# Lightweight Deformable Mirrors
## for Space Telescopes

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Mirror Technology/SBIR/STTR Workshop
Northrop Grumman Aerospace Systems Aerospace Presentation Center

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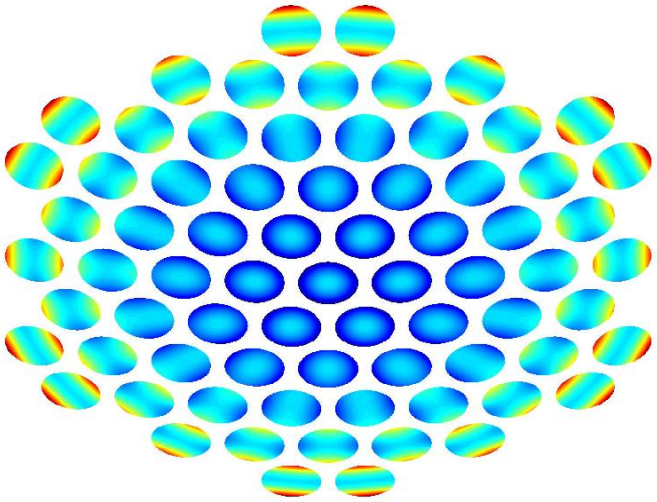
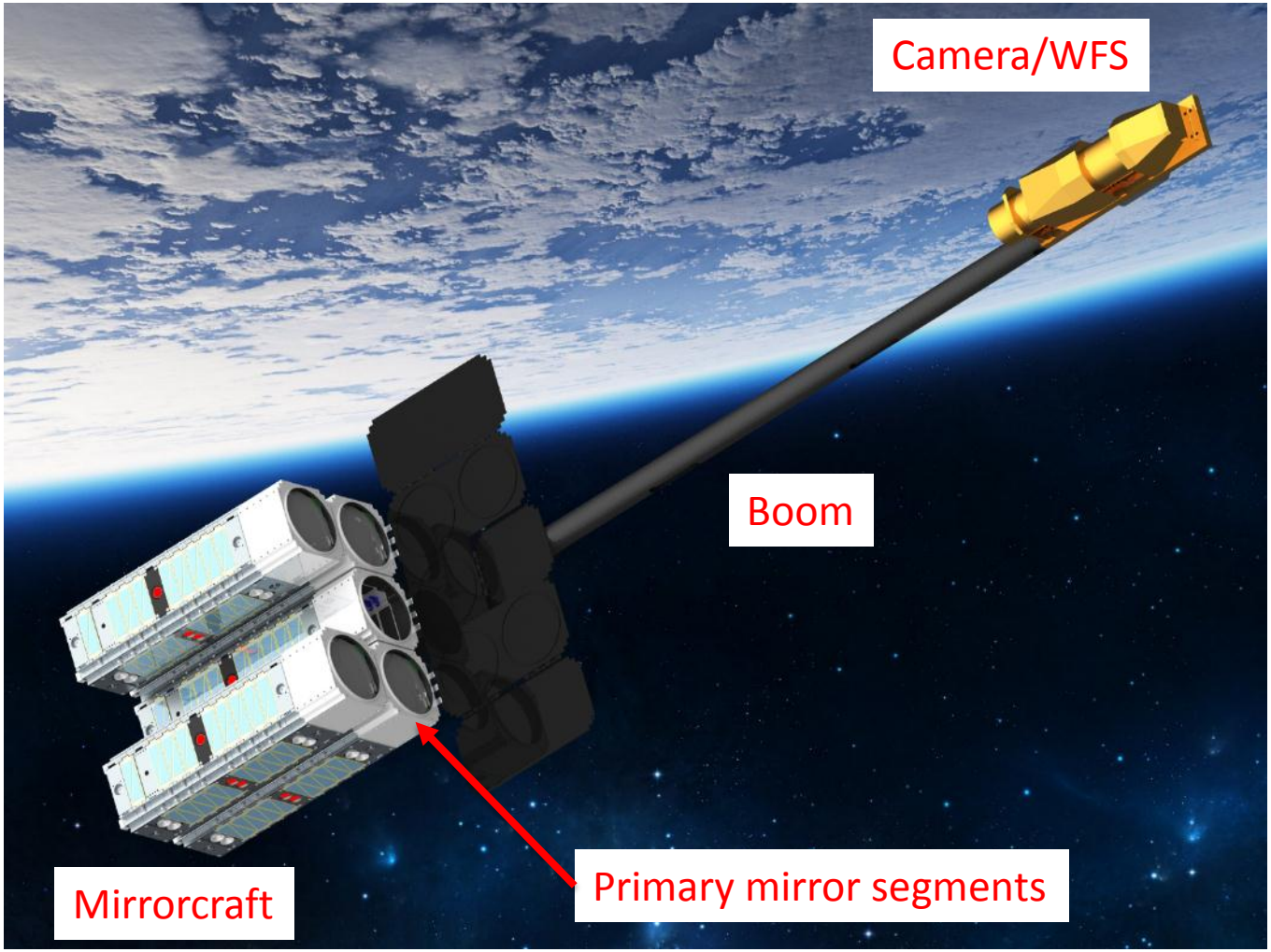
# Future Large Space Telescopes

- How to build low cost aperture > 10 meters in diameter?
  - Segmented primary mirror
  - Many segments
  - Multiple launches, expandable
  - On-orbit autonomous assembly

- Mirror segments
  - Lightweight
  - Identical (nominally spherical)
    - Lower cost
    - Redundancy
    - Ease of manufacture and test
  - Active



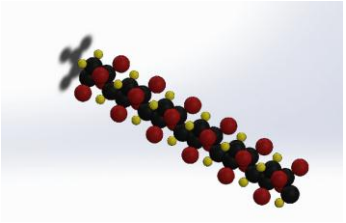
# AAReST Mission



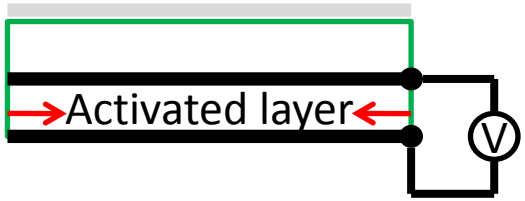
# General Mirror Concept

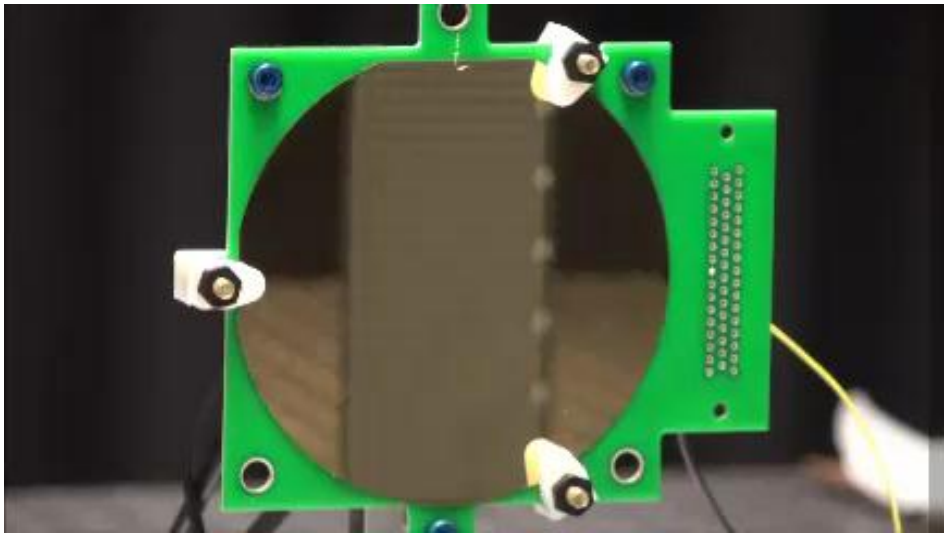
- Thin laminate
  Polished glass wafers
  - Piezopolymer coating
  - 0.5 kg/m^2
- Bimorph actuation
  - In-plane strains create mirror curvature
  - Thin, low areal density
- Actuation patterns
  - Independent regions for fitting of mirror surface shapes

Fluoropolymer



Bimorph actuation:

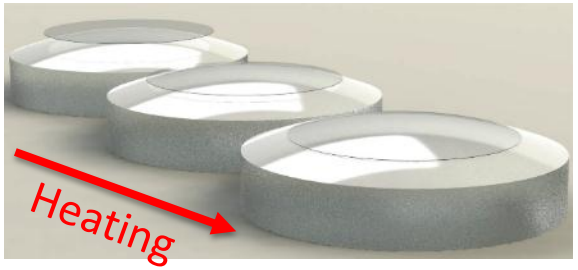


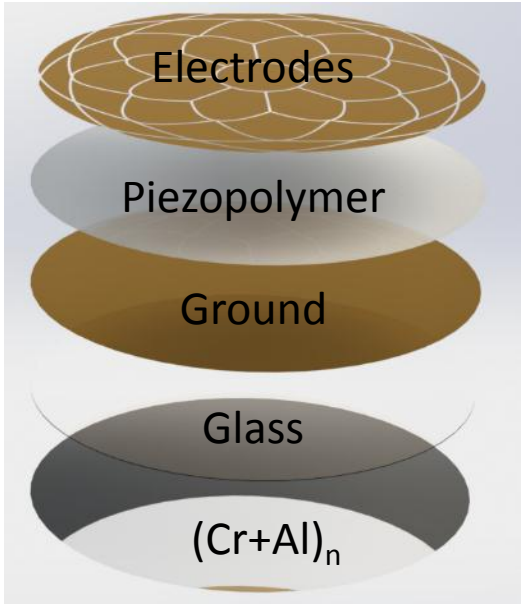



# Mirror Fabrication Process

1. Polished glass wafer (~225µm)
2. Slump at ~650C over FS/quartz mandrel*
3. Coat Cr+Al laminate (~3µm total)*
4. Roughen mirror backside with HF vapor
5. Sputter ground layer (Ti+Au+Ti, 10+50+10nm)
6. Spin coat + bake piezo layers 140C (20µm)
7. Sputter blanket electrode (Ti+Au, 10+10nm)
8. Evaporate electrode pattern (Au, 100nm)
9. Pole active material layer to 100 V/µm
10. Ion mill etch back blanket electrode
11. Wirebond electrodes and mount mirror onto PCB

Substrate slumping



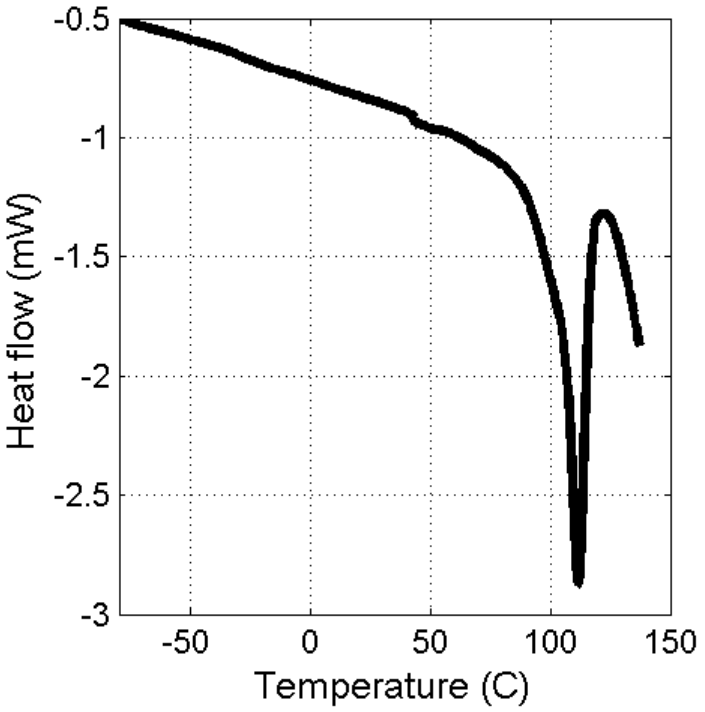

reflective side

*process steps still under development

# Piezo Polymer Properties

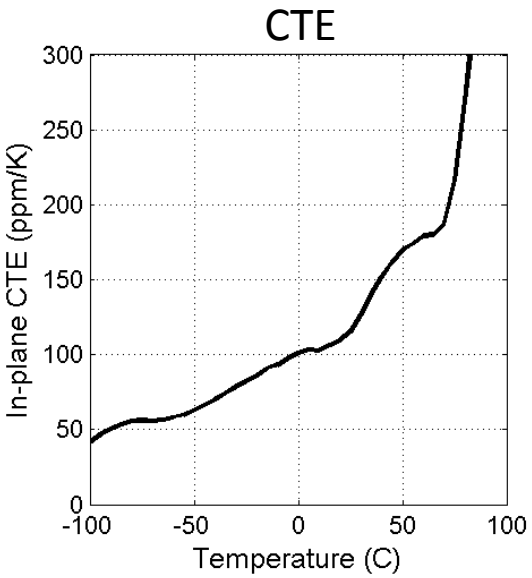
- Critical temperatures
  - Tg: ~ -40C , glass transition (very gradual)
  - Tc: +110C, Curie
  - Tm: >140C, melting
  - Td: >400C, decomposition
- Low moisture absorption (<0.01%)
- Viscoelastic
  - Creep master curve to be measured soon
  - Good news: glass substrate will dominate shape over time and maintain molded shape

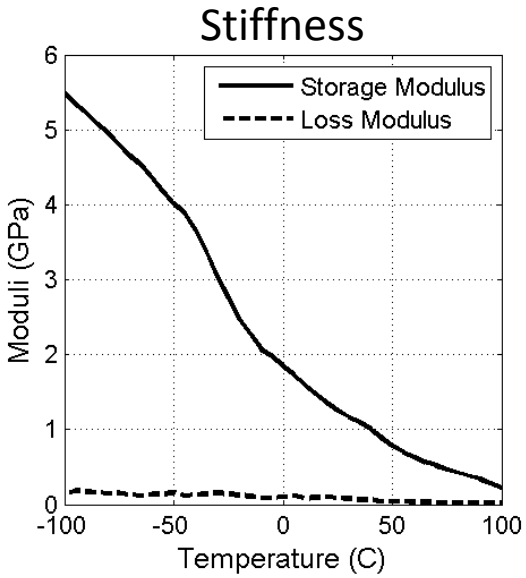
Differential Scanning Calorimetry

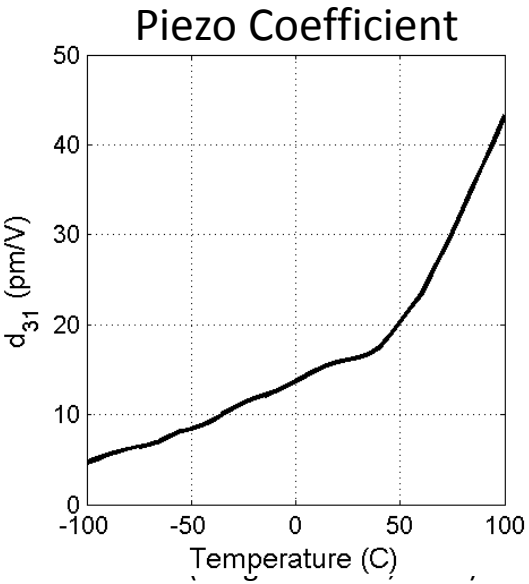


# Piezo Polymer Properties

- Material characterization
  - Data from
    - JPL polymer lab (TMA, DMA, DSC, TGA)
    - Caltech material testing (Instron, optical measurements)
    - Sandia (Dargaville, 2006) report on piezopolymers in space (piezo measurement)
  - Large variation in properties across temperatures
  - Stiffness and piezocoefficient have opposing trends, somewhat balance out

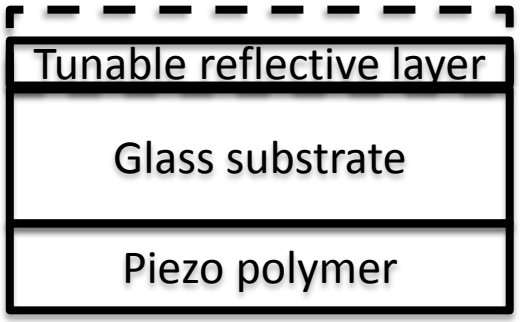


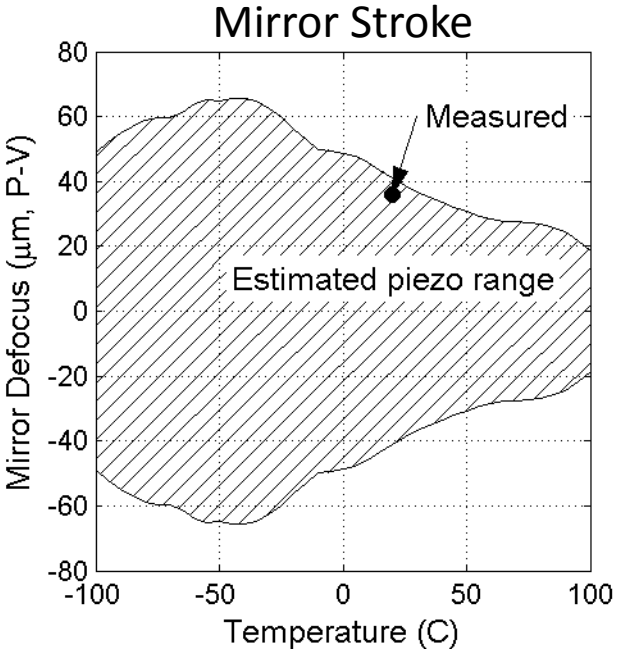



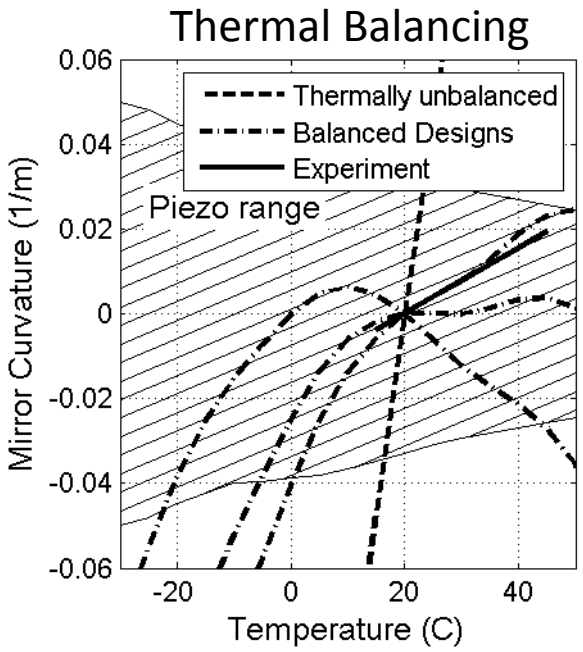



# Operating Temperature Range

- Actuation stress fairly flat, optimal peak ~-40C
- Mirror stroke (for defocus mode)
  - +/-40 microns at 20C, +/- 60 microns at -40C
- Thermal balance important!
  - Thermal expansion overrides piezo range in <10C
  - Tuned balancing of mirror can extend operational range

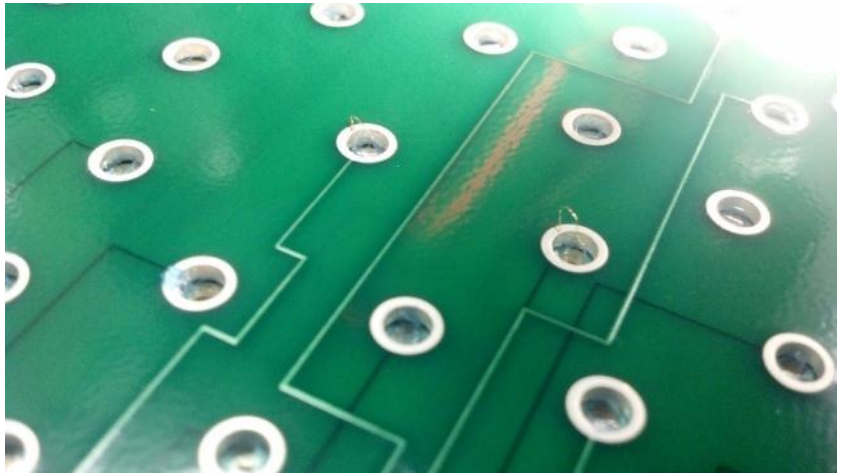


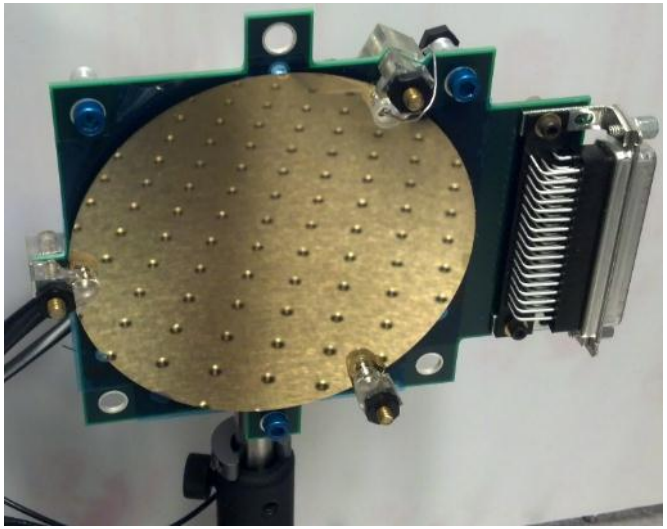



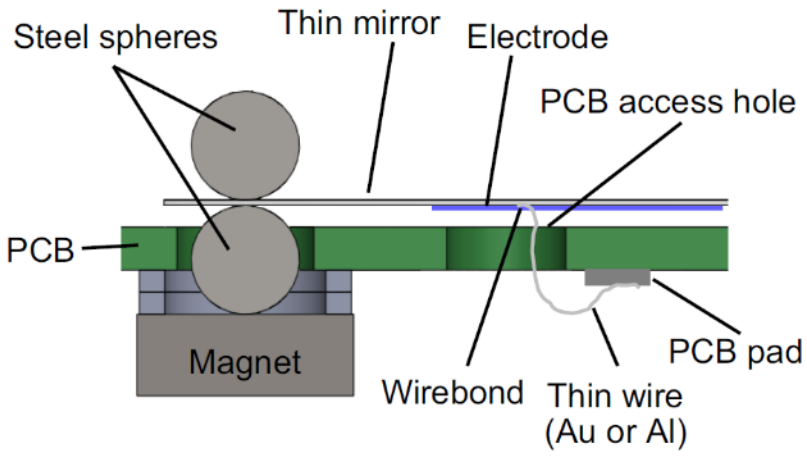



# Kinematic Mirror Mounting

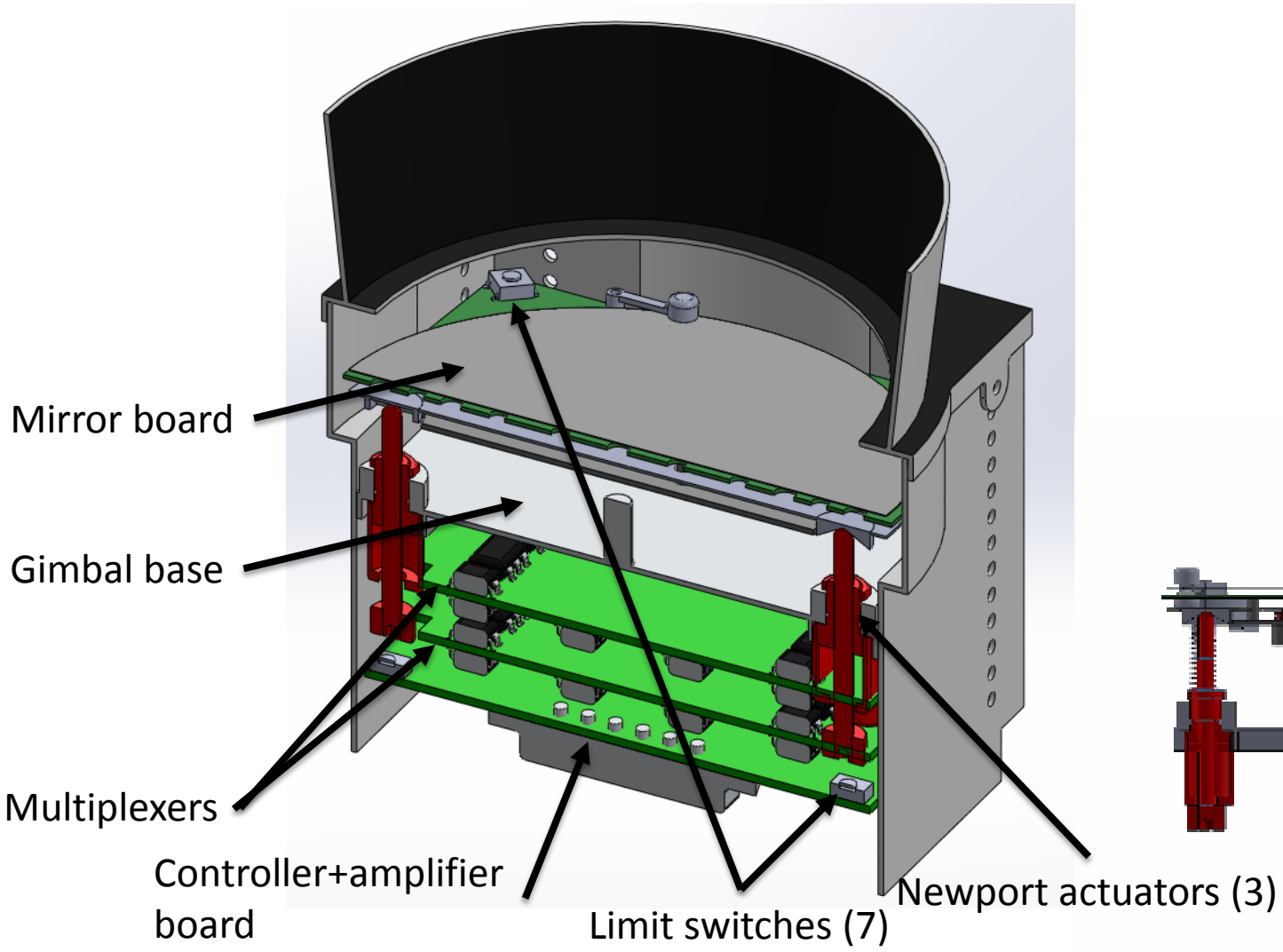
- Tiny Au wirebonds connect mirror electrodes to PCB pads
(via holes)
- Kinematic mounting to PCB
  - Spheres pinch mirror in 3 places, preloaded and aligned using a magnetic field

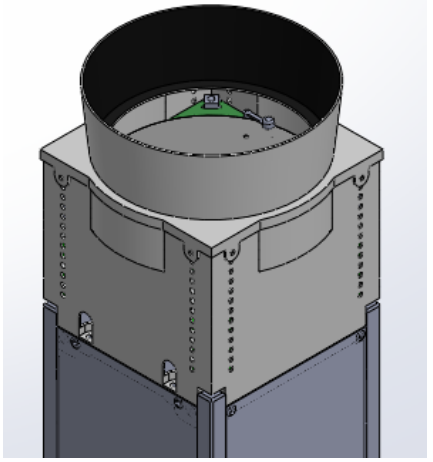


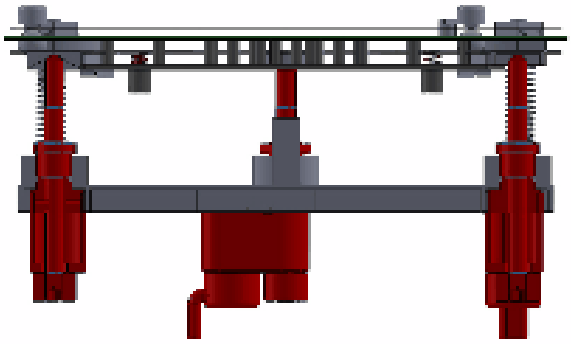




# Current Configuration

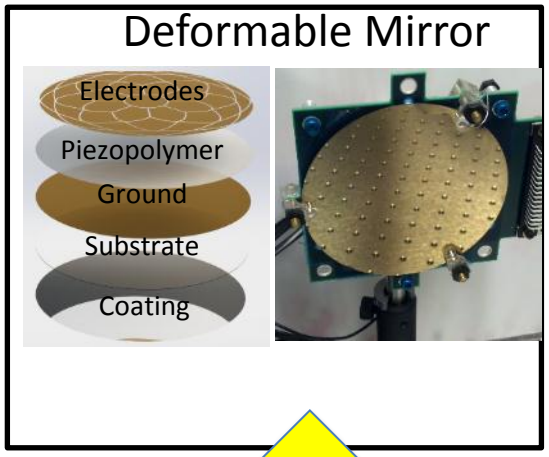




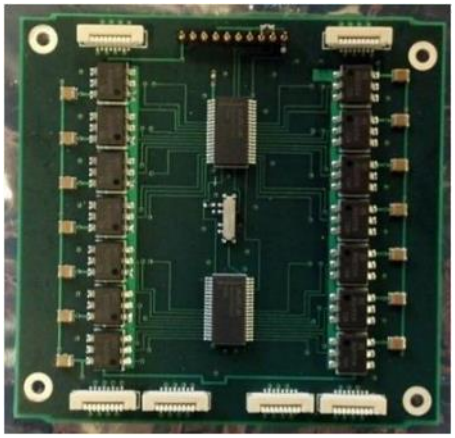
# Control Electronics - Alternatives

- High voltages required (+/- 500V)
- Current multiplexer weighs ~10x more than the mirror itself
- Future investigation into printable flexible OFET multiplexing integrated onto DM substrate

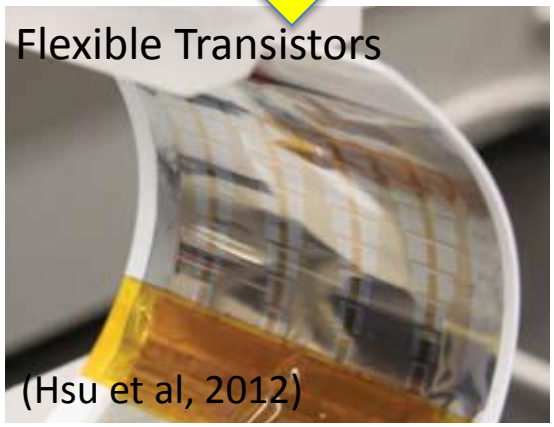



Integrate

**-Rigid PCB**
**-Discrete components**

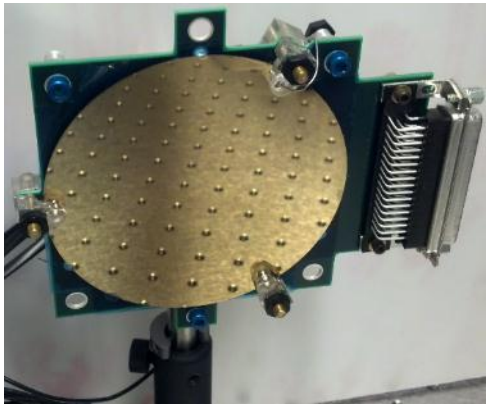


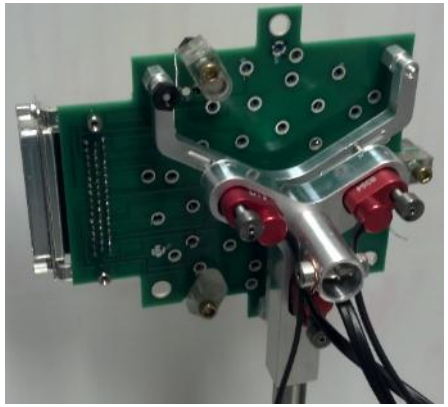
**-Flexible PCB**
**-Discrete components**

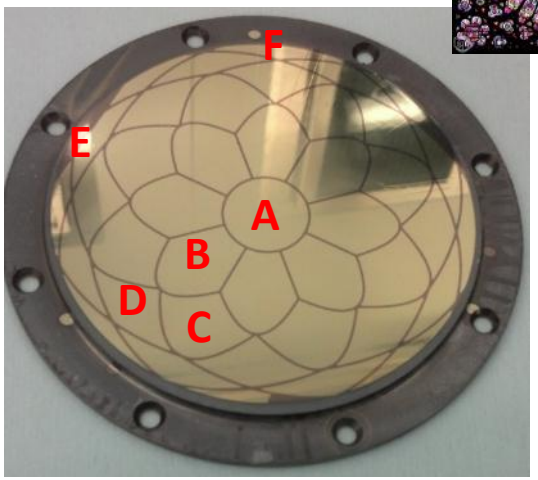


# 41 Channel Lab Prototype

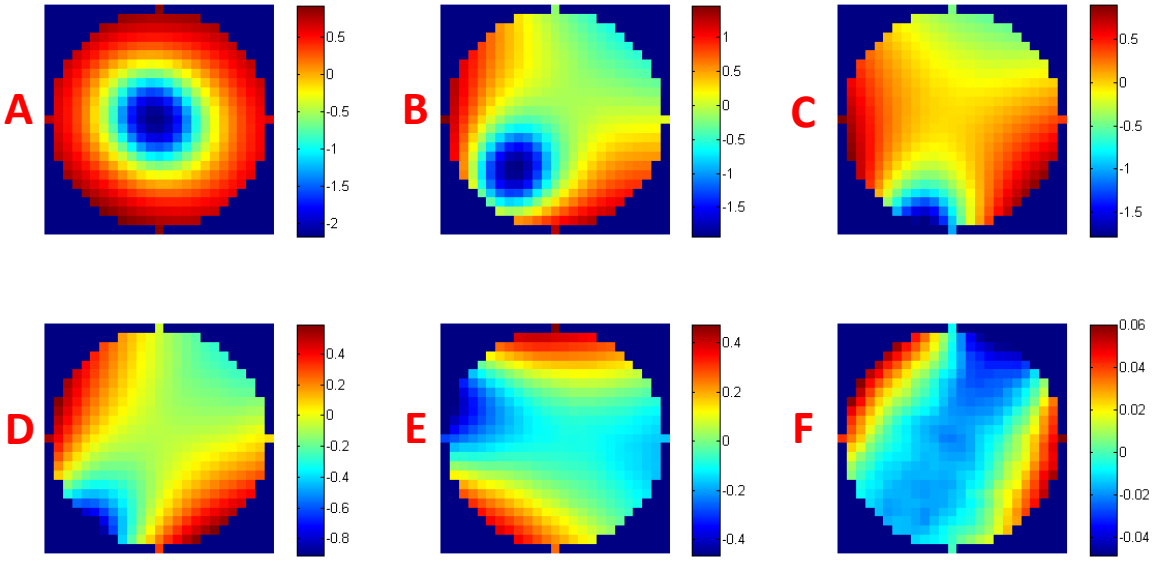
- Upgrade from previous 16 channel design
- Marie's optimized "Notre Dame" actuation pattern
- Process improvements still ongoing
  - Reliability
  - Quality





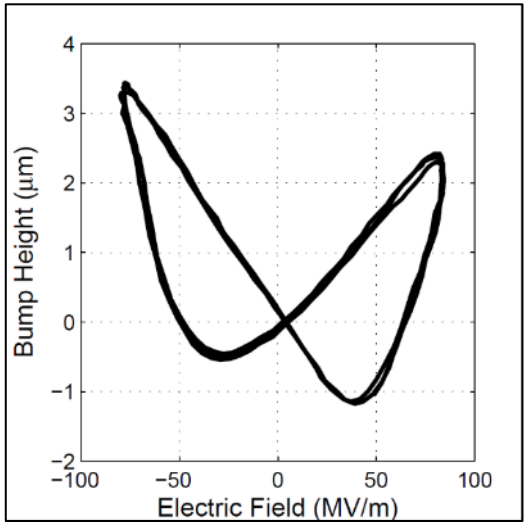


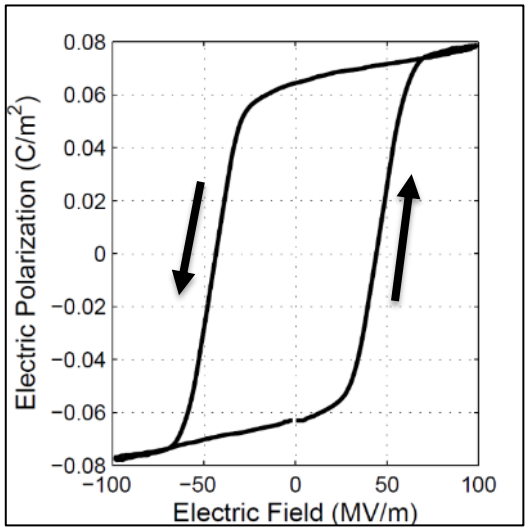

Influence function measurements via Shack-Hartmann



# Development Functional Tests

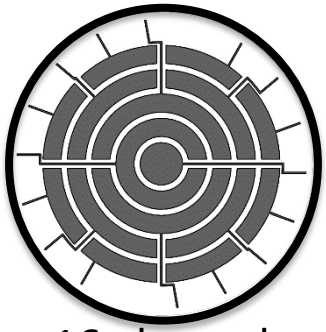
- Optical
  - Demonstrated 16-channel and 41-channel prototypes
- Electrical
  - Multiplexer prototype tested to +/- 500V
- Thermal
  - Piezopolymer survival retained functionality down to -70C and >90C (for 1 hour)
- Mechanical
  - Future test:  launch restraint acoustic testing



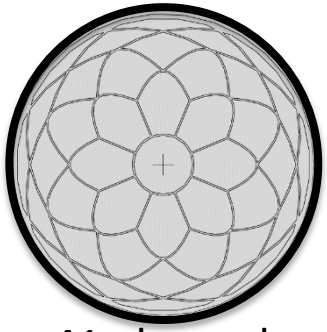



# Performance Tests

- Optical
  - 16 channel prototype on 200 micron Si substrate
    - Achieved 1.3 microns RMS WFE error in lab environment
  - 41 channel prototype on 200 micron glass substrate
    - ~10% channels shorted, 0.5 microns RMS WFE corrected (assuming 100% working channels), trying again soon
  - Current limitations
    - Substrate initial figure (need slumping)
    - Polymer coating quality (shorts during poling step)

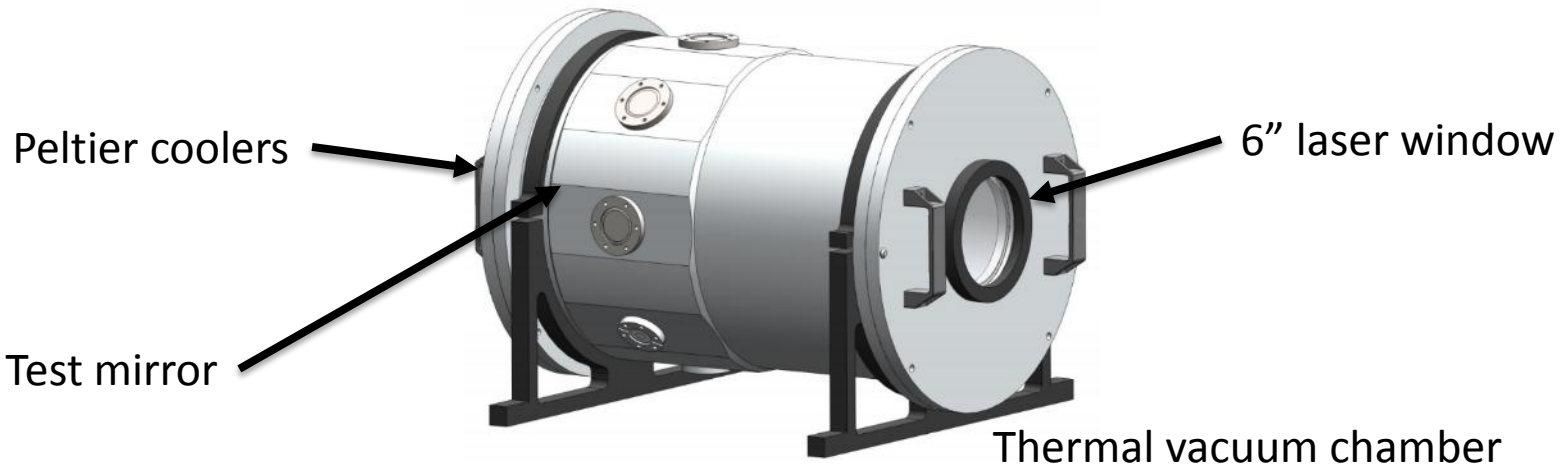


16-channel

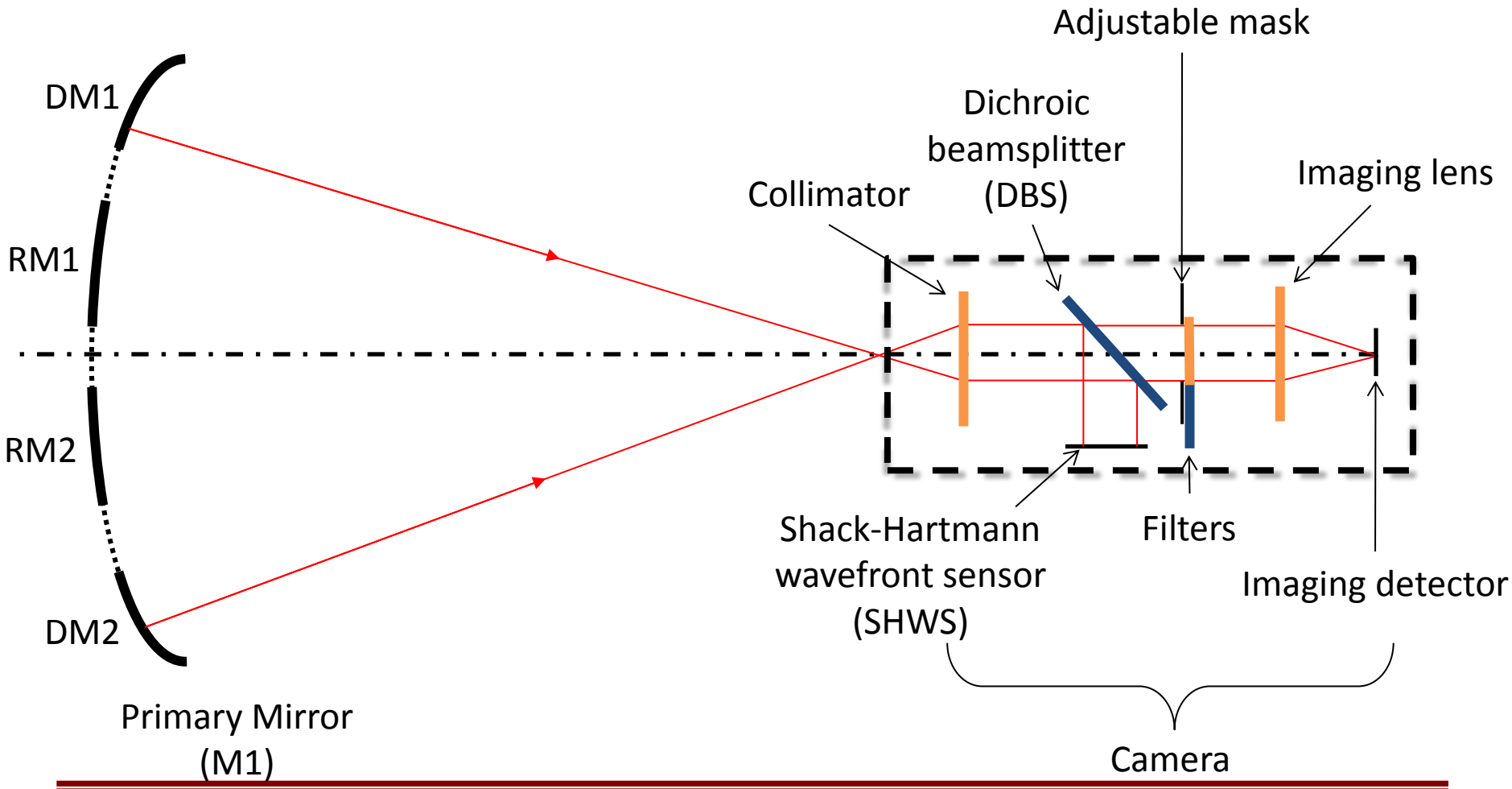


41-channel

- Thermal
  - Future: mirror thermal shape stability and actuator stroke verification

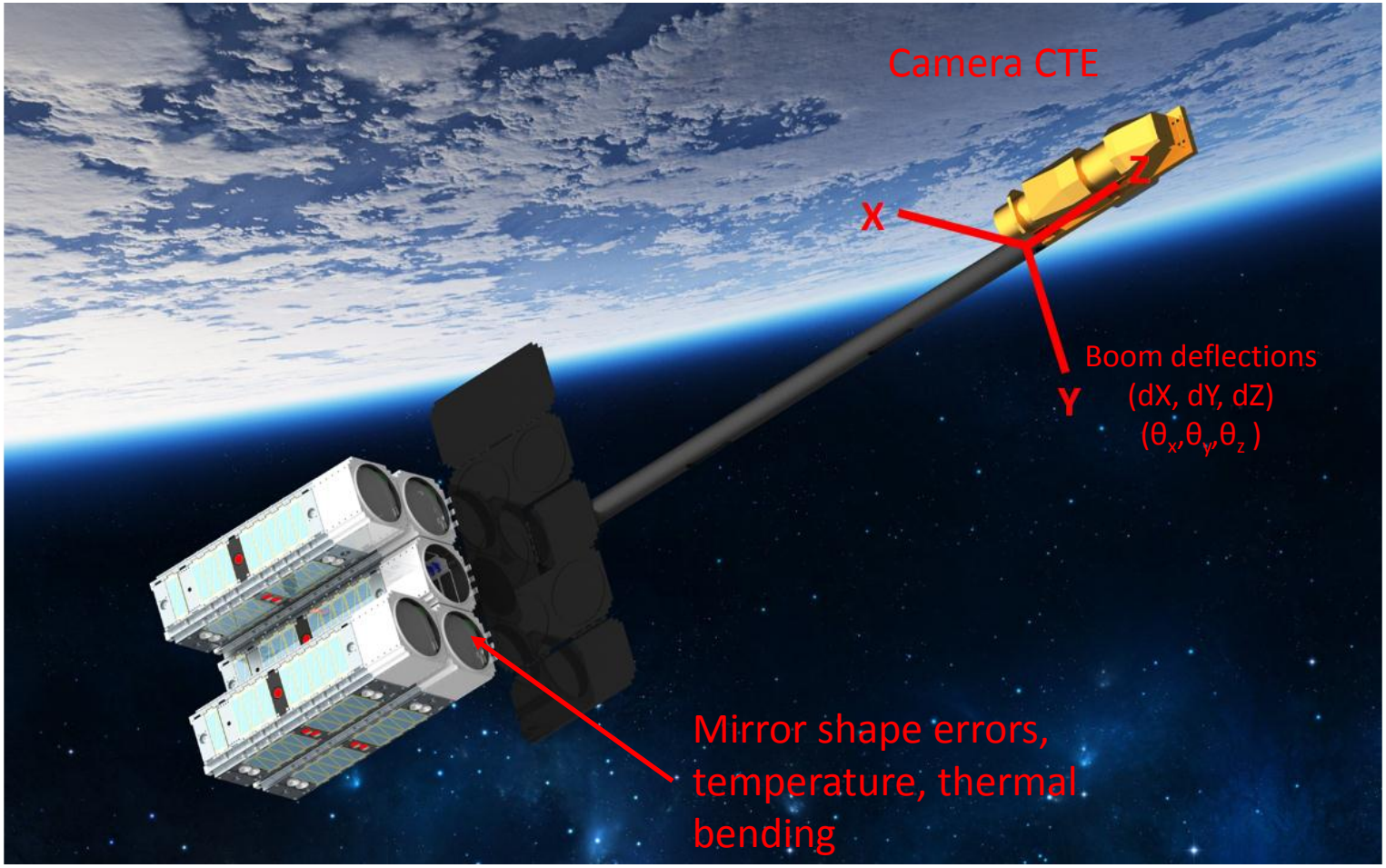


# AAReST Optical Layout

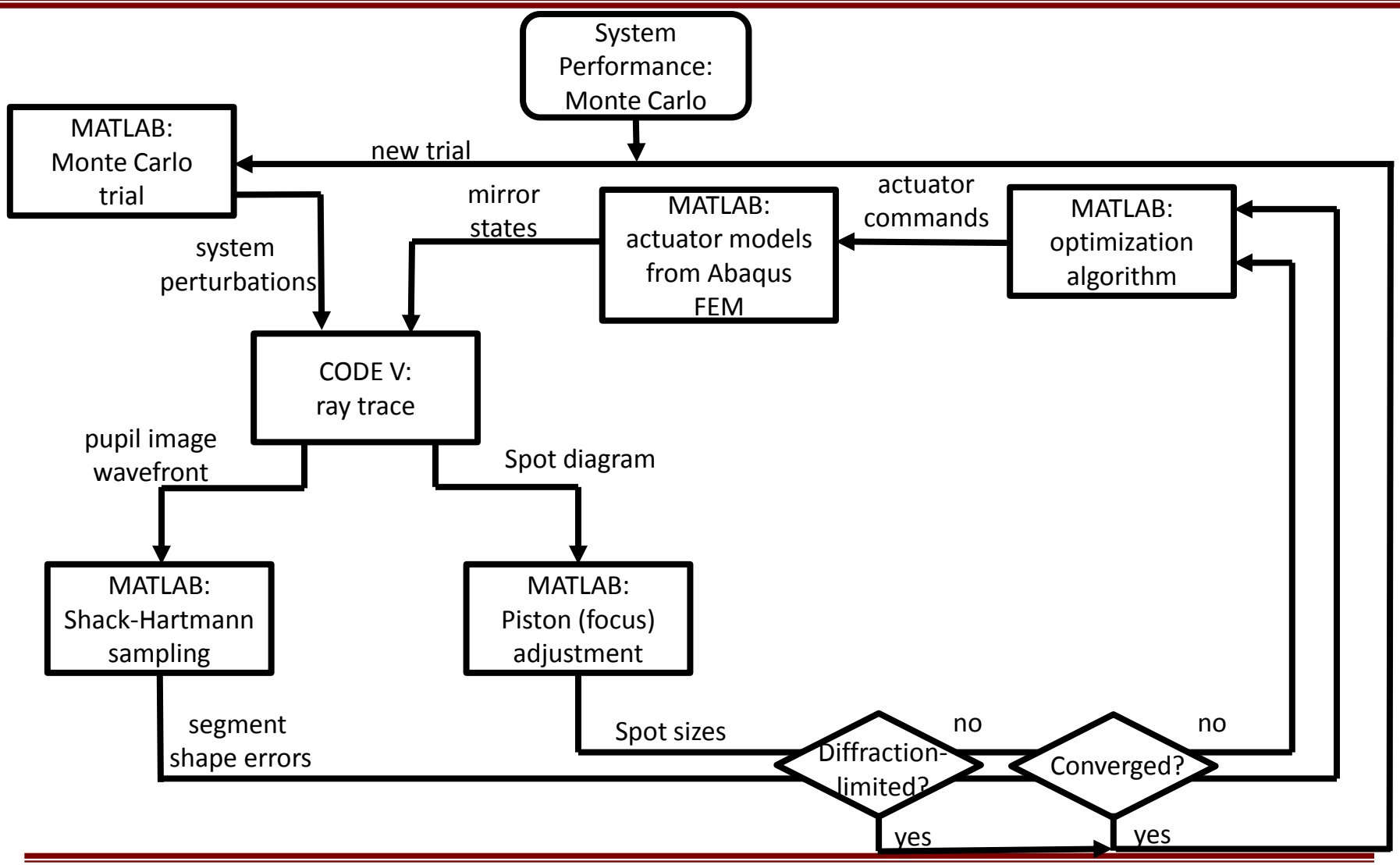


# AAReST Performance Simulation

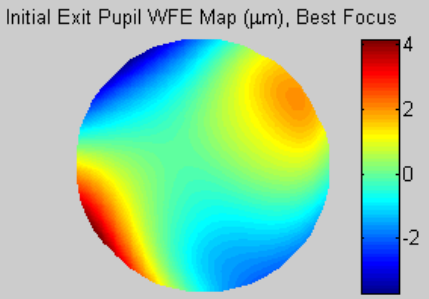
Error sources:

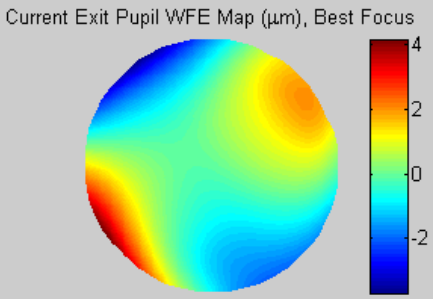


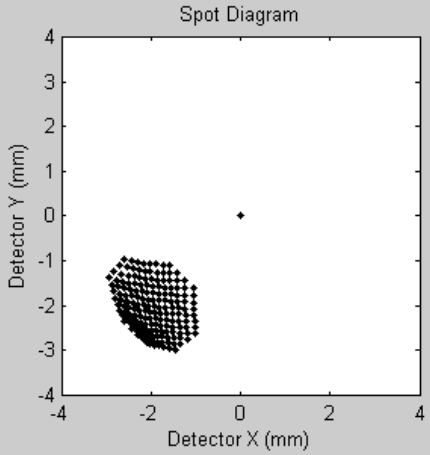
# Performance Analysis Model

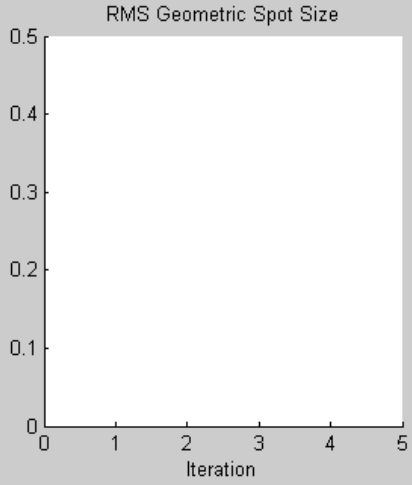


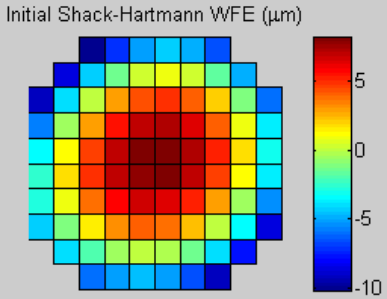
# Example Performance Trial

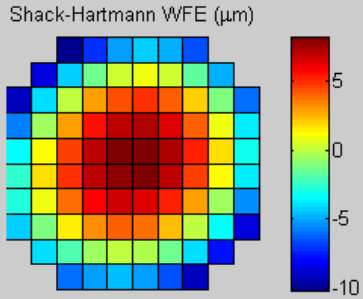


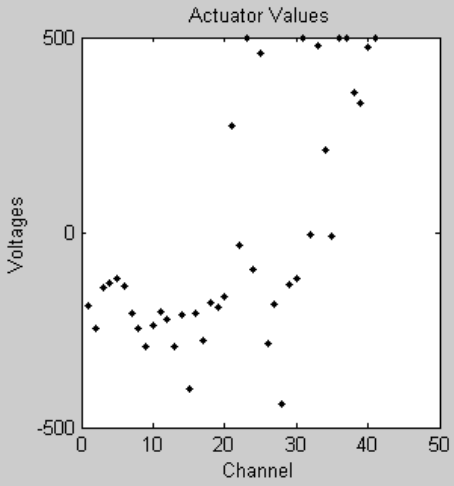



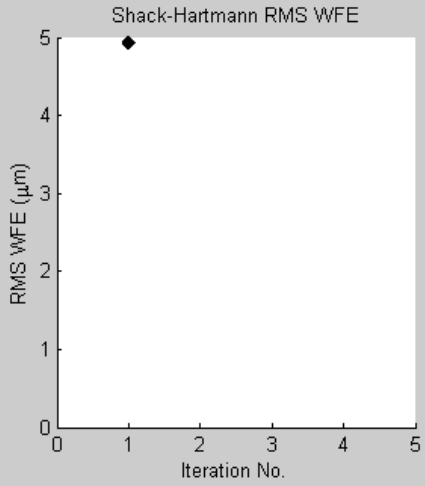



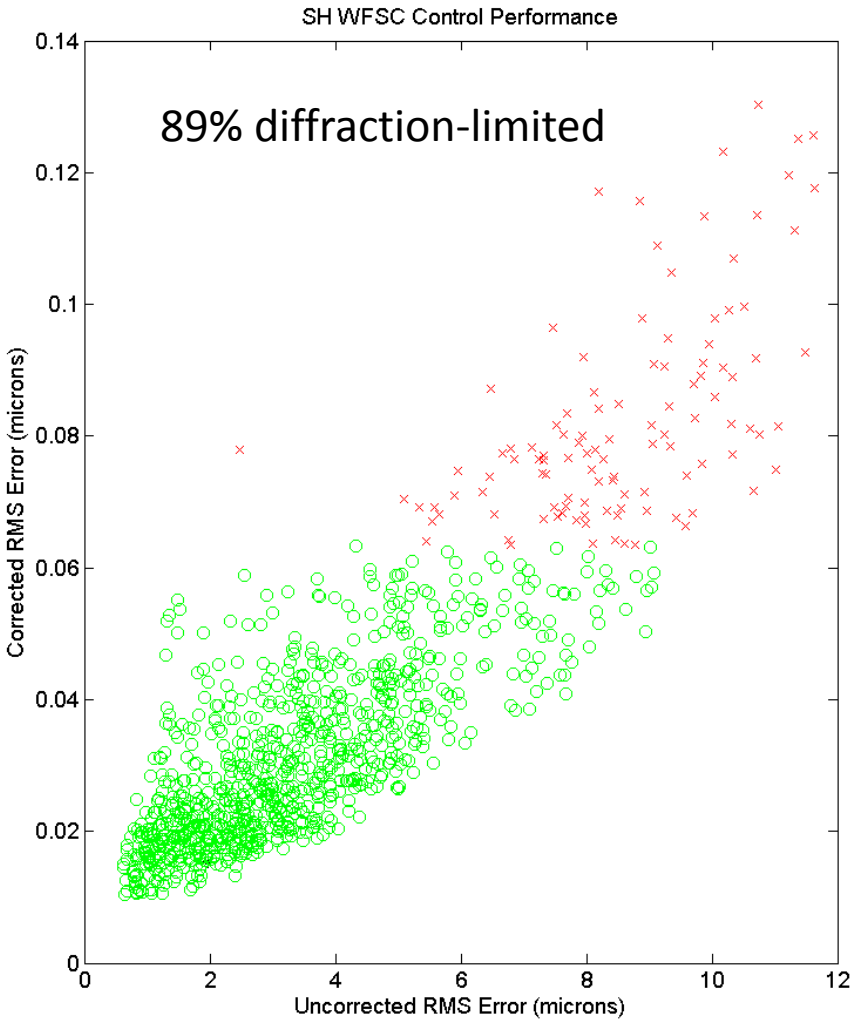



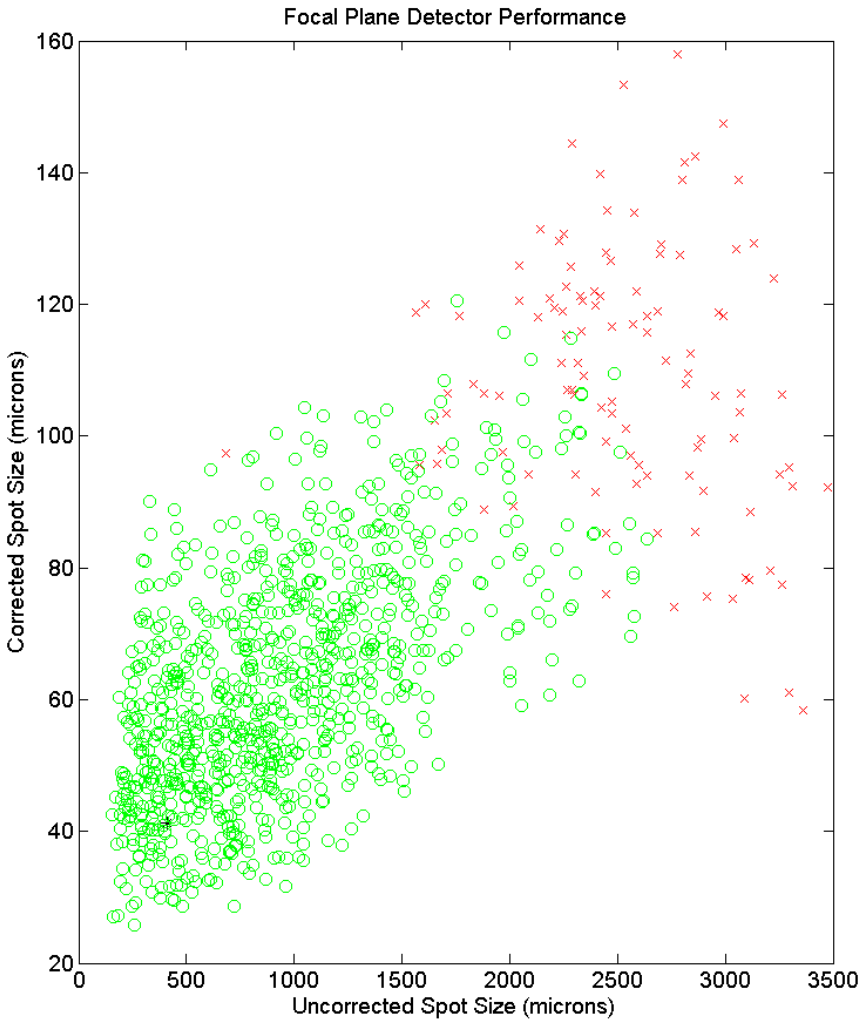



# Performance Results (Compact)



# Conclusion

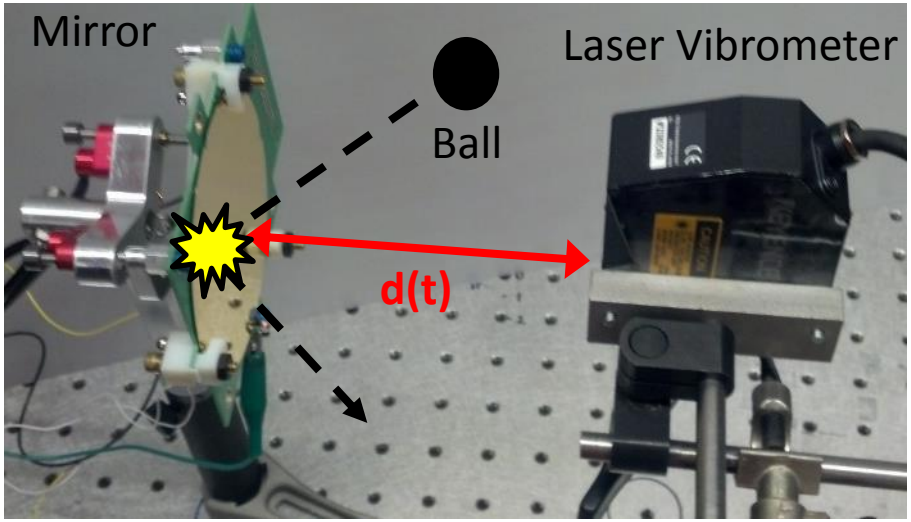
- Lightweight mirror concept has been demonstrated
- Material properties data collected and functional testing completed, no insurmountable roadblocks (as yet)
- Refinement of fabrication processing ongoing
- Environmental testing needs to be done
- Hope to fly mirrors in AAReST Cubesat tech demo in late 2015/early 2016

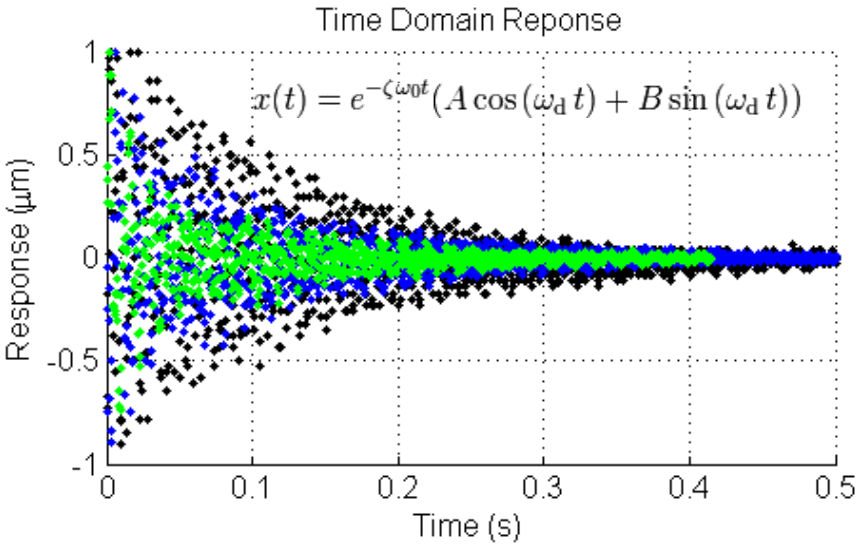
# Acknowledgements


- Sergio Pellegrino, Marie Laslandes, John Steeves, Jim Breckinridge, Erin Evans, Kristina Hogstrom (Caltech)
- Caltech Ae105 classes
- Namiko Yamamoto, Risaku Toda, Victor White, Harish Manohara, Andrew Shapiro, Bill Warner (JPL)
- Keck Institute for Space Studies
- A part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA)

# backup

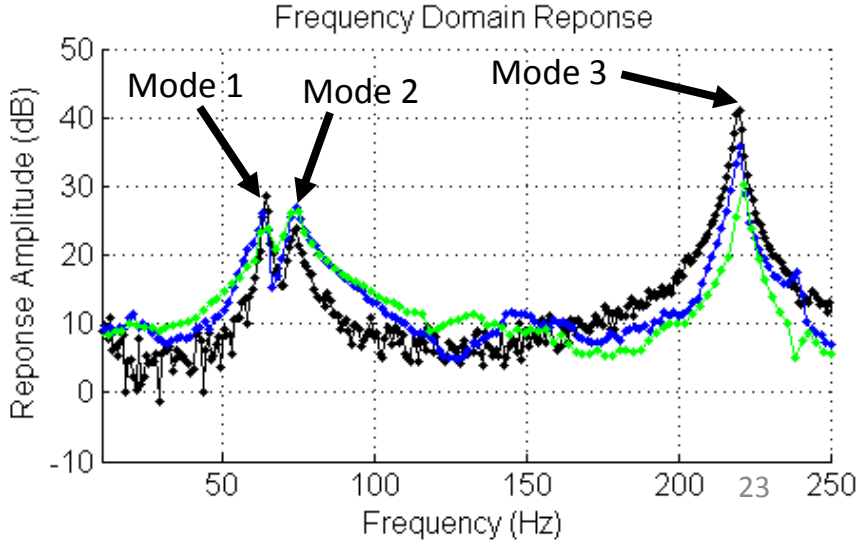
# Dynamic Behavior




**Substrate: Glass**

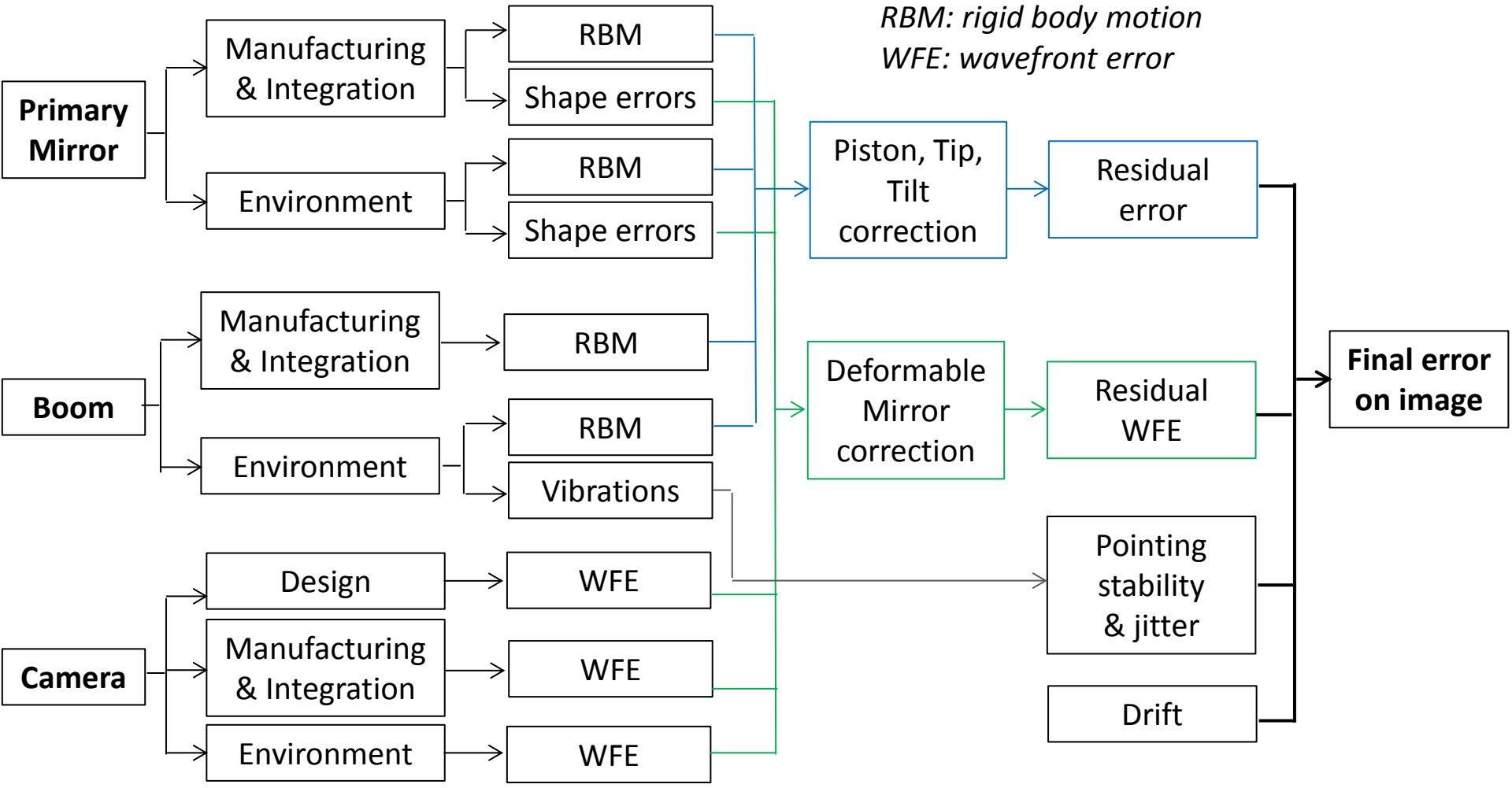
| | Experiment | FEM |
|---|---|---|
| **Damping Ratio, ζ** | 0.12 | (0.12) |
| **Mode 1** | 63 Hz/3800 RPM | 70 Hz |
| **Mode 2** | 74 HZ/4500 RPM | 81 Hz |
| **Mode 3** | 220 Hz/ 13000 RPM | 257 Hz |



# Error Budget Values

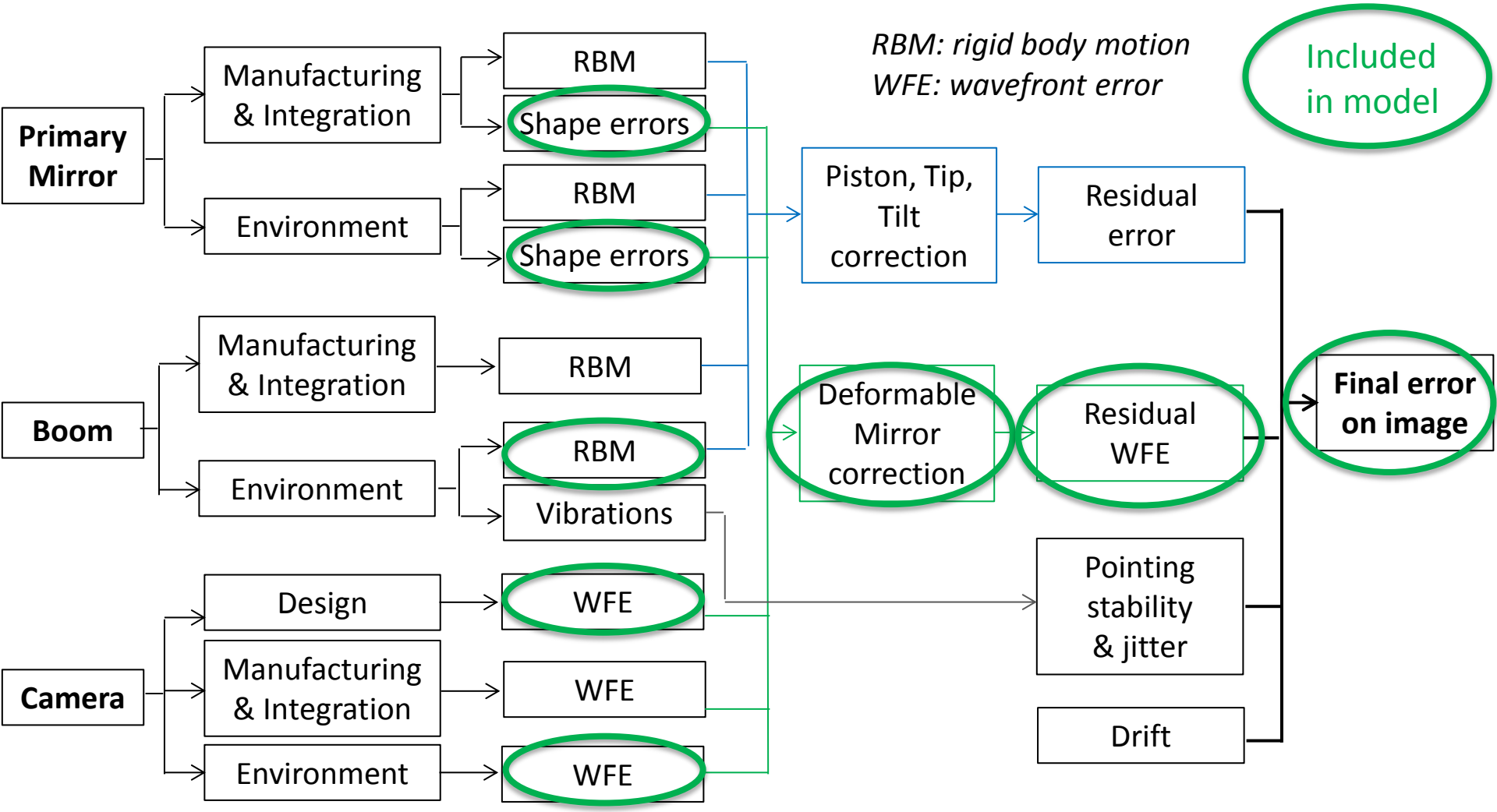
- Mirror temperature: -20C to +20C
- Camera temperature: -20C to +20C
- Mirror initial shape bounds (surface amplitudes, non-normalized, microns, +/-):
  - Z4 = .002; astigmatism_0
  - Z5 = .005; defocus
  - Z6 = .002; astigmatism_45
  - Z7 = .001; trefoil_x
  - Z8= .001; coma_x
  - Z9 = .001; coma_y
  - Z10 = .001; trefoil_y
  - Z11 = .0005; tetrafoil_y
  - Z12 = .0005; 2_astigmatism_0
  - Z13 = .001; spherical
  - Z14 = .0005; 2_astigmatism_45
  - Z15 = .0005; tetrafoil_y
  - Z16:66 = .0001; higher order modes
- Boom deflection bounds (+/-):
  - X: 0.625 mm
  - Y: 0.625 mm
  - Z: 0.127mm
  - Tip: 0.04 deg
  - Tilt: 0.04 deg

# Error Sources



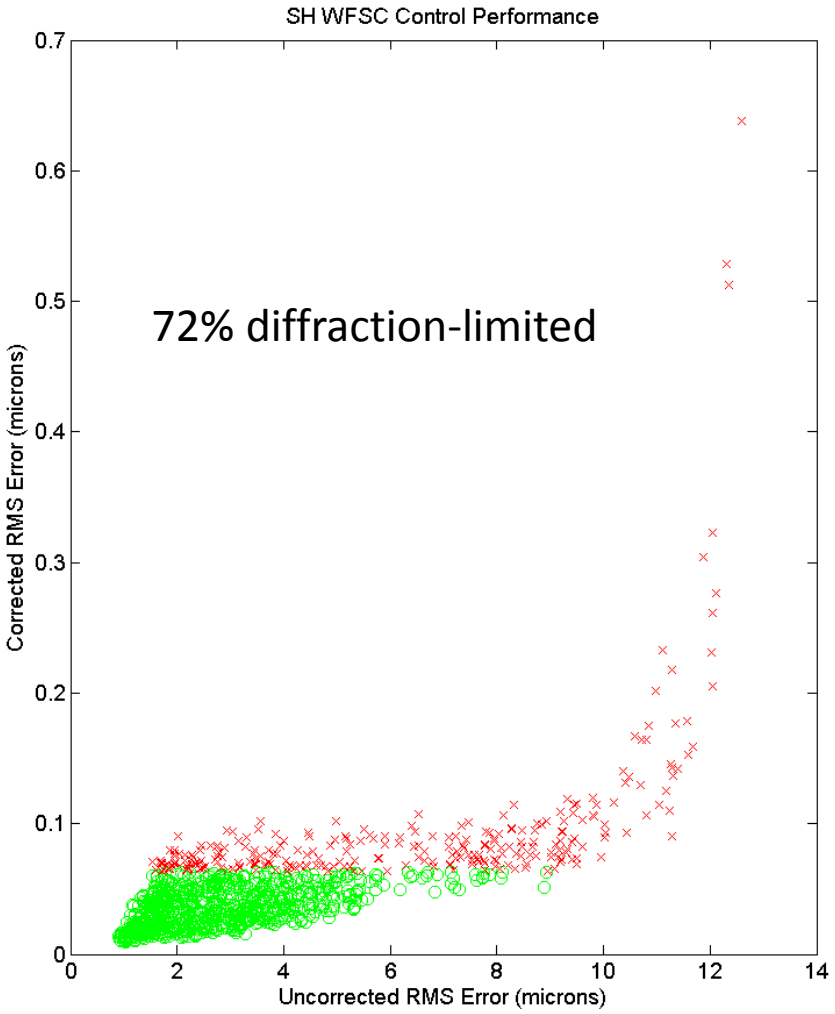

| Initial | Calibration | Imaging |
|---|---|---|

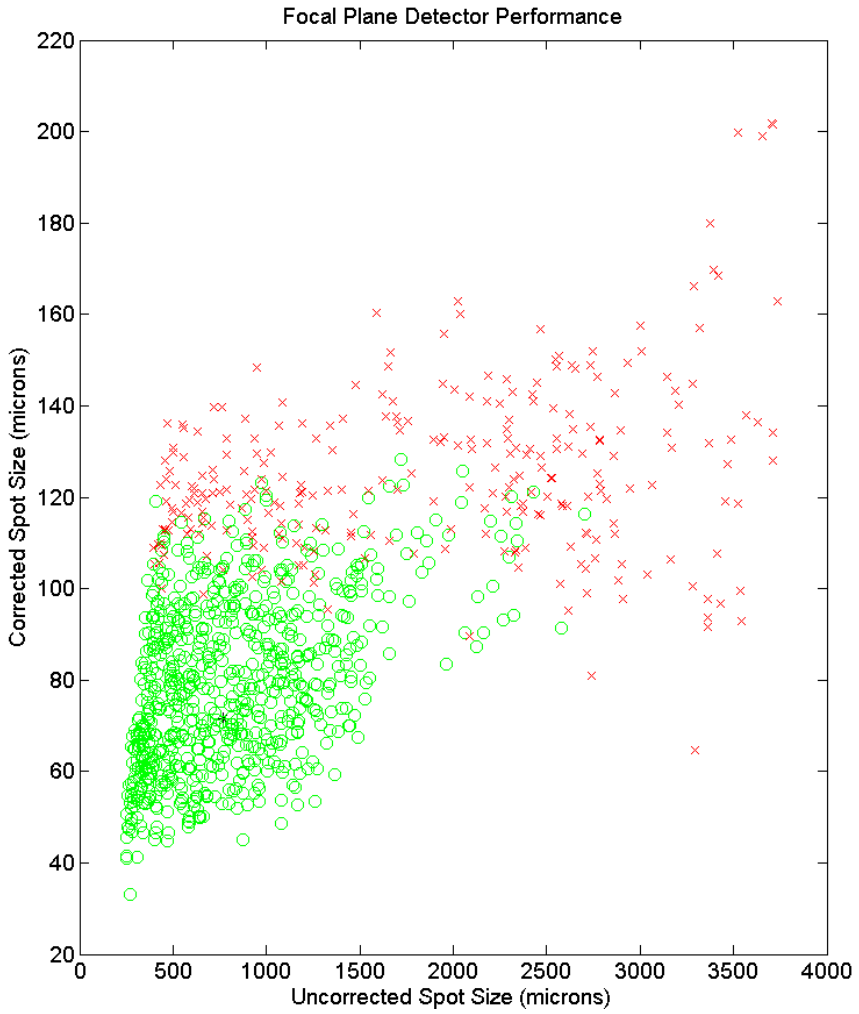
# Error Sources




*Initial* | *Calibration* | *Imaging*

# Performance Results (Wide)

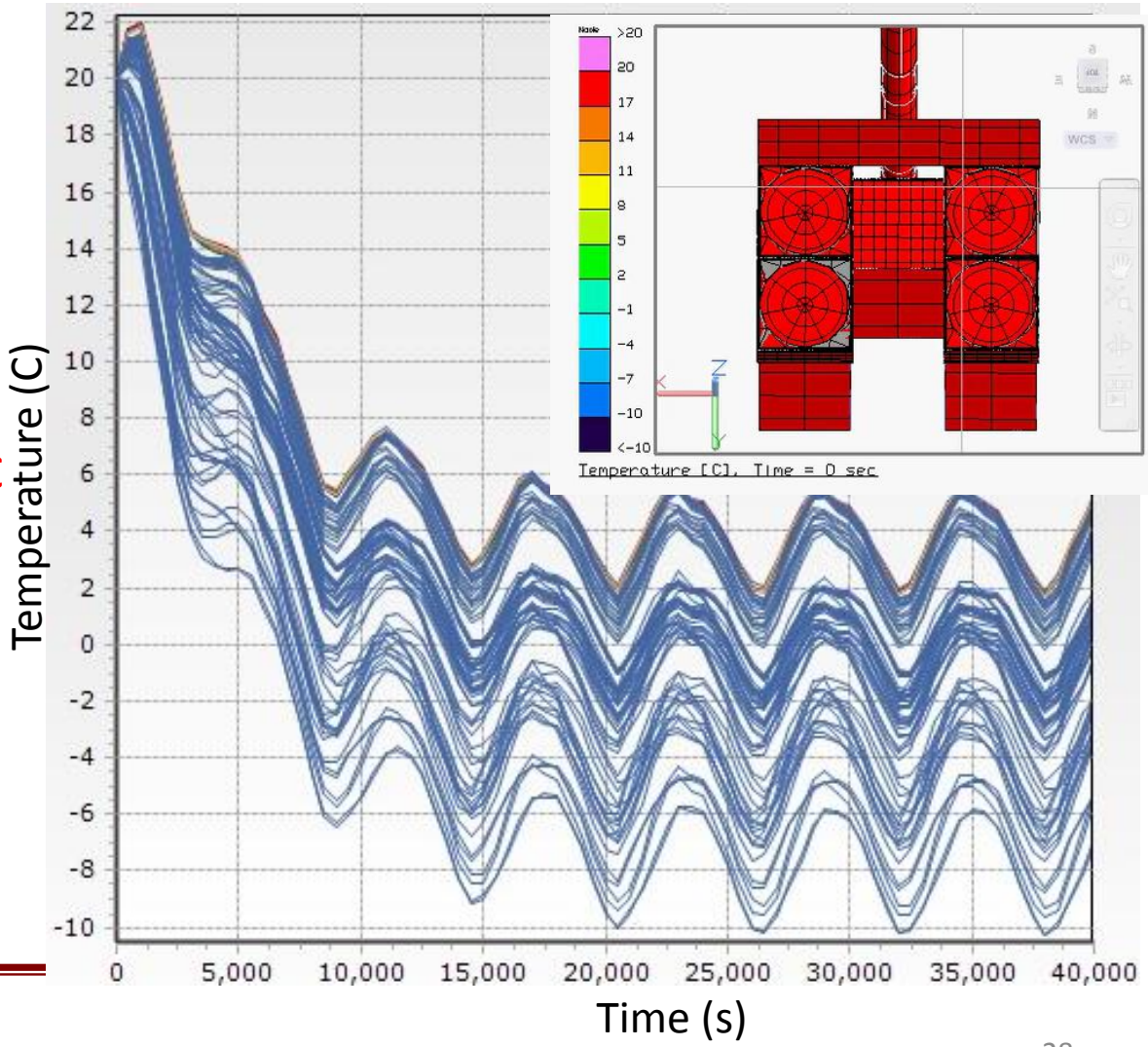


# Thermal Traces: 11am/11pm SSO

The Model:

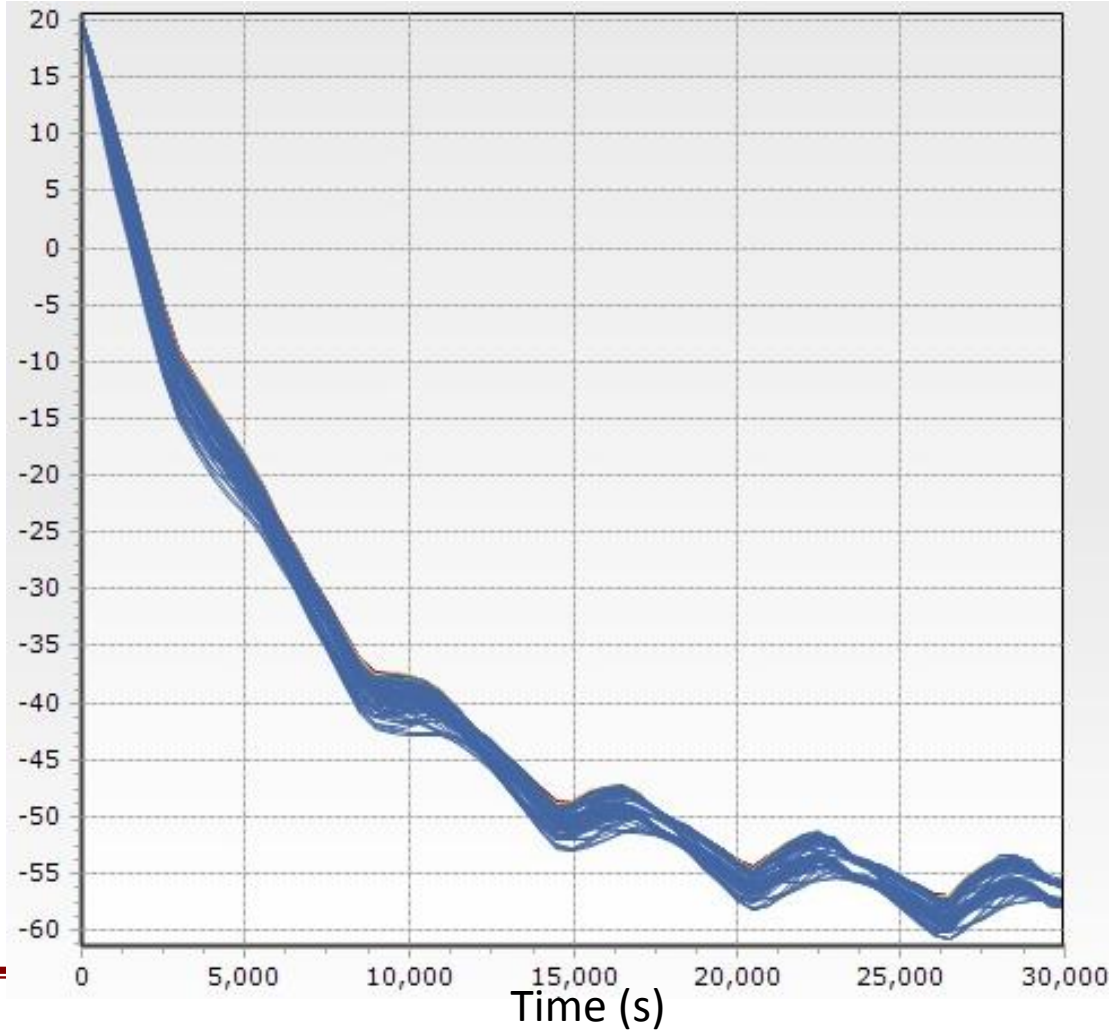
- Planetshine on
- Albedo on
- Sunshield (white paint, black chrome)
- .5 W generated/circuit board
- Temperatures between -10C and +10C
- Some radial thermal gradient present (due to board heat)
- Want surface temperature and emissivity underneath mirrors as uniform as possible to minimize gradients



# Cold Case: No Power

The Model:

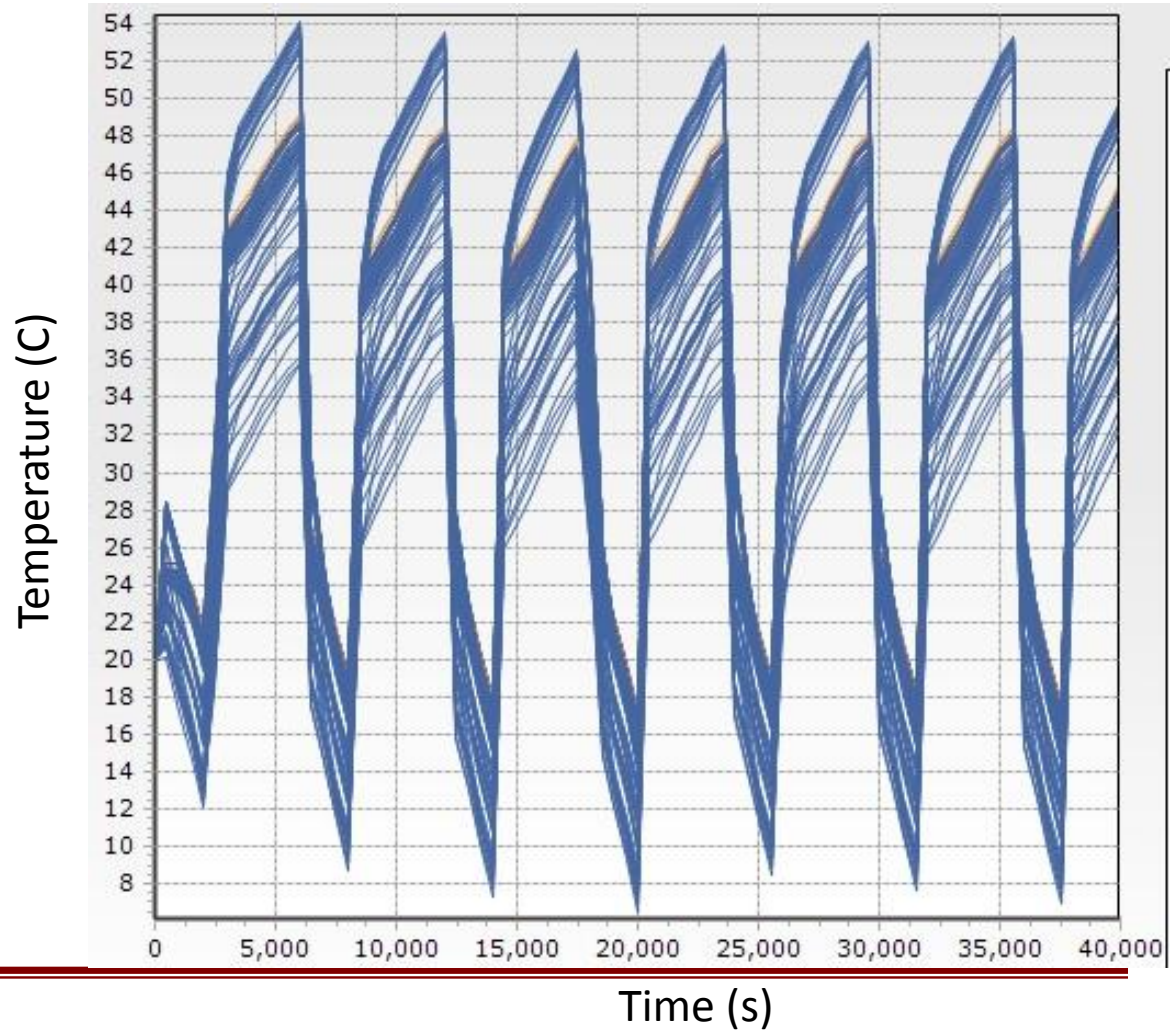
- 11 AM 11 PM Sun-synchronous orbit
- Planetshine on
- Albedo on
- Sunshield (white paint, black chrome)
- 0 W generated/circuit board
- Drops down to -60C
  - Need to ensure mirror survival here
  - Can improve conduction to mirrorcraft
- Minor thermal gradient



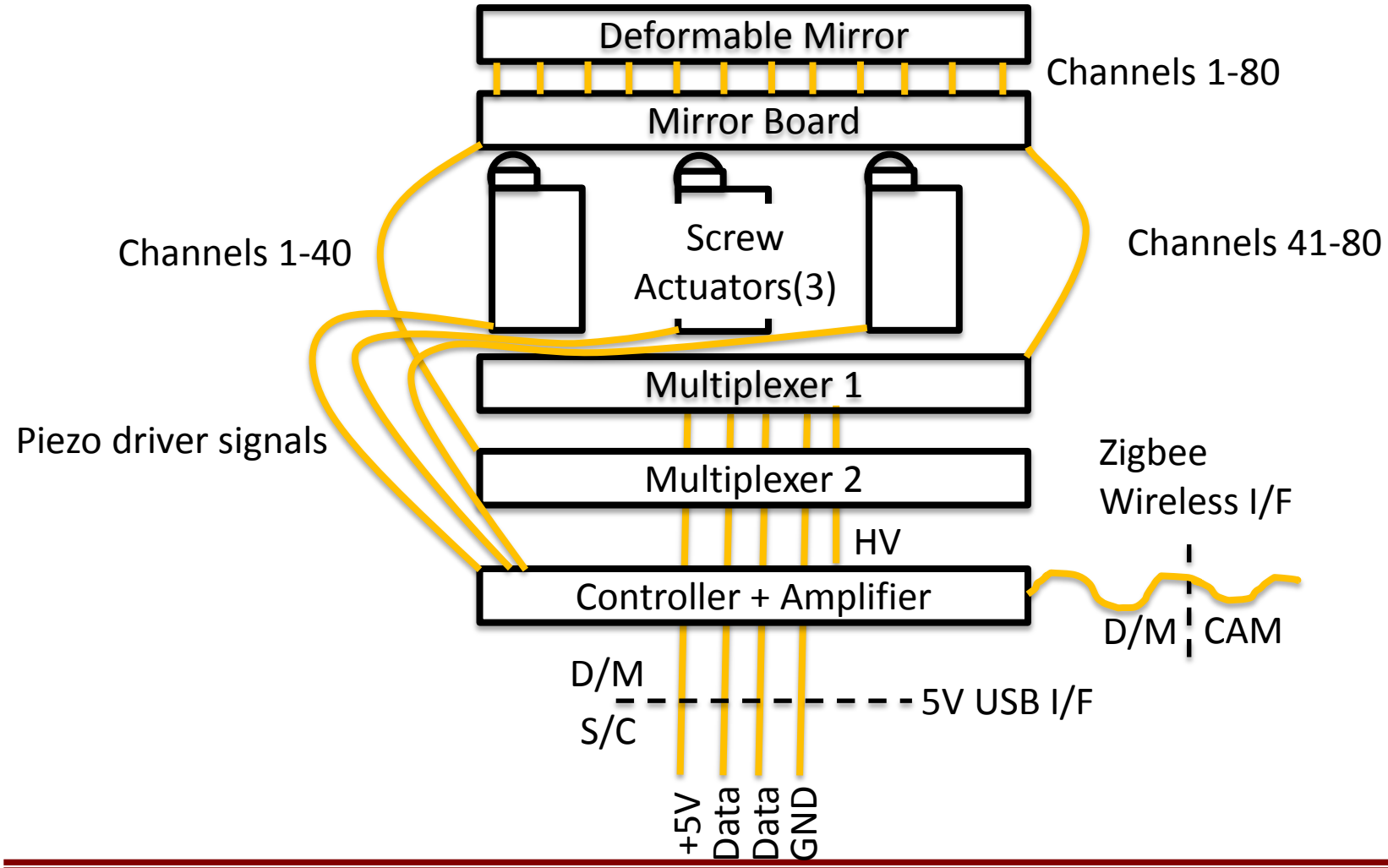
# Sun Pointed (Lost Control) – Hot Case

The Model:

- 11 AM 11 PM Sun-synchronous orbit
- Planetshine on
- Albedo on
- Sunshield (white paint, black chrome)
- .5 W generated/circuit board
- Telescope orbits with mirrors facing the sun
- Mirrors warm but still within survival range
- Solar irradiance may reflect into camera if mirrors are aligned

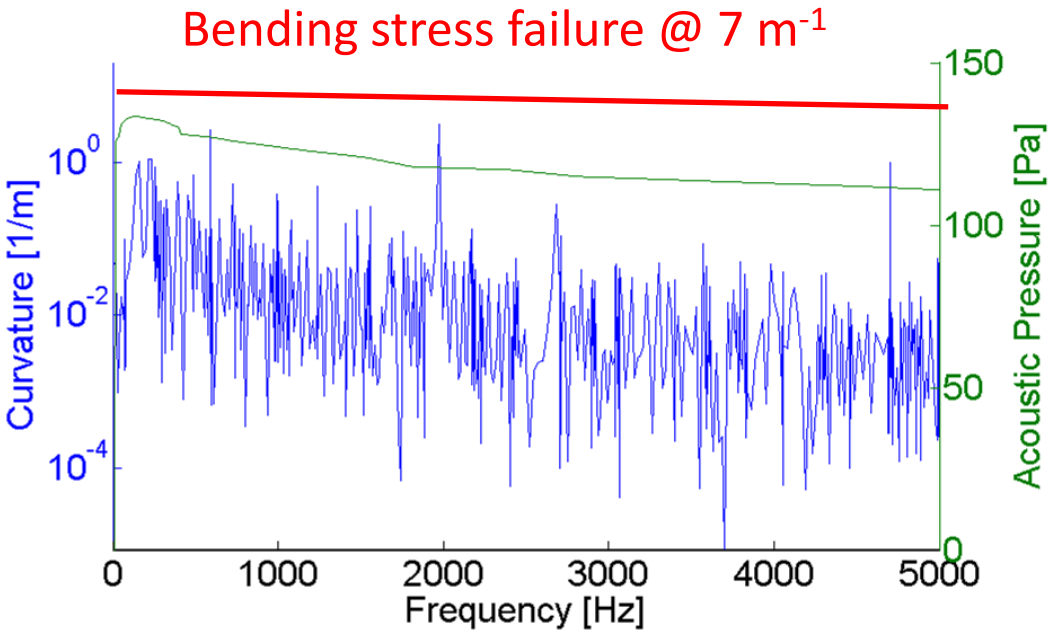


# DM Package Block Diagram

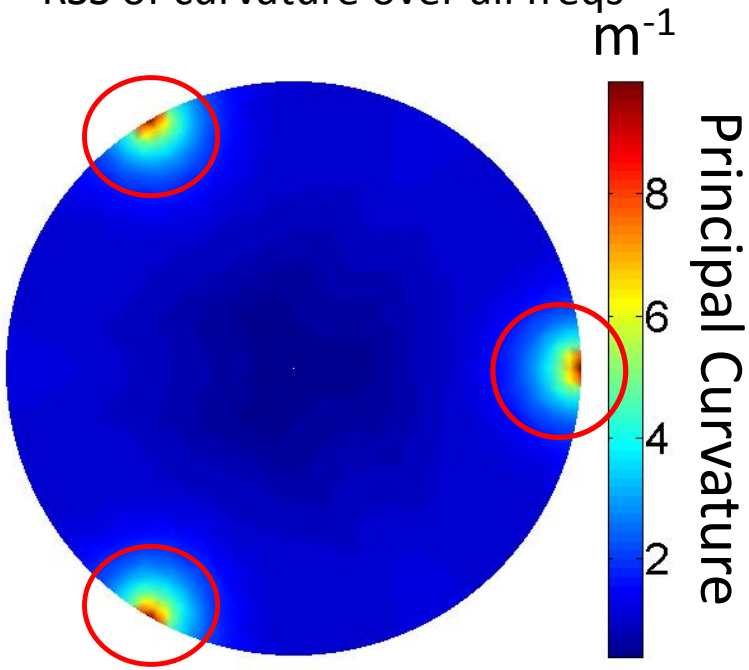


# Launch Survival

- Mirror mass is ~4 grams (0.5 kg/m^2)
- Acoustics are most concerning
  - Delta IV-Heavy acoustic loads (conservative case)
  - Clamping points have critical stresses
- **Likely will require mirror launch restraint**




RSS of curvature over all freqs



# Primarily COTS Components

- Mirror board
  - Mirror
  - PCB
  - Launch restraint system
- Gimbal
  - 3 Newport Picomotors (8301-UHV)
- Multiplexer boards
  - Panasonic AQV258 PhotoMOS relays (1 per channel)
  - Maxim MAX6956AAX+ LED driver IC's
- Controller board
  - M/C options
    - Rascal micro (Atmel ARM9)
    - MBED M/C (ARM Cortex-M3)
  - Apex/Cirrus HV Opamp (PA89A)
  - EMCO (AH06N-5T, AH06-5T) DC-HV DC converters
  - Zigbee wireless (TI CC2520)

Relays

HV Opamp

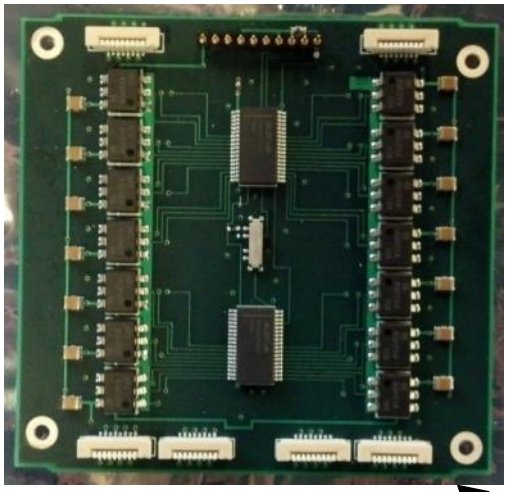

DC->HV DC

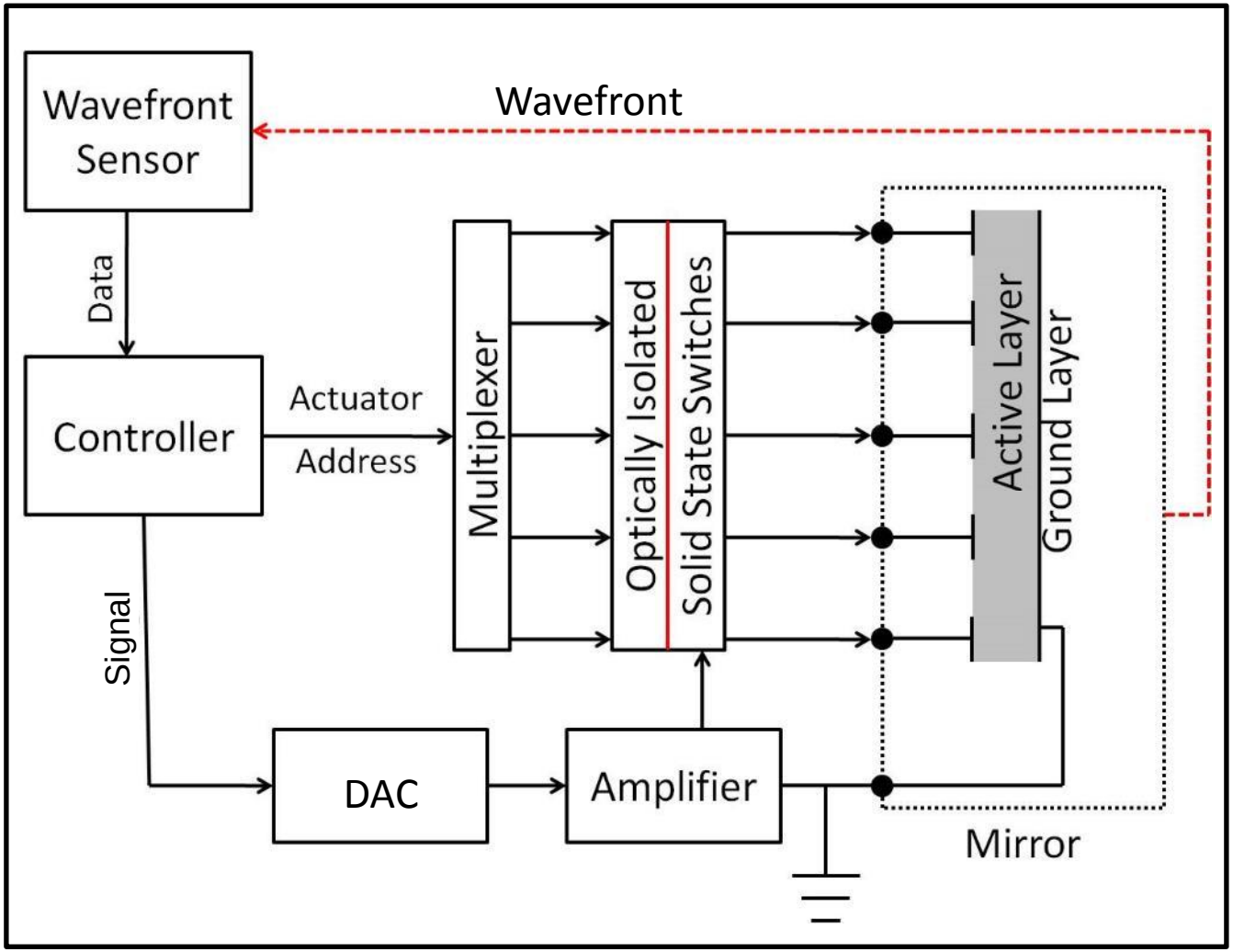
M/C's


Zigbee

# Mirror Control Architecture

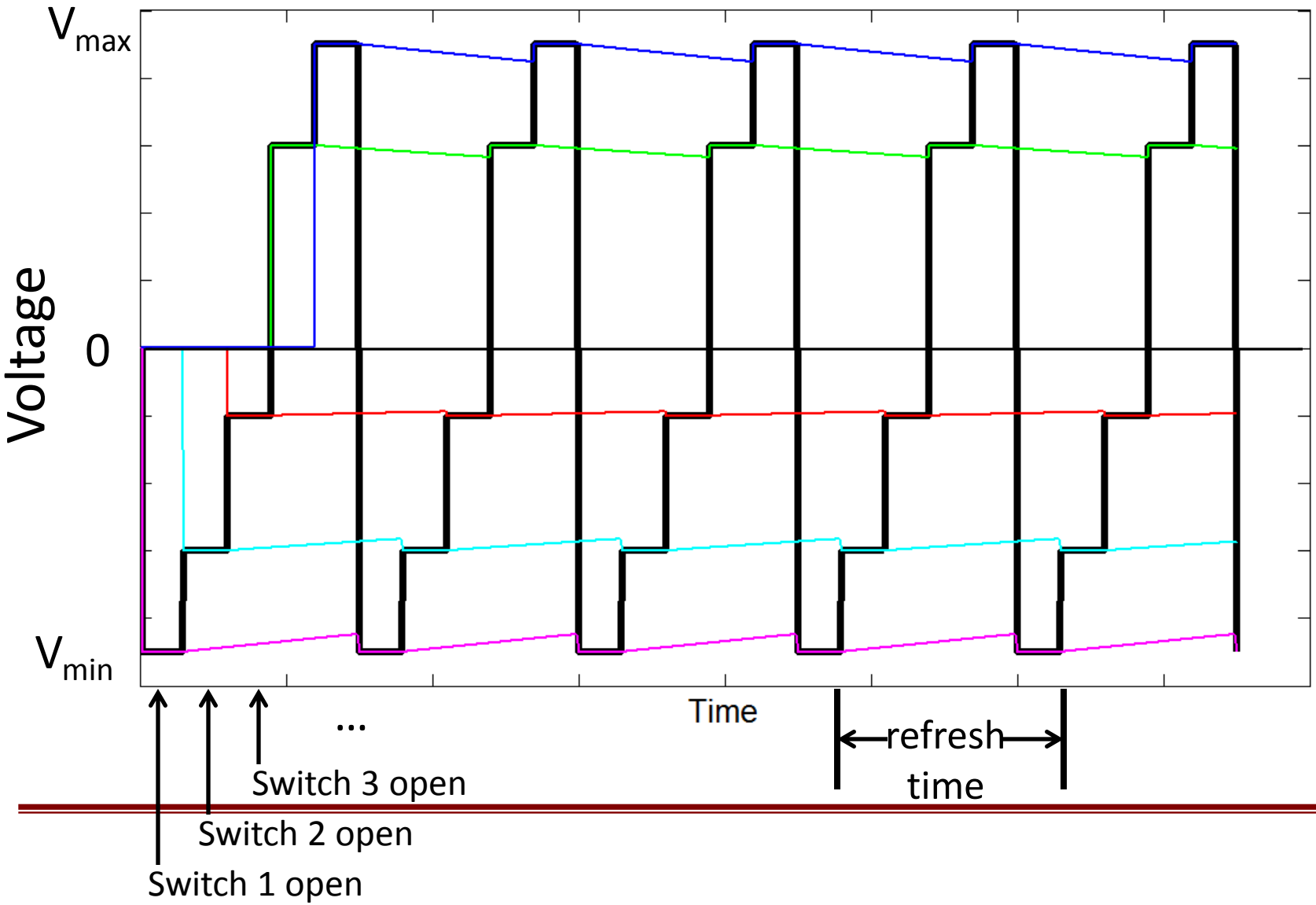
- Single high voltage signal multiplexed into N channels
- Trades bandwidth for mass, power, volume



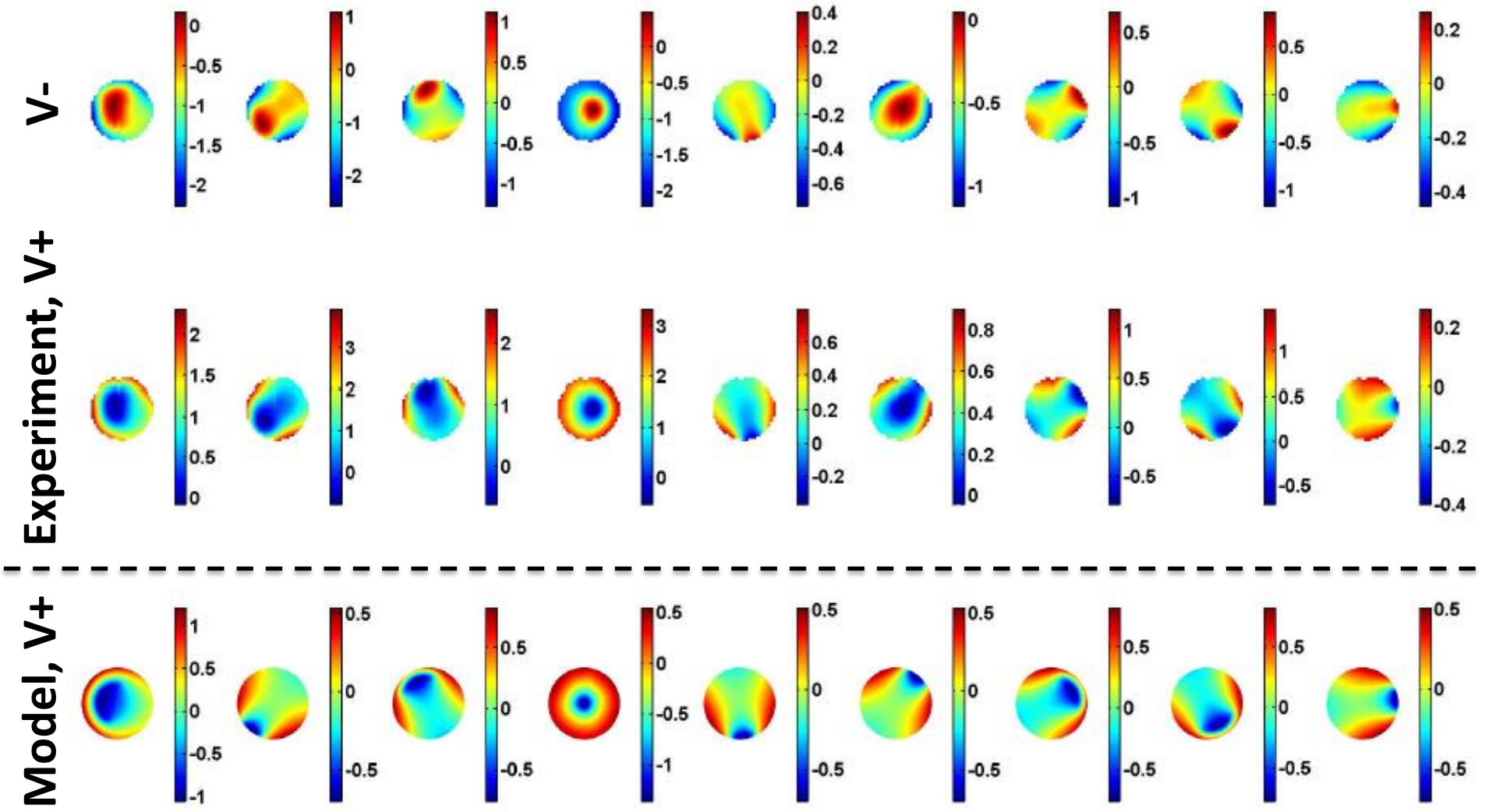




Multiplexer Prototype (42 chnls, +/- 500V)

# Multiplexing Concept

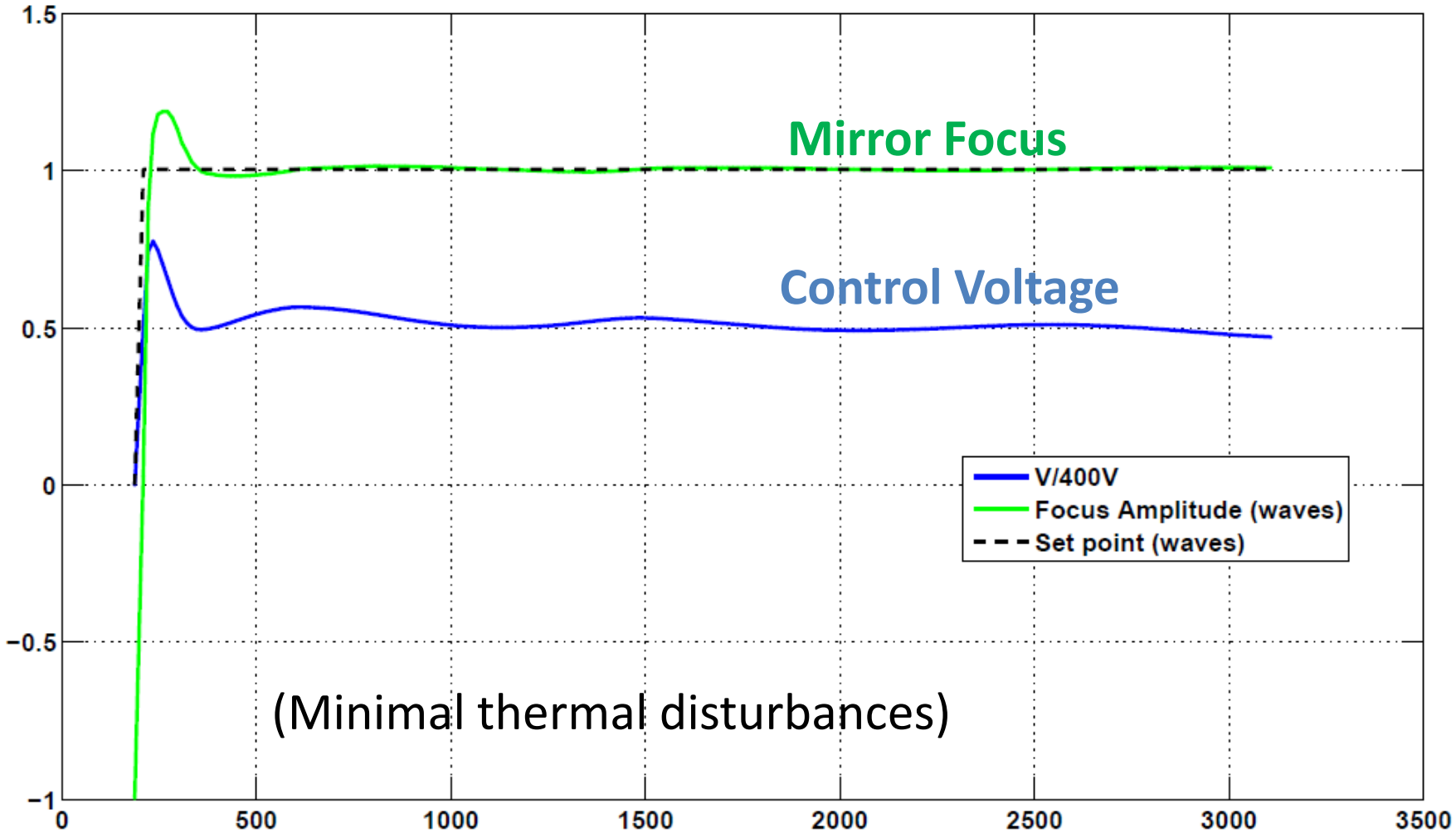


# Mirror Actuation Modes

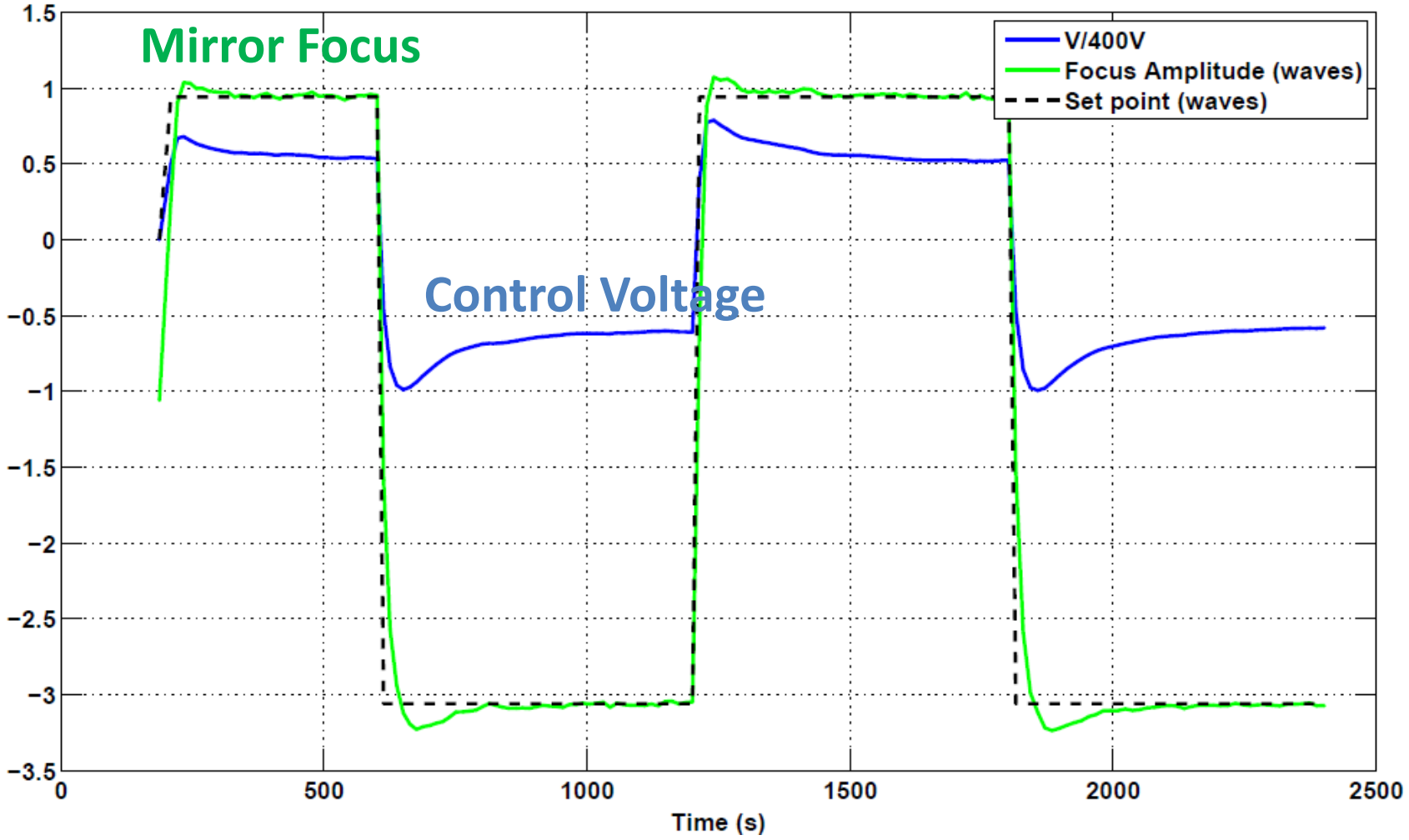



(Color scales in waves at 633 nm)

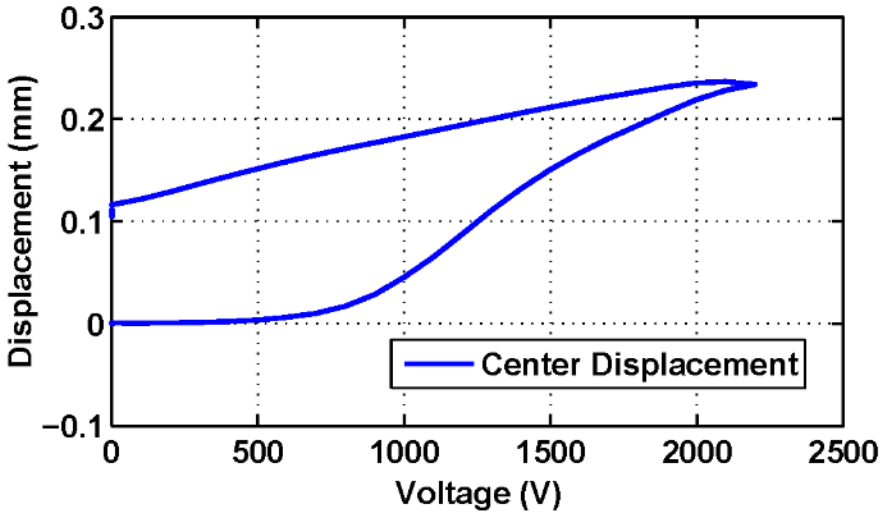
# Mirror Control Experiments

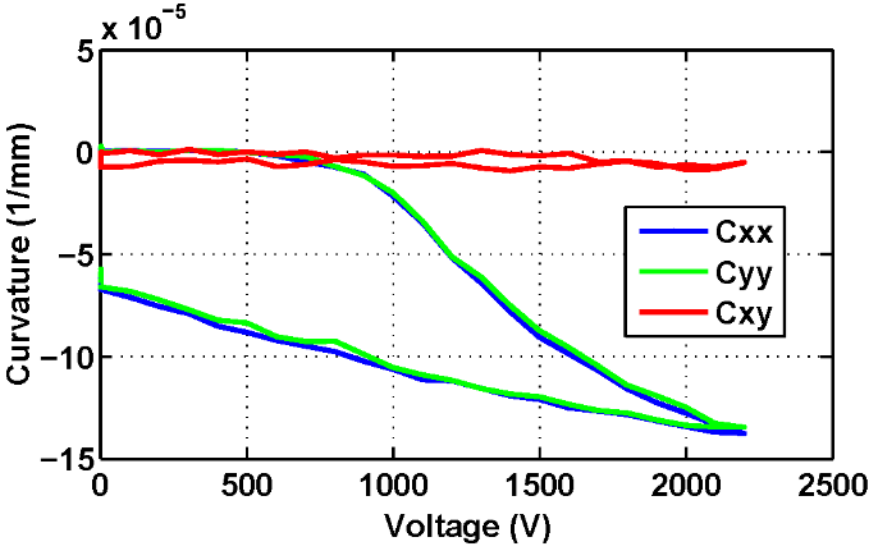


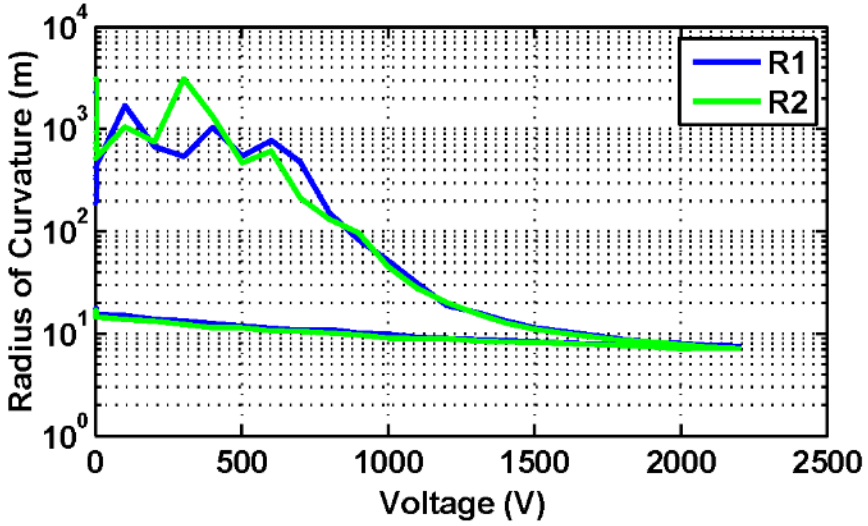
# Mirror Control Experiments

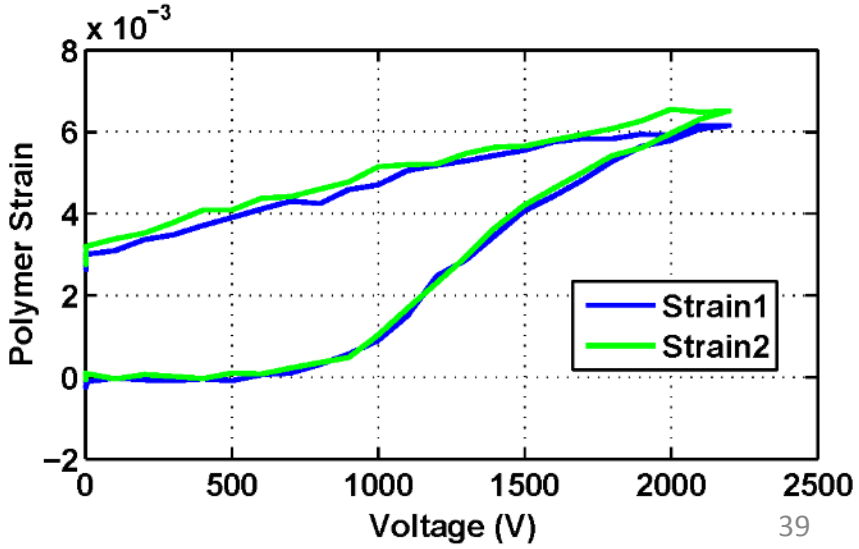


# Poling Data


Displacement (mm)
0.3
0.2
0.1
0
−0.1
0
500
1000
1500
2000
2500
Voltage (V)
Center Displacement


x 10^−5
Curvature (1/mm)
5
0
−5
−10
−15
0
500
1000
1500
2000
2500
Voltage (V)
Cxx
Cyy
Cxy


Radius of Curvature (m)
10^4
10^3
10^2
10^1
10^0
0
500
1000
1500
2000
2500
Voltage (V)
R1
R2


x 10^−3
Polymer Strain
8
6
4
2
0
−2
0
500
1000
1500
2000
2500
Voltage (V)
Strain1
Strain2

# Operating Data