Deformable Mirrors for TMT

Jerry Nelson, Don Gavel
Outline

• TMT Adaptive Optics Systems Concepts
• MEMS vs conventional DMs
• Deriving MEMS requirements
• MEMS requirements for particular sub systems
TMT Adaptive Optics Instruments

- **Diffraction-limited imaging spectrometer $\lambda = 1-5\mu m$**
  - Diffraction-limited (~7-14 mas)
  - 10 arcsec field
- **Near-infrared wide field spectrometer $\lambda = 1-5\mu m$**
  - Multiple Integral Field Units
    - Multiple 2 arcsecond fields, R=5000
    - 50 milli-arcsecond slit
  - 5 arcminute field of regard
- **Mid-IR spectrometer $\lambda = 5-28\mu m$**
- **Multi-conjugate adaptive optics moderate field imager $\lambda=1-2.5\mu m$**
  - Diffraction-limited
  - 30 arcsec field
- **Extra-solar planet imager (ExAO) $\lambda = 1-2.5\mu m$**
  - ~1 arcsec field
  - 50-100K? Actuators ($>10^8$ contrast)
Other possible MEMS applications in TMT AO systems

- Wavefront sensor non-common path aberration correction
- Laser pulse tracking
TMT Adaptive Optics Modes

Tomography System
Adaptive Optics Modes

Small Field, Diffraction Limited Near IR Spectroscopy

5 sec

Tomography System

Near IR Echelle Spectrograph

532x532 Adaptive Optics Modes - Small Field, Diffraction Limited Near IR Spectroscopy

2004 August 19
Adaptive Optics Modes

Multi-Object AO IFU Spectroscopy

MOAO “buttons”

IFU Spectrograph

Tomography System

5 min

2004 August 19

MEMS workshop UCSC
Adaptive Optics Modes

Mid-Infrared AO using Laser Guide Star Tomography and an Adaptive Secondary

- Mid IR Echelle Spectrometer: 10'' slit view
- 2nd gen Mid IR Imaging Spectrometer: >2' FOV

2004 August 19

MEMS workshop UCSC
Adaptive Optics Modes

Mid-Infrared AO using Laser Guide Star Tomography and a Cryo DM

- Mid IR Echelle Spectrometer: 10'' slit view
- 2nd gen Mid IR Imaging Spectrometer: >2’ FOV

Tomography System

MIRAO

Cryo Dewar

Mid IR Echelle

60 sec
Adaptive Optics Modes

Mid-Infrared AO
Using a Natural Guide Star
and cryo DM

- Mid IR Echelle Spectrometer: 10" slit view
- 2nd gen Mid IR Imaging Spectrometer: >2' FOV
Adaptive Optics Modes

Multi-conjugate AO for wide field imaging

Adaptive Secondary

30 sec

Woofer MCAO

DM1 DM2 DM3

Tomography System

Wide field IR Imager
Adaptive Optics Modes

Extreme Adaptive Optics
Planet Imaging

 Coronagraph or Nulling Interferometric Imager

ExAO

5 sec

WFS
DM type drawbacks

• **Non-MEMS**
  – DM’s larger, leads to larger AO optical system
  – DM may have hysteresis, requiring interferometric DM monitor
  – Cryo DM may be difficult to achieve needed stroke
  – Precise repeatability required for open loop operation
  – Impractical for MOAO

• **MEMS**
  – Stroke may be insufficient for our need
  – May be too small for some applications

• **Adaptive secondary**
  – Very expensive
  – Diameter limited, restricts non AO science uses
  – Still requires additional DM’s, as # actuators limited

• **All**
  – Not available
  – Order of correction does not meet our need
## Derivation of DM requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Driver</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Stroke</td>
<td>Atmospheric phase P-V</td>
</tr>
<tr>
<td>• Size</td>
<td>Physical size of AO package</td>
</tr>
<tr>
<td>– Actuator Spacing</td>
<td></td>
</tr>
<tr>
<td>– Package size</td>
<td></td>
</tr>
<tr>
<td>• Number of actuators</td>
<td>Degree of correction, ( r_0 )</td>
</tr>
<tr>
<td>• Fill factor</td>
<td>Throughput</td>
</tr>
<tr>
<td>• Flatness</td>
<td>Strehl performance</td>
</tr>
<tr>
<td>• Linearity</td>
<td>Dynamic range, open loop system</td>
</tr>
<tr>
<td>• Face sheet (continuous or segmented)</td>
<td></td>
</tr>
<tr>
<td>• Speed</td>
<td>Wind speed, turbulence spectrum, ( \tau_0 )</td>
</tr>
<tr>
<td>• Operating temperature</td>
<td>Cryo for mid-IR, cold (-30°C) for near IR</td>
</tr>
<tr>
<td>• Repeatability (open loop)</td>
<td>Go-to system(s) – e.g. IFUs</td>
</tr>
<tr>
<td>• Mountable on tip-tilt stage</td>
<td>minimizes physical size, surface count</td>
</tr>
<tr>
<td>• Environment</td>
<td>necessary in Cryo environment</td>
</tr>
<tr>
<td>– Open vs window</td>
<td></td>
</tr>
<tr>
<td>– Operate in vacuum</td>
<td></td>
</tr>
<tr>
<td>• Coatings - want silver</td>
<td>best R for near-mid IR</td>
</tr>
<tr>
<td>• Surface roughness</td>
<td>( \leq 10 ) nm rms</td>
</tr>
<tr>
<td>• When</td>
<td>TMT AO implementation time frame</td>
</tr>
<tr>
<td>• Cost</td>
<td>Competitive with alternatives</td>
</tr>
</tbody>
</table>
Calculating requirements

• How to calculate stroke given $r_0$, $L_0$
• How to calculate dynamic range
• Offload options (“woofers”)
  – Conventional DM
  – Deformable secondary
Stroke Requirements

• Atmosphere assumptions
  – $r_0 = 15\text{cm (}\lambda = 500\text{nm)}$ is median
  – $r_0 = 10\text{cm}$ is worst case for design to allow adequate performance over wide range of atmospheric conditions
  – $L_0$ may be finite, but probably highly variable and predominantly effects tilt, and not well known at any sites: we conservatively assume $L_0$ is infinite (Kolmogorov)
  – Rms wavefront error (tip-tilt removed)
    \[
    \sigma = 0.366 \frac{\lambda}{2\pi} \left( \frac{D}{r_0} \right)^{5/6} = 3.38 \mu\text{m} \quad \text{For } r_0 = 10\text{cm}
    \]

• DM stroke
  – Assume 5x for peak to valley, another 20% for systematics
  – so total stroke requirement is $10.1 \mu\text{m}$ (2x for wavefront)
Calculating requirements

- **How to calculate dynamic range**
  - Total error budget is ~130nm, digitization error is an error budget contributor

- **Offload options (“woofers”) reduce MEMS range required**
  - Conventional DM
  - Deformable secondary
  - Residual Stroke ($d_w =$ woofer inter-actuator spacing):
    \[ \sigma = \sqrt{0.3 (d_w / r_0)^{5/6}} \]

- **Inter-actuator stroke ($d_a =$ MEMS inter-actuator spacing):**
  \[ \sigma = \left\{ \phi(x) - \phi(x + d_a) \right\}^{1/2} = \sqrt{6.88 (d_a / r_0)^{5/6}} \]
Stroke requirements with woofer

• **Assume a low order, high stroke, high bandwidth DM is available**
  – Adaptive secondary
  – Conventional DM (will add extra surfaces)
  – Bimorph collimator (may be at an unpleasant conjugate height)

• **Residual stroke requirements for MEMS**
  – Tip tilt removed (2dof) \(10.1\mu m\)
  – 2nd order removed (5dof) \(7.0\mu m\)
  – 3rd order removed (9dof) \(5.5\mu m\)
  – 4th order removed (14dof) \(4.6\mu m\)

• **Field of view impact**
  – Woofer is not conjugate to source of all low order errors
  – So wide field of view will increase demands on MEMS stroke
Other MEMS requirements

- **Repeatability, dynamic range (and linearity if practical)**
  - Want rms wavefront repeatability errors ≤20 nm
  - Fractional requirement ~ 0.020/3.38 = 0.0059 (~ 0.5%)
  - Woofer reduces fractional requirement

- **Size**
  - Varies with system, ~ 40mm up to ?

- **Number of actuators**
  - 64x64 possibly acceptable
  - ~ 100x100 desired (varies with system)

- **When**
  - We need to make system design choices ~ 2 years from now
  - Requires cost estimates and confidence demonstrations by then
  - Require operational hardware for testing ~ 6 years from now

- **Cost (MEMS + all associated electronics)**
  - Inexpensive, affordable spares
  - Funds for needed development ~10^6-10^7 $
Number of DM’s

- **MOAO**
  - 20 MEMS + 5 tt
- **Tomography**
  - 0-7
- **MIRAO**
  - 1-2 +1 tt
- **Narrow field**
  - 1-2 + 1 tt
- **MCAO**
  - ~7+3 tt
The importance of “Go-To” or open loop control

- Optical system greatly simplified (optical systems with both starlight and laser common paths is daunting for 30m)
- The measurement errors (from tomography) are a new error source and must be included in error budget and tightly limited
- The measured errors (from tomography) must be applied to the DM, yet the correction will not be sensed by the tomographic system (open loop)
- The DM correction errors (non repeatability) is a new error source and must be included in error budget and tightly limited
- Control bandwidth is relaxed, allowing smaller time delay errors or longer integration (lower laser power)
Stroke requirements for multi-conjugate AO imager

- Multiple DMs at conjugate altitudes, each DM covers integrated OPD over a range of altitude
- 2 DM’s:

<table>
<thead>
<tr>
<th>r0</th>
<th>DM1 (0 km)</th>
<th>DM2 (13 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>8.42</td>
<td>1.72</td>
</tr>
<tr>
<td>0.15</td>
<td>6.01</td>
<td>1.22</td>
</tr>
<tr>
<td>0.2</td>
<td>4.73</td>
<td>0.96</td>
</tr>
</tbody>
</table>

- 3 DM’s:

<table>
<thead>
<tr>
<th>r0</th>
<th>DM1 (0 km)</th>
<th>DM2 (5 km)</th>
<th>DM3 (12 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>7.35</td>
<td>1.62</td>
<td>1.17</td>
</tr>
<tr>
<td>0.15</td>
<td>5.24</td>
<td>1.16</td>
<td>0.84</td>
</tr>
<tr>
<td>0.2</td>
<td>4.12</td>
<td>0.91</td>
<td>0.66</td>
</tr>
</tbody>
</table>
Open loop: non-common path aberration correction

- AO relay optics (closed loop case)
- Dispersion (589 nm to near-IR)

\[ \delta \phi = \frac{n_{589} - n_{\lambda}}{n_{589} - 1} \phi \]

\[ = 0.0125 \times \phi \text{ at } \lambda = 1 \mu m \]
\[ \phi = 6.6 \mu m; \delta \phi = 83 \text{ nm (for } r_0 = 15\text{cm)} \]
## Summary: DM requirements matrix

<table>
<thead>
<tr>
<th>Requirement</th>
<th>DL spectrograph</th>
<th>NIR wide field spectrograph</th>
<th>Mid IR spectrometer</th>
<th>Multi-conjugate imager</th>
<th>Extra-solar planet imager</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke, µ</td>
<td>10 microns</td>
<td>10 microns</td>
<td>10 microns</td>
<td>8 microns</td>
<td>10 microns</td>
</tr>
<tr>
<td>Size, mm</td>
<td>20 mm</td>
<td>20 mm</td>
<td>20 mm</td>
<td>60-300 mm</td>
<td>60 mm</td>
</tr>
<tr>
<td>Actuator Spacing</td>
<td>200 microns</td>
<td>200 microns</td>
<td>200 microns</td>
<td>3 mm</td>
<td>200 microns</td>
</tr>
<tr>
<td>Package size</td>
<td>50 mm</td>
<td>50 mm</td>
<td>50 mm</td>
<td>400 mm</td>
<td>50 mm</td>
</tr>
<tr>
<td>Number of actuators</td>
<td>100 across</td>
<td>100 across</td>
<td>100 across</td>
<td>100 across</td>
<td>300 across</td>
</tr>
<tr>
<td>Flattness, rms nm</td>
<td>&lt; 20% stroke</td>
<td>&lt; 20% stroke</td>
<td>&lt; 20% stroke</td>
<td>&lt; 20% stroke</td>
<td>&lt; 20% stroke</td>
</tr>
<tr>
<td>Linearity, %</td>
<td>&lt;0.5%</td>
<td>&lt;0.5%</td>
<td>&lt;0.5%</td>
<td>&lt;0.5%</td>
<td>&lt;0.5%</td>
</tr>
<tr>
<td>Face sheet</td>
<td>continuous</td>
<td>continuous</td>
<td>continuous</td>
<td>continuous</td>
<td>continuous</td>
</tr>
<tr>
<td>Speed, ms</td>
<td>0.5 ms</td>
<td>0.5 ms</td>
<td>0.5 ms</td>
<td>0.5 ms</td>
<td>0.1 ms</td>
</tr>
<tr>
<td>Operating temperature, C</td>
<td>77 K</td>
<td>77 K</td>
<td>5 K</td>
<td>-30 C</td>
<td>-5 C</td>
</tr>
<tr>
<td>Repeatability, nm</td>
<td>~ 5 nm</td>
<td>~ 5 nm</td>
<td>~ 5 nm</td>
<td>~ 5 nm</td>
<td>&lt; 1 nm</td>
</tr>
<tr>
<td>Mountable on tt stage</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Environment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open vs window</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operate in vacuum</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Operate in cryo</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Coating</td>
<td>silver</td>
<td>silver</td>
<td>silver</td>
<td>silver</td>
<td>silver</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>1 nm</td>
<td>1 nm</td>
<td>1 nm</td>
<td>1 nm</td>
<td>1 nm</td>
</tr>
<tr>
<td>When</td>
<td>2 years</td>
<td>2 years</td>
<td>2 years</td>
<td>3 years</td>
<td>3 years</td>
</tr>
<tr>
<td>Cost, $</td>
<td></td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>
Laser pulse tracking

- Segmented (tip/tilt mirrors) – one per Hartmann subaperture
- Tracks laser pulse as it traverses the sodium layer

\[ \Delta \text{OPD} = 30 \text{ cm} \times 4 \text{ arcsec} = 5.7 \mu \text{m}; \ \Delta \theta = 5.7\mu \text{m} + 300 \mu \text{m} = 19 \text{ mr} \]

\[ t = \Delta h/c = 10\text{km}/3 \times 10^8 \text{m/s} = 30\mu\text{s} \]