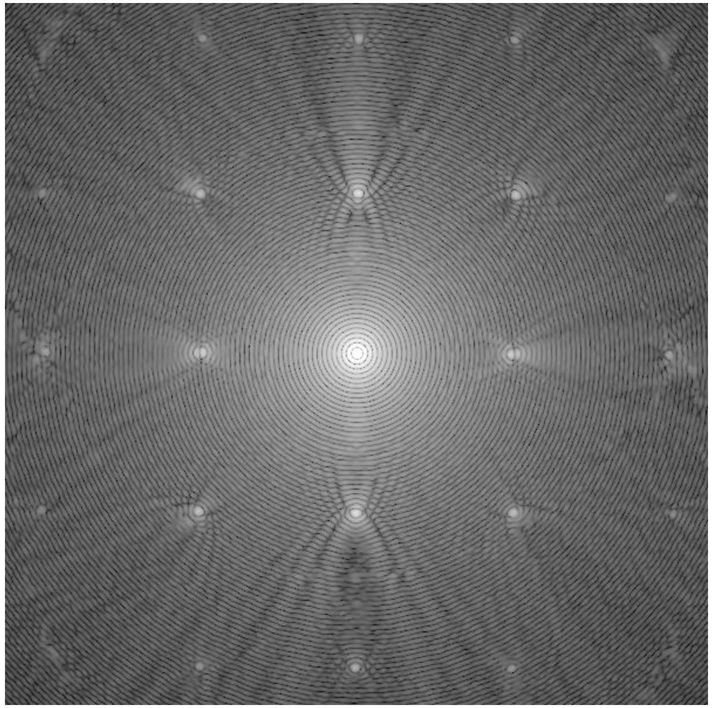


6.6nm PV focus, 2.9nm PV 45 deg astig, 0.3nm PV 90 deg astig, 7.6nm RMS higher order terms

Point Spread Function for the best flat setting



PSF with mathematically flat surface

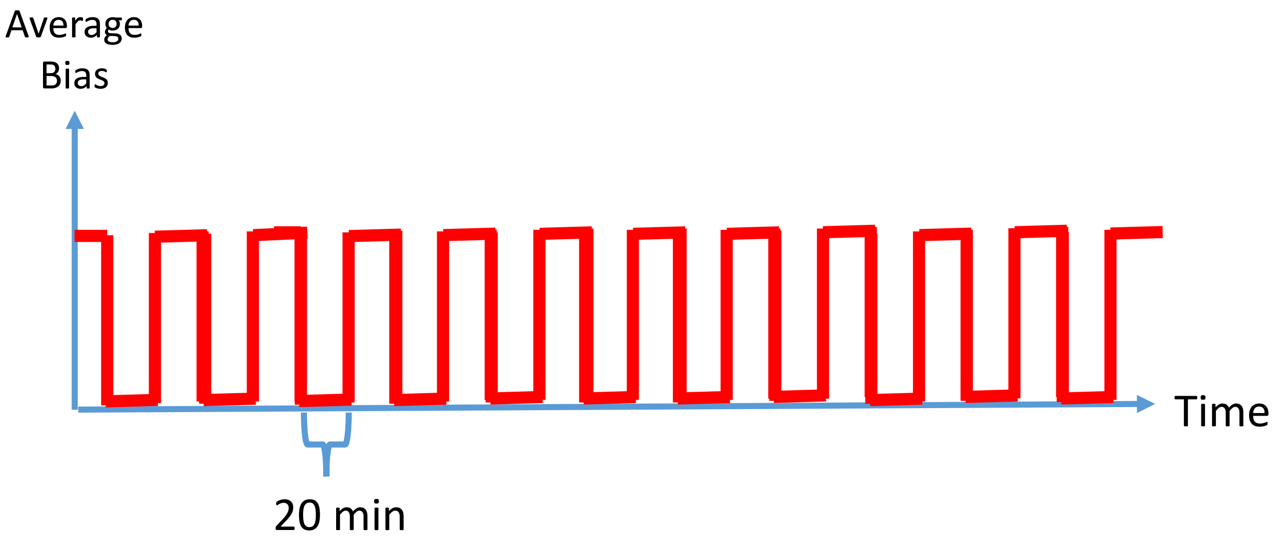


PSF with best flat BMC
(quilting = 7.5 nm RMS)

Strehl at 633 nm wavelength for the quilted BMC surface = 0.96

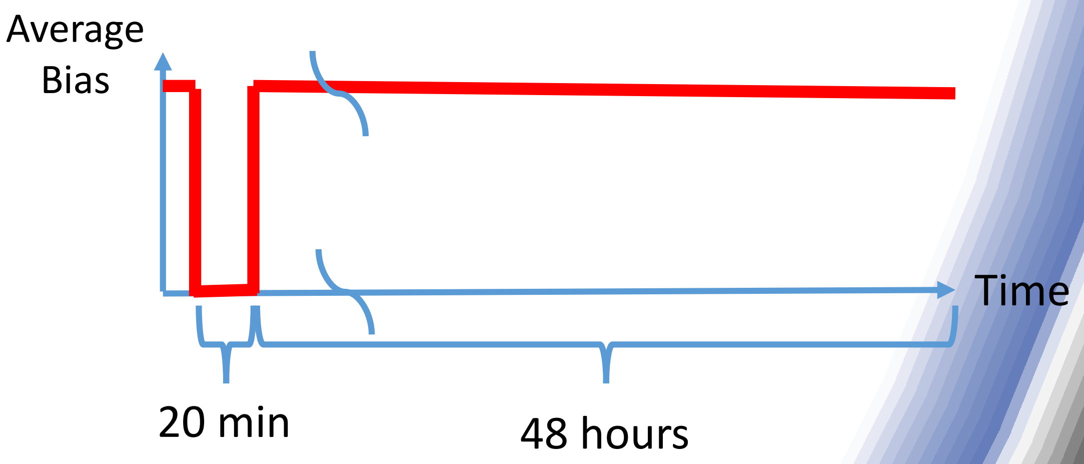
Accuracy and Stability Protocols
(using the flattened DM)

- **Tested repeatability of a flat surface figure solution ten times, passing through an unpowered state each time prior to applying the "flat surface figure solution".**



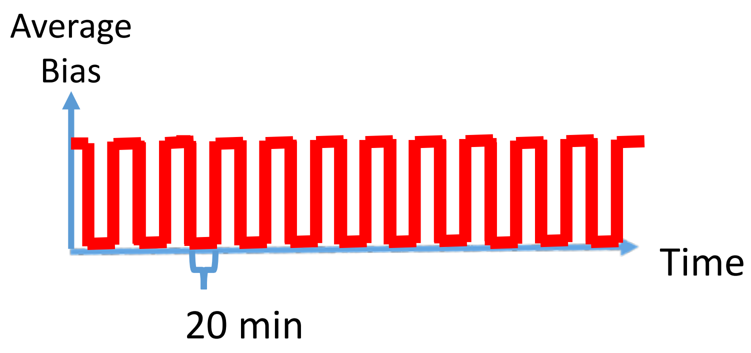
Two phase retrievals completed at the biased and unbiased condition for every repetition

- **Tested settling time for the BMC mirror when applying the "flat surface figure solution" passing through an unpowered state for ~20 minutes prior to the beginning of the experiment.** The mirror was left powered for with this solution and was characterized frequently over a 48 hour period.

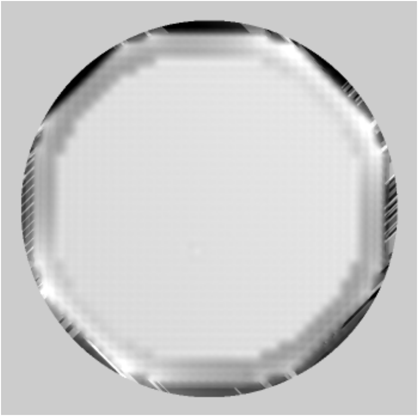


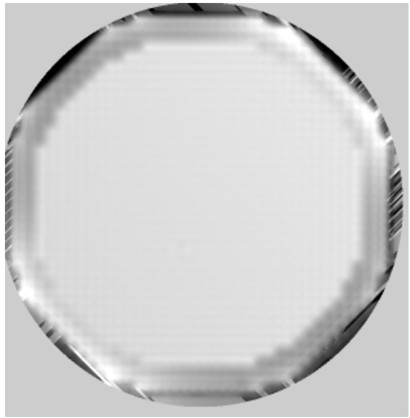
Phase retrievals completed after the following waiting periods:
20 min, 1 hour, 2 hours, 4 hours, 8 hours, 16 hours, 24 hours, 32 hours, 40 hours, 48 hours

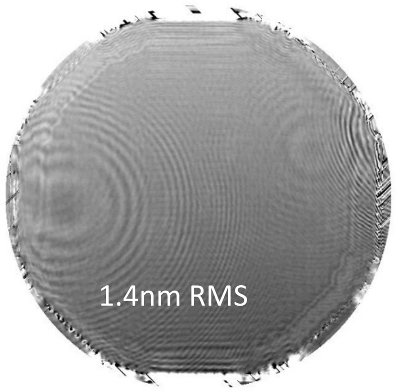
Repeatability Test Results



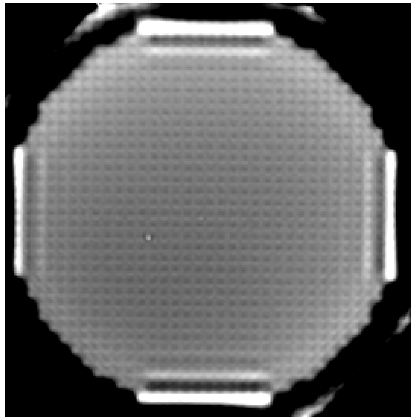
DM1

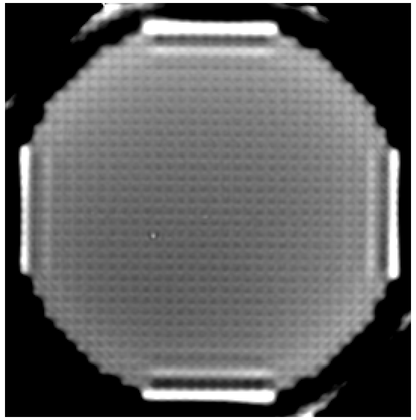


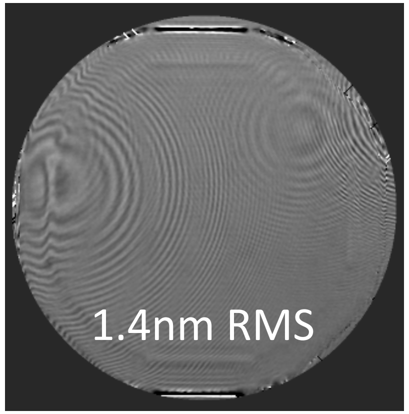




DM2







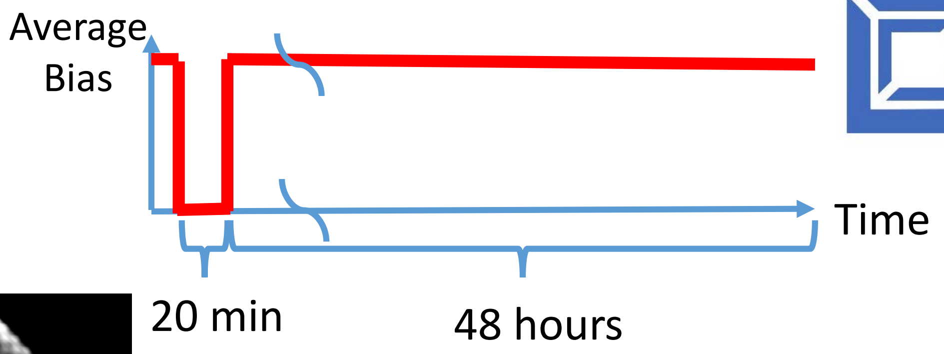
Initial “Flat” solution

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

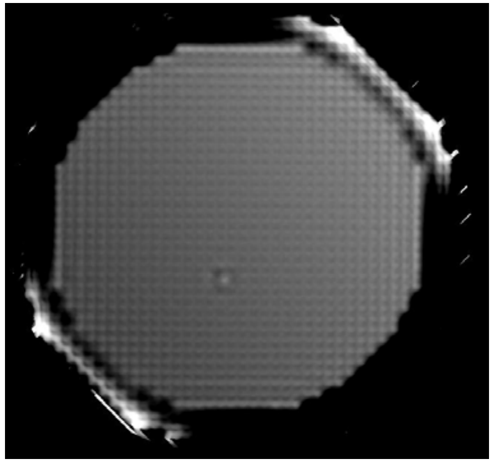
Difference Phase Map

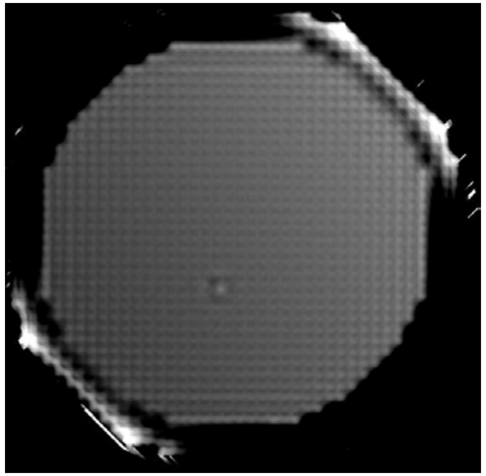
No obvious differences between maps.

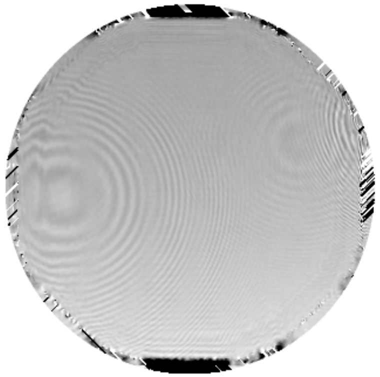
Comparison of flats from settling test



DM1

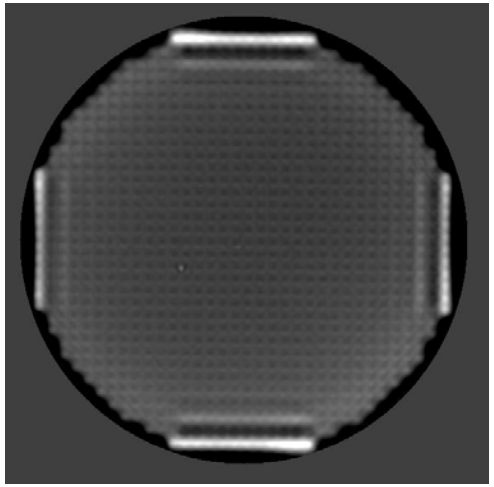


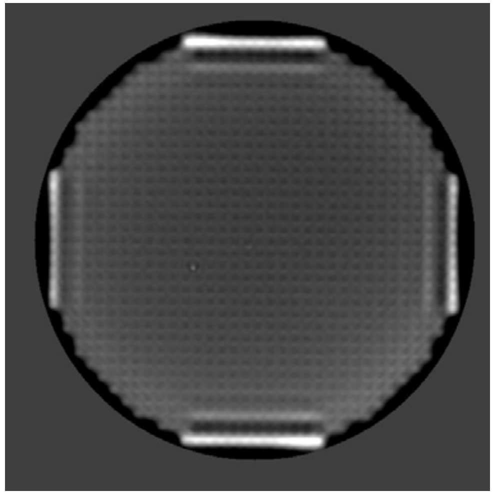


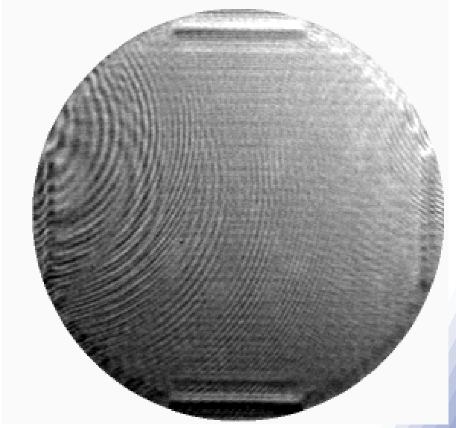


2.1nm RMS difference

DM2







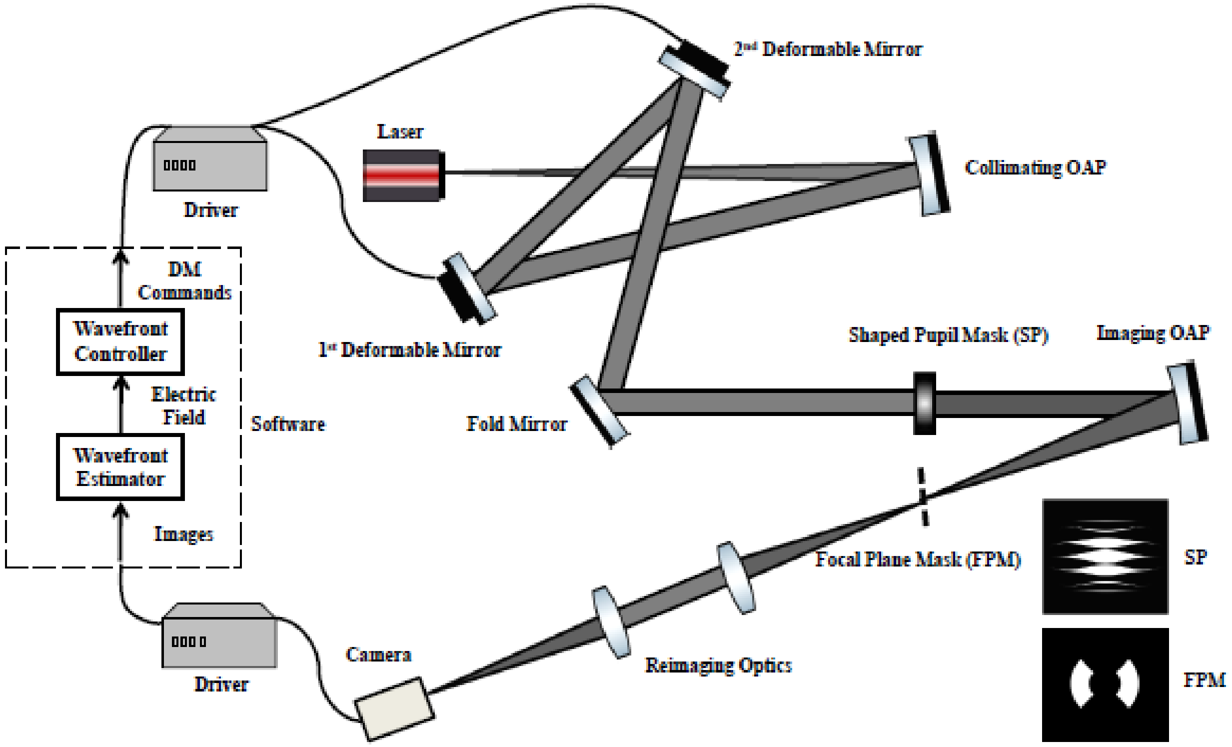
First map

Last map

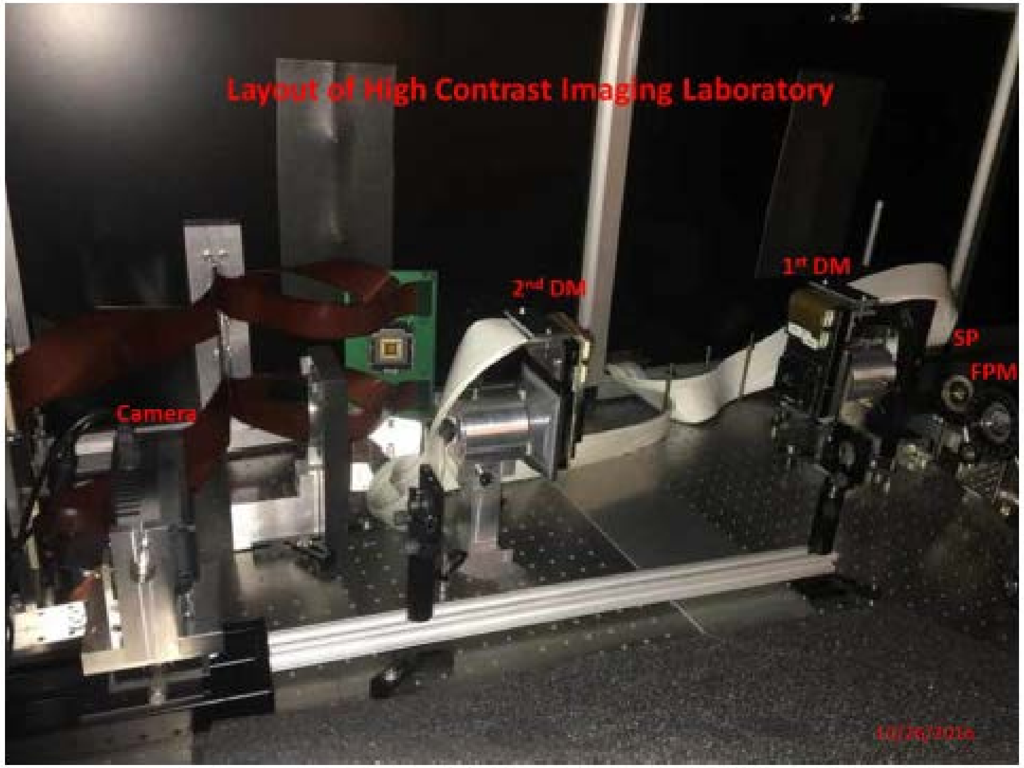
0.9nm RMS difference

No significant changes observed in the settling time test ()

High Contrast Imaging Laboratory(HCIL)
Kasdin Lab, Princeton University



Concept diagram of HCIL layout.



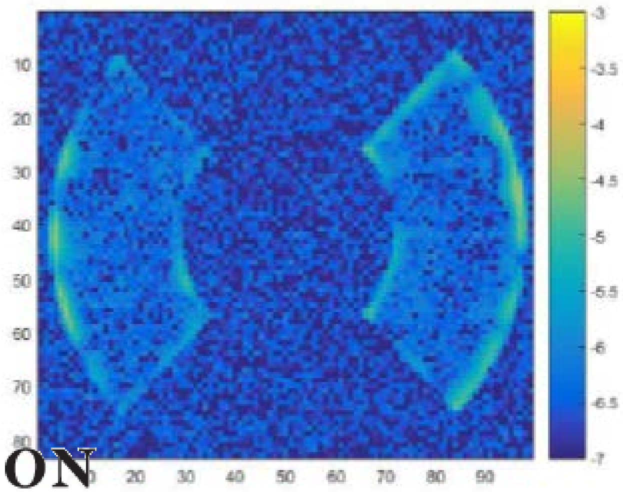
HCIL testbed image after implementing new DMs.

PRINCETON UNIVERSITY

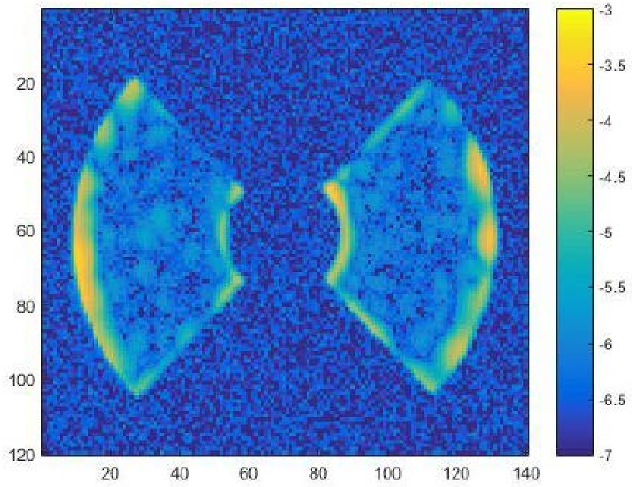
He Sun and N. Jeremy Kasdin

Recent Lab Results

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



6-11 λ/D



5-14 λ/D

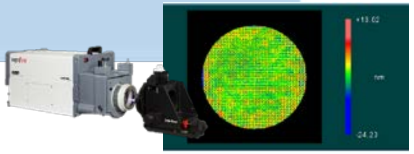
PRINCETON UNIVERSITY

Project Flow

MEMS Mirror Fabrication

12 Devices

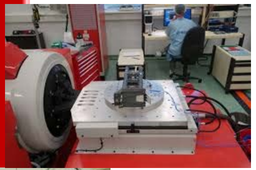
BMC Characterization



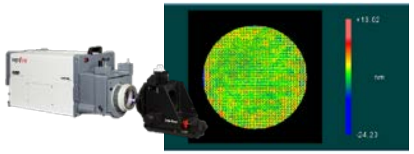
Coronagraph Test Bed Component Insertion and Baseline Null Testing

Jet Propulsion Laboratory

Launch Environmental Testing



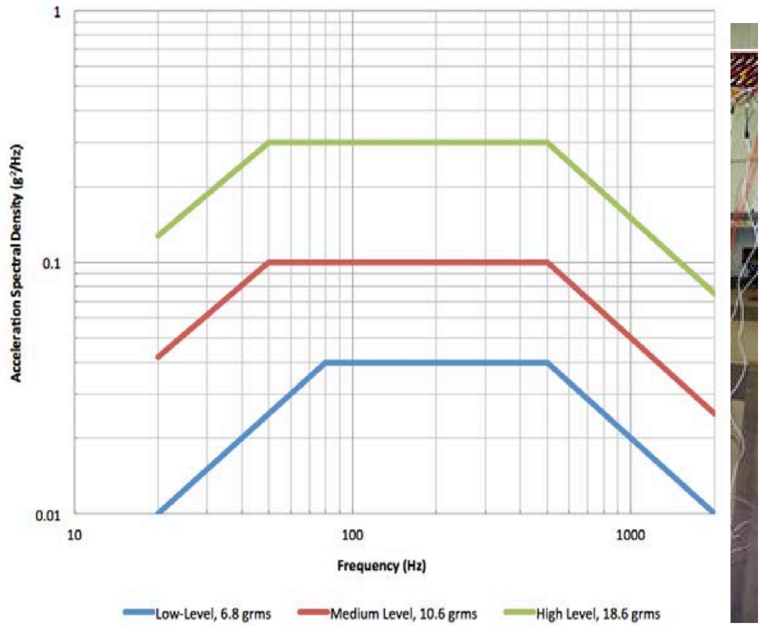
BMC Characterization



Coronagraph Test Bed Component Insertion and Baseline Null Testing

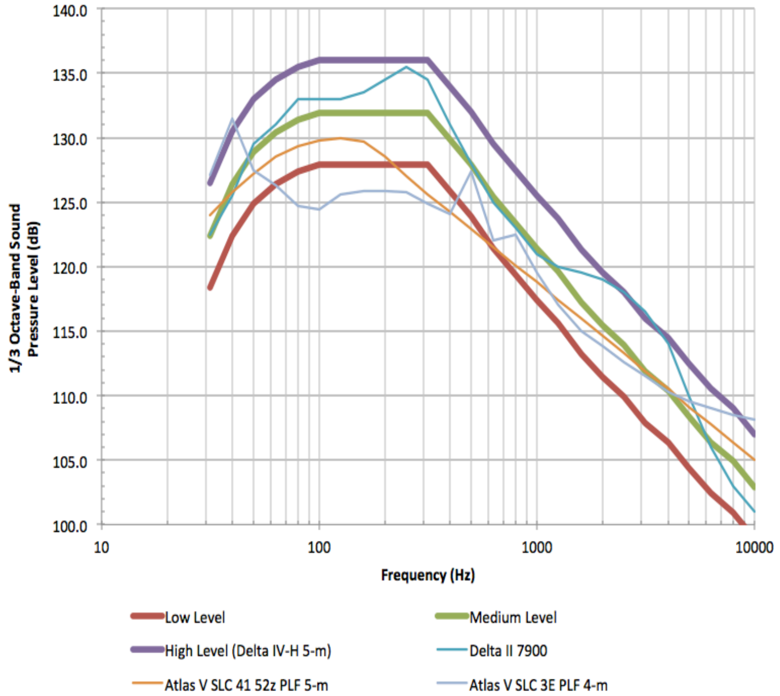
Jet Propulsion Laboratory

Environmental Testing

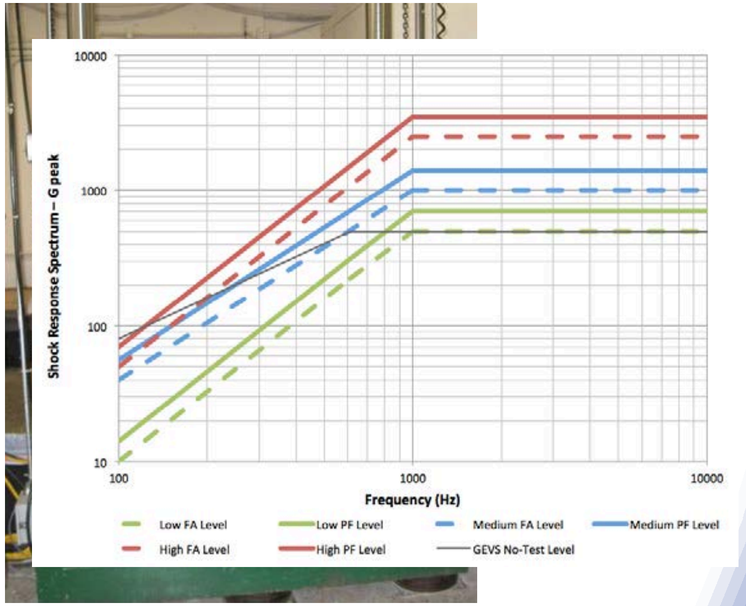


Vibration

Random and Sinusoidal



Acoustic



Shock

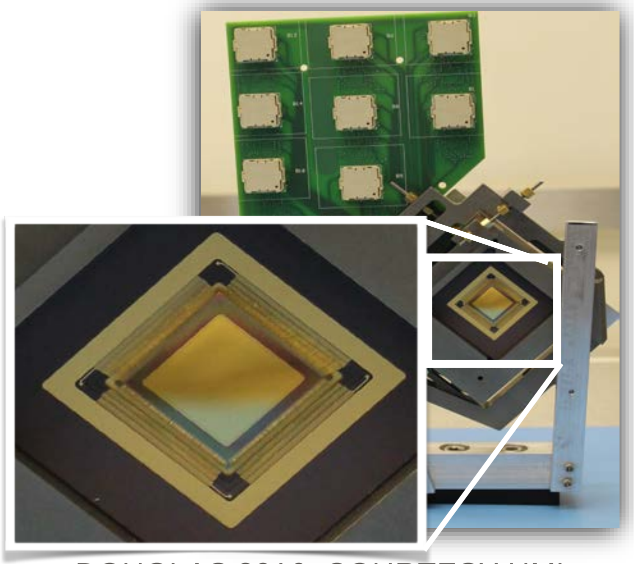
Outline

- BMC DM Technology
- DM Technology Development and Advancement
- Space astronomy operations
- Ground astronomy operation
- Conclusion

THE PICTURE(-B) SOUNDING ROCKET

PI: Supriya Chakrabarti, UMASS Lowell
November 2015

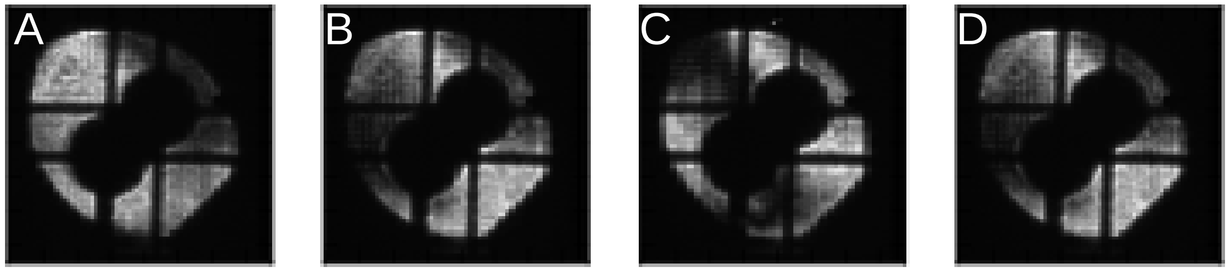
- Reflected light from Exoplanets
- Scattered Light from Exozodi
- Visible Light Coronagraphy (in space)
- Active wavefront control

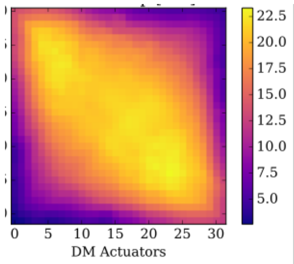


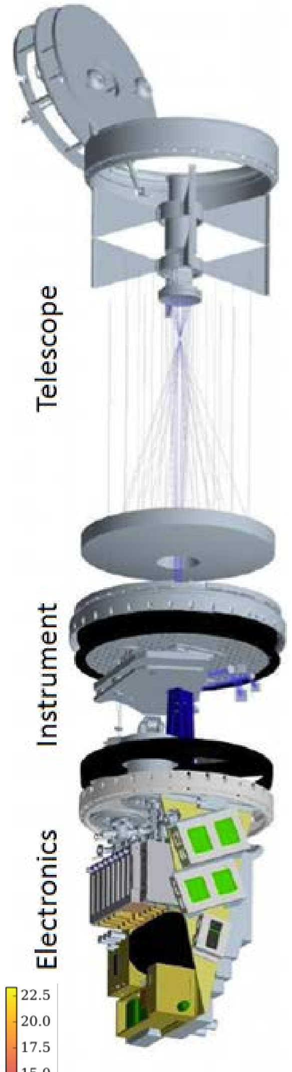
DOUGLAS 2016, COURTESY UML

The DM was powered in flight.
Deformable mirror "flat" map applied in flight to remove curvature:

Flat *Flight* Wavefront Sensor Measurements of Pupil Plane Fringes:







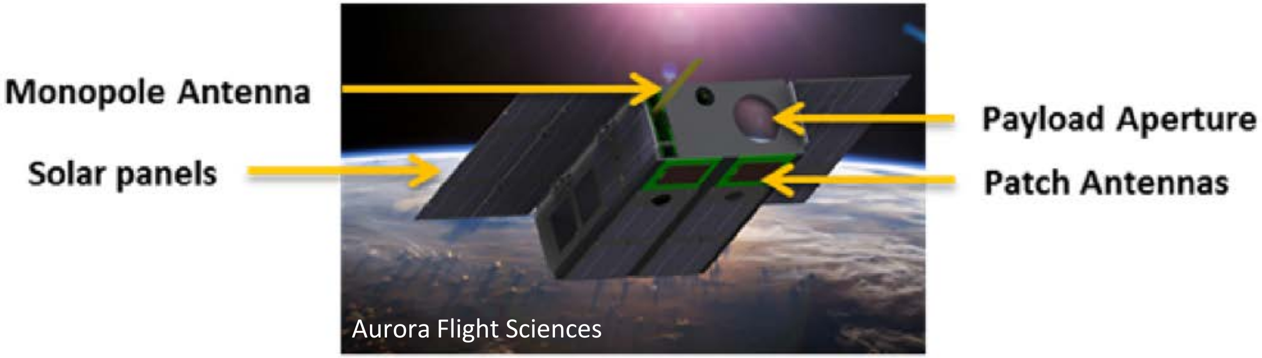
DOUGLAS 2016

Cubesat: Deformable Mirror Demonstration Mission (DeMi)

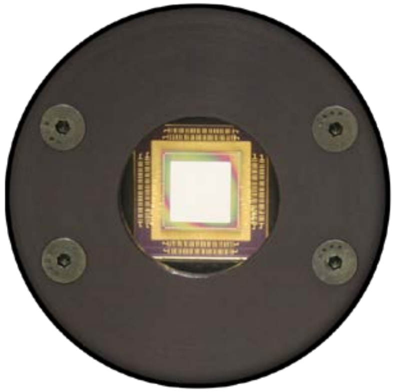
PI: Keri Cahoy, MIT ,John Merk, Aurora Flight Sciences

- DARPA Funded Cubesat program
- Validate and demonstrate the capabilities of high actuator count MEMS deformable mirrors for adaptive optics in space.
- Characterize MEMS deformable mirror operation using both a Shack Hartmann wavefront sensor as well as sensorless wavefront control.

Space Telecommunications, Astronomy, and Radiation Lab



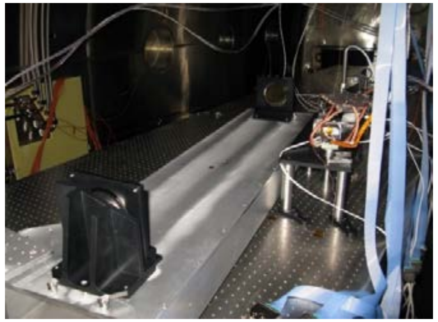
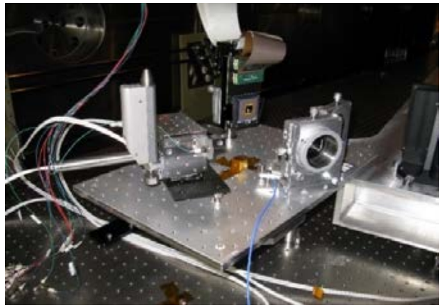
Proposed mission configuration



Planned use of Multi-DM

EXoplanetary Circumstellar Environments and Disk Explorer (EXCEDE)

Final Broadband Milestone Results


Lockheed Martin Vacuum Chamber

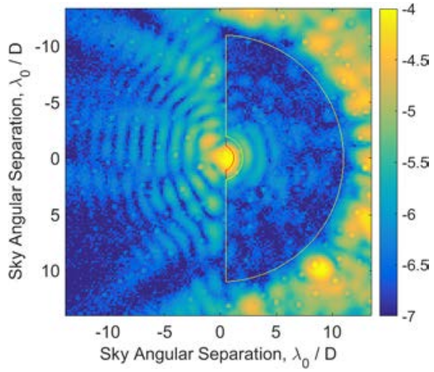
λ_0 = 650nm, Bandwidth = 10%

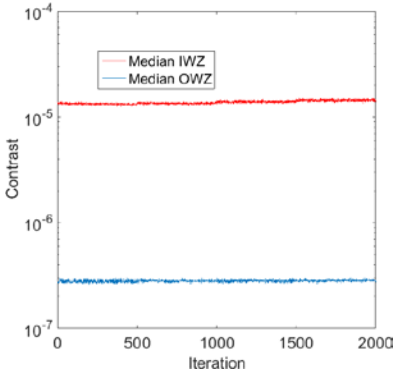
- Test A

  Time interval: 67 min

  1.2– 2.0 λ_0/D: 1.35×10^{-5}

  2.0–11.0 λ_0/D: 2.82×10^{-7}



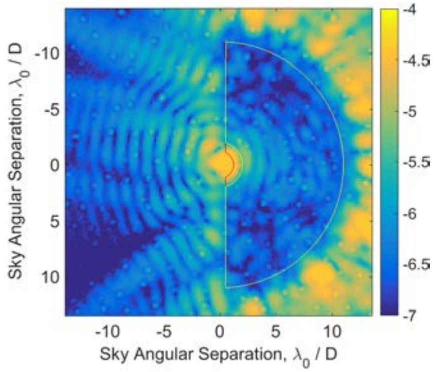


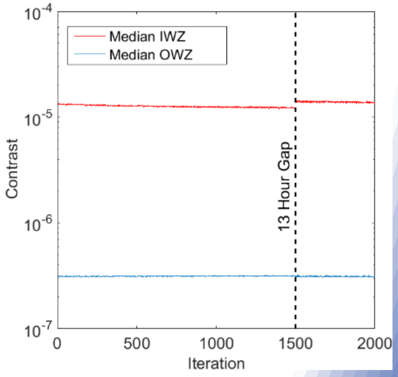
- Test B

  Time interval: 816 mins

  1.2– 2.0 λ_0/D: 1.29×10^{-5}

  2.0–11.0 λ_0/D: 3.14×10^{-7}



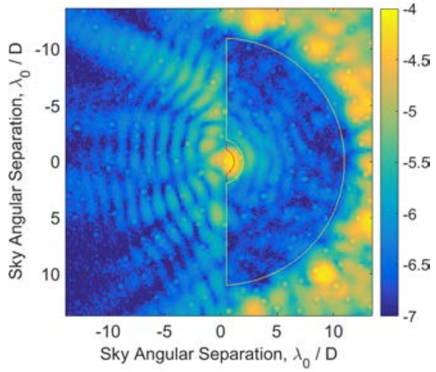


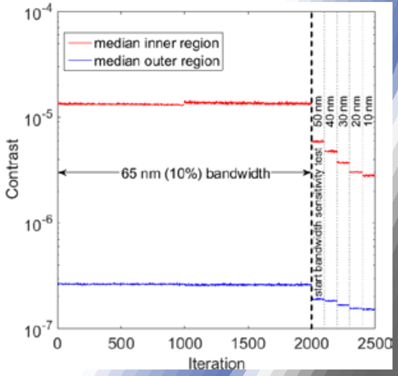
- Test C

  Time interval: 61 mins

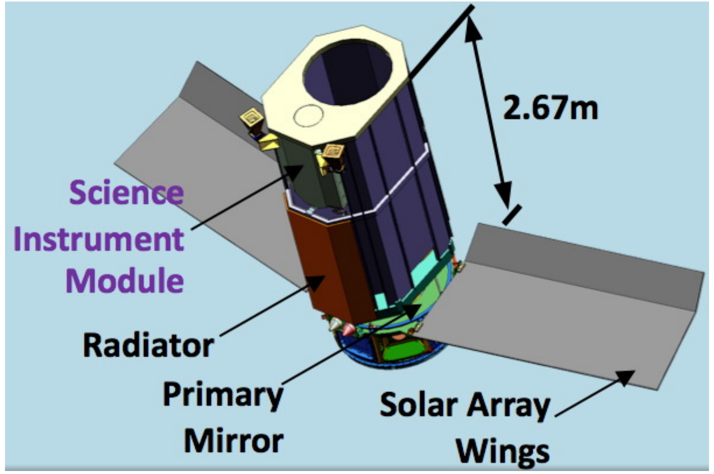
  1.2– 2.0 λ_0/D: 1.33×10^{-5}

  2.0–11.0 λ_0/D: 2.63×10^{-7}

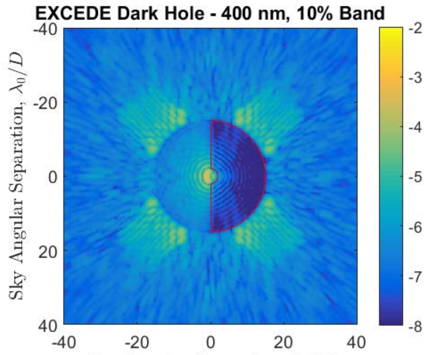




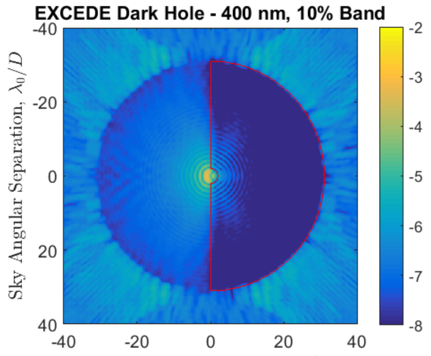
EXCEDE Proposing for the 2016 MidEX AO



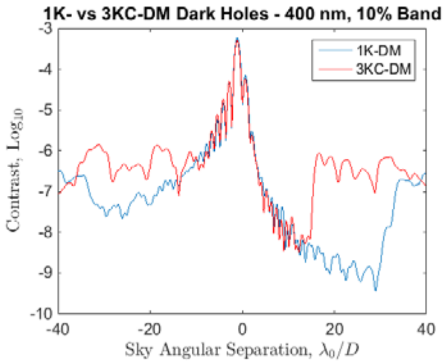
- Technical specs:
  - 0.7m primary, TMA unobstructed optical telescope
  - PIAA Coronagraph
- Mission overview
  - Survey of ~ 350 nearby exoplanetary systems
- Science Capabilities
  - Circumstellar debris systems including the habitable zone
  - Gas giants (if sufficiently bright)

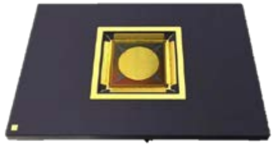


1K Boston MEMS DM
Outer Working Angle – 15 L/D

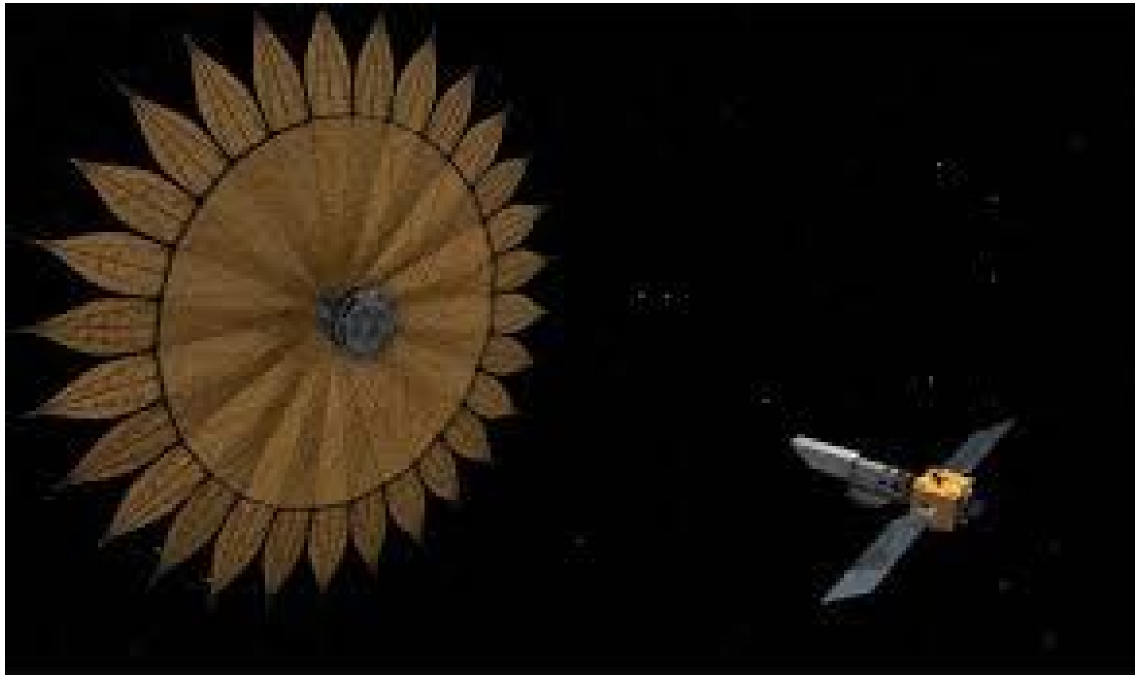


3K-C Boston MEMS DM
Outer Working Angle – 31 L/D

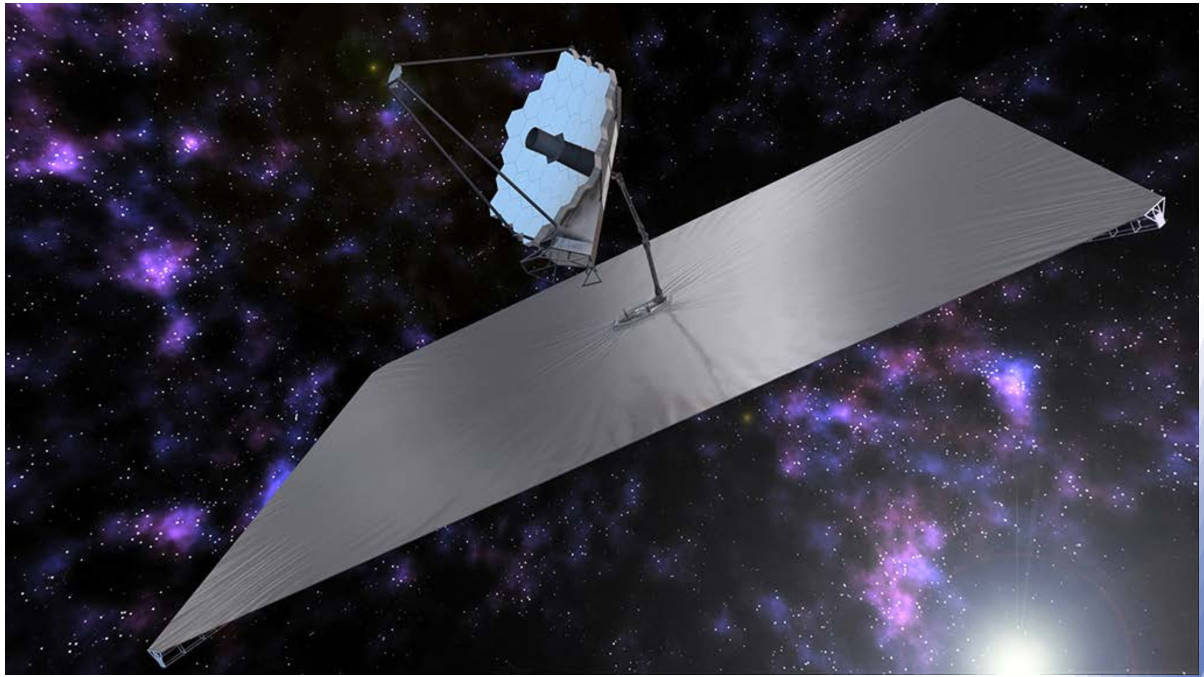




Future Space Telescope Mission Concepts



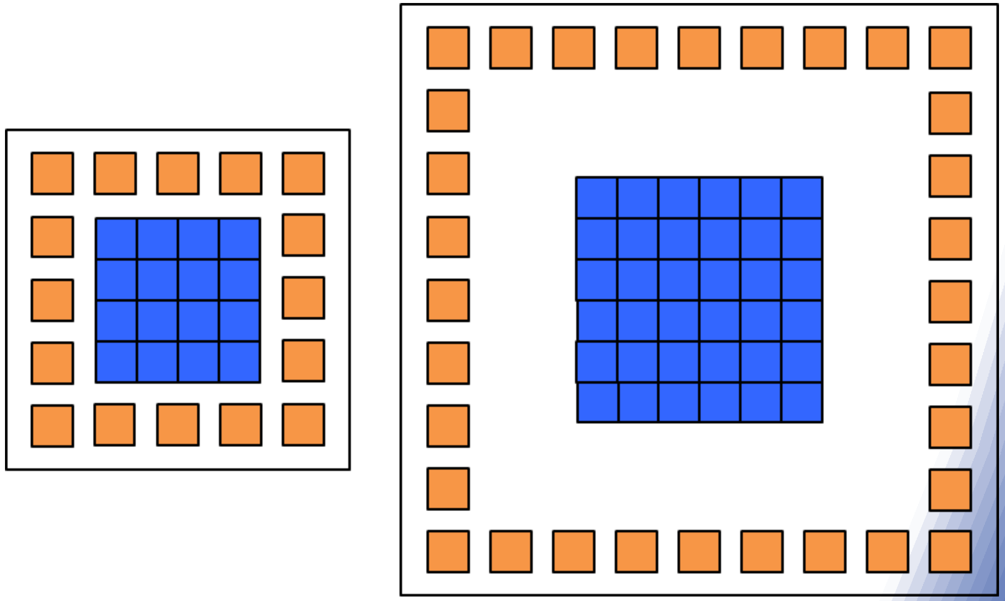
Habitable Exoplanet Imaging Mission (HabEx)



Large UV/Optical/IR Surveyor (LUVOIR)

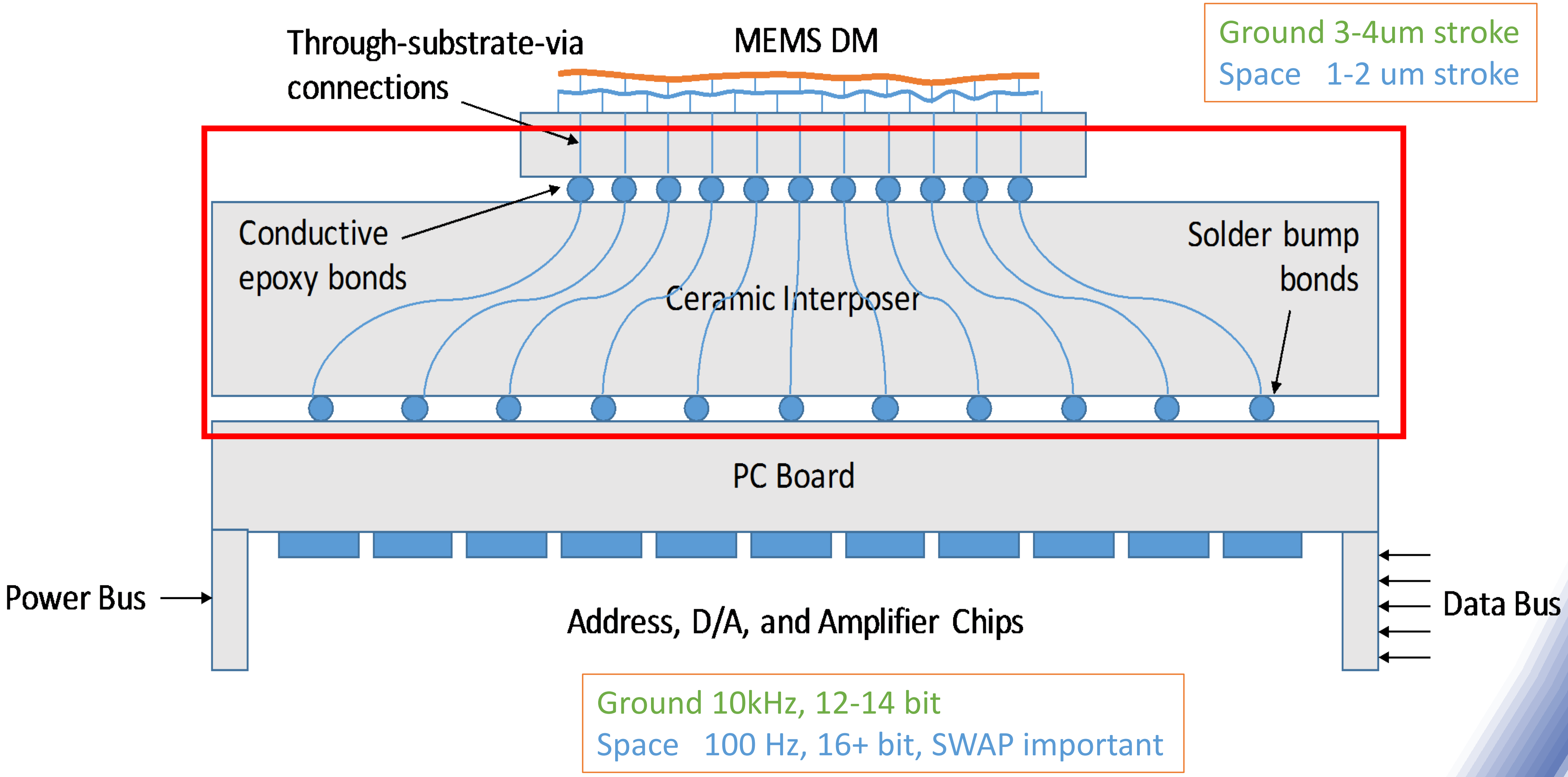
Need for Even Higher Actuator Count DM (10k +)

- For many next generation instruments, 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

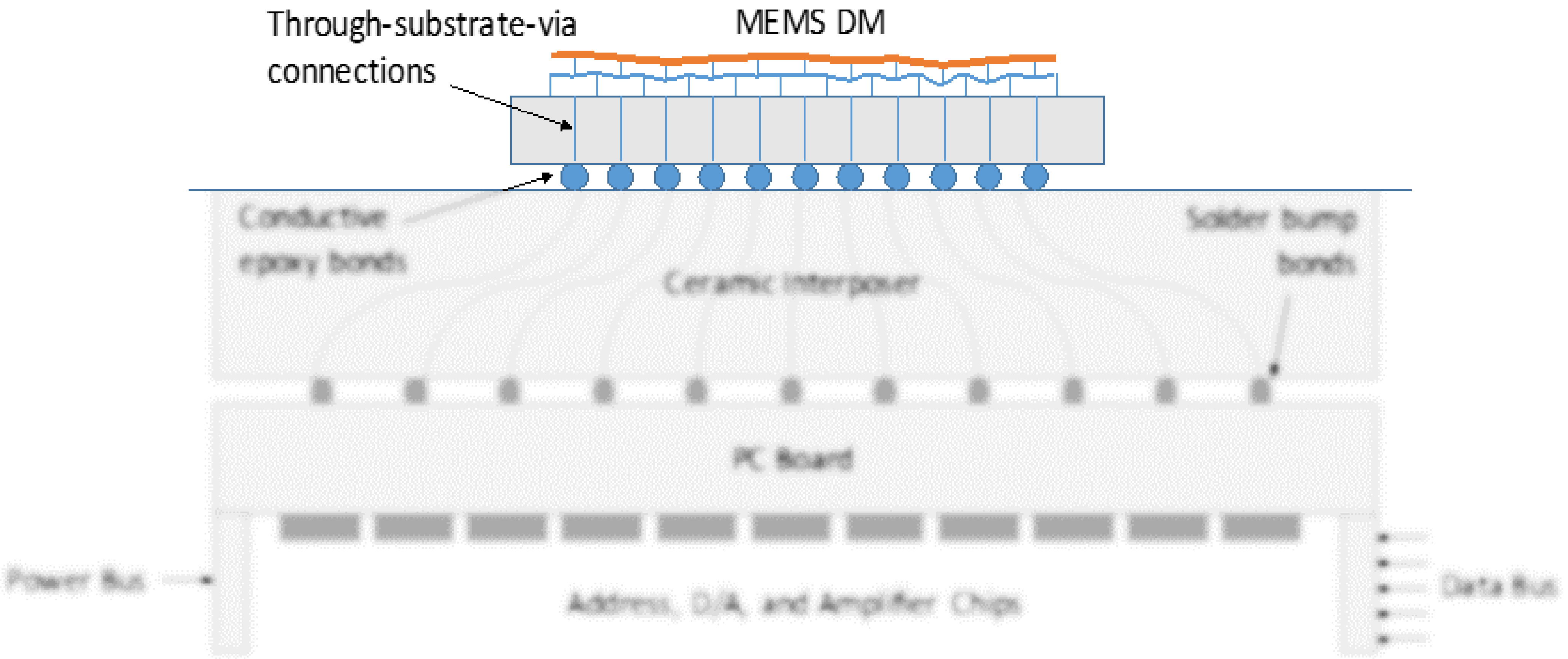


By adding 2 more actuators across the aperture, the die size increased by ~3x

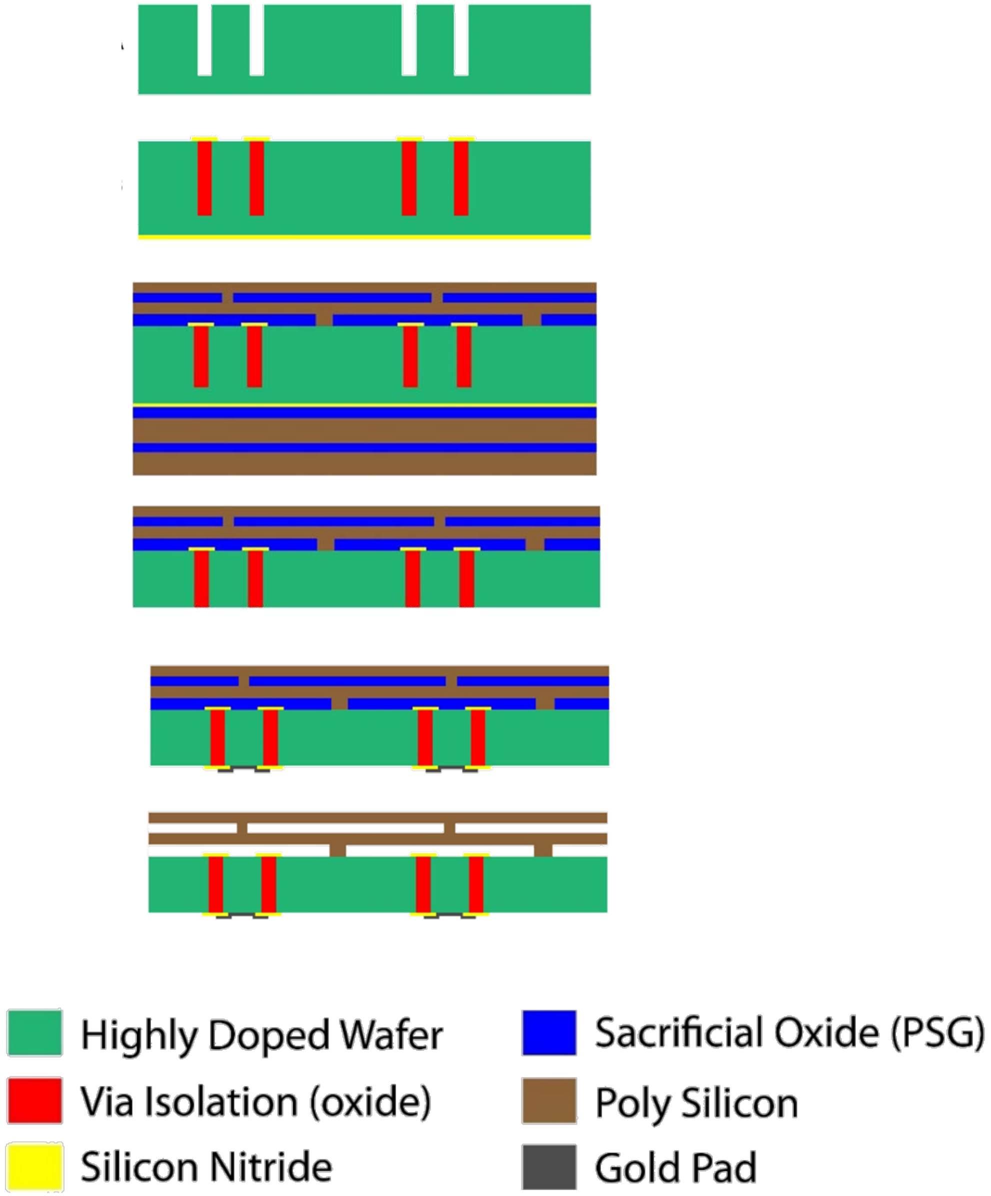
Proposed Architecture (Concept 1)



Proposed Architecture (Concept)



Through-Wafer-Via DM Fabrication Prototype



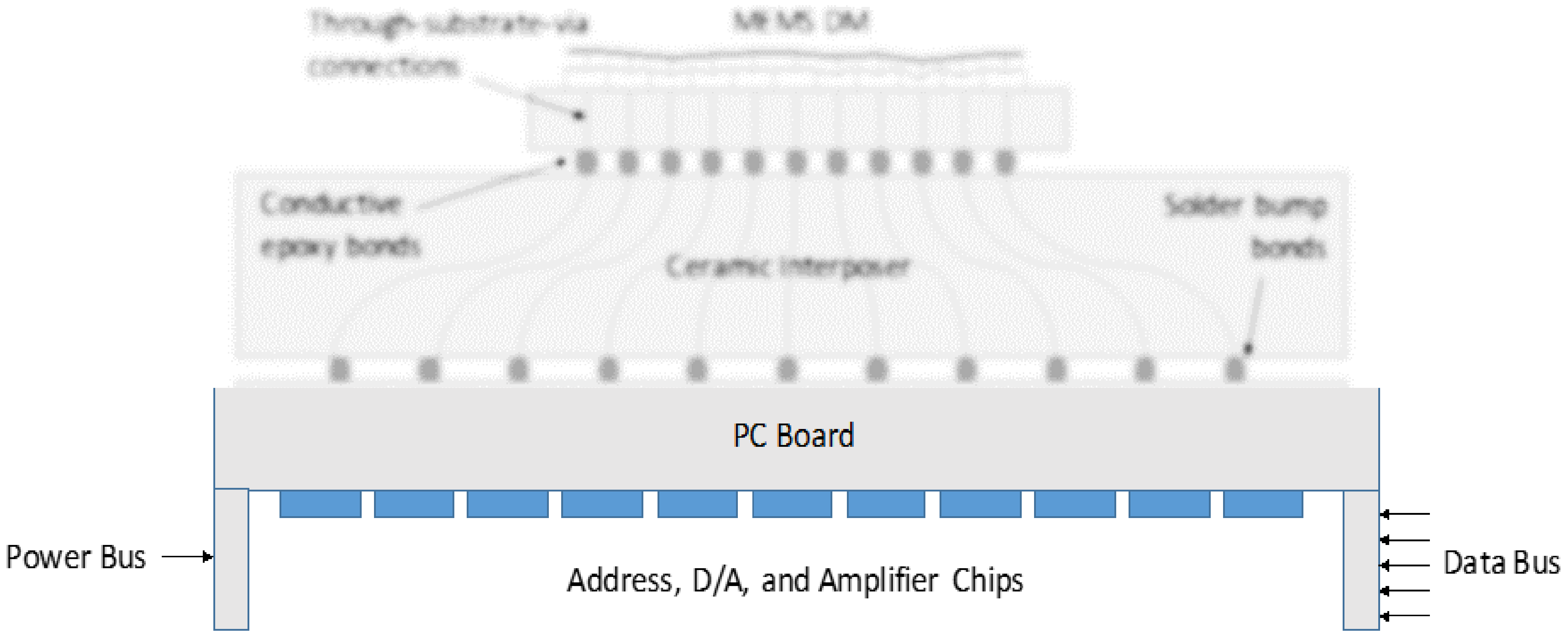
New process (and new foundry for manufacturing) relies on BMC heritage actuator and mirror design, but eliminates wire bonds and instead uses through-wafer-via (TWV) technology

TWV is single crystal silicon: exceptionally low defect level allows major increase in device yield and reliability

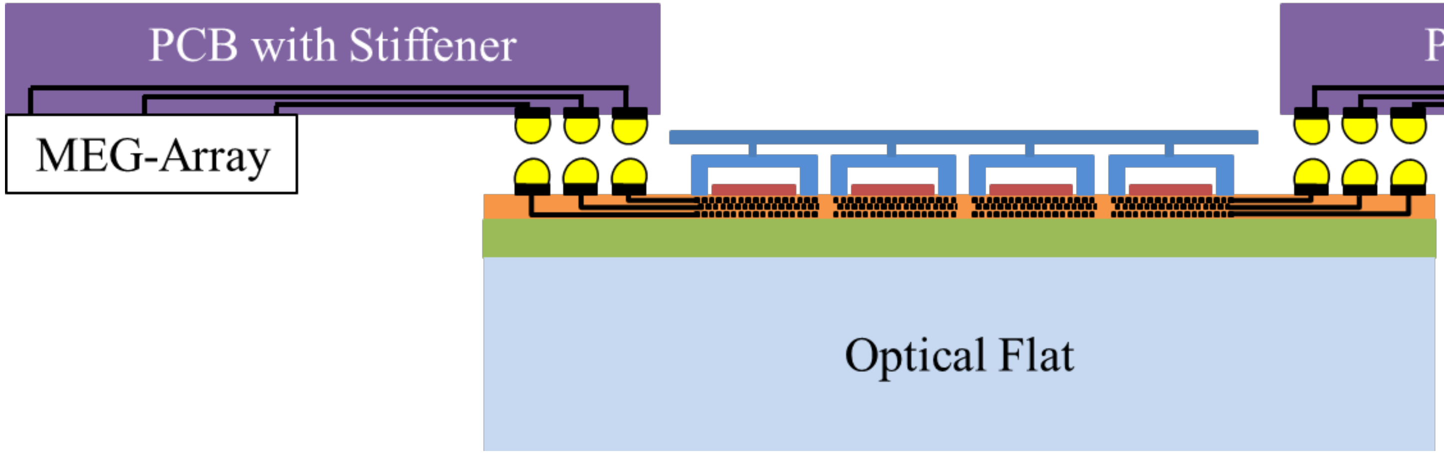
Manufacturing challenge is shifted to packaging of TWV devices

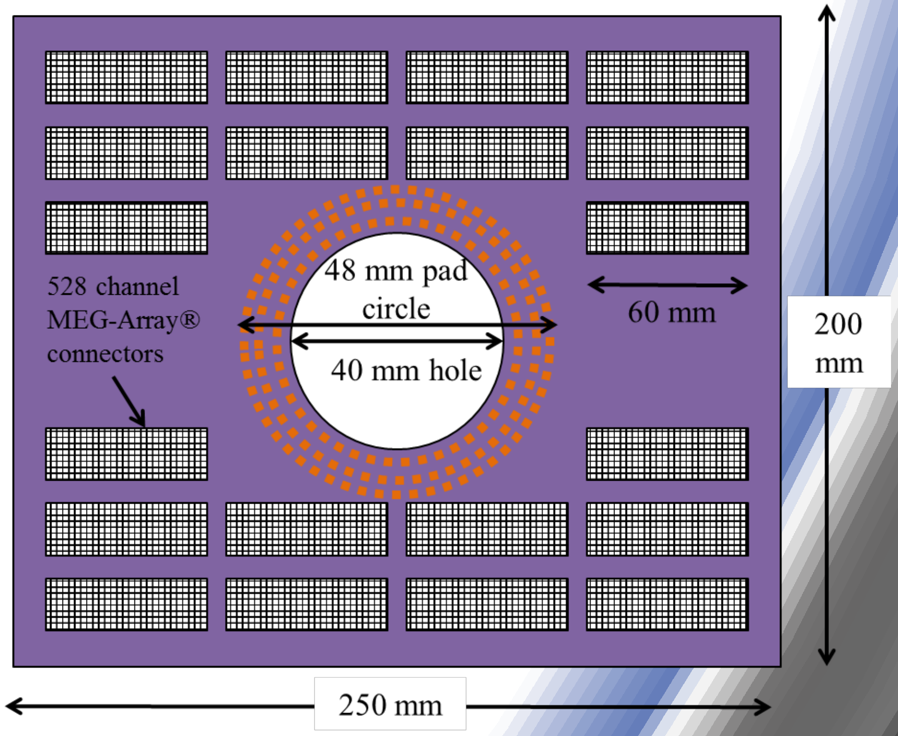
In prototype project, 140 actuator, 500 actuator, and 2000 actuator devices were fabricated and tested

Proposed Architecture (Concept)

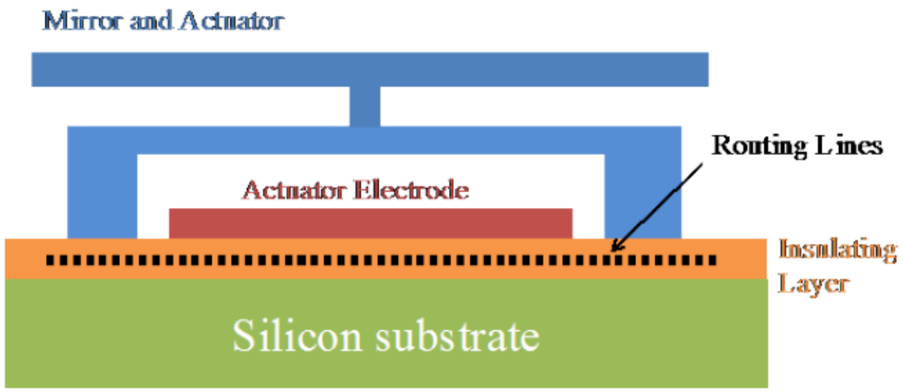


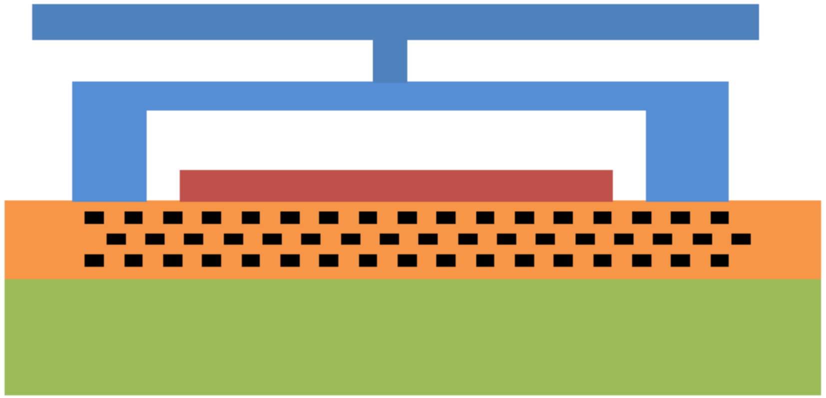
Proposed Architecture (Concept 2)





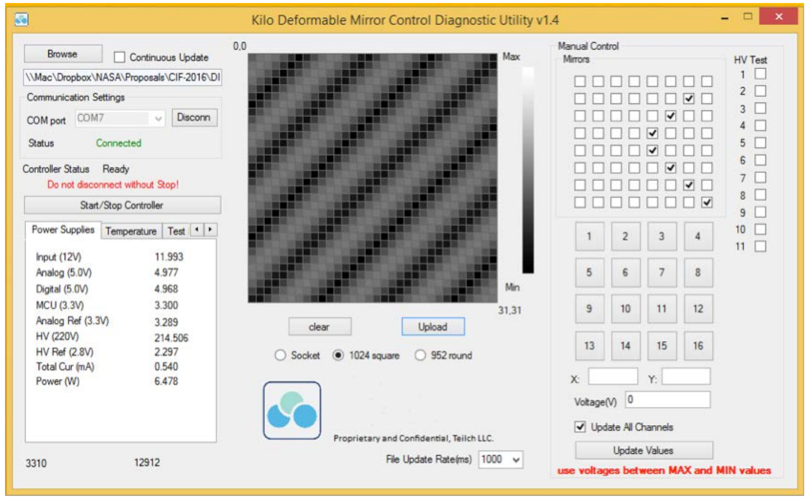
Proposed Architecture (Concept 2)





Multiple routing layers leading to high-density flip chip bond pads

Electronics Design



- 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

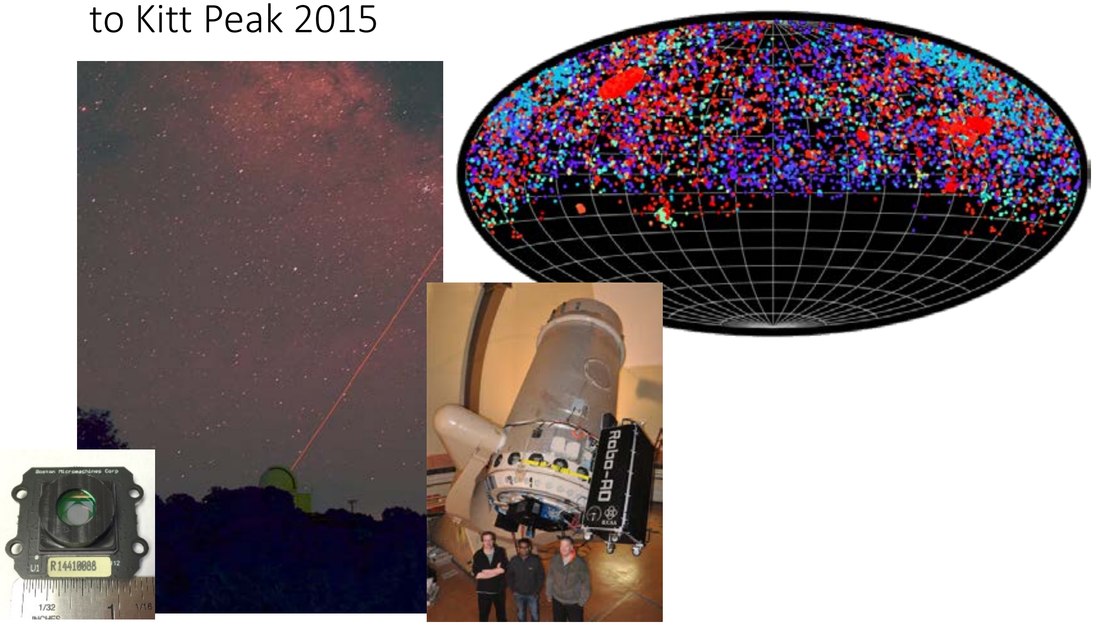
Outline

- BMC DM Technology
- DM Technology Development and Advancement
- Space astronomy operations
- Ground astronomy operation
- Conclusion

On-Sky Instruments using BMC Mirrors

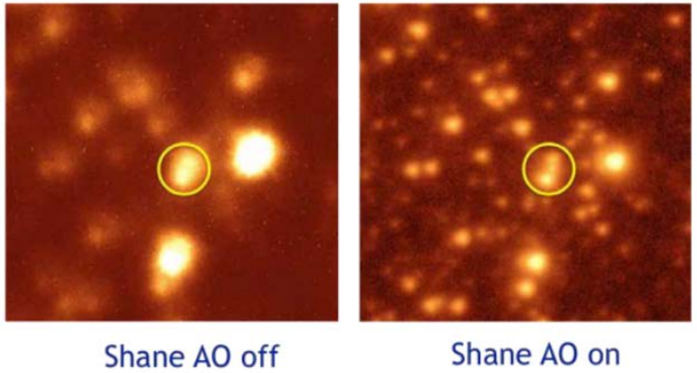
ROBO-AO

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

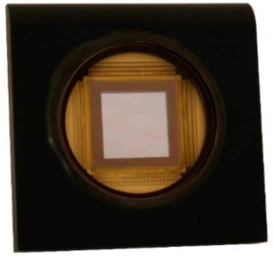


Shane-AO, Lick Observatory

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

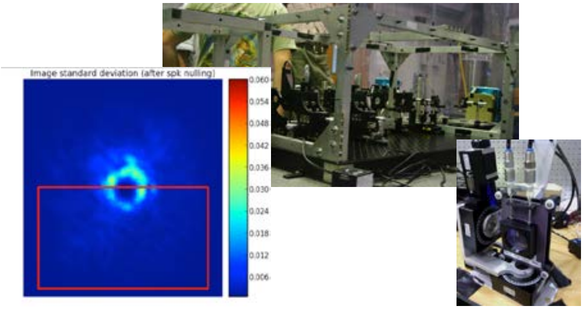


Portion of the M92 globular cluster taken in H band.



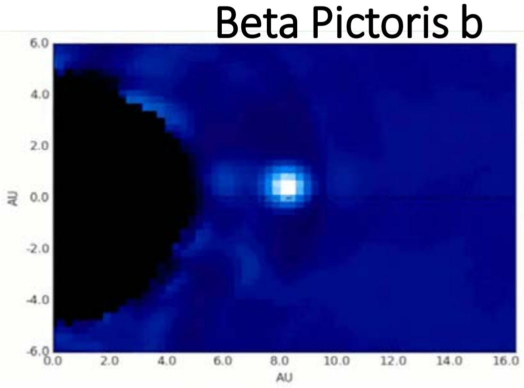
SCExAO, Subaru telescope

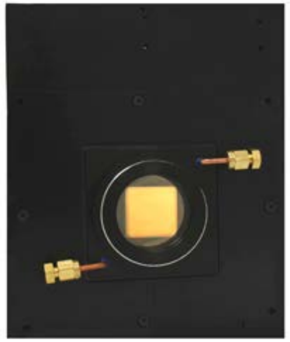
- 2040 installed 2013



Gemini Planet Imager, Gemini South

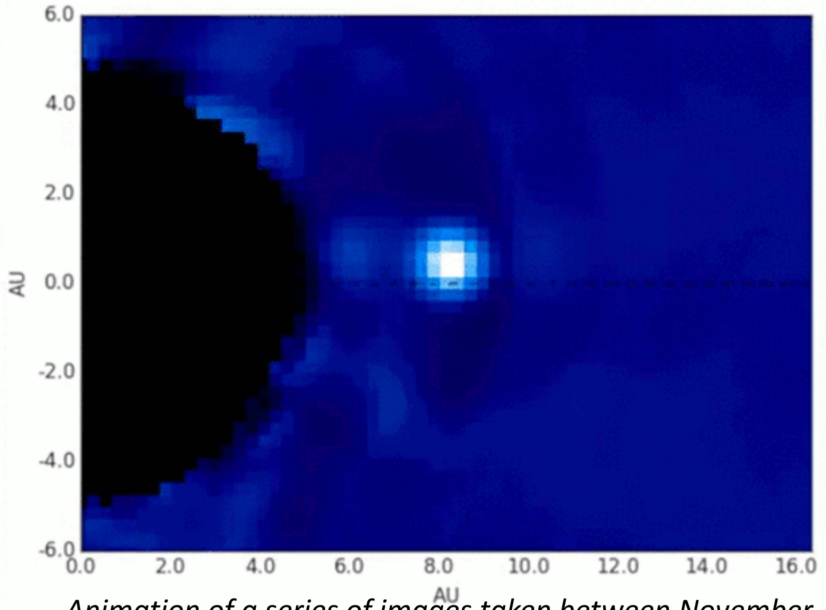
- 4092 installed 2013



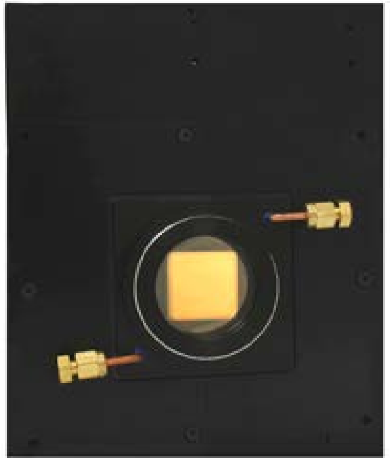


Gemini Planet Imager: 4K DM

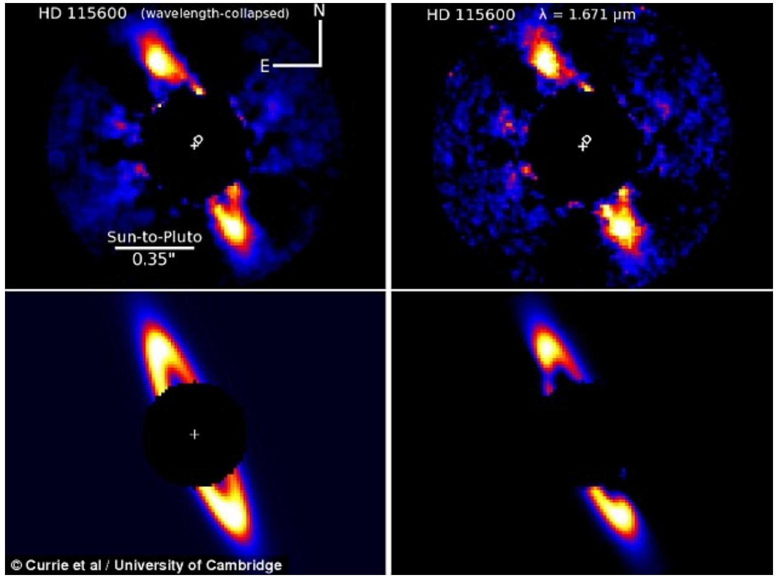
Beta Pictoris b



Animation of a series of images taken between November 2013 and April 2015 with the Gemini Planet Imager (GPI) Image credit: M. Millar-Blanchaer, University of Toronto; F. Marchis, SETI Institute

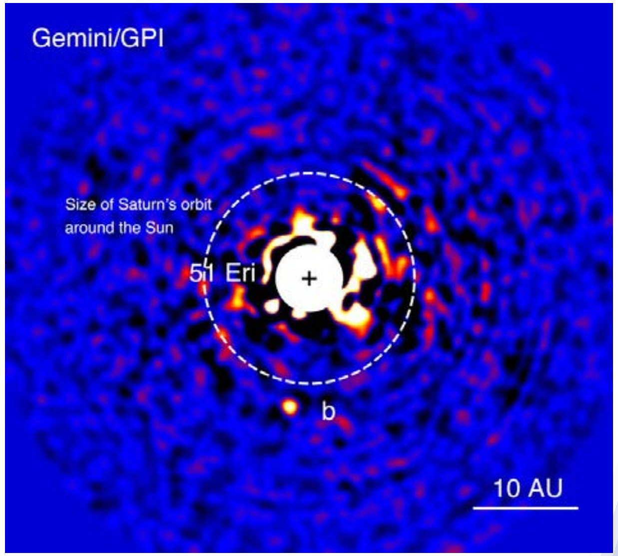


HD 115600 ring of dust and gas



The bright disc is located at a distance similar to Pluto from the sun in our own solar system, which is in the Kuiper Belt.

Young Jupiter 51 Eridani b



Discovery image of the exoplanet 51 Eridani b taken in the near-infrared light with the Gemini Planet Imager on Dec. 21, 2014. Image credit: Gemini Observatory and J. Rameau (UdeM) and C. Marois NRC Herzberg

Young star HR4796A

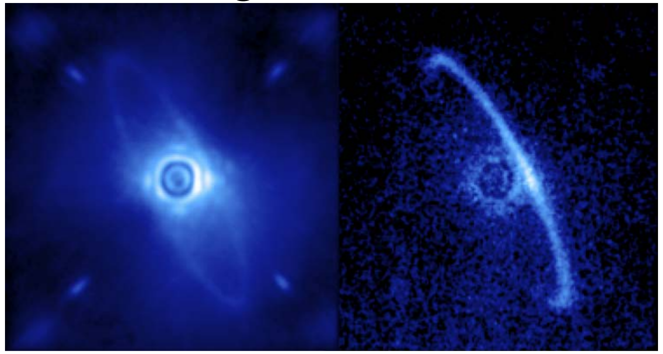
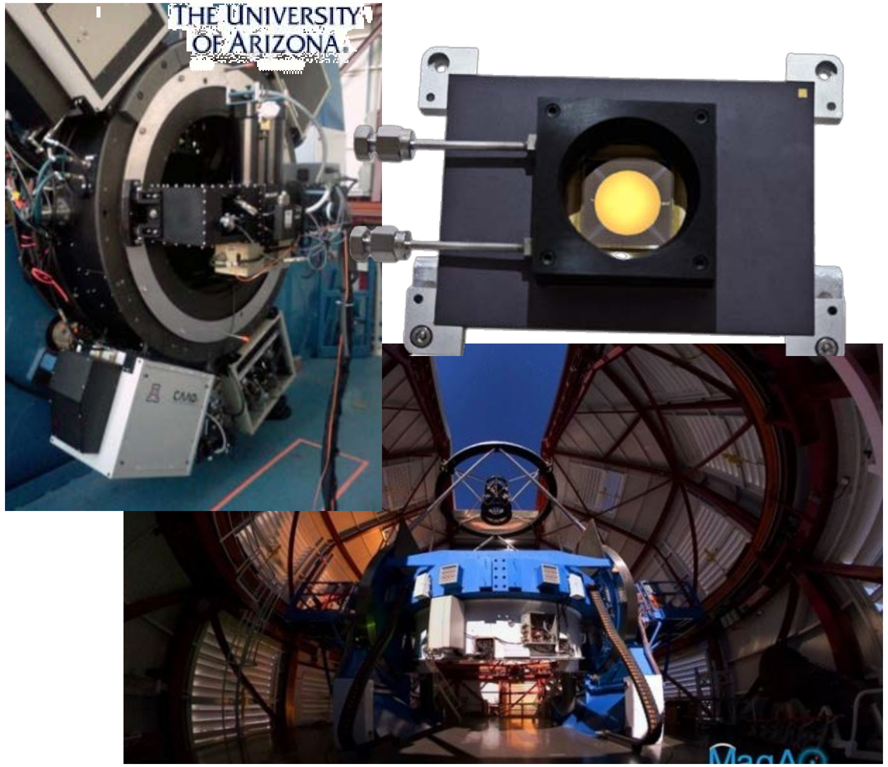


Image credit: Processing by Marshall Perrin, Space Telescope Science Institute

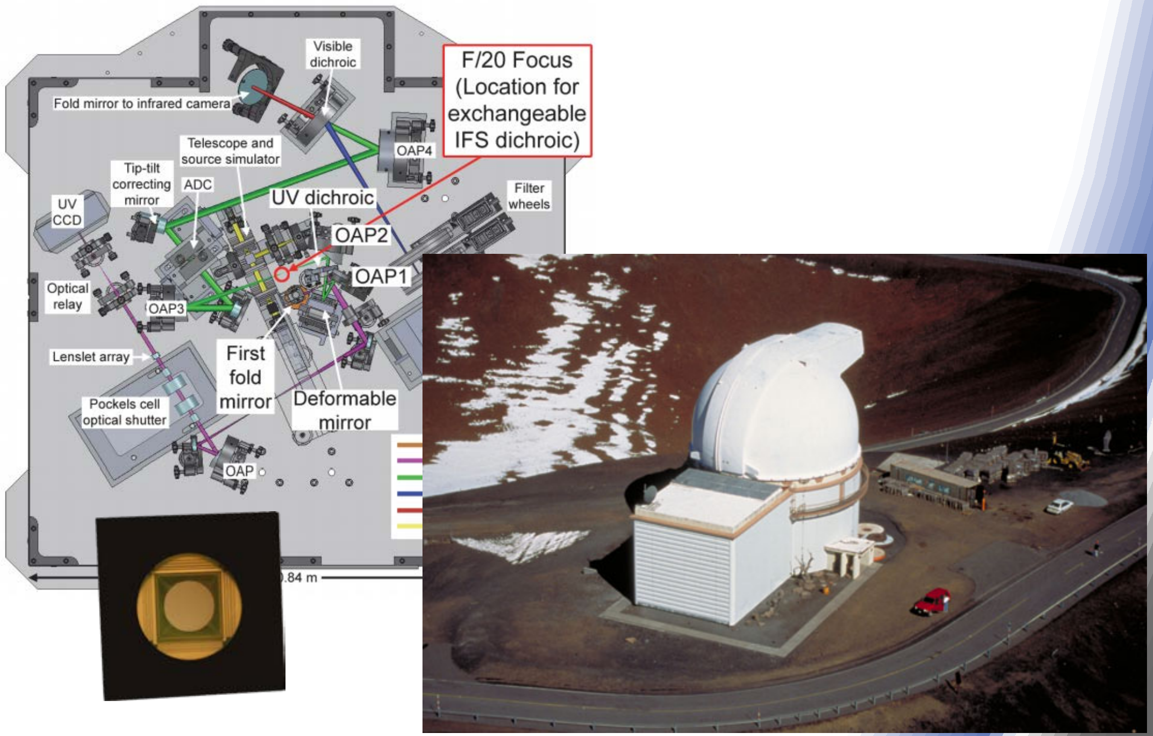
Next Instruments

THE UNIVERSITY OF ARIZONA



MagAO-X

University of Hawaii Institute for Astronomy



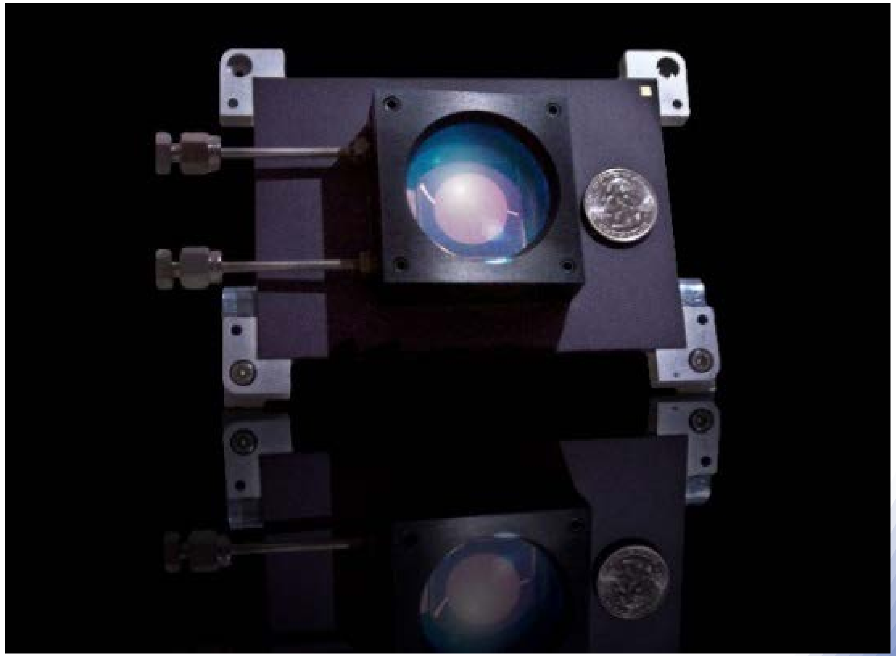
Rapid Transit Surveyor

Conclusion

- MEMS DM have been proven in astronomical instrumentation
- Continued technology development is ongoing
- Poised for next generation instruments, but development needs to occur.

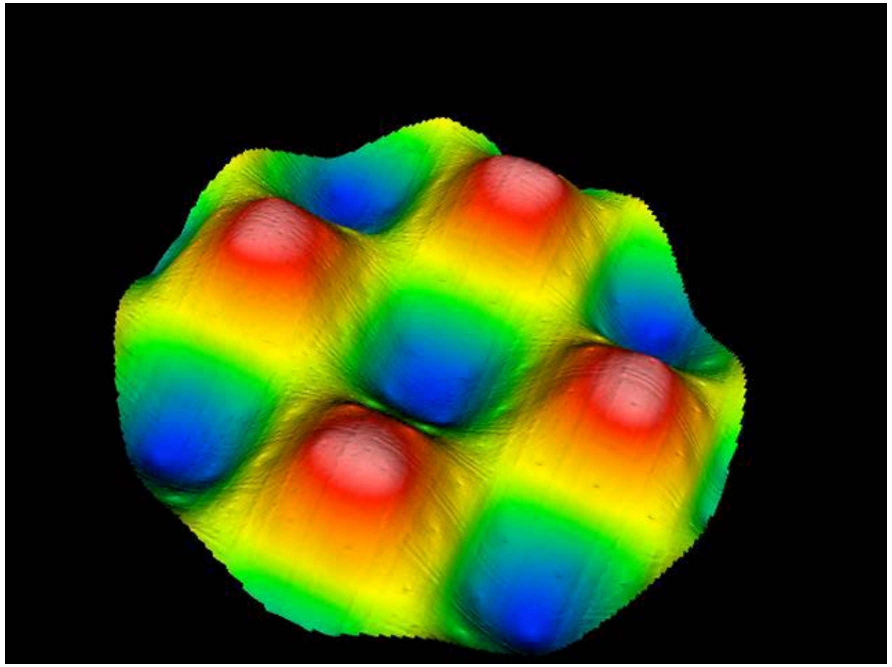
Acknowledgements

- Funding from NASA
  - **Contract#: NNH12CQ27C TDEM/ROSES**
  - **Contract #: NNX16CP14C NASA Phase II SBIR**
  - **Contract#: NNX15CP39P NASA Phase I SBIR**



Thank You

Questions?



Paul Bierden, pab@bostonmicromachines.com