Recent Progress in Developing High Actuator Count MEMS DMs

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BOSTON MICROMACHINES CORPORATION
SHAPING LIGHT

Mirror Technology/SBIR/STTR Workshop

Greenbelt, Maryland, United States
3 November 2016

SPIE.
CONNECTING MINDS. ADVANCING LIGHT.

Outline

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

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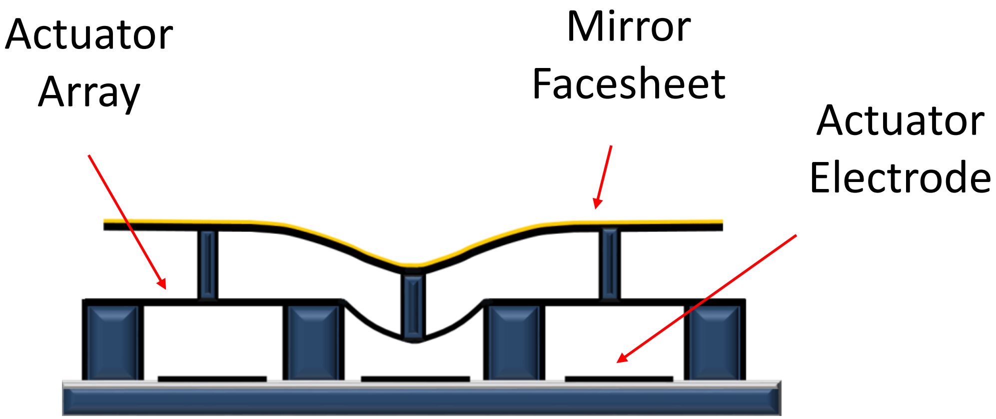
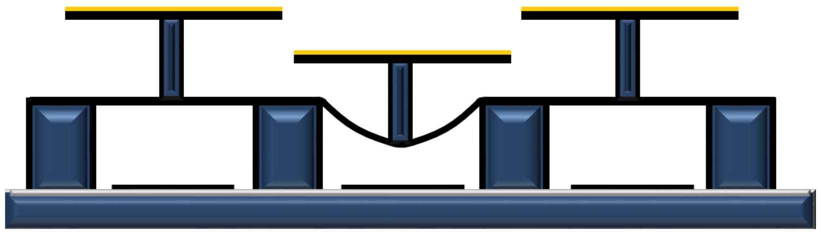
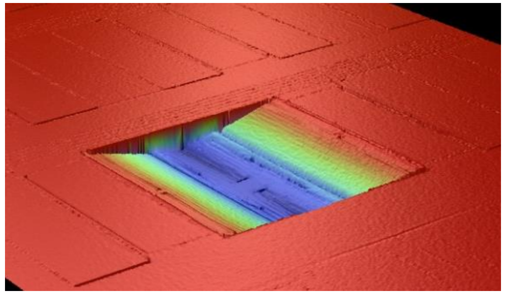
MEMS DM Architecture



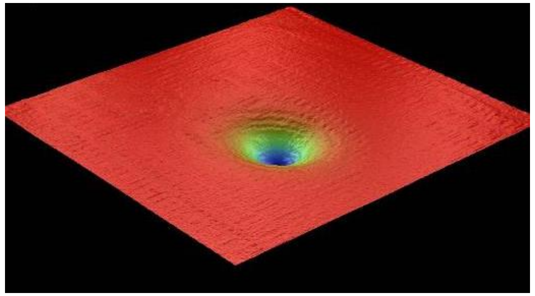
Continuous mirror
(smooth phase control)



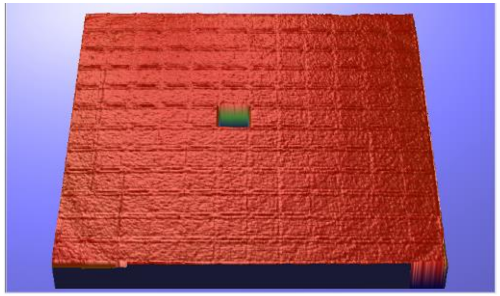
Segmented mirror
(uncoupled control)



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

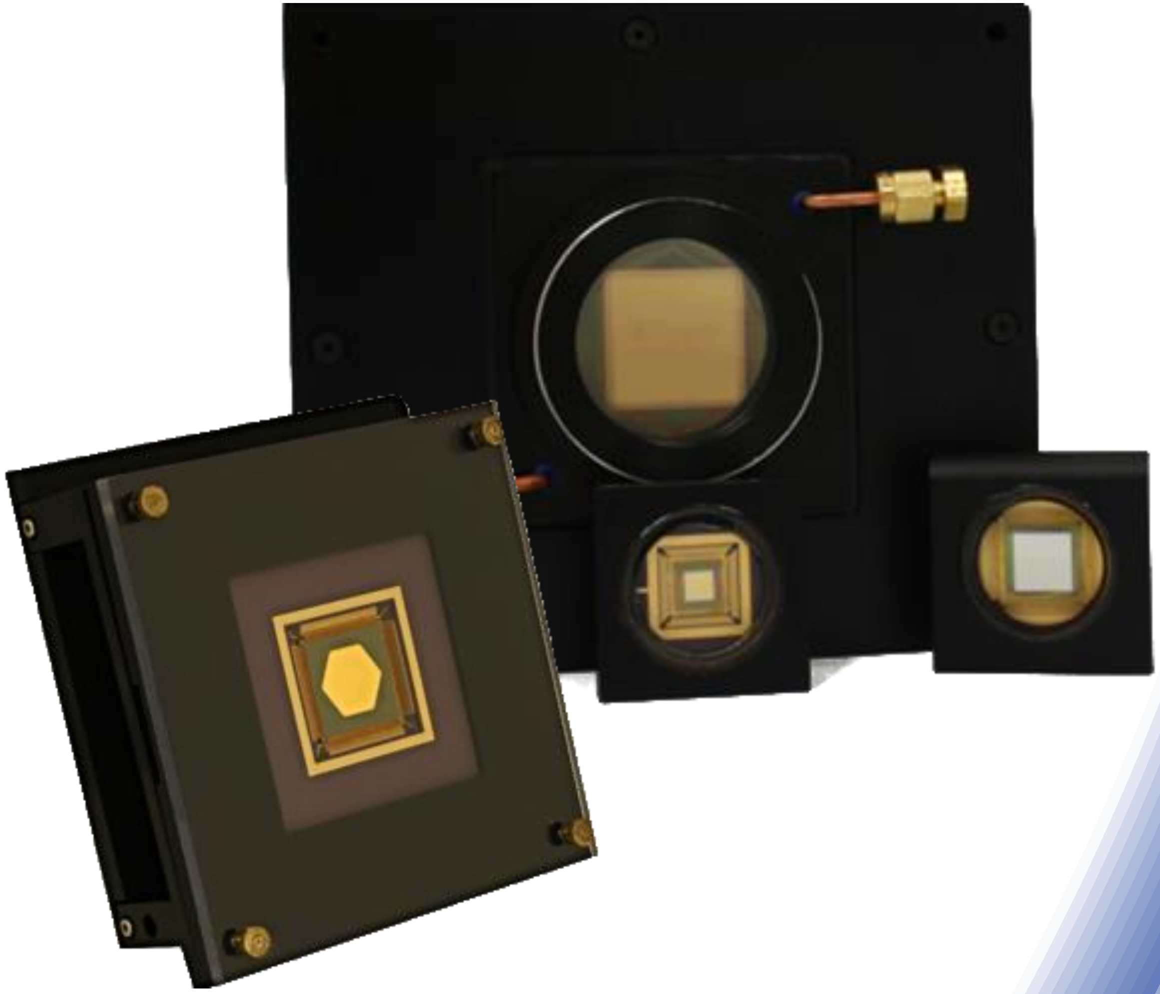
- Square and circular arrays from 492 to **1020**
- 1.5µm & 3.5µm stroke

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

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- BMC DM Technology
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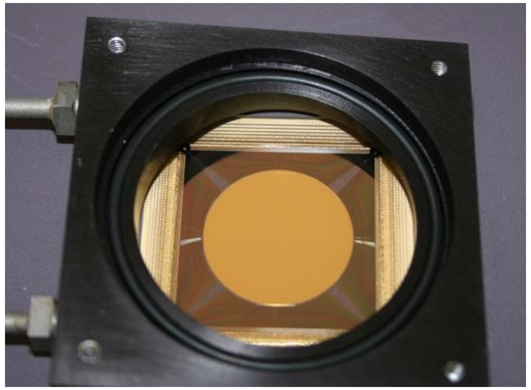
NASA Phase I SBIR

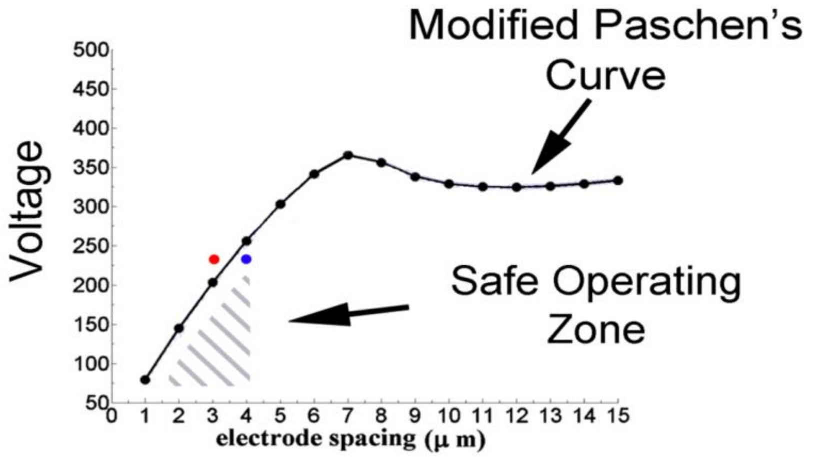
Improved yield, performance, and reliability of high-actuator-count deformable mirrors

Contract Number: NNX15CP39P

- **Objective**:
  - Address known fabrication issues for high actuator count deformable mirrors
    - Surface topography
    - Electric breakdown

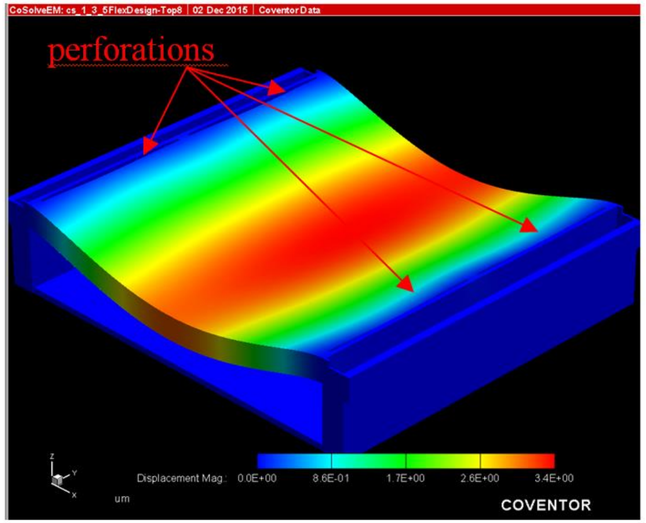


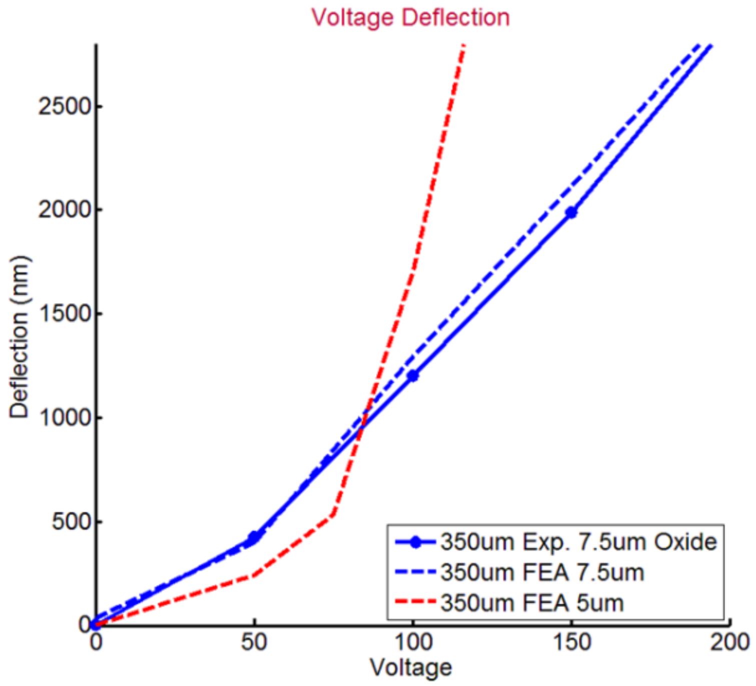
Phase I results



Reduced Operating Voltage

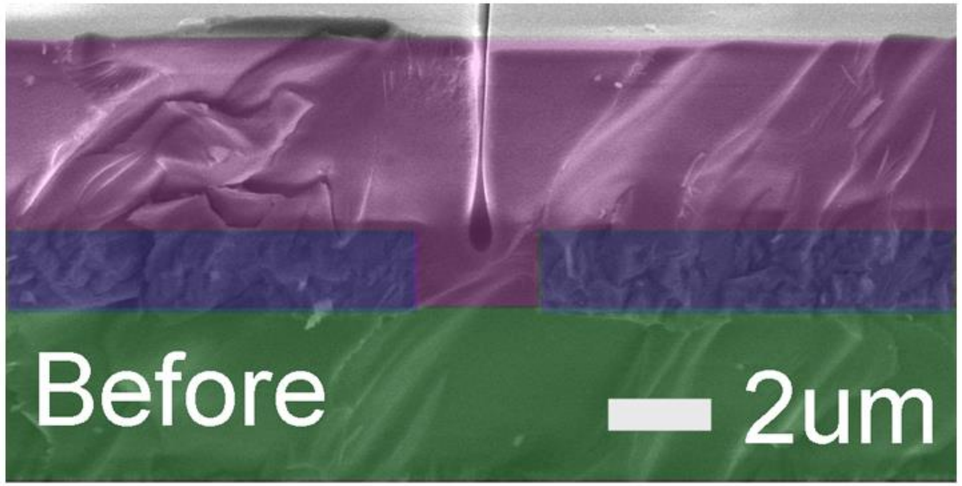
- Lower power usage
- Easier electronics
- Safer operation



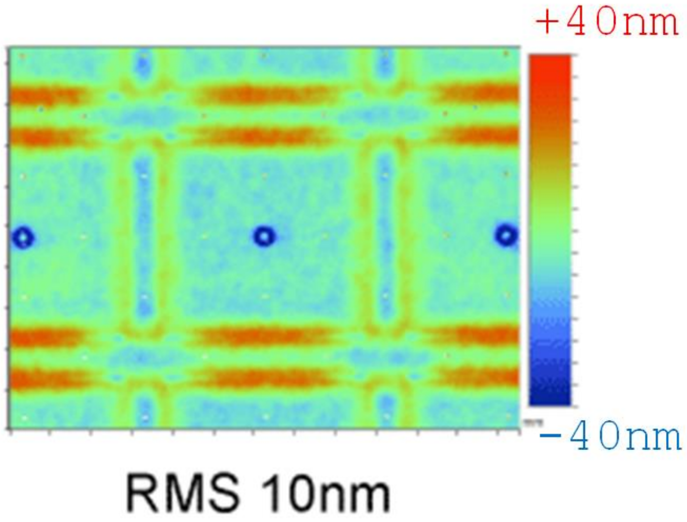


Modified design allows full actuation at lower voltage

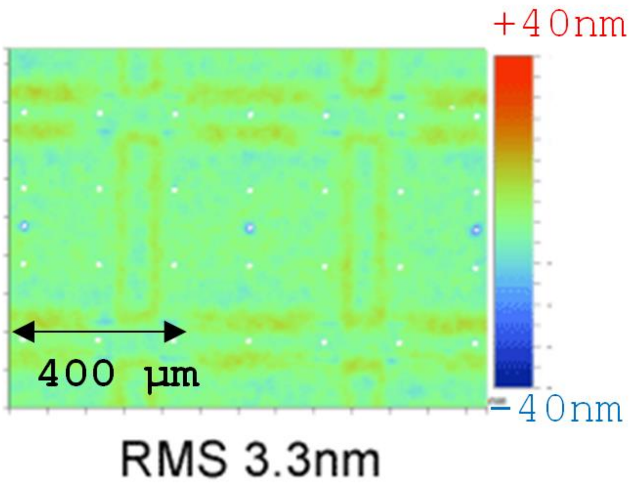
Improved Surface Finish



Nano gaps in the oxide layer result in surface topography

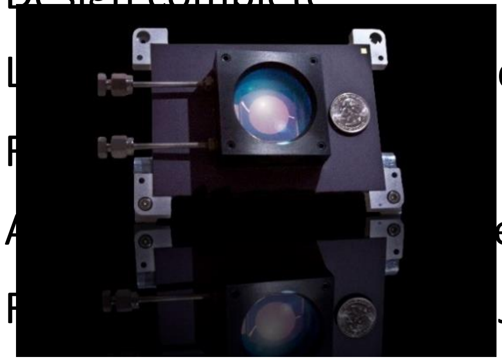


Modification to fabrication process eliminates gaps. Resulting in better finish



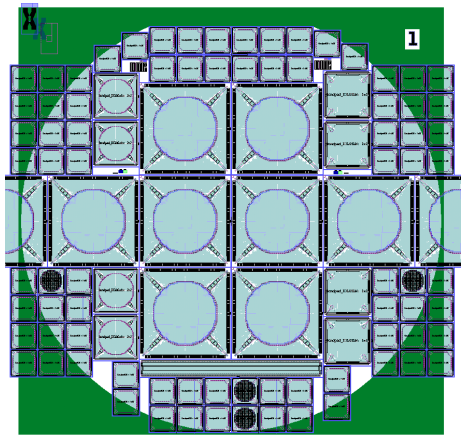
Phase II

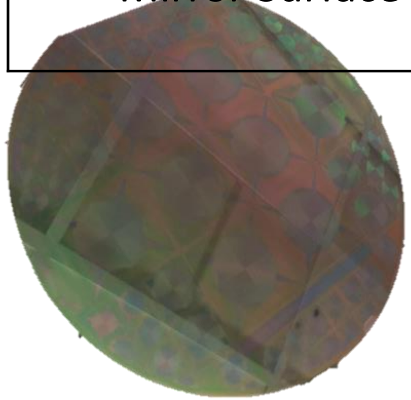
- *Improved Yield, Performance and Reliability of High-Actuator-Count Deformable Mirrors*
- Contract Number: NNX16CP14C (Start 4/2016)
- Design complete
- L … dry
- F … polished
- A … eeks
- F … June

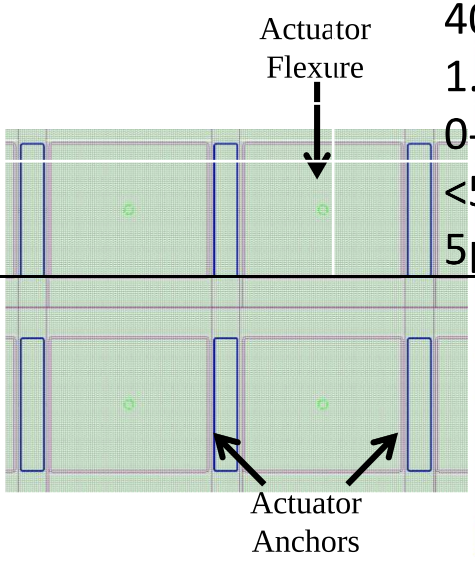


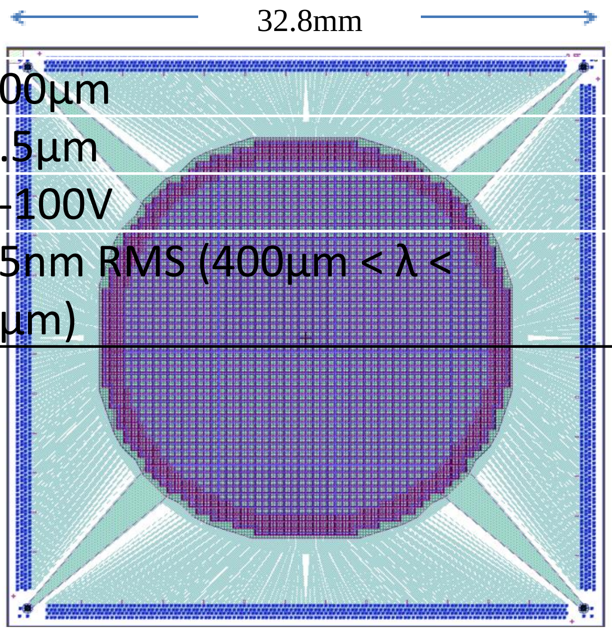
Proposed Deliverable

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 (400µm < λ < 5µm)









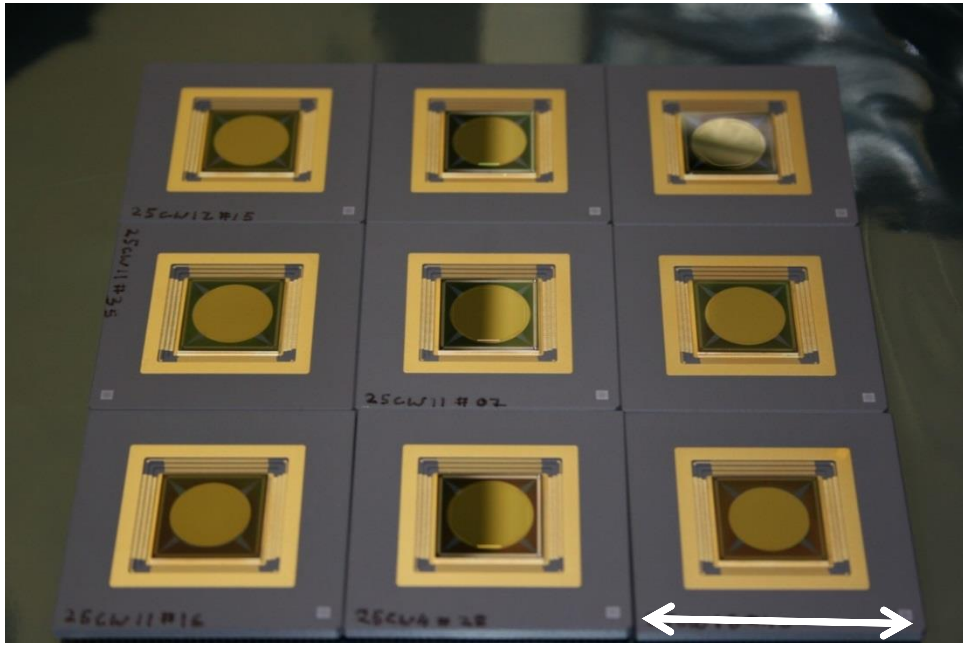
Layout of a 2040-actuator device design (Right), showing all nine mask layers required to form the MEMS deformable mirror.

TDEM Program

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

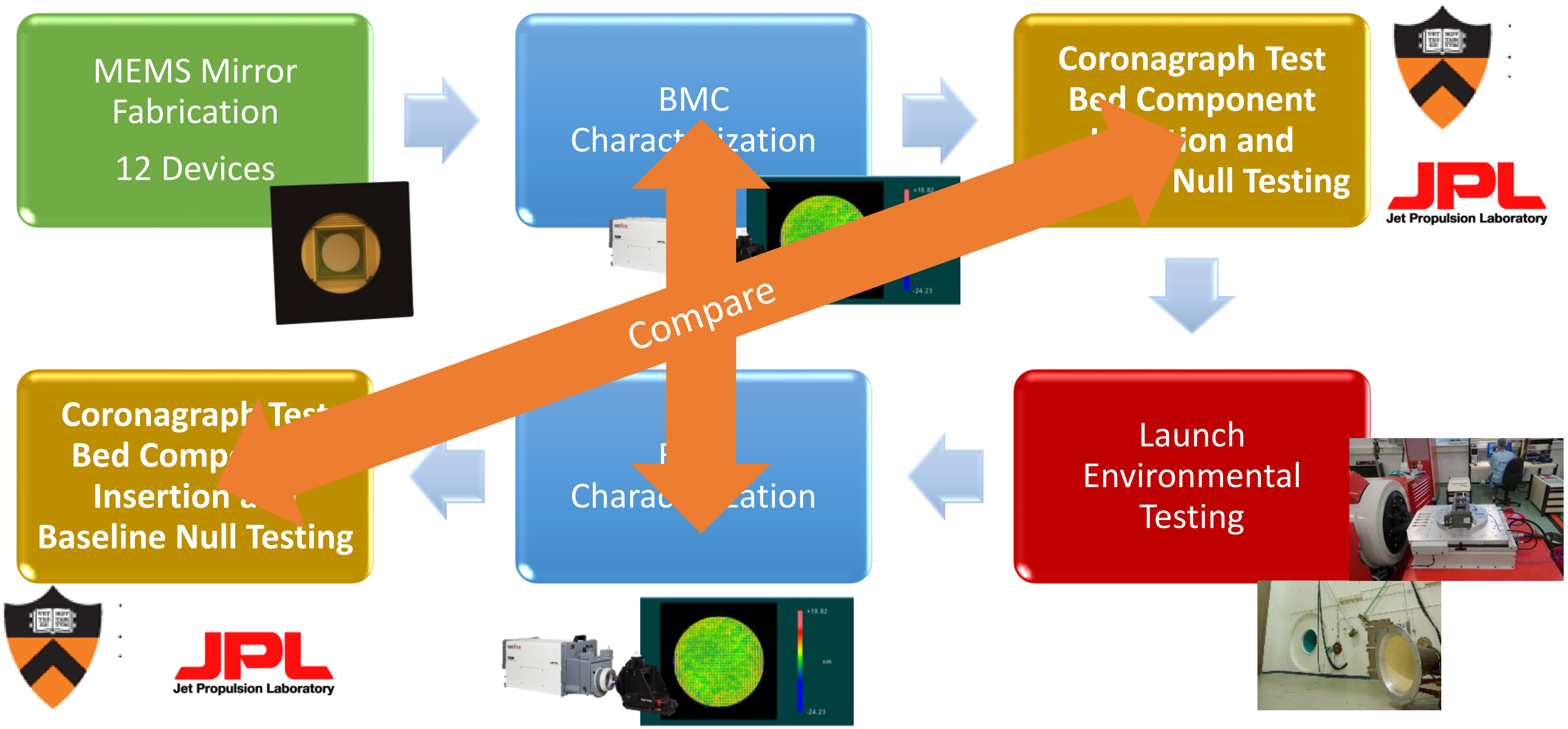
Objective: Demonstrate survivability of the BMC MEMS Deformable Mirror after exposure to dynamic mechanical environments close to those expected in space based coronagraph launch.

9 Mirrors ready for testing



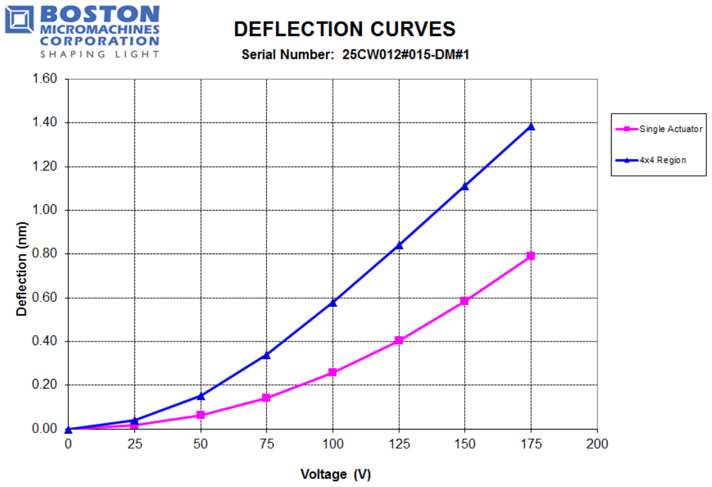
5cm

Project Flow

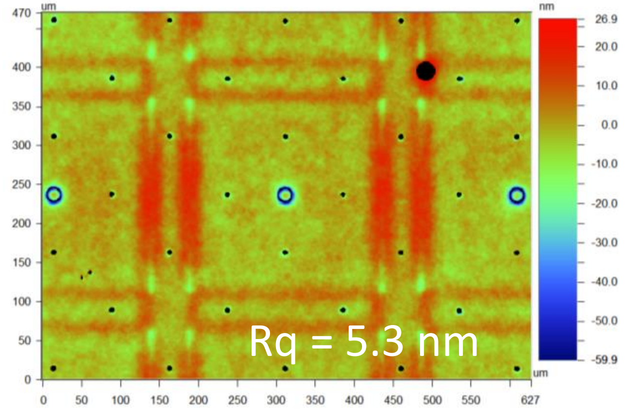


12 DMs Fabricated and Characterized

Voltage v. Deflection

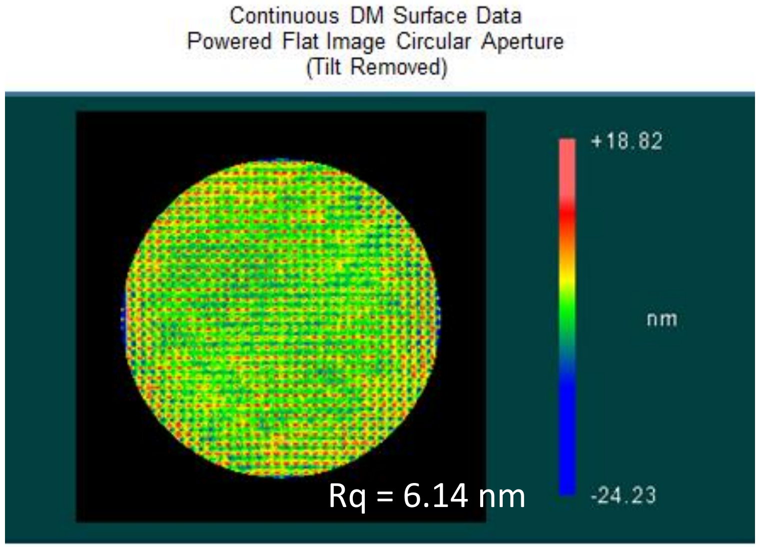


Single Actuator Surface Figure



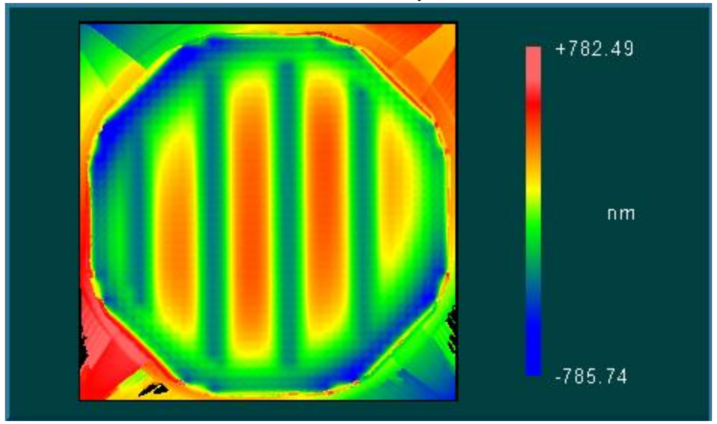
Delivered to JPL (2) and Princeton (2)

Active Flattening of DM Surface



Sinusoid Shape

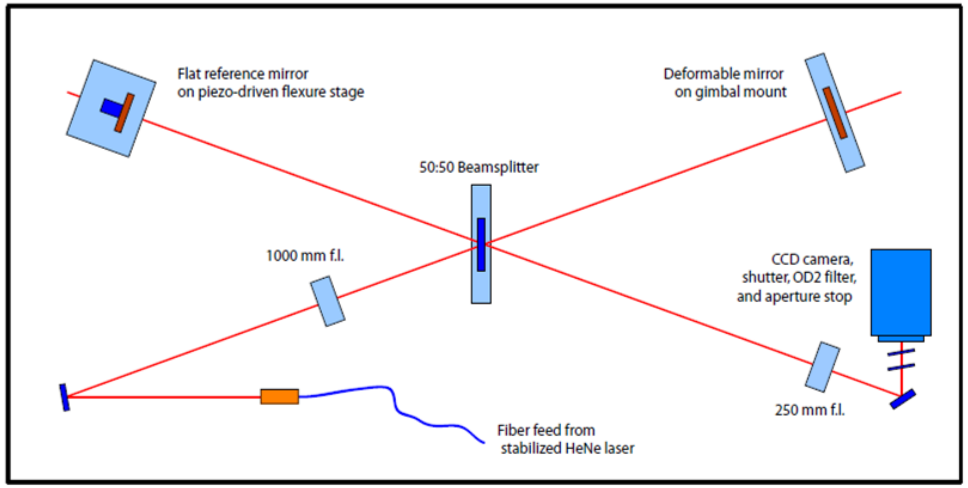
4 Period, 400nm Amplitude



Vacuum Surface Gauge (VSG) Measurements

Two 952 actuator MEMS DMs (tested separately)

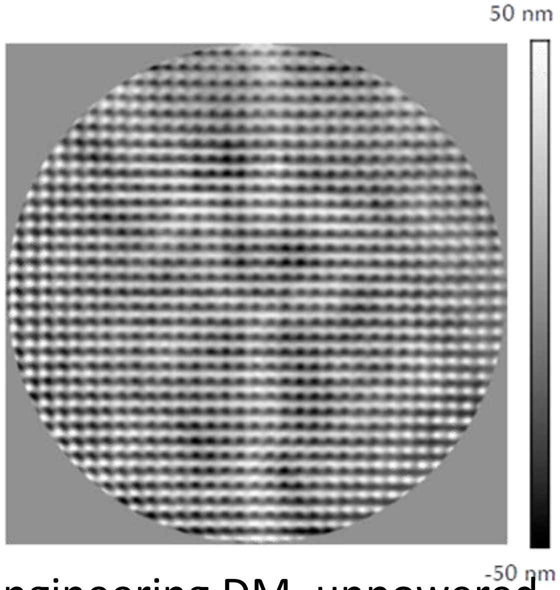
- Surface figure of DM at zero bias
- Surface figure of DM for flat surface
- Actuator gains for all 952 actuators for small up/down pokes about the flat surface condition
- Drift in surface for “flat” condition for 48 hour period
- Repeatability from “flat” and BMC/JPL solution for 10 repeats



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.

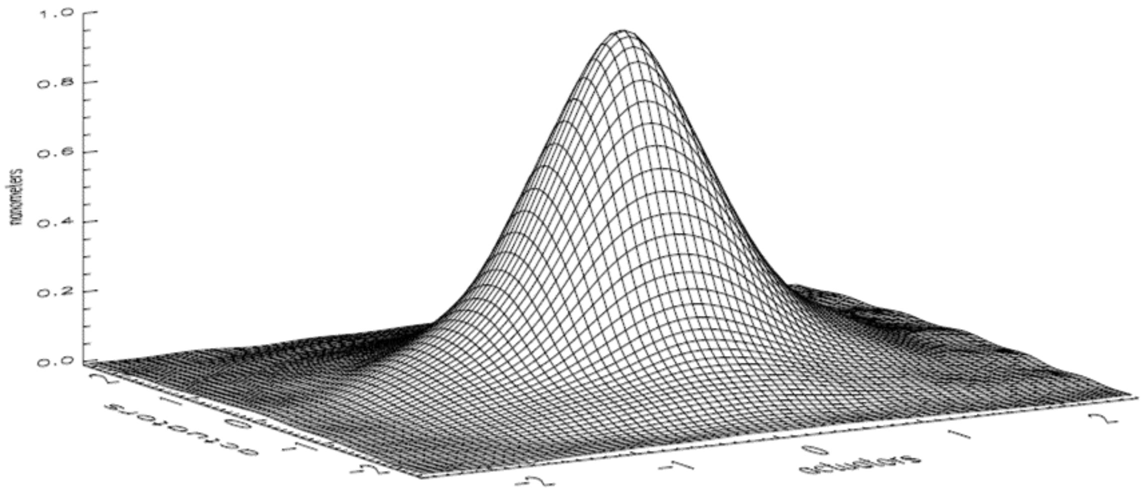
- VSG is a Michelson interferometer mounted in a vibration isolated vacuum chamber
- Light source is 632.8 nm frequency HeNe laser
- Reference mirror is mounted on a piezo-driven flexure translation stage
- Deformable mirror under test is on a gimbal mount with a temperature controlled stage

Initial Testing Results



BMC Engineering DM, unpowered –

- Zernike fit to the central actuators to the diameter = 34 actuators
- 37 zernikes removed, dominated by:
  - defocus = 121 nm rms = 420 nm PV
  - 45 astigmatism = 19nm rms = 48nm PV
  - 90 astigmatism = 10 nm rms = 101nm PV
  - spherical = 46 nm rms = 155 PV
  - Residual high order surface beyond z37 = 18nm rms = 130 PV



Influence Function Measurements, BMC DM1

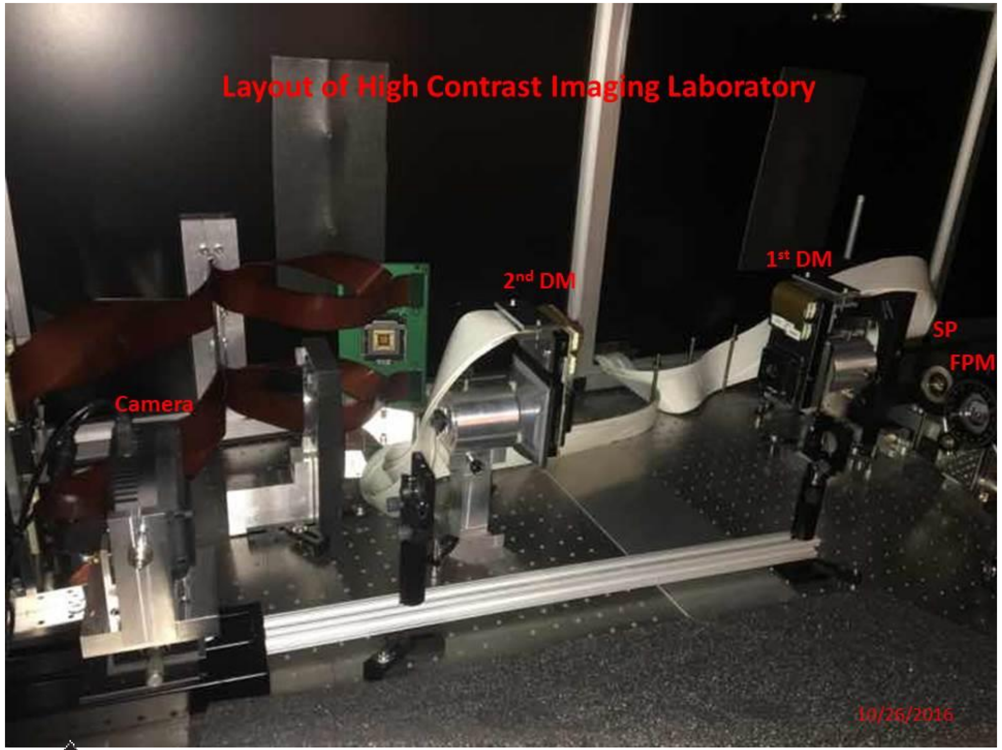
- Average of 20 individual pokes, 42 volt pokes over 50 volt bias
- Individual poke images have been subsampled, centroided and coadded
- Peak displacement is 336 nm
- Coupling factor to nearest adjacent actuator = 28%

John Trauger, Frank Greer
9/30/2016

High Contrast Imaging Laboratory(HCIL)

Kasdin Lab, Princeton University

Focal Plane Wavefront Correction (FPWC) for Exoplanet Coronagraph Imaging



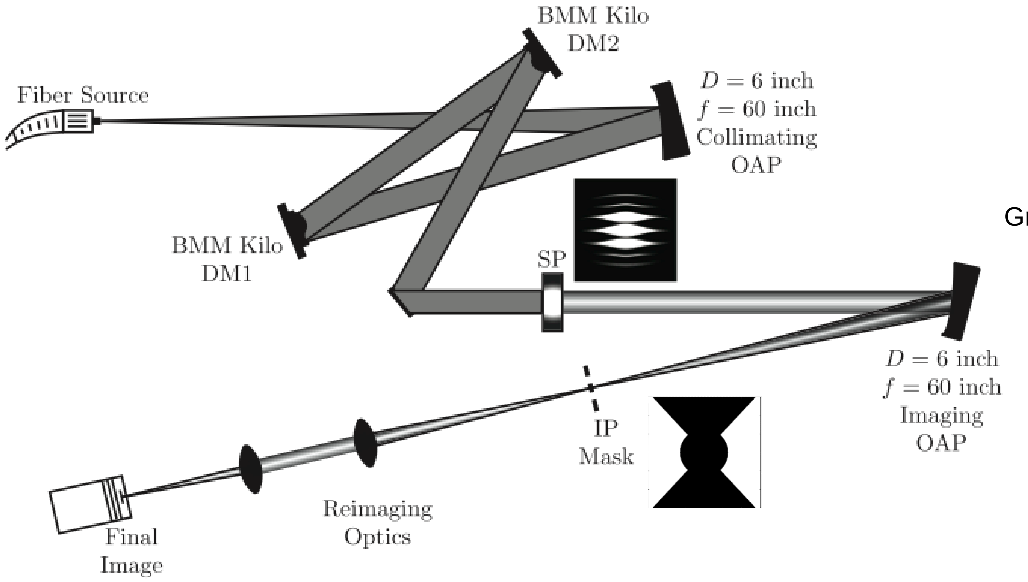


Image Credit:
Groff & Kasdin 2013

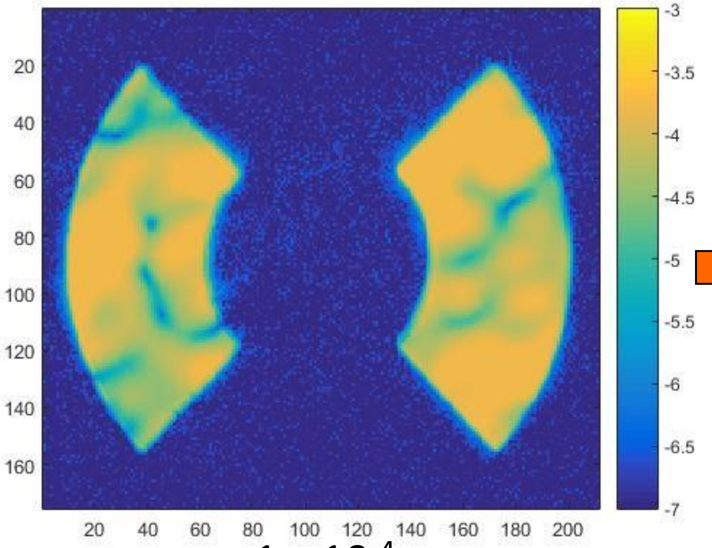
- **Shaped pupil coronagraph** technique is used to achieve high contrast for exoplanet direct imaging.
- 2 BMC **deformable mirrors** are included to compensate optical aberrations in the system.

PRINCETON UNIVERSITY

Recent Lab Results

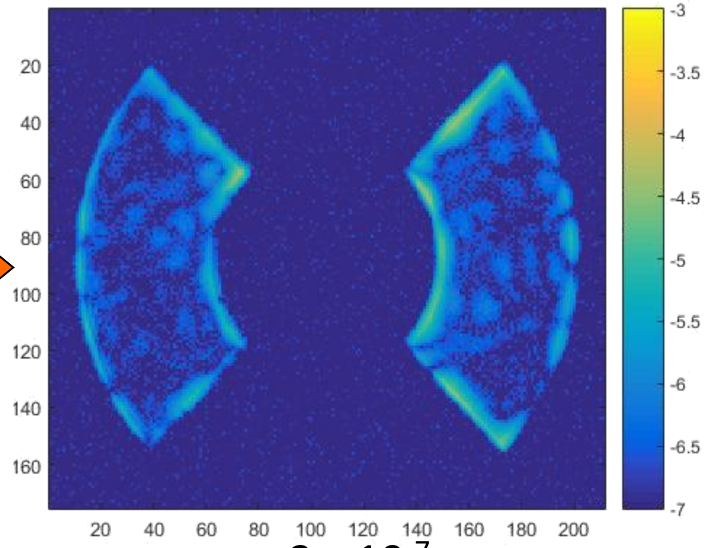
- Batch process estimator with two pairs of probes
- Stroke minimization controller
- Two BMC DMs with 952 actuators on each
- Achieved 3×10^{-7} contrast within 30 iterations 5.5-10.5 λ/D

Initial Image



1×10^{-4}

Final Image

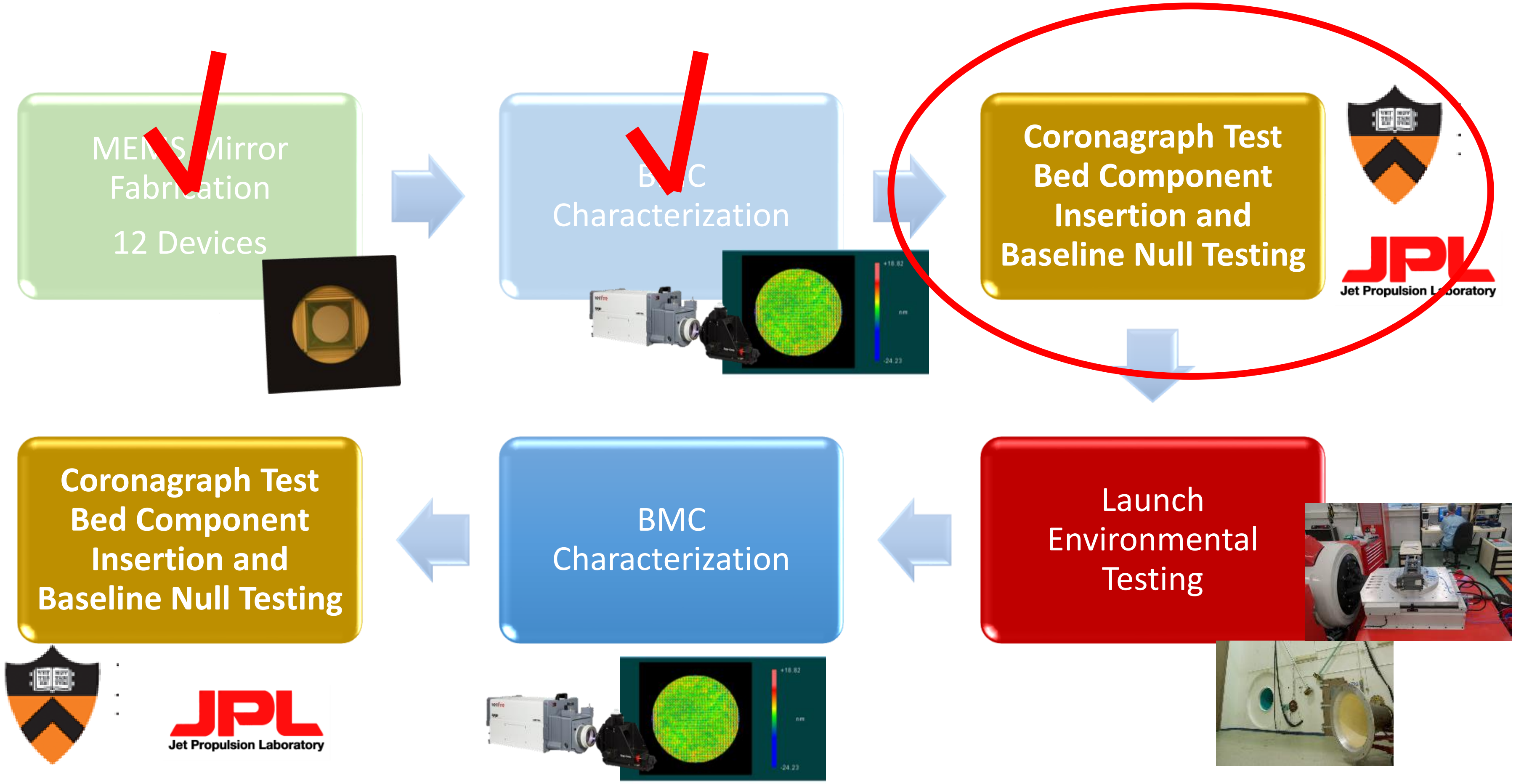


3×10^{-7}

Next Steps

1. Measure the inner working angle and the outer working angle, i.e. the largest high contrast region the DM can achieve
2. Run wave front controller with and without knowing flat map to see whether controller can cancel high frequency DM surface topgraphy
3. Test better Kalman filter and extended Kalman filter estimator and new controllers

Project Flow



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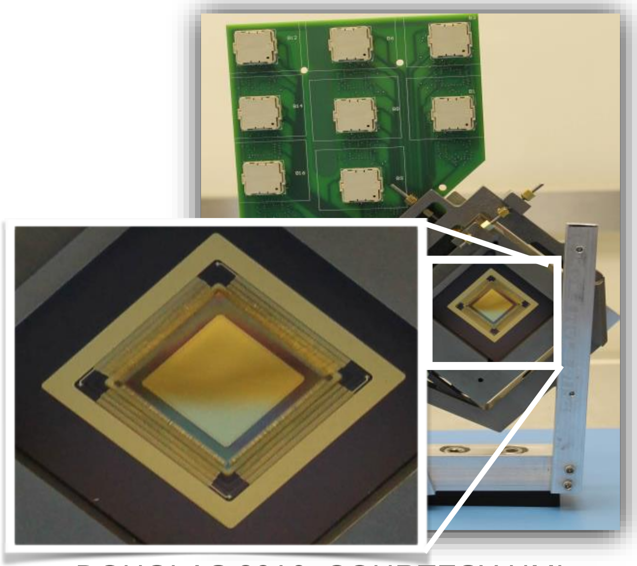
THE PICTURE(-B) SOUNDING ROCKET

PI: Supriya Chakrabarti, UMASS Lowell
November 2015

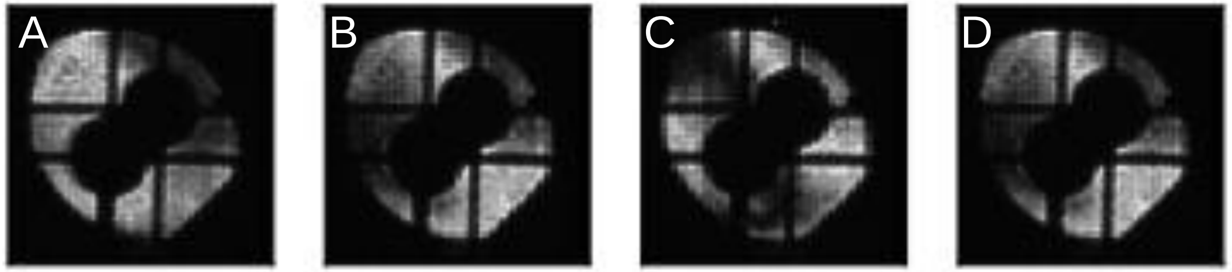
- Reflected light from Exoplanets
- Scattered Light from Exozodi
- Visible Light Coronagraphy (in space)
- Active wavefront control

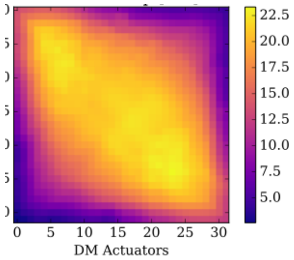


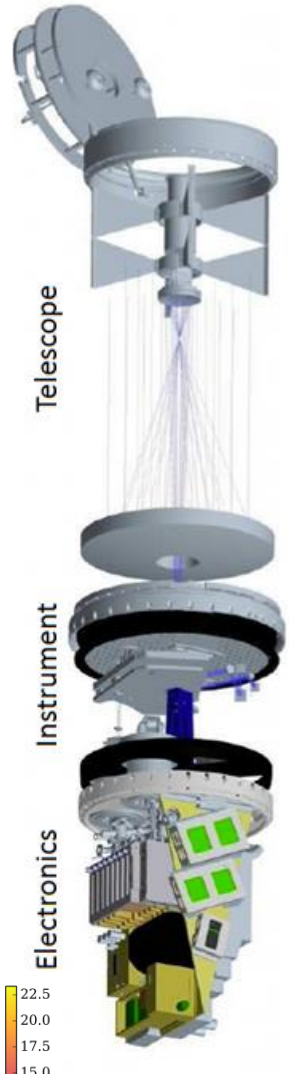
DOUGLAS 2016, COURTESY UML

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

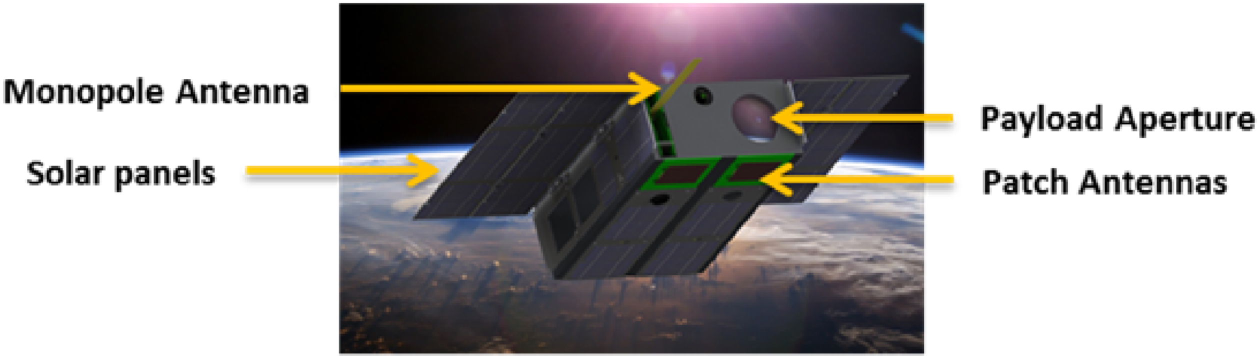
- Validate and demonstrate the capabilities of high actuator count MEMS deformable mirrors for high contrast astronomical imaging.

- Characterize MEMS deformable mirror operation using both a Shack Hartmann wavefront sensor as well as sensorless wavefront control.

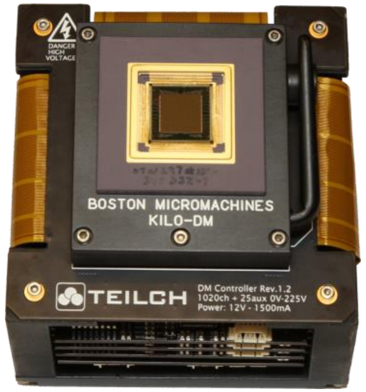
Aurora FLIGHT SCIENCES

MIT STAR Lab

Space Telecommunications, Astronomy, and Radiation Lab

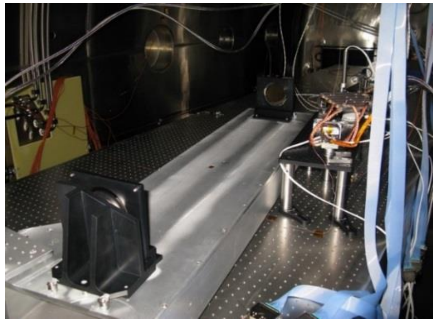


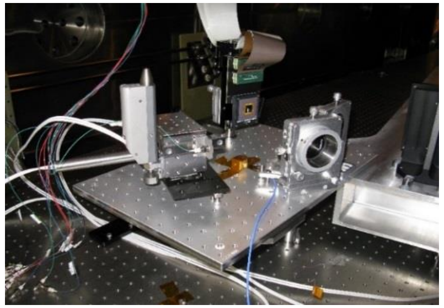
Proposed mission configuration



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: 1.35x10^{-5}

  2.0–11.0 λ_0/D: 2.82x10^{-7}

- Test B

  Time interval: 816 mins

  1.2– 2.0 λ_0/D: 1.29x10^{-5}

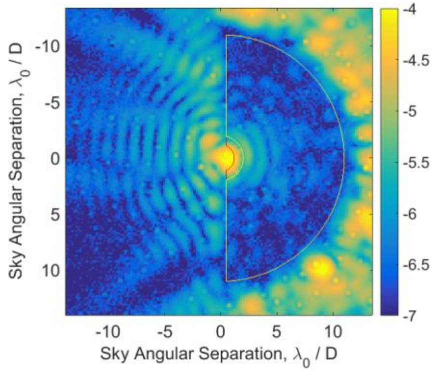
  2.0–11.0 λ_0/D: 3.14x10^{-7}

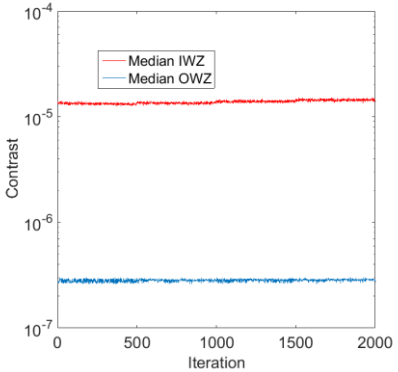
- Test C

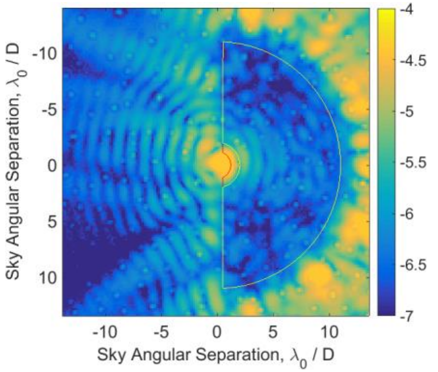
  Time interval: 61 mins

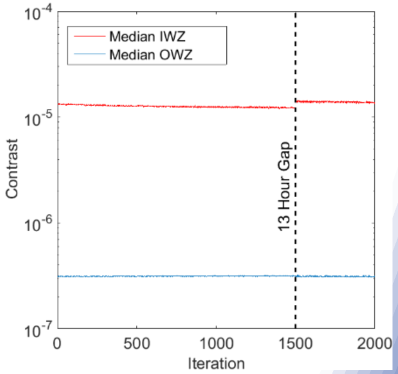
  1.2– 2.0 λ_0/D: 1.33x10^{-5}

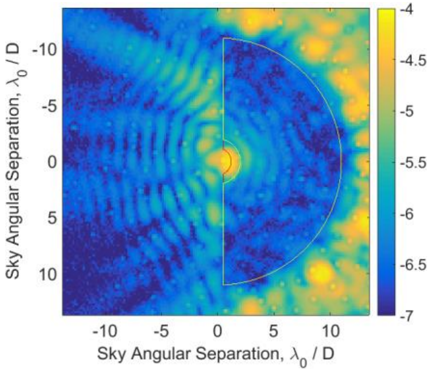
  2.0–11.0 λ_0/D: 2.63x10^{-7}

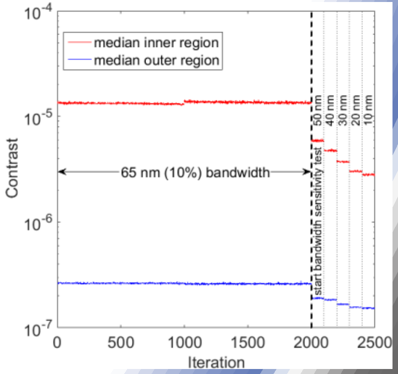




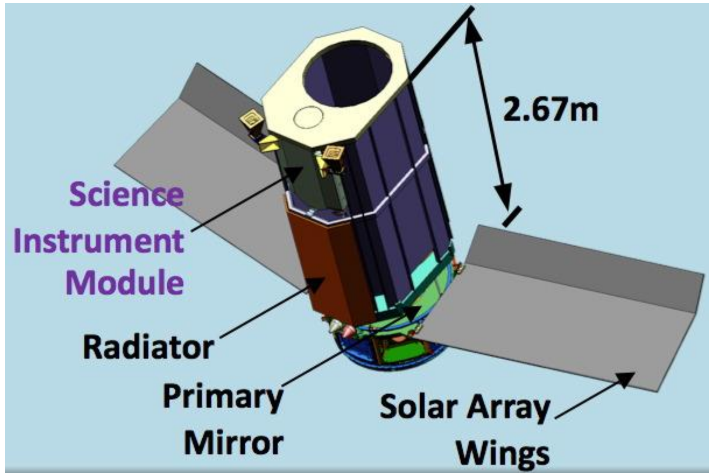




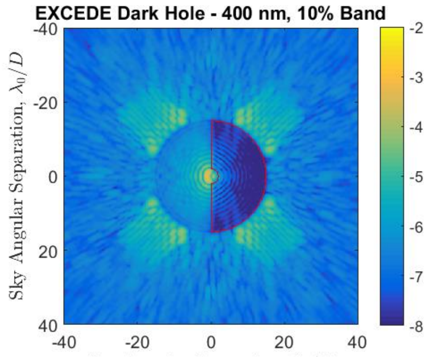




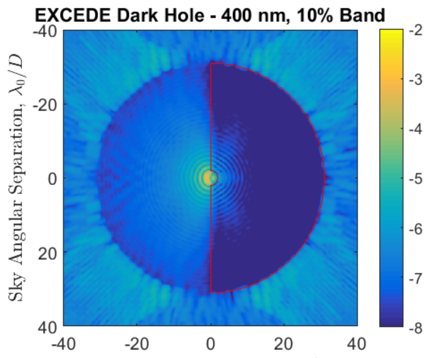
EXCEDE Proposing for the 2016 MidEX AO



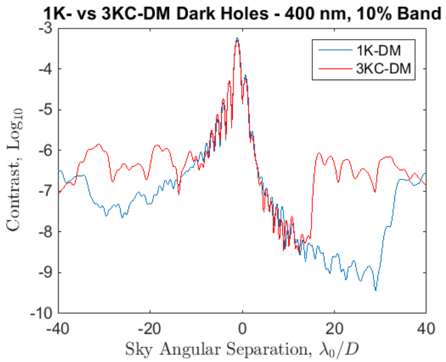
- Technical specs:
  - 0.7m primary, TMA unobstructed optical telescope
  - PIAA Coronagraph
- Mission overview
  - Survey of ~ 350 nearby exoplanetary systems
- Science Capabilities
  - Circumstellar debris systems including the habitable zone
  - Gas giants (if sufficiently bright)

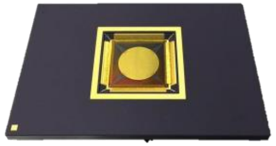


1K Boston MEMS DM
Outer Working Angle – 15 L/D



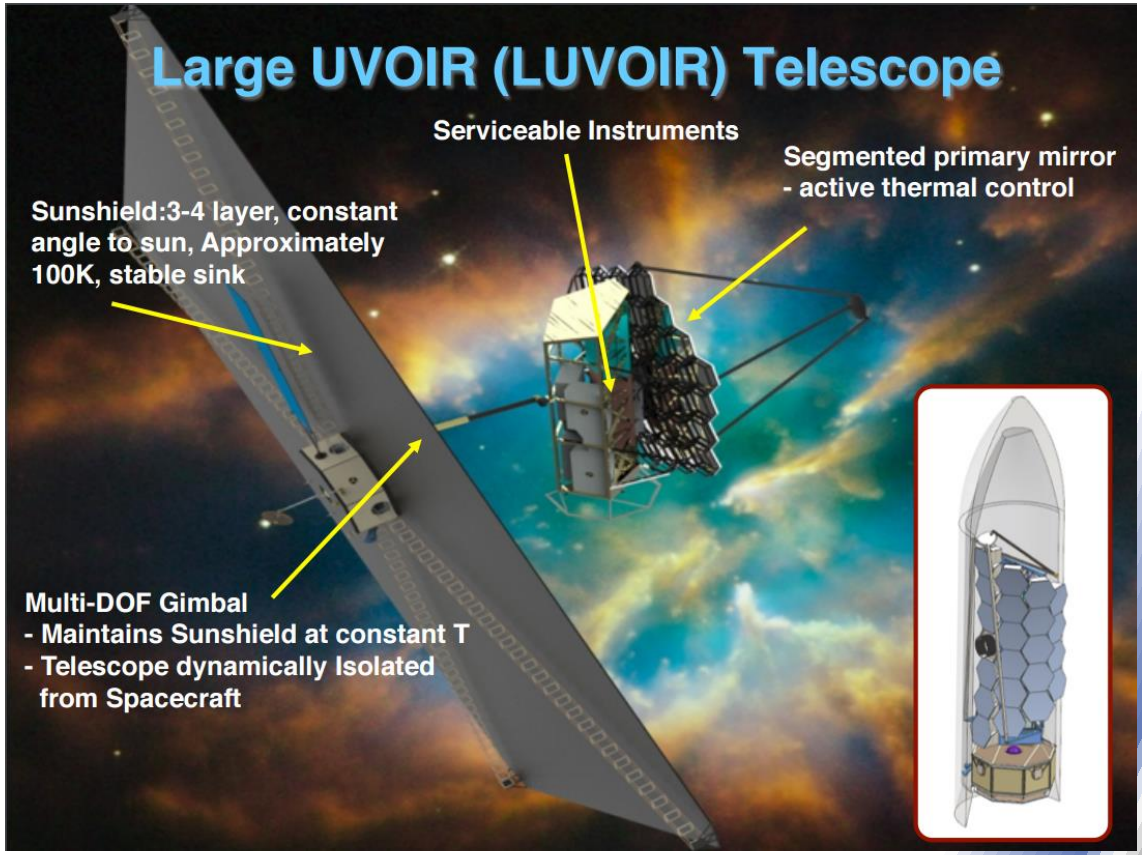
3K-C Boston MEMS DM
Outer Working Angle – 31 L/D





Large UV/Optical/Infrared Surveyor

- Deformable mirror needs
  - 10k+ actuators
  - Space qualified
  - TRL 6
  - …
- Instrument Components subgroup of the Technical Working Group
- Targeted Performance
- Demonstrated Performance
- Technology Readiness Levels



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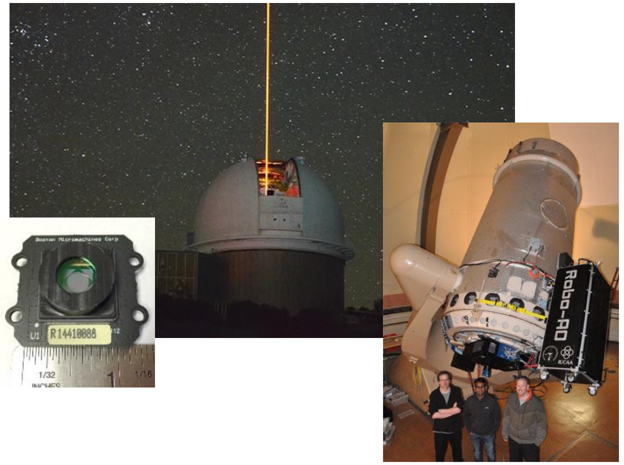
On-Sky Instruments using BMC Mirrors

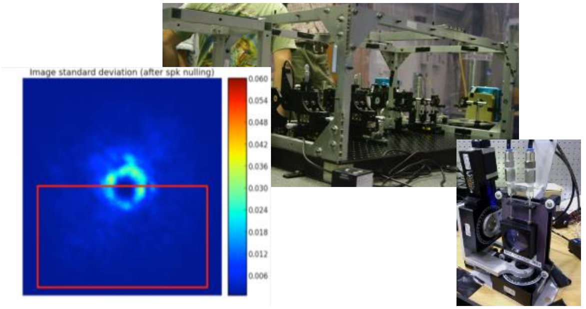
ROBO-AO

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



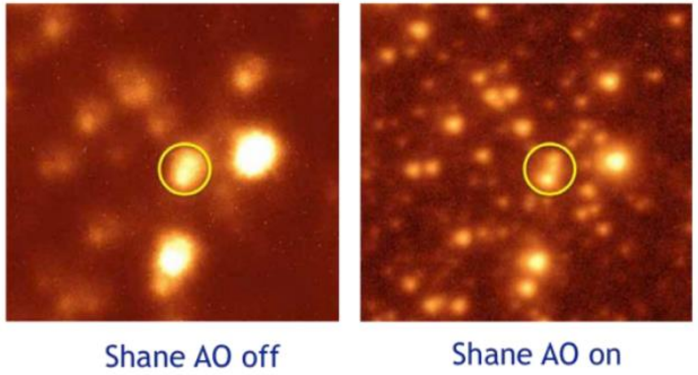
SCExAO, Subaru telescope

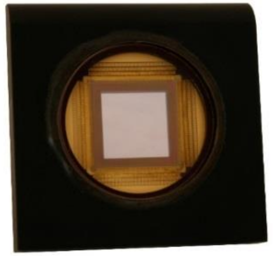
- 2040 installed 2013



Shane-AO, Lick Observatory

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



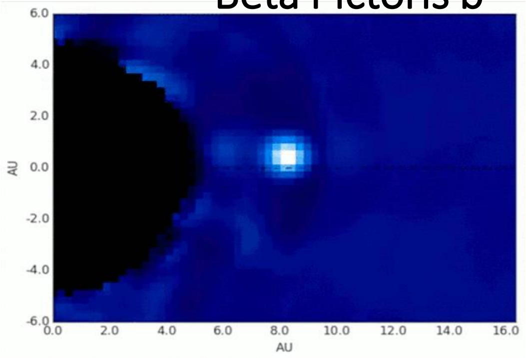


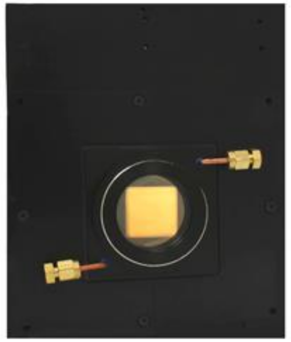
Portion of the M92 globular cluster taken in H band.

Gemini Planet Imager, Gemini South

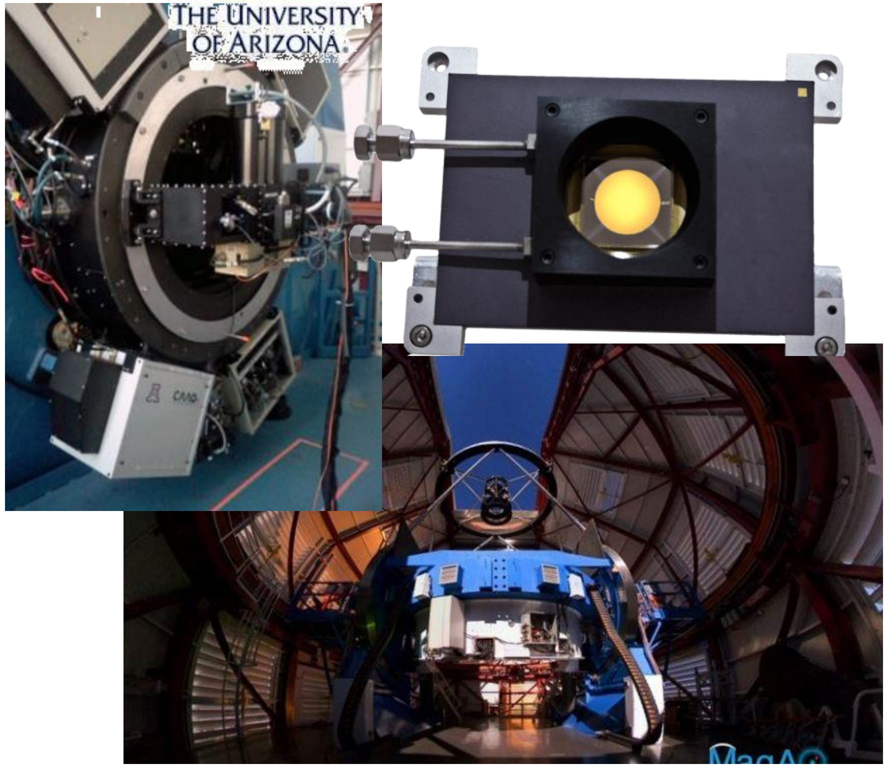
- 4092 installed 2013

Beta Pictoris b

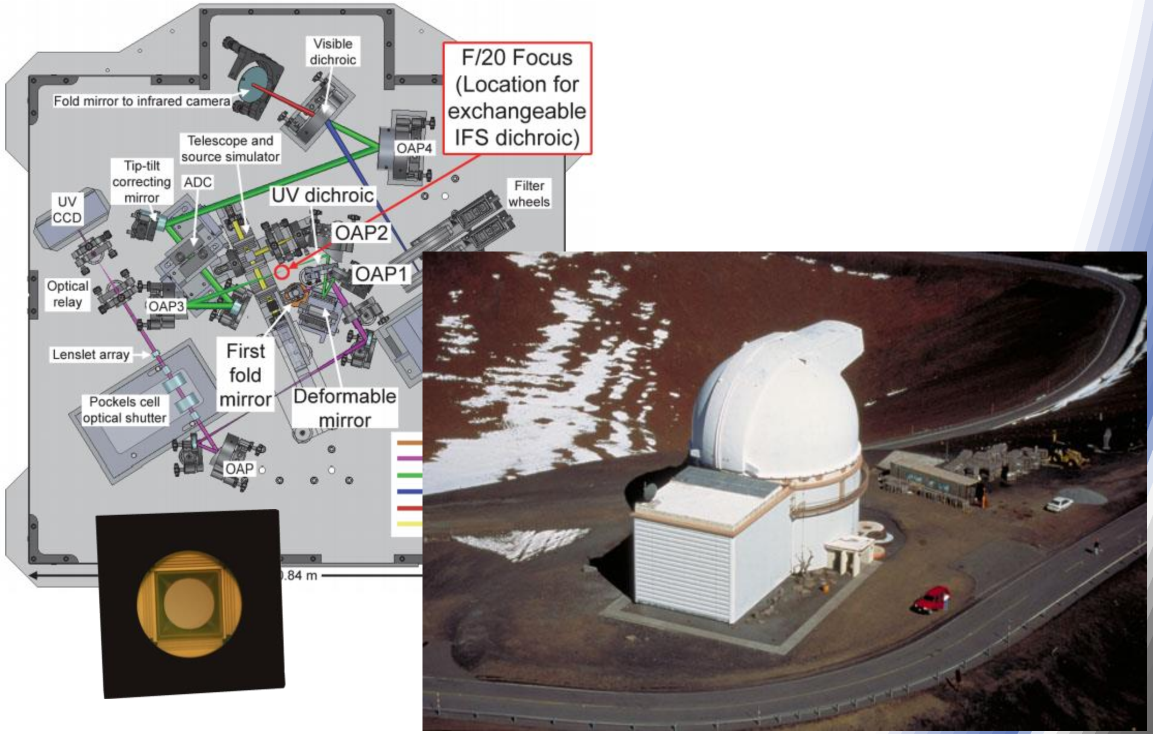




Next Instruments



MagAO-X



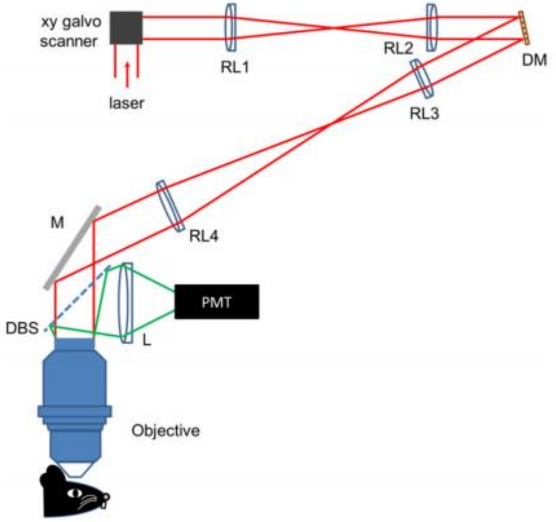
Rapid Transit Surveyor

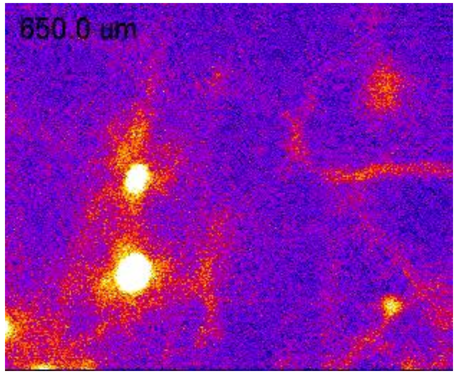
Outline

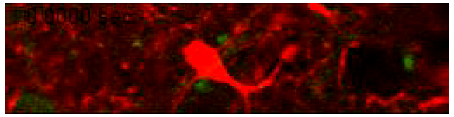
- BMC DM Technology
- NASA funded mirror technology programs
- Space astronomy operations
- Ground astronomy operation
- Non-astronomy operation

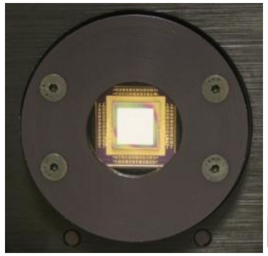
Other Applications Of MEMS DMs

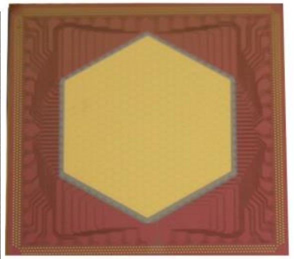
In vivo imaging of functional mouse brain through the skull

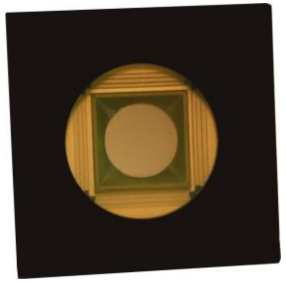




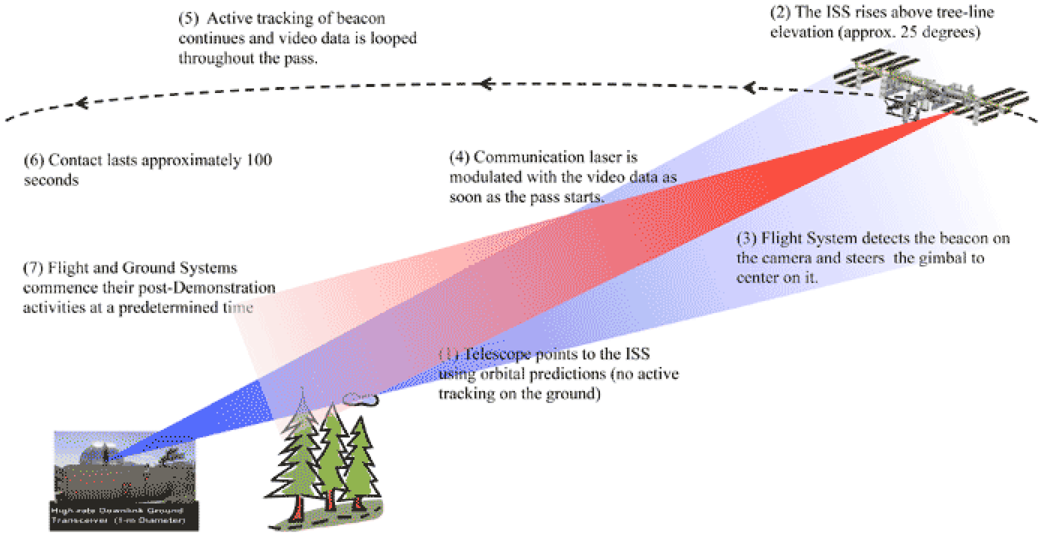




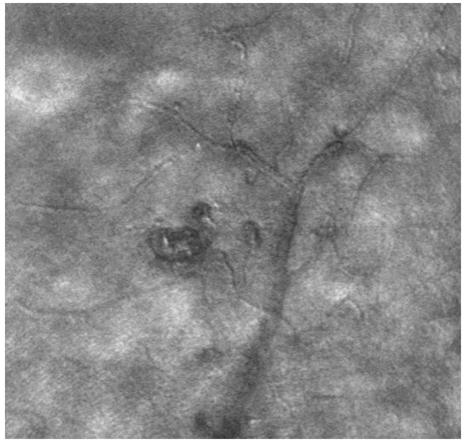


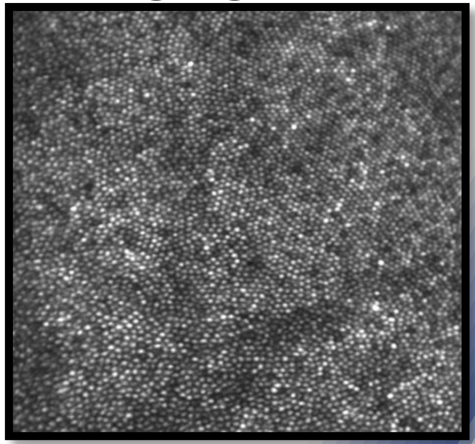


Free Space Optical Communication



In vivo Retinal Imaging





Conclusion

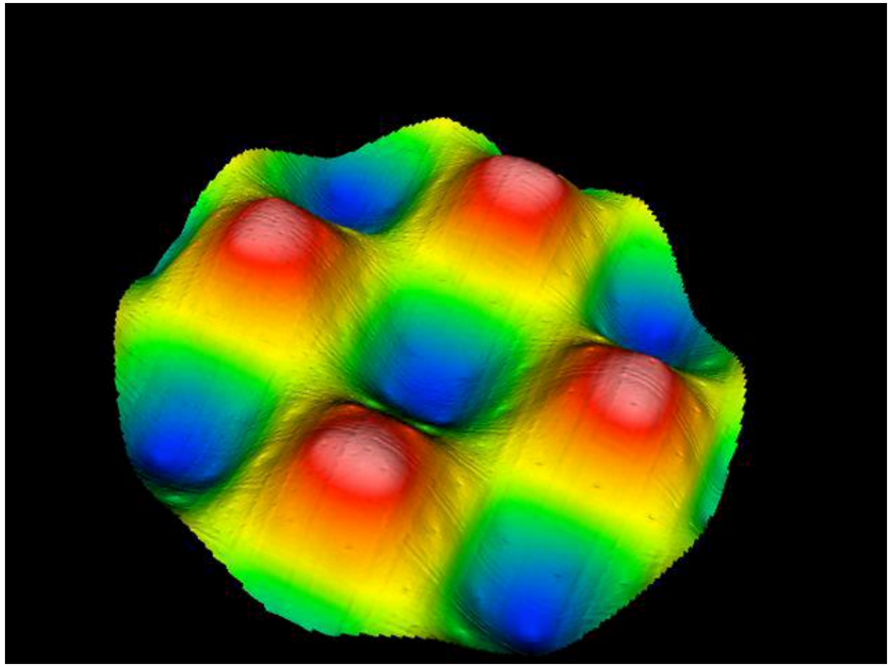
- Results from our Phase I and II program show good promise for next generation MEMS DMs.
- Testing is ongoing with our TDEM program. Parts are undergoing testing at JPL and Princeton.
- MEMS DMs are being used in a variety of areas for image enhancement

Acknowledgements

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

Thank You

Questions?



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EXTRA SLIDES

MTD 2016

Background

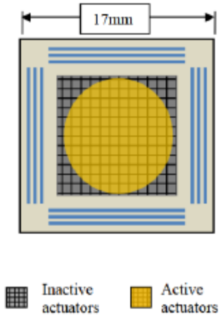
- Boston Micromachines (BMC) DMs sent to JPL under TDEM for characterization
- Milestone Whitepaper (dated 12/9/2013) involving BMC, Boston University, Princeton University, and JPL written to outline tests for BMC MEMS DMs that:
  - “Demonstrate survivability and functional performance repeatability of the BMC 952-actuator MEMS CDM (Continuous Surface Deformable Mirror to within the noise floor of the various test equipment after exposure to dynamic mechanical environments representative of a range expected in coronagraph launch.”
    - Characterize the degree of degradation in CDM optical and electromechanical performance through functional test and interferometric surface mapping.
    - “The level of measurement repeatability in this series of tests will be 5nm using the BMC interferometer and <100pm using the JPL Vacuum Surface Gauge.” (currently measured to be ~50pm for VSG)
    - 33 µm per pixel resolution promised
      - VSG pixel scale will be modified from the current 60.6 to 20.2 µm/pixel
- DM model to be tested: BMC Kilo 32x32 (952-active actuators)

Table 1: Characteristics of MEMS Deformable Mirror

Mirror architecture	952 actuator continuous facesheet
Active aperture	9.9 mm Circular, 34 actuators across diameter
Actuator pitch	300µm
Fill Factor	99.6%
Surface figure error	<5nm RMS, λ<400µm
Surface Roughness	<2nm RMS
Mirror segment material	Silicon, 1000 Å gold coating
Actuator stroke	2µm

952 Actuator MEMS DM Die Configuration

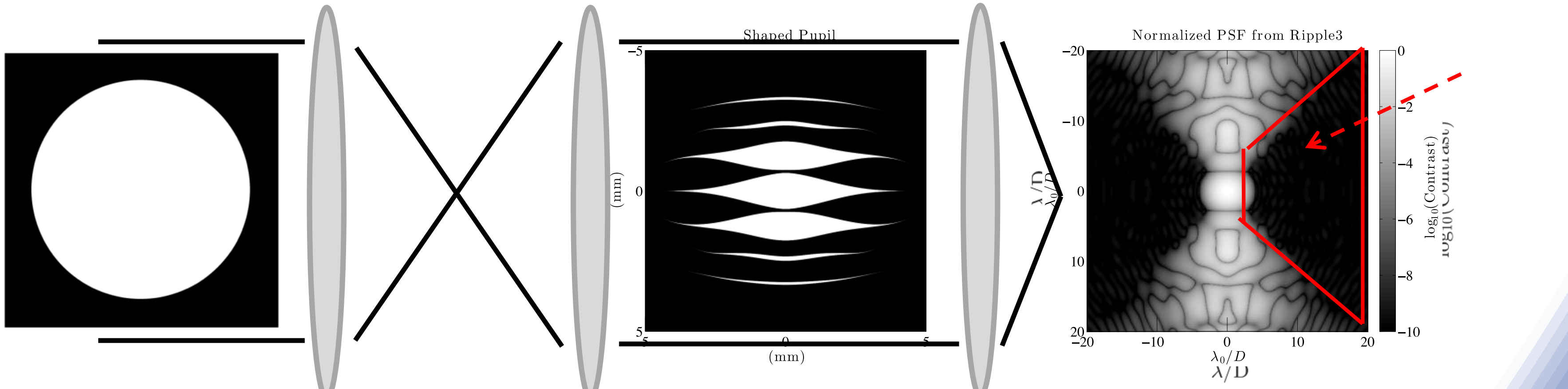
Ø9.9mm active aperture
(34 actuators across, 300µm pitch)



BMC DM specs
Stability: 100pm
Gain: 10 nm/V
LSB: 3 mV
30 pm/step

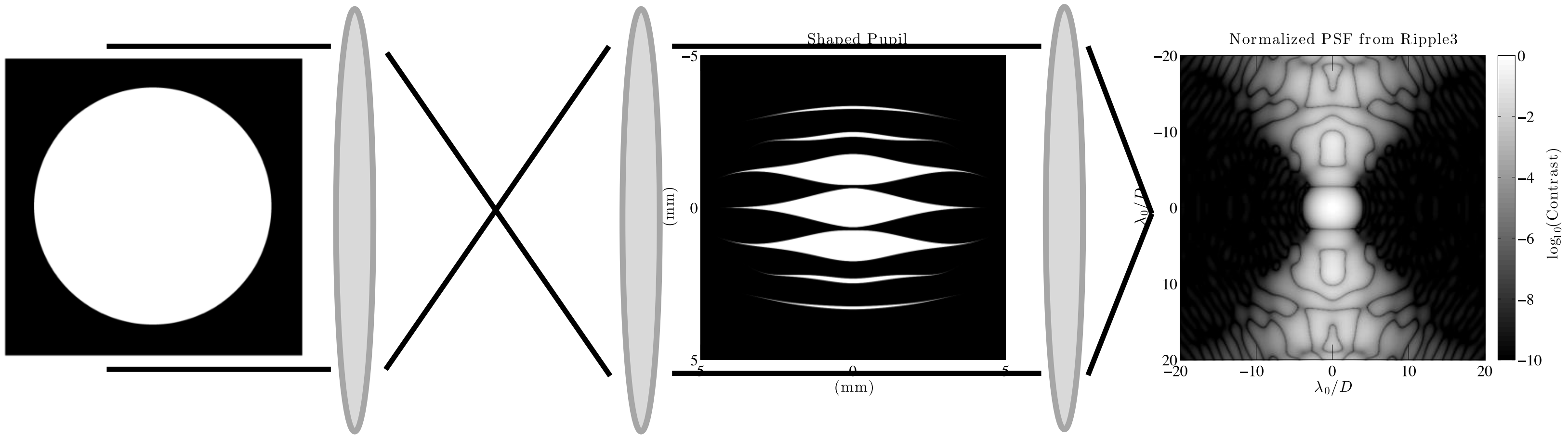
Coronagraphs

- **Coronagraph:** A system of masks, stops and/or apodizers to remove starlight and create high contrast in the image plane.
- Different Types of Coronagraphs
  1. Hybrid Lyot Coronagraph (HLC)
  2. **Shaped Pupils (SP)** (in HCIL)
  3. Phase Induced Amplitude Apodization (PIAA)
  4. Apodized Pupils (APP)
  5. 4 or 8 Quadrant Phase Mask
  6. Optical Vortex
  7. Some combined types: APLC, SPLC



Optical Aberrations

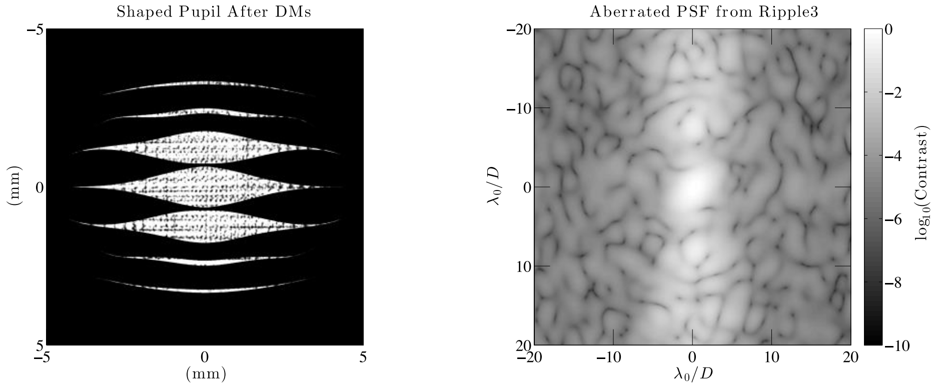
- No optical system is perfect
- **Quasi-static aberrations** cause contrast degradation in the search area
  - Quasi-static = static for hours or longer, from surface imperfections, misalignments and thermal flexing



3×10^{-10} contrast

11/3/2016

With Optical Aberration



1×10^{-4} contrast

Deformable Mirrors (DMs)

- Surface shape can be controlled to compensate phase aberrations.
- Continuous facesheet and an array of actuators behind it.

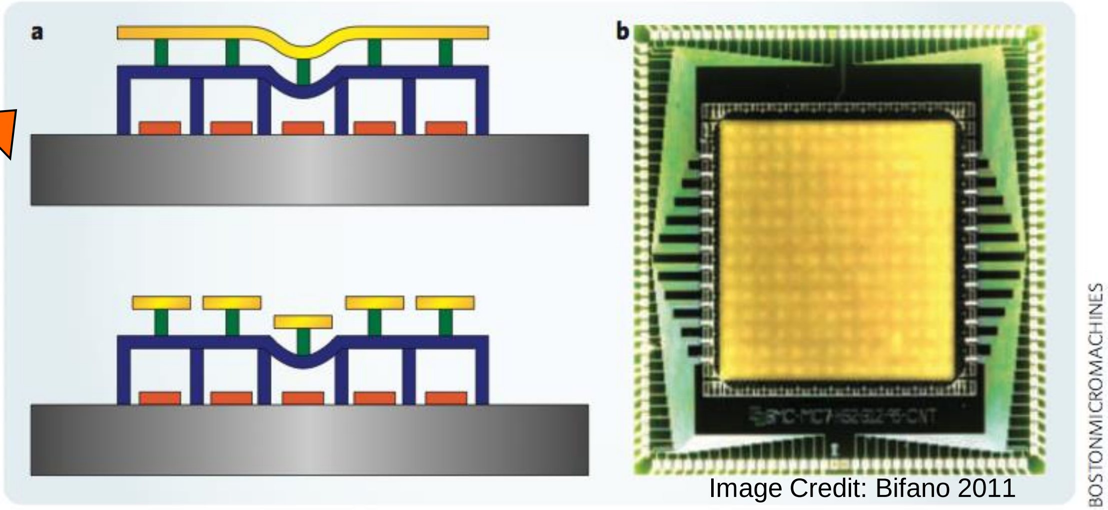
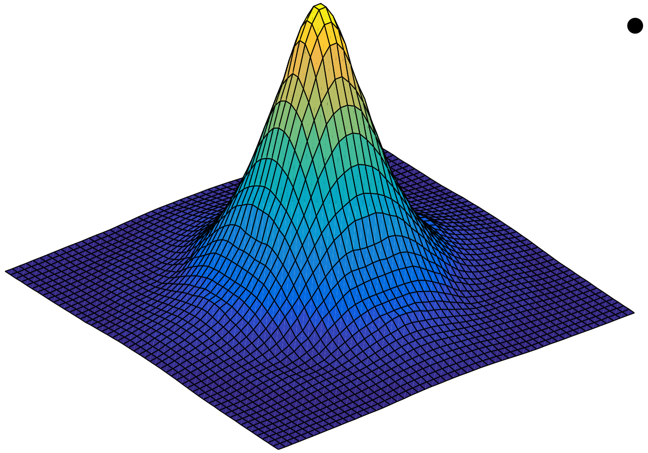


Image Credit: Bifano 2011

- Small phase perturbation at DM well-approximated as linear **superposition** of actuator **influence functions**:

$$\phi(x,y) = \frac{2}{\lambda}\sum_{q}^{N_{act}} u_q f(x - x_q, y - y_q)$$

$$\boxed{\begin{aligned} \lambda &= \text{Wavelength of light} \\ u &= \text{DM actuator displacement commands} \\ \phi &= \text{Phase change from DM} \end{aligned}}$$



Influence Function

$f(x,y)$

Linear Model of Coronagraphic Imaging System

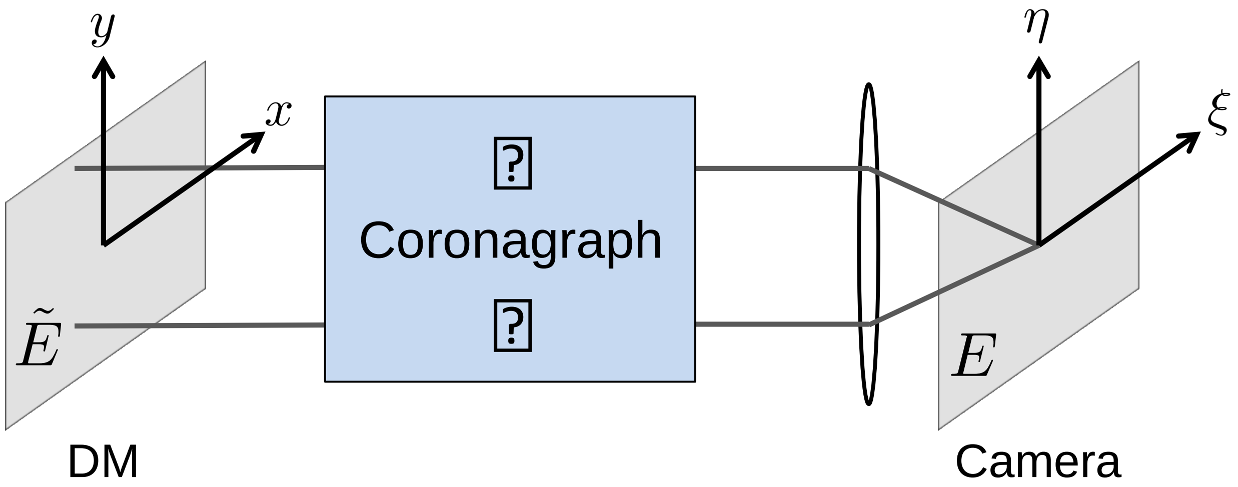


Image Credit: A J Eldorado Riggs

$\tilde{E}$ = E-field at DM
E = E-field at camera
k = Correction iteration #
$\Delta\phi$ = Change in phase at DM
Δu = Change in DM commands
$i = \sqrt{-1}$
$\mathcal{C}\{\}$ = Linear operator
G = DM response matrix

- DM adds small phase perturbations to pupil E-field

$$\tilde{E}_k(x,y) = \tilde{E}_{k-1}(x,y)e^{i\Delta\phi_k(x,y)}$$

- Phase changes are very small at each step → Tayler expansion

$$e^{i\Delta\phi(x,y)} \approx 1 + i\Delta\phi(x,y)$$

- Propagate the pupil E-field to the image plane

$$\begin{aligned} E_k(\xi,\eta) &= \mathcal{C}\{\tilde{E}_{k-1}(x,y)\} + \mathcal{C}\{i\tilde{E}_{k-1}(x,y)\Delta\phi(x,y\} \\ &= E_{k-1}(\xi,\eta) + G_{k-1}\Delta u_k \end{aligned}$$

→ Transition Model

Estimation by DM Pair-wise Probing

$$\begin{aligned} k &= \text{Correction iteration \#} \\ j &= \text{Probe \#} \\ \mathbf{p_{k,j}} &= \mathbf{G_k u_j} = \text{probe field at camera} \\ I_{k,j} &= \text{Measured intensity} \\ I_{inco} &= \text{Incoherent intensity} \\ n_{k,j\pm} &= \text{Measurement noise: shot,} \\ & \quad \text{readout, dark current} \end{aligned}$$

- Create a linear observation of the state
  - Take images for +/- probe shapes on DM

$$\begin{aligned} I_{k,j\pm} &= |E_k \pm p_{k,j}|^2 + I_{inco,k} + n_{k,j\pm} \\ &= |E_k|^2 + |p_{k,j}|^2 \pm 2\mathcal{R}\{E_k^* p_{k,j}\} + I_{inco,k} + n_{k,j\pm} \end{aligned}$$

  - Get the cross term by subtracting +/- probed images

$$\begin{aligned} \Delta I_{k,j} &= I_{k,j+} - I_{k,j-} = 4\mathcal{R}\{E_k^* p_{k,j}\} + n_{k,j} \\ &= 4\begin{bmatrix} \mathcal{R}\{p_{k,j}\} & \mathcal{I}\{p_{k,j}\} \end{bmatrix} \begin{bmatrix} \mathcal{R}\{E_k\} \\ \mathcal{I}\{E_k\} \end{bmatrix} + \begin{bmatrix} n_{k,j} \end{bmatrix} \end{aligned}$$

  - At least 2 pairs of probed images

$$\begin{bmatrix} \Delta I_{k,1} \\ \vdots \\ \Delta I_{k,N_{pp}} \end{bmatrix} = 4 \begin{bmatrix} \mathcal{R}\{p_{k,1}\} & \mathcal{I}\{p_{k,1}\} \\ \vdots & \vdots \\ \mathcal{R}\{p_{k,N_{pp}}\} & \mathcal{I}\{p_{k,N_{pp}}\} \end{bmatrix} \begin{bmatrix} \mathcal{R}\{E_k\} \\ \mathcal{I}\{E_k\} \end{bmatrix} + \begin{bmatrix} n_{k,1} \\ \vdots \\ n_{k,N_{pp}} \end{bmatrix}$$

Give'on+ 2007

State

Measurement

$$z_k = H_k x_k + n_k$$

Observation Model

Least Squares Estimate:

Batch Process Estimator (BPE)

$$\boxed{\hat{x}_k = (H_k^T H_k)^{-1} H_k^T z_k}$$

Compensating Aberrations Using DMs

- The controllers are based on the previous state space model

$$E_k = E_{k-1} + G_{k-1} u_k \qquad I_k = E_k^\star E_k$$

I_k	Intensity	G_k	Control Jacobian
E_k	Electric Field	u_k	Control Input

- **No need** to update control Jacobian at each step $G_k = G$
- **Stroke minimization** and **EFC** are two major controllers in our lab, both of which try to improve the image contrast with small DM voltage commands.

Stroke Minimization

$$min \quad J = u_k^T u_k$$

$$s.t. \quad I_k = C_k$$

$$\Downarrow$$

$$min \quad J' = u_k^T u_k + \mu(I_k - C_k)$$

$$\Downarrow$$

$$u_k = -(\frac{1}{\mu} I_k + G^\star G)^{-1} \Re\{G^\star E_{k-1}\}$$

Electric Field Conjugation (EFC)

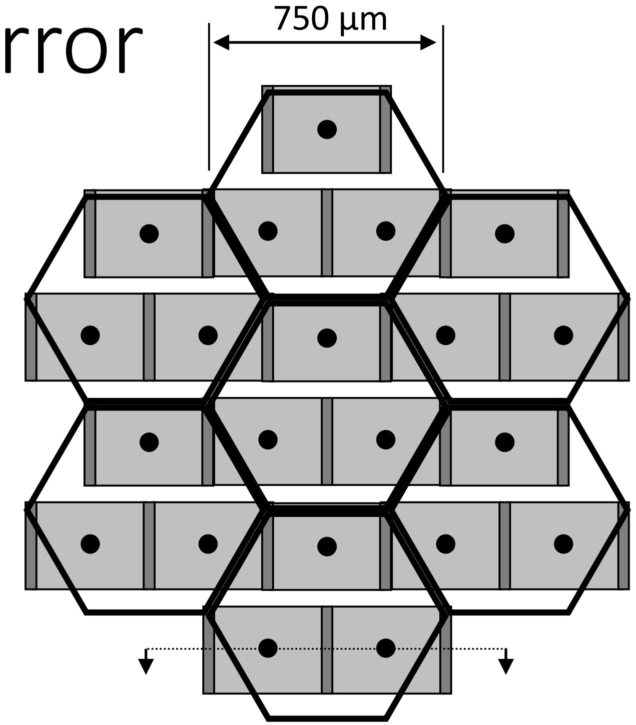
$$min \quad J'' = E_k^\star E_k + \alpha u_k^T u_k$$

$$\Downarrow$$

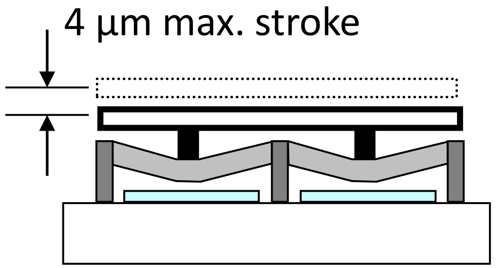
$$u_k = -(\frac{1}{\mu} I_k + G^\star G)^{-1} \Re\{G^\star E_{k-1}\}$$

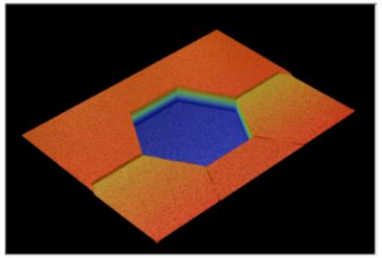
Pueyo 2009, Give'on 2007

Hex Tip-Tilt-Piston Deformable Mirror

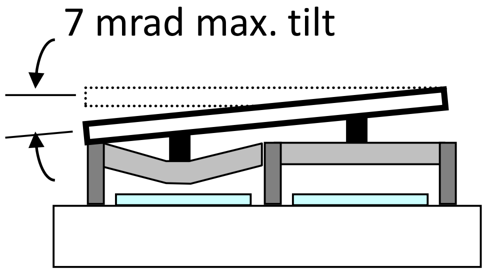


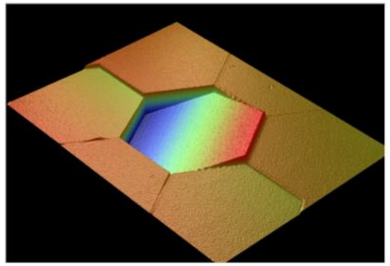
- Up to 3063 actuators
- Independent hexagonal segments
  - 3 actuators per segment



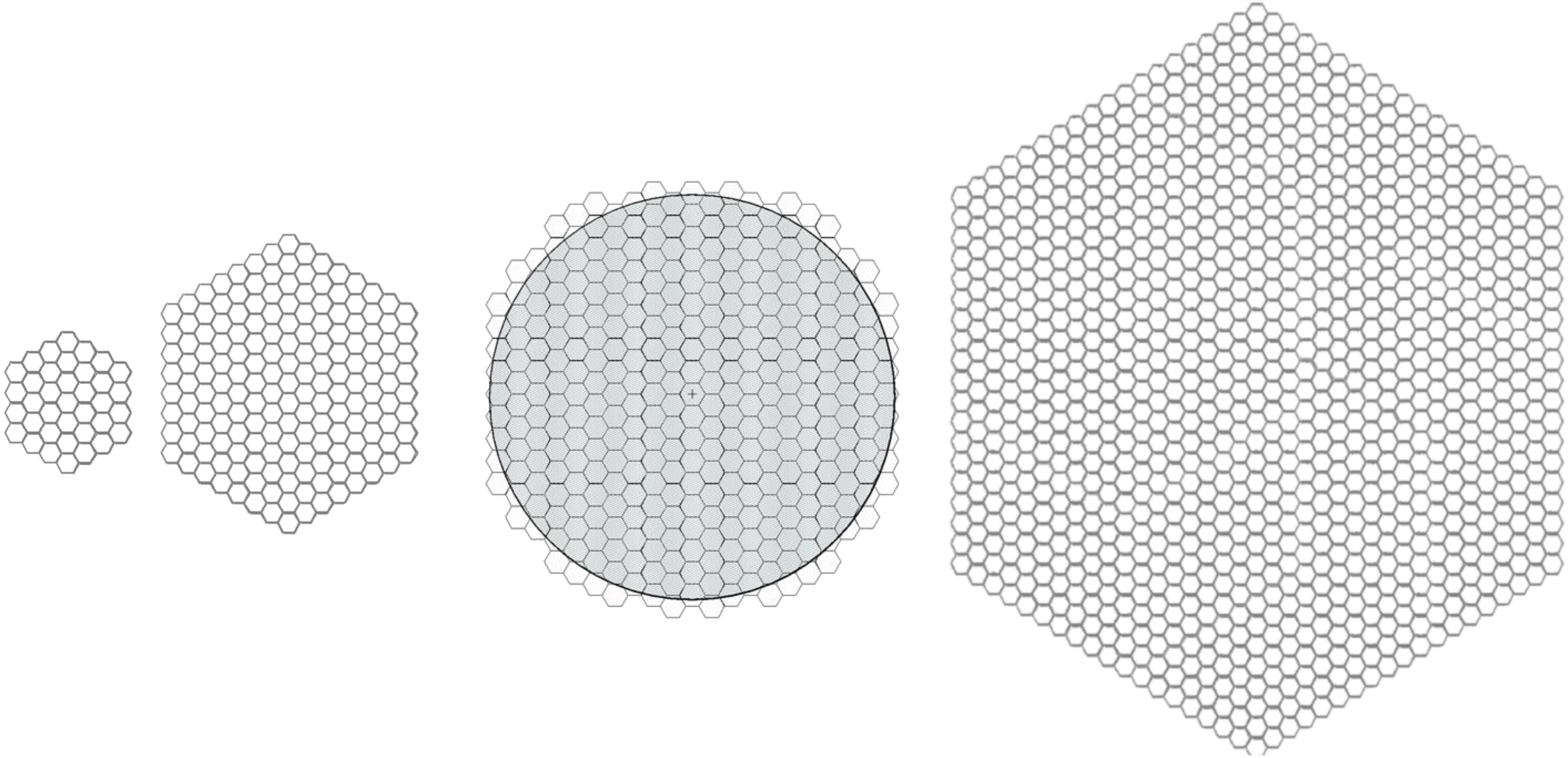


- 4 µm max. stroke
- 7 mrad max. tilt angle





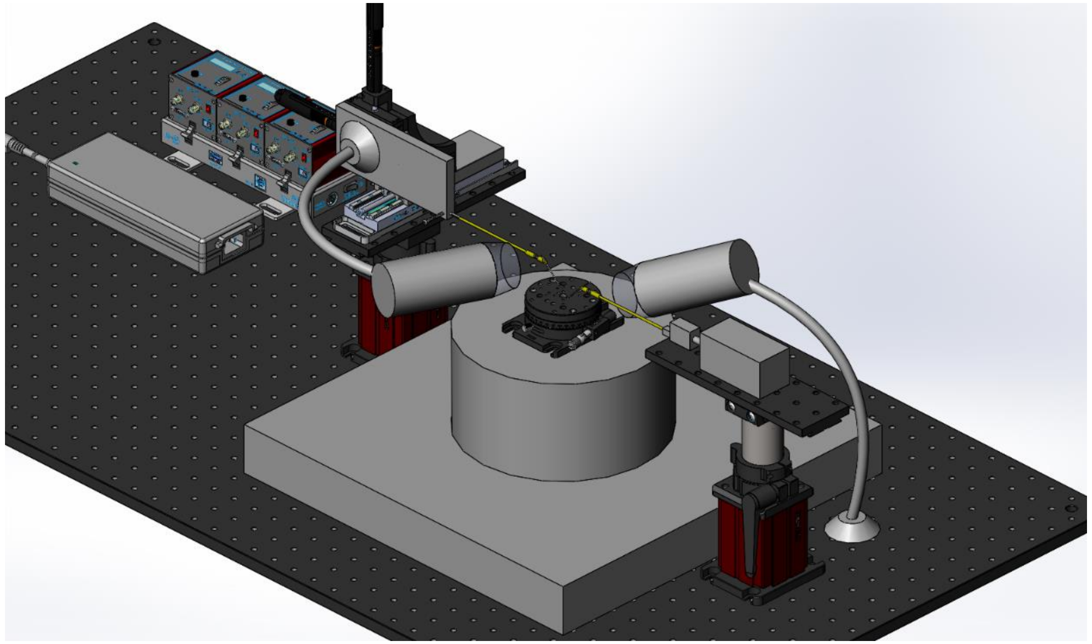
Hex-TTP Deformable Mirror Models



	Hex-111	Hex-507	Hex-1011	Hex-3063
Actuator Count	111	507	1011	3063
Segments	37	169	337	1021
Stroke	3.5 µm	3.5 µm	3.5 µm	1.5 µm

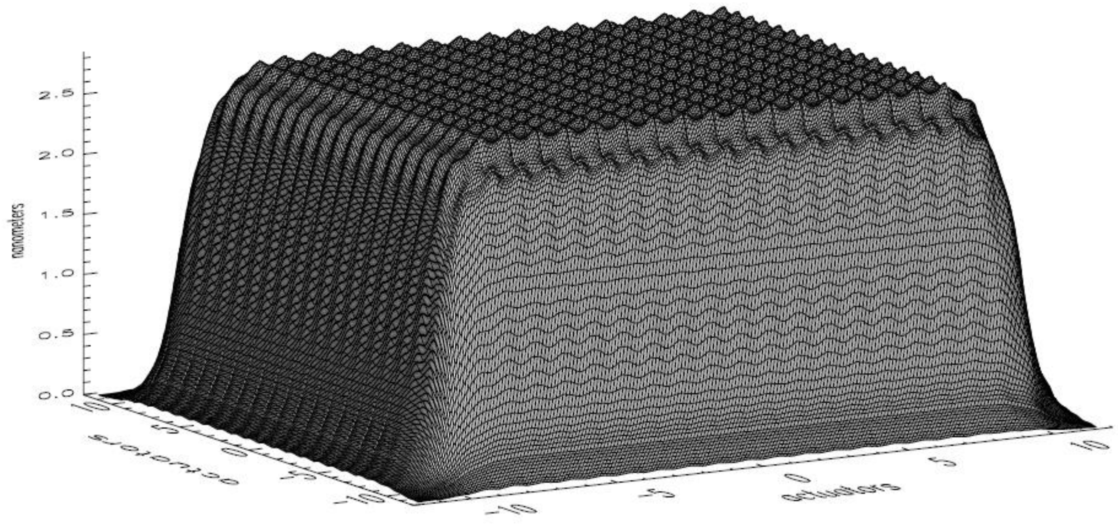
K+ Probe Station

- Current Process for 2k
  - Clean
  - Coat
  - Die attach
  - Wirebond
- 20+ hours, $2k+ parts



Can test device before coating and packaging to see if it is good. Can be used for Kilos, too.

Prediction of BMC DM1 Flat surface by summation of influence profiles



- Summation of 20x20 poke pattern, each is a 42 volt poke over 50 volt bias
- Surface sample rate is 1.50 pixels per actuator
- Peak displacements 2.85*336 nm = 958 nm
- RMS deviation from flat = 12.5 nm rms = 1.3% rms of average deviation
- PV deviation from flat = 43.7 nm PV = 4.6% PV of average deviation

John Trauger, Frank Greer
9/30/2016