Extreme-Precision MEMS
Segmented Deformable Mirror
(NASA Phase II SBIR)

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Mirror Technology Days
Precision DMs & Electronics

Compact

Robust

Easy to Use
Outline

• Iris AO DM Segment
• NASA Phase II SBIR Progress
  ▪ Precision MEMS DM
  ▪ Precision drive electronics
• DM Scaling
  ▪ NIH Phase II SBIR Progress
    • 163 segment DM
  ▪ $10^3$ segment scaling demonstration
Segmented MEMS DM Schematic

- Robust single-crystal-silicon assembled mirror surface stays flat (0.56 nm/°C PV)
- Temperature-insensitive bimorphs elevate mirror above substrate (14 nm/°C, σ=0.8 nm/°C)
- Piston/tip/tilt electrostatic actuation
- 2.3 kHz frequency response
  - 170/200 μs rise/fall times, 10-90%
### Phase II SBIR Goals

**Performance Period:** Jan 29 2007 – Jan 28, 2009

<table>
<thead>
<tr>
<th>Specification</th>
<th>Start of Phase II</th>
<th>Phase II Demo Goal*</th>
<th>Phase II Study Goal</th>
<th>Today (8/2008)</th>
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</thead>
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<tr>
<td>Surface Figure Errors (nm <em>rms</em>)</td>
<td>6-20</td>
<td>1-3</td>
<td>0.1</td>
<td>5-11</td>
</tr>
<tr>
<td>Open-loop positioning accuracy (<em>rms</em>)</td>
<td>20-30 nm</td>
<td>10 nm</td>
<td>Not Specified</td>
<td>8 nm (flattened)</td>
</tr>
<tr>
<td>Positioning resolution (nm <em>rms</em>)</td>
<td>5 (elect noise limited)</td>
<td>0.14</td>
<td>0.04</td>
<td>0.45 (0.11 PWM)</td>
</tr>
<tr>
<td>Stability (nm <em>rms</em>)</td>
<td>0.2-1.2 (5 elect. noise)</td>
<td>0.2</td>
<td>0.04</td>
<td>TBD</td>
</tr>
</tbody>
</table>

Failure Testing: Continue testing and determine techniques to eliminate potential snap-in failures

* Independent verification by the Lab for AO at UC Santa Cruz
Surface Figure Errors

- Current designs: 5-11 nm $rms$
  - Single-crystal-silicon segments
  - Segment thickness = 25 $\mu$m
- Thicker $\Rightarrow$ Flatter
  - Surface figure errors $\propto 1/t^{2-3}$
  - DMs with 50 $\mu$m-thick mirrors will be fabricated by end of contract
    - Expect 4-8X improvement in $rms$ figure errors
Closed-Loop Flattened DM

Surface Data

Mag: 1.4 X  
Mode: PSI

Surface Statistics:
Ra:  6.04 nm
Rq:  7.74 nm
Rz:  55.73 nm
Rt:  69.79 nm

Set-up Parameters:
Size: 736 X 480
Sampling: 6.06 um

Processed Options:
Terms Removed: Tilt
Filtering: None

Title: FSC37-01-07-0614
Note: Closed-Loop Flattened
Open-Loop Flattened DM

Surface Data

Surface Statistics:
- Ra: 7.28 nm
- Rq: 9.21 nm
- Rz: 67.65 nm
- Rt: 90.05 nm

Set-up Parameters:
- Size: 736 X 480
- Sampling: 6.06 μm

Processed Options:
- Terms Removed:
- Tilt
- Filtering:
- None

Title: FSC37-01-07-0614
Note: Open-Loop Flattened

August 26th, 2008
Open-Loop Positioning Example
Extreme Positioning Resolution

1. DM design that uses full scale voltage
   - Actuator fabrication complete

2. Compact, low noise, high resolution electronics
   - 14 bit, 200 V
   - Factory calibrated with on-board calibration values
   - USB interface - (Low speed 150 Hz)
   - Scales to > 10k channels
   - High speed interface options will be available
     - Digital input supports 35 kHz frame rate
     - Analog Output $f_{-3db} > 5$ kHz

Unfiltered Noise: 3.3 mV rms
Noise Filtering

- Noise is mostly high frequency
- Low-speed applications can take advantage of filtering

Unfiltered Output

1st Filter Output
(15.1 Hz $F_{-3dB}$)

2nd Filter Output
(15.9 Hz $F_{-3dB}$)

Ch2 RMS 565μV
Ch3 RMS 1.45mV
Ch4 RMS 2.85mV
Modulation + Filtering = Super Resolution

- LSB modulation with low-pass filtering
  - 16+ bits resolution
- First demonstration modulated at ~35 Hz shows 16-bit resolution
- >5 kHz modulation when implemented in firmware

![Waveform Diagram](https://example.com/waveform.png)
Scalability

- Scalable drive electronics
  - NASA Phase II SBIR
- 163-segment DM
  - NIH Phase II SBIR
- $10^3$ segment DM
  - Funding TBD
  - Preliminary experiments where possible
Mirror Technology Days

Smart Driver II Electronics – 512 Channels

Last Year

Today

Today

Dec. 2008

August 26th, 2008
163 Segment (S163-X) DM Development

• Funded by NIH Phase II SBIR
  ▪ Sept 2007 – August 2009
• Actuator wafer process development underway
  ▪ 1st Run: Electrode and mechanical layer only
  ▪ 2nd Run: Includes wiring layer
    • Fabrication begins 9/2/08
• Mirror-wafer fabrication to begin 10/2008
  ▪ Mirror-wafer process already developed

13.4 mm
10^3 Segment DM

- Path-finding research into 10^3 segment class DMs
- Developing along with S163-X
  - Multi-project wafer
  - 1st and 2nd fabrication runs
- 925 actuators w/ganged electrodes to reduce wiring
- Segment pitch matches EPIC point design
  - Extrasolar Planetary Imaging Coronagraph (EPIC) - Discovery Mission Concept
    - Clampin/Lyon GSFC
- Additional funding TBD
  - Proposing Phase I SBIR to NASA GSFC
Summary

• On our way to meeting Phase II SBIR goals
  ▪ Low-noise electronics
  ▪ Super-resolution technique
  ▪ DM flatness improving (2X since start of contract)
    • Expect to reach 1-3 nm rms surface figure error goal
• Developing larger mirrors
  ▪ S163-X prototype development
  ▪ $10^3$ segment DM proof-of-concept development
    • Needs additional funding to wire and package
Acknowledgements

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• NASA – Phase II SBIR, (Extreme Precision DM Testing and Development)
  ▪ NNG07CA06C

• Center for Adaptive Optics (DM Process Development)
  ▪ National Science Foundation Science and Technology: No. AST – 9876783

• National Eye Institute – Phase II SBIR (DM Process Development)
  ▪ 2 R44 EY015381-02A1

• US Air Force – Phase II SBIR (DM Control)
  ▪ FA8650-04-M-6518

• National Science Foundation – Phase II SBIR (Ancillary Process Development)
  ▪ DMI-0522321

R&D Fabrication Facility

• Berkeley Microfabrication Laboratory

Research Collaboration

• Berkeley Sensor & Actuator Center