

# MEMS Status and Potential Impact for AO Systems on TMT

Donald Gavel  
UCO/Lick Observatory  
UC Santa Cruz

TMT Science Advisory Committee Meeting  
Pasadena, Ca  
January 23, 2006

# Presentation Outline

---

- ◆ Brief introduction to MEMS role in adaptive optics
- ◆ MEMS development status report
  - Testing at LAO
  - 1k contract
  - 4k contract
- ◆ Application to TMT instruments
  - Staging options for MOAO
  - Alternative architectures or upgrades to NFIRAOS
  - Visible wavelength AO

# Advantages of MEMS

---

- ◆ Small size
- ◆ High actuator count at reasonable cost
- ◆ “Go-to” repeatability

## Ubiquitous MEMS (cheap, and many of them)

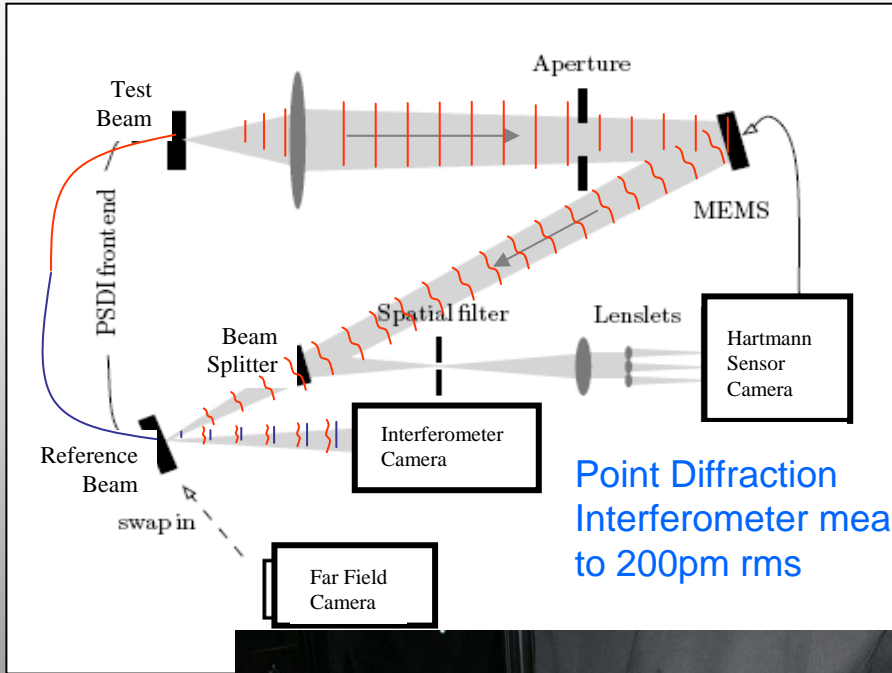
- As science wavefront corrector(s)
  - ◆ Multi-conjugate AO (MCAO)
  - ◆ Multi-object AO (MOAO)
- In the wavefront sensors
- As laser uplink wavefront correctors

# MEMS Risks Perceived by the Project

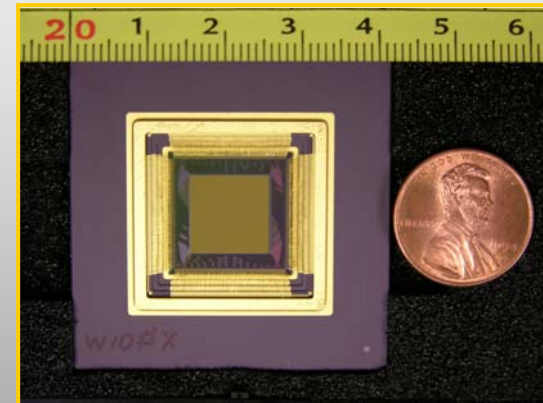
---

- ◆ Low mirror stroke, so requires multiple DMs (woofer/tweeter) and hence extra complexity
- ◆ Reliability –
  - Mountaintop environment, cold environment, failure rates not proven
- ◆ Yield (% working devices per fab, % working actuators per device)
- ◆ Vendor sources
  - Small outfits usually associated with the telecom industry as opposed to large aerospace firms
- ◆ It's never been done before in astronomy

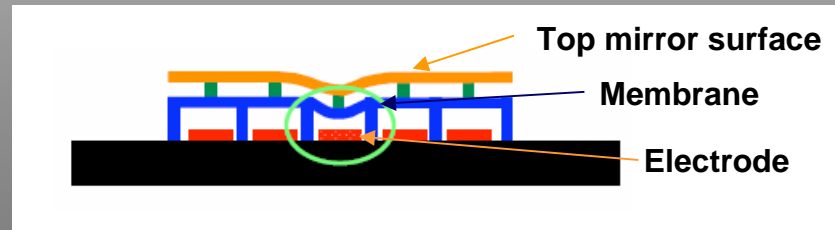
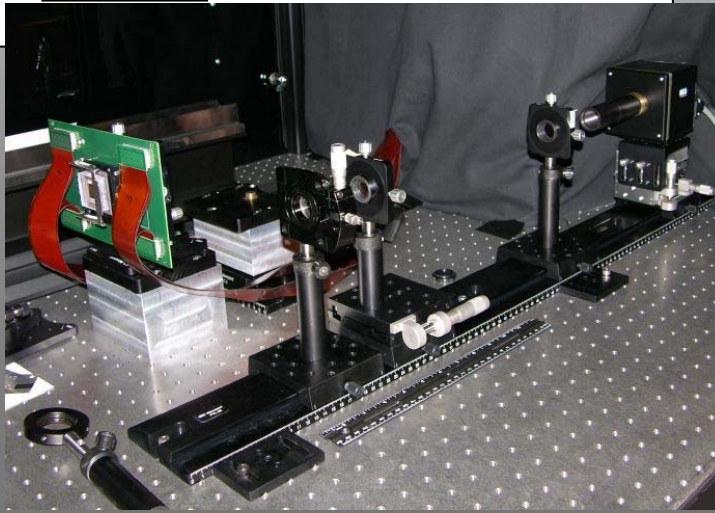
# MEMS Testing at the LAO



Point Diffraction Interferometer measures to 200pm rms



32x32 actuator MEMS DM  
(Boston Micromachines Corp)



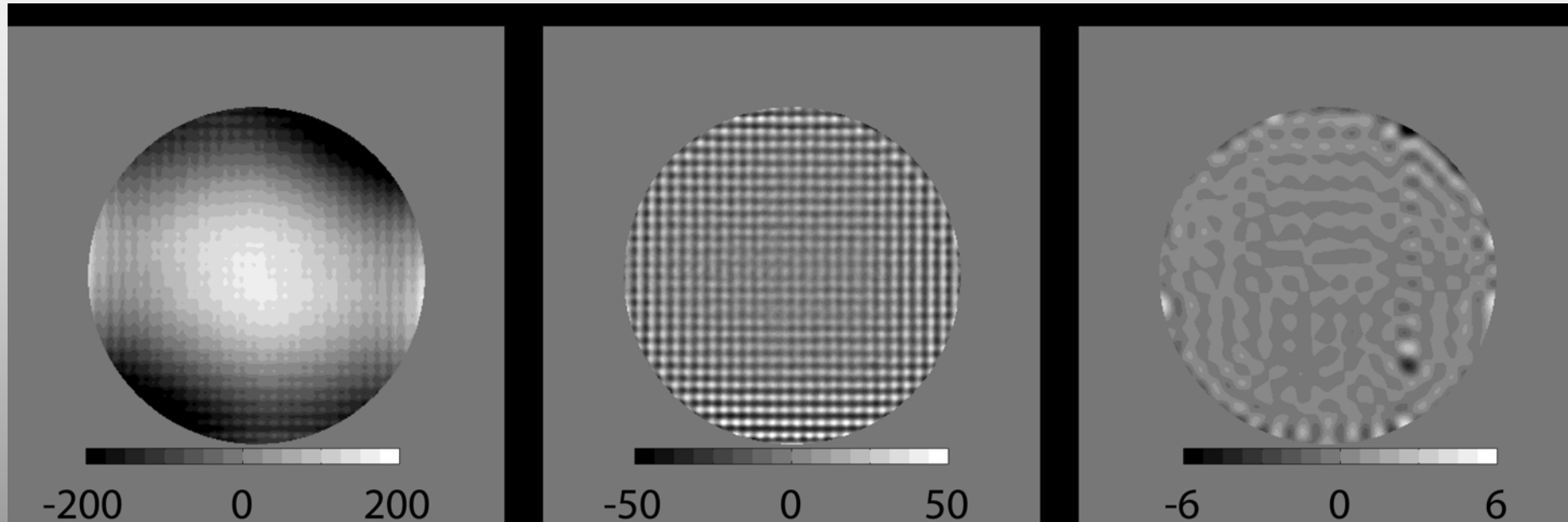
MEMS electrostatic actuator concept  
(Tom Bifano, BMC)

# Closed Loop Performance

Before

After

Lowpass



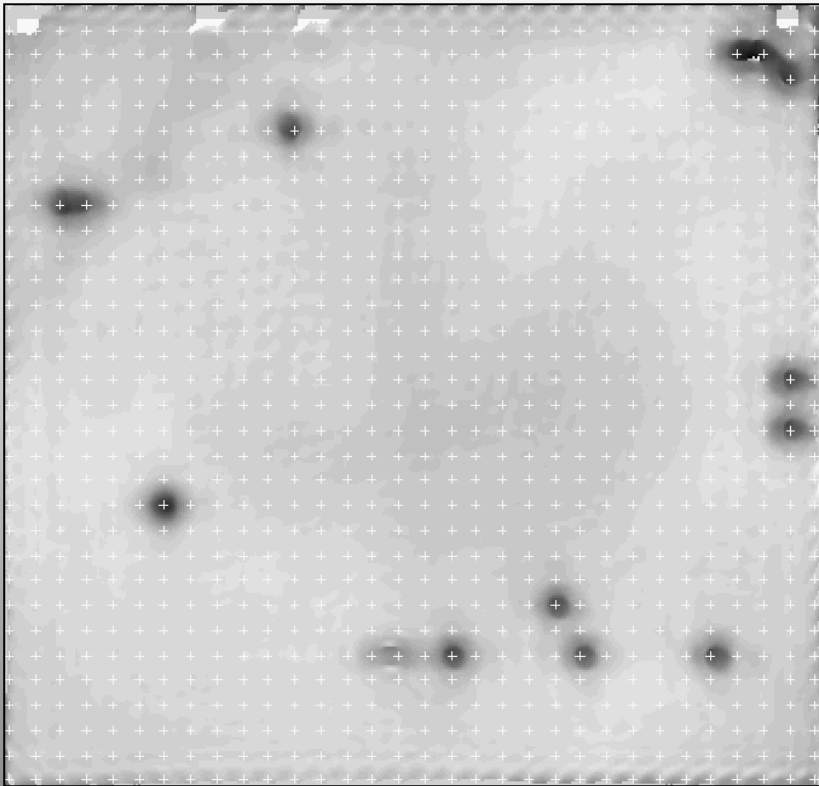
- RMS WFE
- RMS WFE in control band

Before  
 148.1 nm  
 144.1 nm

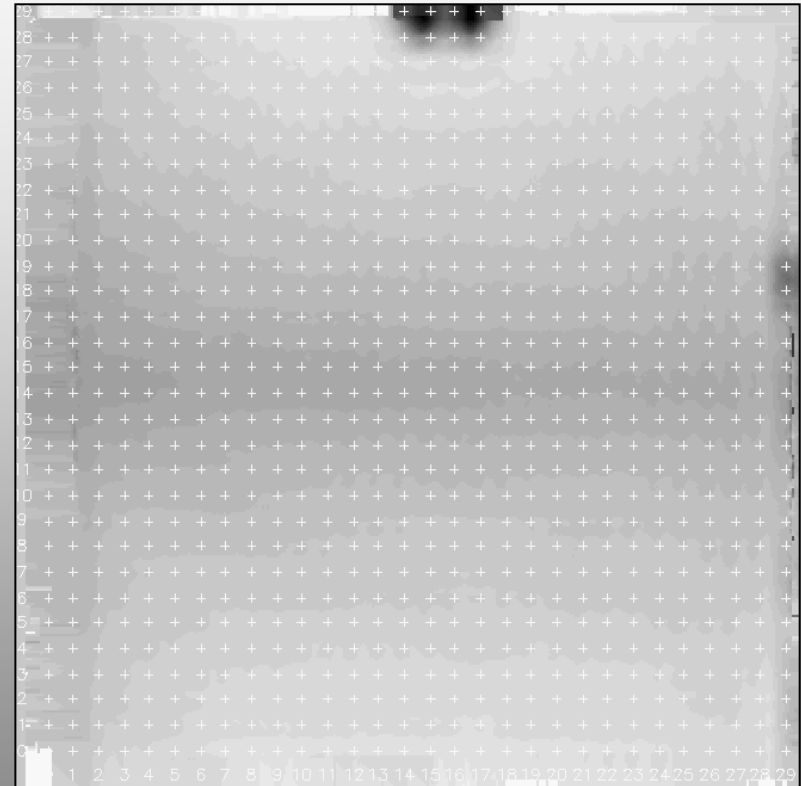
After  
 12.8 nm  
 0.54 nm

# Actuator Yield

Improvement over the course of the 1k contract



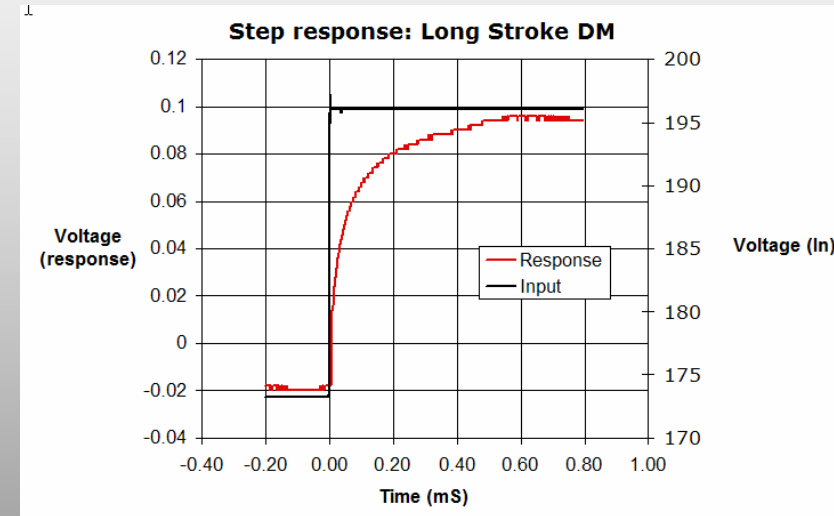
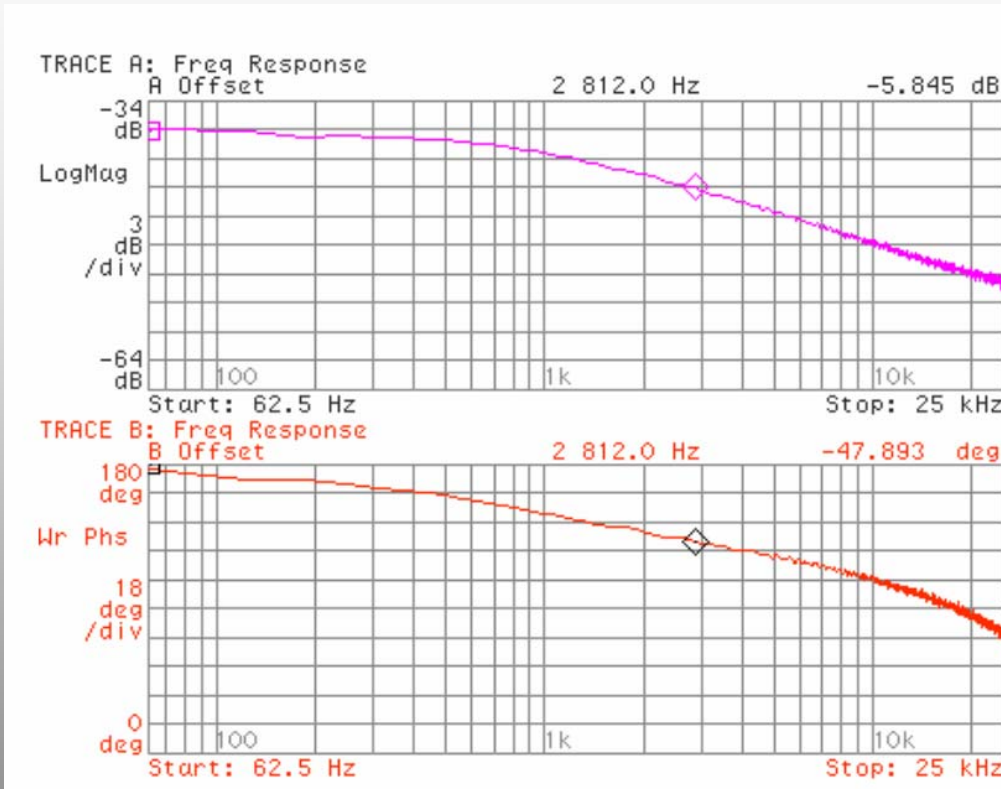
Early Device, Fall 2004



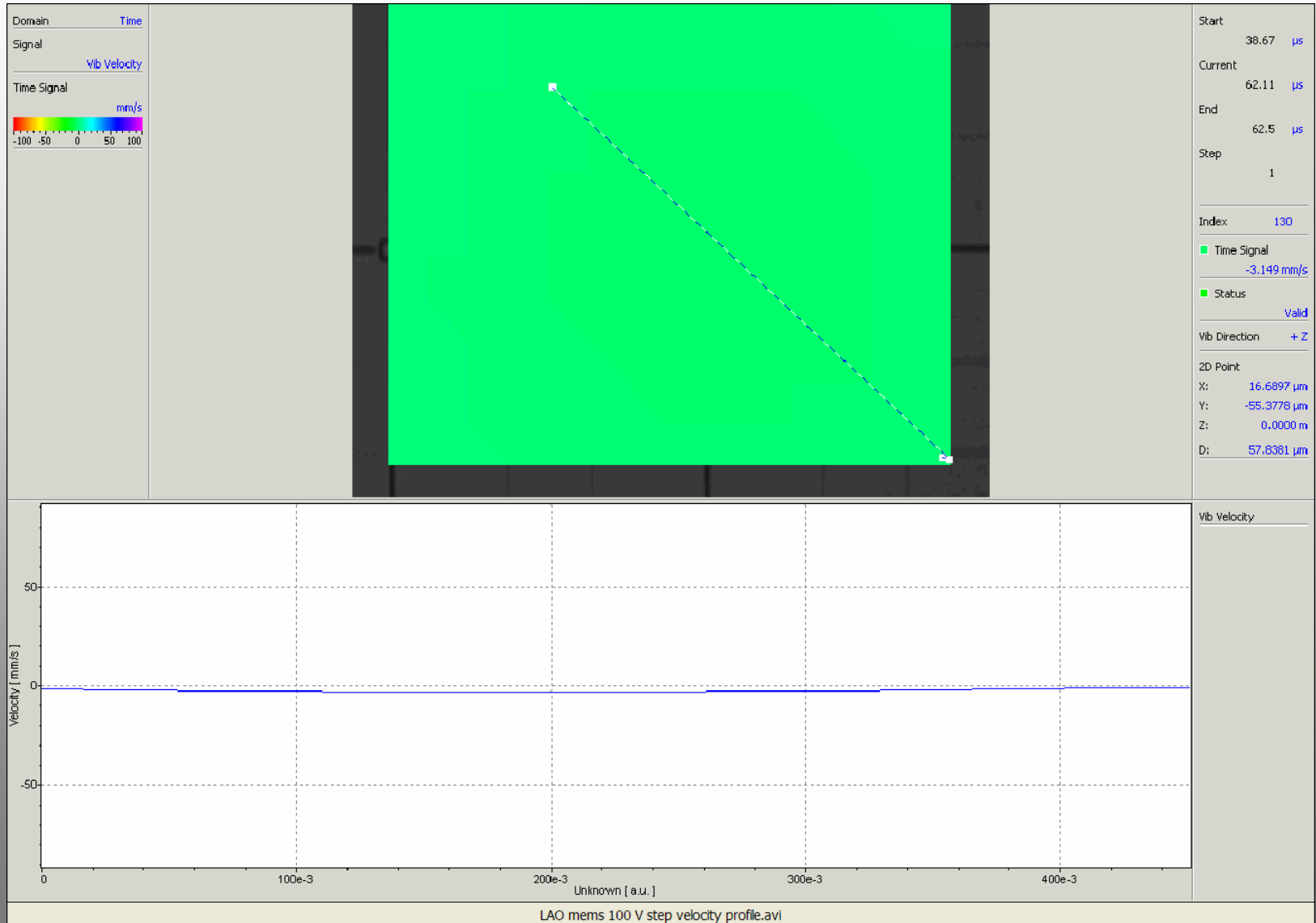
Device W107#X, Fall 2005



# Frequency Response



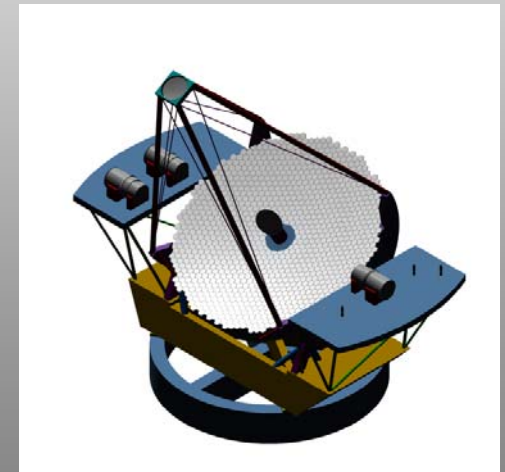
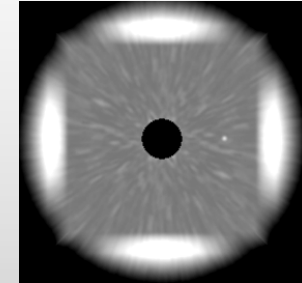
- Tests performed at BMC
- Instrumentation: Polytec 3001 laser vibrometer. OVD-20 displacement card. HP89410A vector signal analyzer
- We also measured a device using a vibrometer at UCSC (Polytec demo of MSA-400 Micro System Analyzer)





# MEMS Consortium

- Joint effort of CfAO, LAO, Gemini (GPI), TMT
- Target Instruments:
  - Gemini Planet Imager
  - Thirty Meter Telescope AO systems
- Specifications: GPI [TMT]
  - Number of actuators 4096 [10,000]
  - Continuous face sheet, gold coated
  - 4 microns surface stroke
  - 1 micron differential stroke
  - < 10 nm open loop accuracy
  - 2 kHz sample frequency
  - -30 C operating temperature
  - Working actuator percentage 100% [99%]
- Relaxed stroke requirement ( $<10\mu$ ) => each instrument will need woofer DMs



# BMC 4K contract 1<sup>st</sup> test results

Custom 10 Device Analysis  
Voltage vs. Actuator Deflection

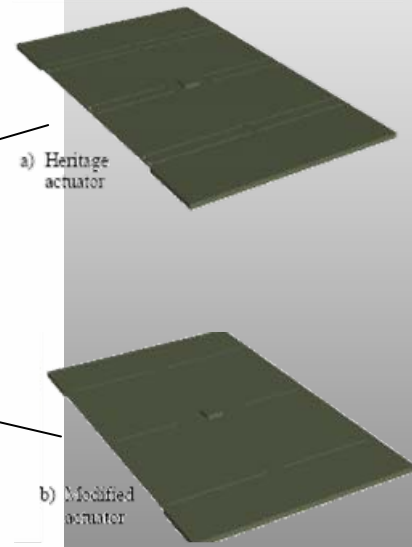
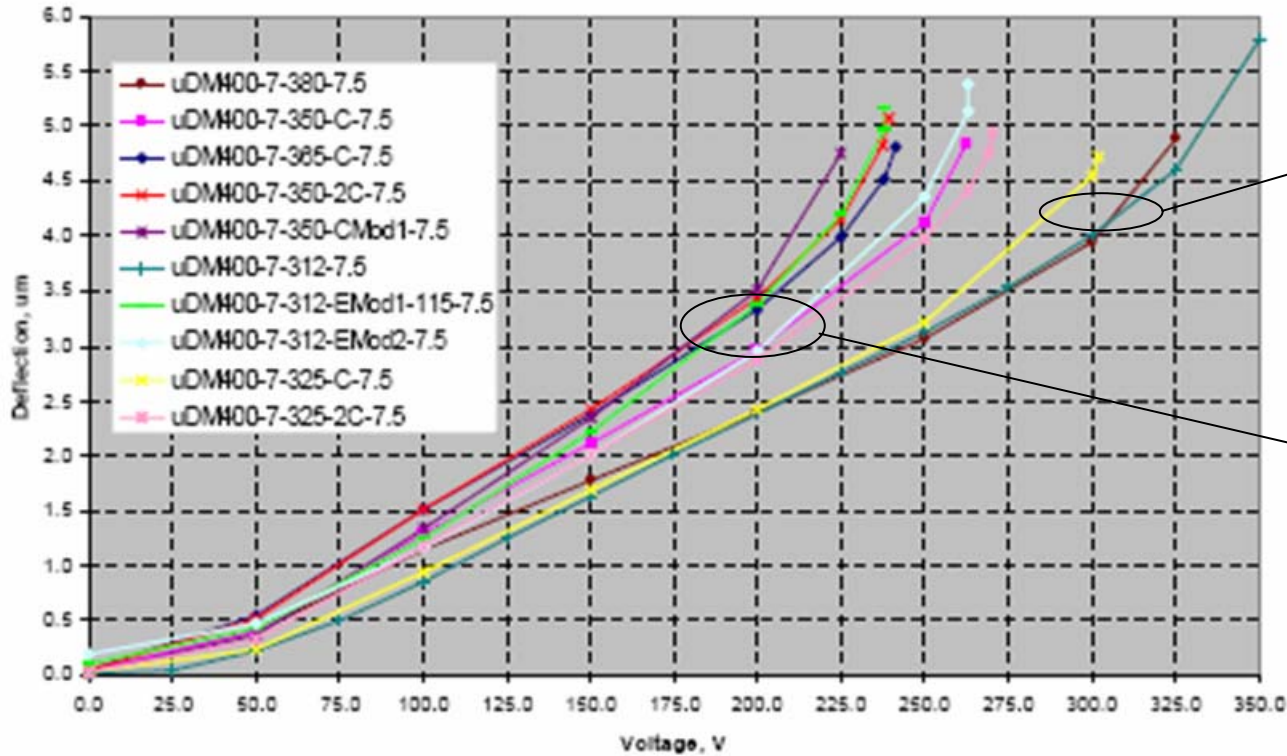
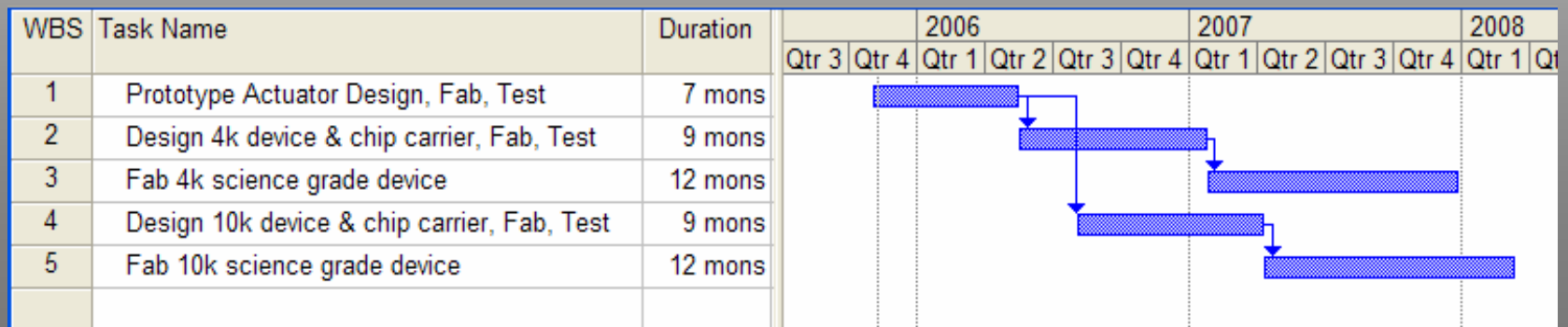


Figure 2. Analytical voltage vs. deflection predictions for the Custom 10 devices

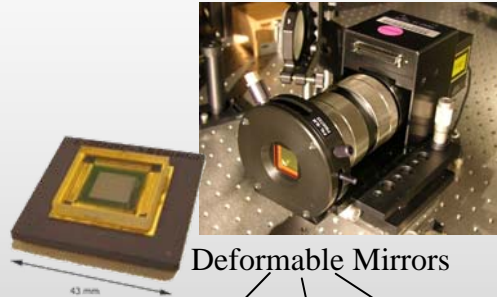
# MEMS Consortium Timeline

- Phase 1 (contract in place)
  - Model electromechanical performance of 4 micron stroke actuator
  - Layout multi-layer mask sets
  - Run through a full fabrication cycle at MEMS foundry
  - Measure device characteristics
- Phase 2
  - Buried wire layer routing and wire bonds
- Phase 3
  - Package and delivery of 4k device (Gemini)
  - Design study and layout of 10k device (TMT)

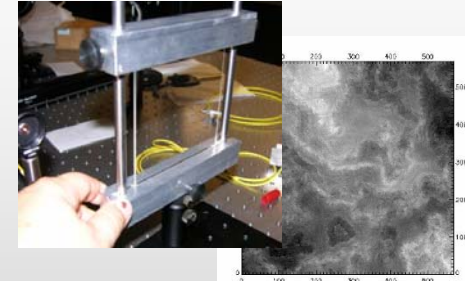




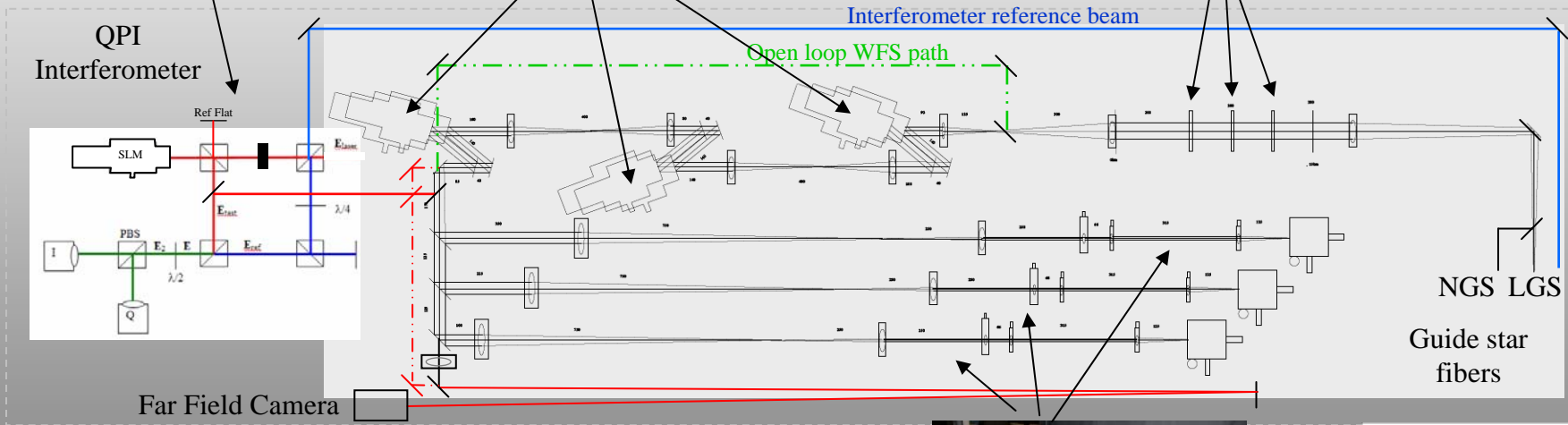
# MCAO / MOAO Testbed



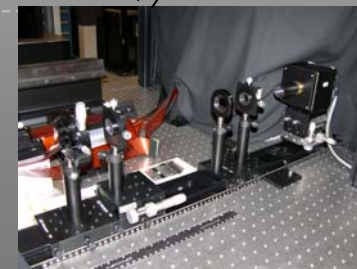
Deformable Mirrors



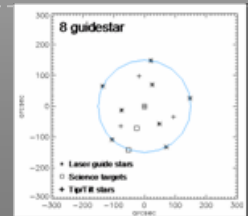
Kolmogorov Atmosphere phase aberrator plates



- Up to 8 wavefront guide stars and 4 tip/tilt stars
- 10,000 DOF per DM (100x100 subaperture Hartmann sensors)
- Up to 3 DMs (MCAO) or 1 DM and open loop WFS path (MOAO)
- 5 Hz sample & control rate
- Moving phase plates (wind)
- Moving LGS fibers in z to simulate LGS elongation, or laser pulse



Hartmann Wavefront Sensors



Configurable guide star constellation



**TMT**

# TMT Instruments / MEMS Summary

THIRTY METER TELESCOPE

---

## ◆ IRMOS

## ◆ NFIRAOS

- Existing architecture
- Alternative architecture

## ◆ IRMOS behind NFIRAOS

## ◆ IRIS behind IRMOS

## ◆ Laser Guidestar uplink correction

- And the path to the future – visible wavelength AO

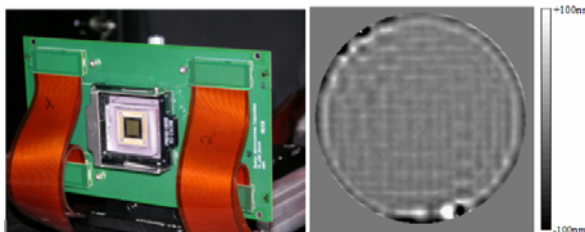
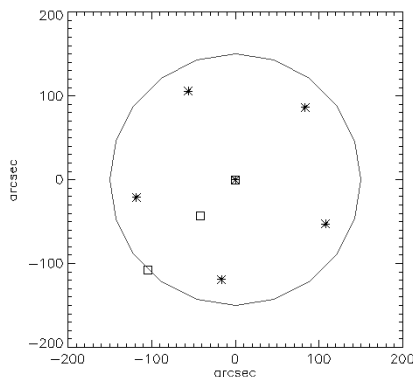
# How MEMS Affect IRMOS

---

- ◆ MEMS DM and woofer in each MOS arm
- ◆ Open-loop: Relies on MEMS “go to wavefront” capability
- ◆ IRMOS staging options
  - 10,000 actuator DM (baseline): 50% EE at  $1.1\mu$
  - 4,000 actuator DM (now being fab’ed for GPI)
  - 1,000 actuator DM (can purchase now): 50% EE at  $2.2\mu$
  - No DM – flat in place of DM for later upgrade

# First-light options for IRMOS

- ◆ Option to get on the sky with existing technology and no additional lasers
- ◆ Laser Guide Stars
  - 6 LGS constellation instead of 8 (redeploy NFIRAOS guide stars)
- ◆ MEMS
  - 32 x 32 MEMS with limited stroke ( $1\mu$ ) is available now in both continuous and segmented face sheet versions.
  - $10\mu$  stroke woofers (both piezo-bimorph and electrostatic membrane) are available now but would need 100 actuator version



- Possible solution without a woofer: wrap the phase at mid band wavelength. Simulations show this has minimal impact on 50mas EE over entire band.
- Possible solution with no MEMS: IRMOS behind NFIRAOS or behind Caltech's Offner relay, with a common woofer

# How MEMS Affect NFIRAOS

---

## ◆ Upgrades to existing architecture

- DMs in WFS paths can eliminate off-axis relay aberrations
- DMs in Tip/Tilt sensor paths greatly improves Strehl of IR Tip/Tilt stars, which greatly enhances sky coverage

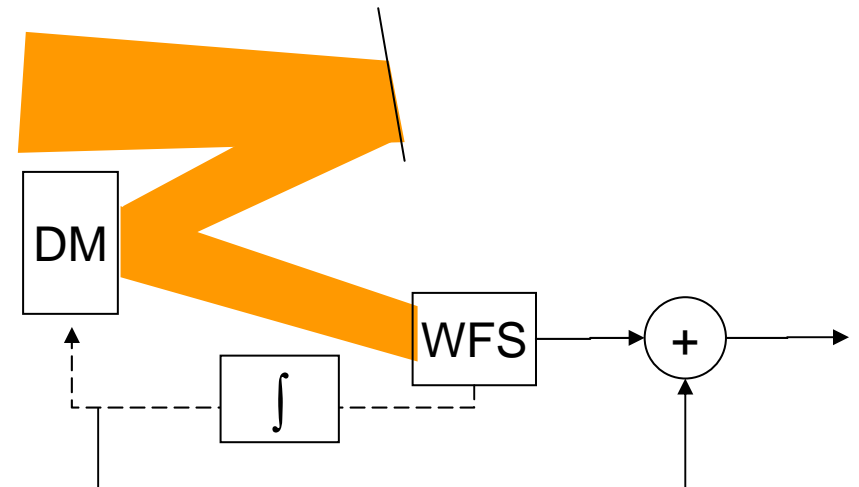
## ◆ Alternative architecture

- MEMS based MCAO relay

Meet SRD requirement without needing AM2

# Full Dynamic Range Wavefront Sensors

- ◆ Hartmann wavefront sensors use quad cells – good for null-seeking control loops but not for high accuracy absolute measurements of wavefront
- ◆ MEMS based solution:
  - DM in wavefront sensor, closed loop – keeps the Hartmann spots on center
  - Wavefront is MEMS surface + WFS residuals
  - Requires good knowledge of the MEMS voltage to surface deflection function



# IRMOS behind NFIRAOS

---

- ◆ Risk Advantage: This is the “no MEMS” option
- ◆ Performance Disadvantages:
  - Much narrower field for IRMOS (2 arcmin vs 5)
  - Significant off axis anisoplanatism will miss 50% EE goals
  - Low sky coverage
- ◆ Does not meet SRD requirements until it is upgraded with MEMS and fed a wider field
- ◆ Caltech Offner relay design is a similar option, but with wider field

# IRMOS behind NFIRAOS vs MOAO-lite – comparison of 1<sup>st</sup> light options

	MOAO-lite		IRMOS behind NFIRAOS	
<b>Multiplex and Field</b>	<b>FoR</b>	<b>M<sub>#</sub></b>	<b>FoR</b>	<b>M<sub>#</sub></b>
	5 arcmin.	~20	2 arcmin.	~5
<b>50% EE dia. (mas)</b>	<b>Center – Edge (2.5')</b>		<b>Center – Edge (1')</b>	
	<b>J-band</b>	<b>K-band</b>	<b>J-band</b>	<b>K-band</b>
<b>No MEMS</b> (woofer only)	350 - 450	150 - 350	150 - 250	30 - 60
<b>MEMS-DM (1k)</b>	300 - 300	30 - 30		

**MOAO-lite meets SRD specs in K band**

NFIRAOS superior in J-band but at significant cost to FoR and Multiplex

# IRIS behind IRMOS

- ◆ On-axis “Superbutton” in IRMOS feeds diffraction-limited beam to IRIS
  - One MEMS / Woofer pair for high Strehl on-axis
  - LGS constellation tucked in (NFIRAOS 5 LGS configuration) for low on-axis tomography error
  - 10,000 actuator MEMS gives low wavefront fitting error
  - Sky coverage:
    - By AO correcting the IR stars (with a MEMS / Woofer pair in each channel) sensing can get down to ~20 mag. => 100% sky coverage
  - Open loop design -> fewer surfaces -> higher throughput and lower emissivity

Meets SRD requirements

# NIR AO development path

## Recommended by the IRMOS teams

<b>MEMS-DM (Staged Development)</b>	<b>Time- frame (notional)</b>	<b>Actuator (Count / Stroke)</b>	<b>Risk assessment</b>	<b>Example Science Cases</b>
<b>IRMOS-1:</b> No MEMS	$T_0 - 1$	---	<b>Zero</b>	Star-Forming Galaxies @ $2 < z < 3$
<b>IRMOS-2:</b> MOAO-lite	$T_0$	1k / $2\mu\text{m}$	<b>Very low</b> (Hybrid control)	Stellar Populations & Dynamics @ $1 < z < 3$ Primeval Galaxies and 1 <sup>st</sup> light
<b>IRIS-1:</b> (NFIROAS-lite)	$T_0$	4k / $1\mu\text{m}$	<b>Low</b> (MEMS-DM contract)	IRIS-lite science
<b>IRMOS-3:</b> MOAO	$T_0 + 1$	4k / $4\mu\text{m}$	<b>Moderate</b> (Industry contract)	Full IRMOS DSC science
<b>IRIS-2:</b> (NFIROAS + AM2)	$T_0 + 1$	10k / $1\mu\text{m}$	<b>High</b> (Industry goal)	Full IRIS DSC science

Hybrid MOAO architecture allows for gradualist approach to achieving full-up IRMOS (and IRIS) capabilities while permitting compelling science throughout.

# Laser Guidestar Uplink

---

- ◆ MEMS can be used to correct the outgoing lasers
- ◆ Could potentially produce a 10x smaller spot – equivalent to 100x increase in laser power! (it's the surface brightness that counts)
- ◆ Implies
  - Lower power lasers needed (cost advantage)
  - Visible wavelength LGS AO enabled
- ◆ Requires large projection telescope (70 cm beam)
  - Could still tuck behind secondary, but needs bigger telescope than currently planned (50cm)

# Laser Pulse Tracking

---

- ◆ MEMS can be used to mechanically track the laser pulse through the sodium layer
- ◆ Signal-to-noise advantage in wavefront reconstruction
- ◆ Comparable to Nelson's charge-shifting CCD, but:
  - Allows for a smaller CCD (fewer pixels)
  - Allows for a spatial filter in the WFS, which removes aliasing error, a significant error term.

## ◆ MEMS are real

- Contract in place to build one for astro AO instrument (Gemini Planet Imager)
- Lab tests showing performance (with the exception of stroke\*) equal to or exceeding piezo mirrors
- They're a whole lot cheaper and smaller, enabling AO architectures not otherwise considered, solving other optical problems not traditionally assigned to DMs.

## ◆ MEMS Path to the telescope:

- Demonstrations in lab testbeds (LAO)
- On-sky demos planned (Lick)
- MEMS in TMT 1<sup>st</sup> light instruments (IRMOS, NFIRAOS)

## ◆ Visible wavelength AO systems are on the horizon

\*Stroke per volt is comparable to recent results with CILAS piezo mirror prototype