THE VALUE OF PERFORMANCE.
NORTHROP GRUMMAN

Advances in Adaptive Mirrors for Advanced Telescope Systems

Mirror Technology Days

3 October 3013
20 minutes

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AOX Setting the Standard for Adaptive Optics Technology

- AOX is a strategic business unit of Northrop Grumman Aerospace (NGAS) division formed in 2010 by the merger of Adaptive Optics Associates (AOA) a leader in wavefront sensing and control, and Xinetics a leader in active and adaptive optical components

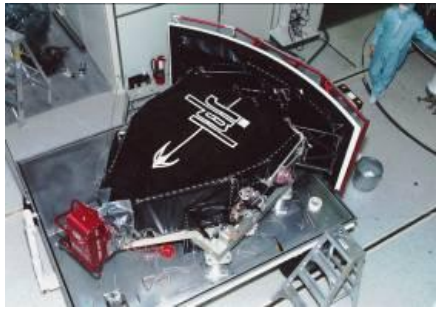
AOA + Xinetics = **AOX**

- AOX focusing on advancing the state of the art of Active Optics (AO) technologies
  - Improving and maturing conventional actuator and Deformable Mirror (DM) technology
  - Inventing new architectures with unique characteristics to expand DM performance and applicability
  - Applying actuator and DM technology to new applications to enable game changing optical systems

AOX continues to built on a legacy of innovative solutions in active and adaptive optics

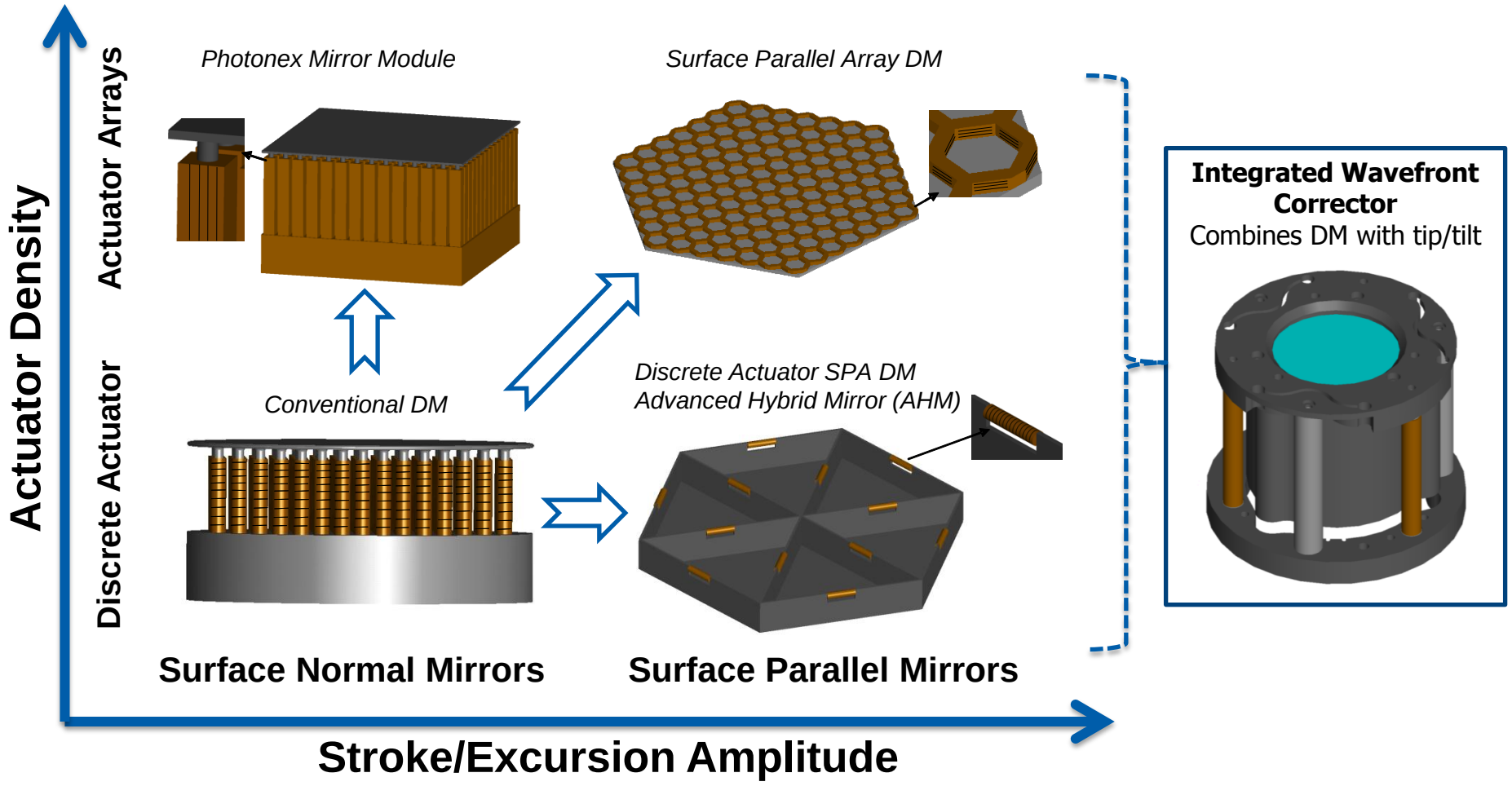
Laser Communications & Compact Laser Terminal

Directed Energy & Lightweight Beam Director



Space Imaging & Segments in the Large

AOX Deformable Mirror Configuration Overview



AOX deformable mirrors utilize novel actuator technologies to address wide range of AO system requirements and applications

Precision Motion with PMN Actuators
… Precision motion from precision actuators

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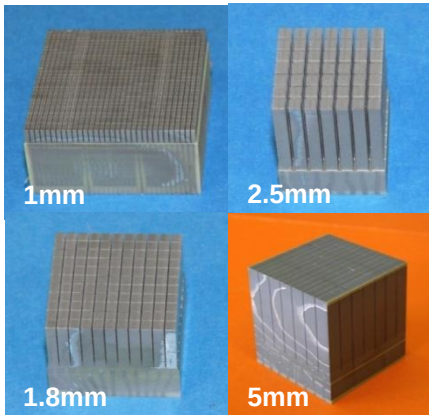
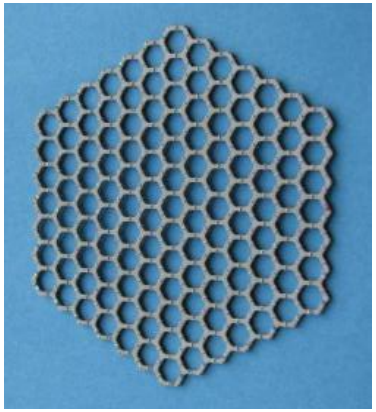
Tailored Actuator Configurations

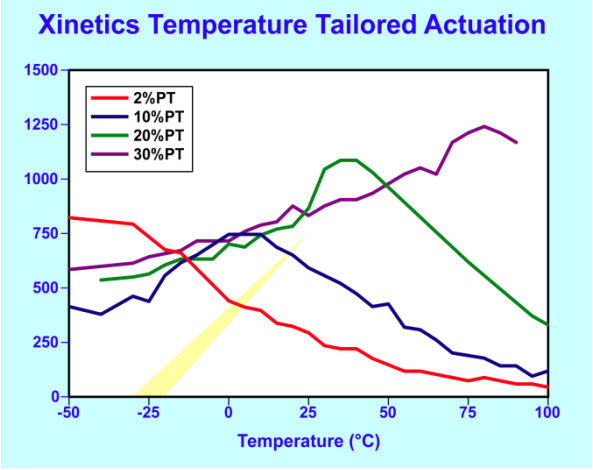
Multilayer Actuator Stacks



High Density Module Arrays

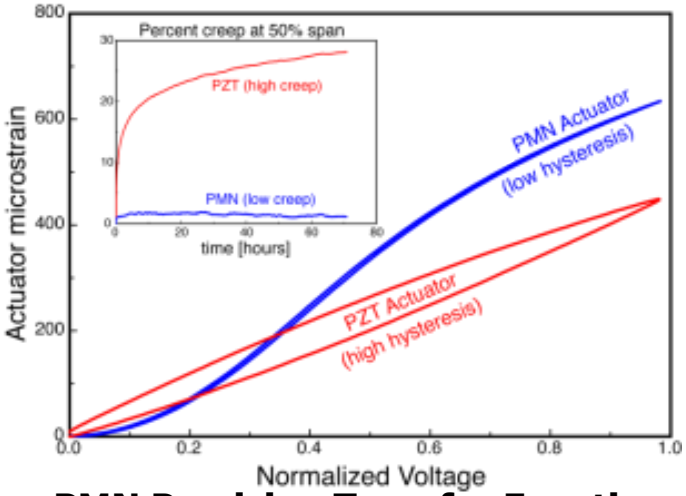


Surface Parallel Arrays (SPA)



Dopant Tailored Response Optimized to Application

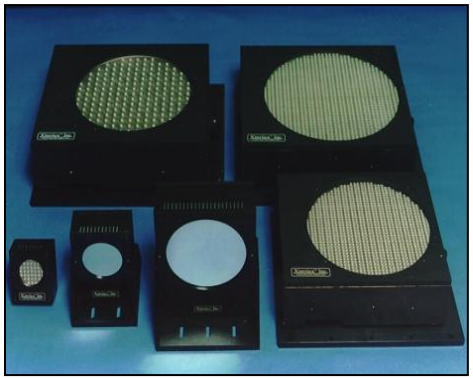
- AOX electrostrictive Lead Magnesium Niobate (PMN) multilayer cofired actuators tailored for deformable mirror applications
- Tailored configurations to meet actuator spacing, stroke and force requirements: Stacks, Modules, SPA arrays
- Tailored material response optimized for displacement and hysteresis over desired operating temperature range
- Exceptional precision compared to other actuator technologies
  - Exhibits little to no hysteresis, aging or creep
  - Fabricated for 0-100V operation



PMN Precision Transfer Function

Deformable Mirrors for Compensated Imaging Systems

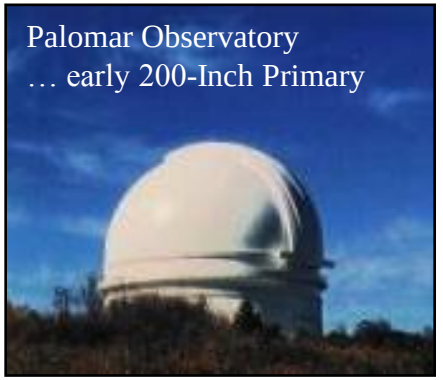
… Atmospheric Compensation via Adaptive Optics



Conventional Deformable Mirrors
- Standard 5 & 7-mm Spacing
- Standard 4-mm Stroke
- 37 to 941 Channels

Module Deformable Mirrors
- 1.8, 2.5 & 5mm Spacing
- Stroke of 1.5 to 4.0 microns
- Up to 3369 Channels

SPA Deformable Mirrors
- 4, 6 & 10 mm Actuator Spacing
- Stroke of up to 50 microns
- Up to 420 Channels



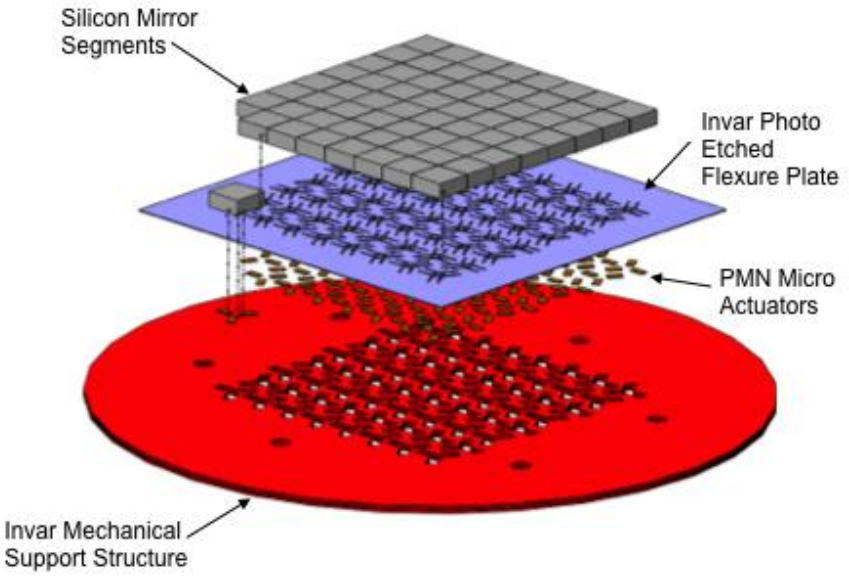
- Industry standard deformable mirror
  - ~200 mirrors in operation around the world
- ULE facesheet typically used to reduce thermal distortion
- Stroke range typically ±2 micron
- High bandwidth required for atmospheric compensation
- Designed for near infinite life
  - Numerous mirrors have been in operation for nearly 20 years
  - >32 giga cycles without performance degradation

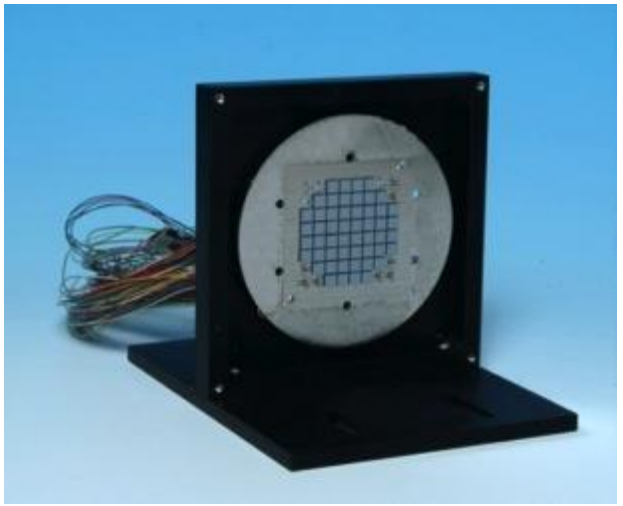
Advanced deformable mirror technology furthering the ability of ground based astronomy to see through the atmosphere

AOX Segmented Deformable Mirror

New Developments in DMs for Compensated Imaging

- Segmented deformable mirrors developed to address issues associated with branch points in conditions of strong turbulence and scintillation
- AOX segmented DM based on PMN actuation and ULE facesheet is compatible with HEL coatings with high residual stress
- Micro-machined unimorph PMN actuators move 5mm X 5mm segments in piston, tip and tilt
  - >5µm piston range, ±2mrad tilt
- Unimoph PMN actuators produce high force and mechanical leverage without snap back limitations or contamination concerns that are typical of electro-static MEMs devices
- Piston/tip/tilt capability reduces number of segments 9X compared to piston only DM for same fitting error
- Prototype devices fabricated and tested
  - 8X8 and 5X5mm segment arrays scalable to much larger arrays





Integrated Wavefront Corrector (IWC) Mirrors

…Combines wavefront control with beam steering functionality

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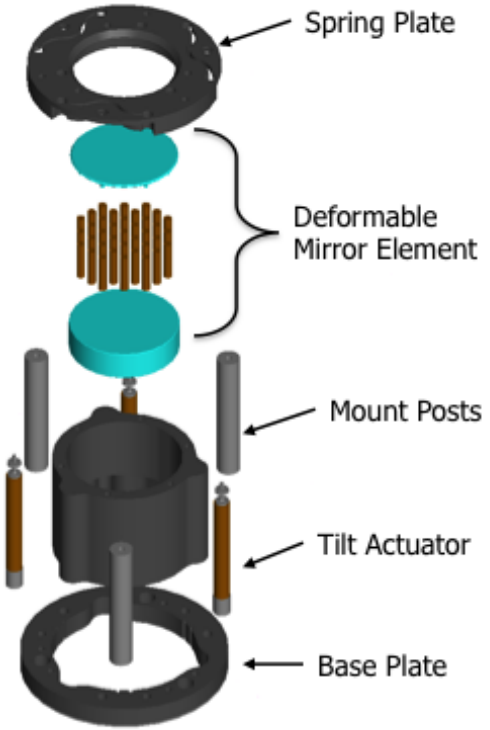
- Integrated wavefront corrector combines a deformable mirror with a fast steering mirror (FSM) into one component for compact AO
  - Eliminates need to relay pupil from FSM to DM reducing number of optical elements in system
- Tilt Stage Element
  - Discrete PMN Actuators
  - Tilt range of ±0.5 mrad
  - Piston range of up to 22µm
  - High Bandwidth
- Deformable Mirror Element
  - Works with either SNA or SPA mirrors
  - Designs produced with
    - Conventional DM 37 & 177 channel
    - SPA DM 76, 285 & 420 channel
    - Module DM 1024 channel




76 Channel SPA IWC
5-mm Array Spacing


177 Channel IWC
7-mm actuator Spacing

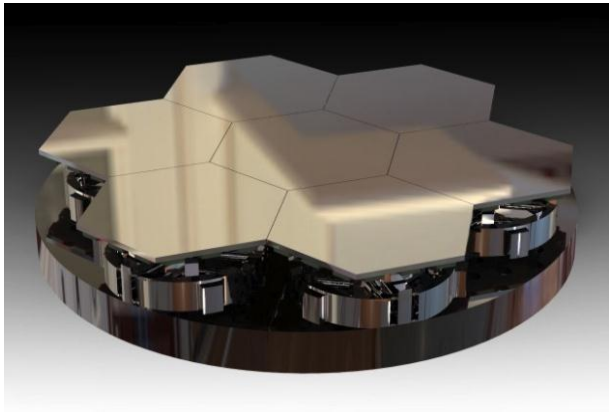

420 Channel SPA IWC
4-mm Array Spacing

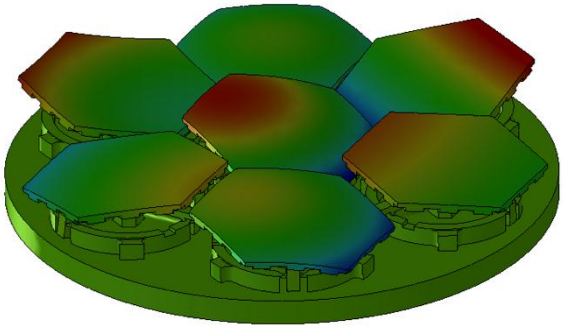
Integrated wavefront corrector mirrors enable more compact and robust adaptive optics by combining FSM and DM functions in single component

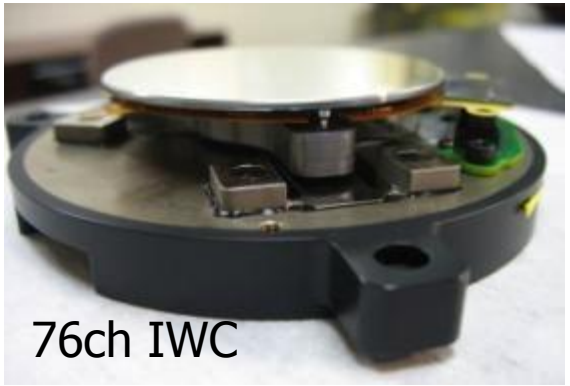
AOX Compact Integrated Wavefront Corrector (CIWC)

New Developments in DMs for Compact Adaptive Optics

- Compact IWC developed to address phasing and figure correction for large segmented primary mirror applications
  - Can be used to correct phasing and figure errors on segmented PM
  - Alternately, can be used to simulate phasing and figure errors of a segmented PM in a test bed
- Each CIWC in a close packed array provides piston/tip/tilt phasing and SPA DM correction
  - SPA DMs combine large amplitude low spatial correction with high spatial correction
    - DM Segment Tilt >±1mrad
    - DM Segment Piston ±20µm range
    - DM Segment Focus >±40µm
- Current designs fabricated with 76ch SPA DM as well as 180ch Module DMs

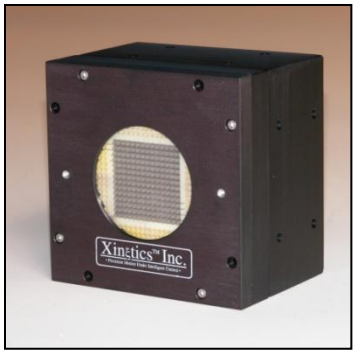






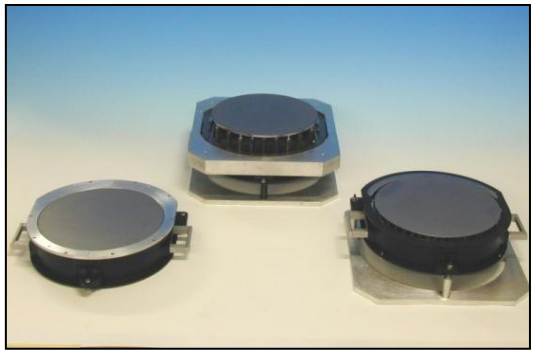
Deformable Mirrors for Directed Energy Systems

… Larger Amplitude stroke & VLA coatings to Mitigate Thermal Errors



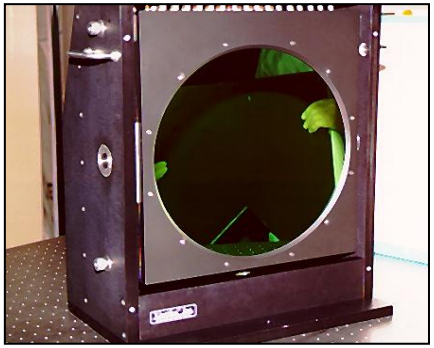
Solid State Laser

- Uncooled ULE facesheet
- 2.5mm PMN Module Mirror
- 196 Channel



HEL Deformable Mirrors

- Uncooled silicon facesheet
- Woofer – large amplitude stroke
- Tweeter – high spatial frequency correction



SBL Deformable Mirror

- Uncooled silicon facesheet
- VLA multi-layer dielectric coating
- PMN Multilayer Actuators

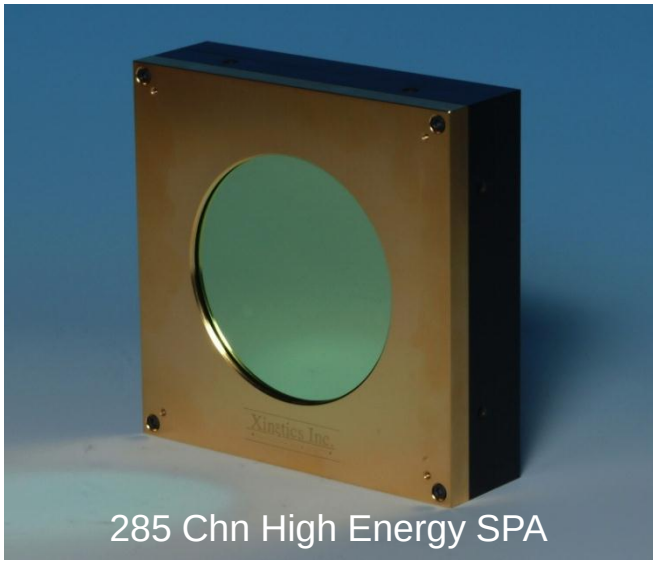
- Very Low Absorption (VLA) optical coatings reduce thermal loads and need for active cooling
  - Mirror must be compatible with VLA deposition temperatures and high residual stress
- Single crystal silicon facesheet typically used to diffuse thermal gradients
- Near IR and IR wavelengths require greater actuator stroke

Advanced deformable mirrors enable propagation of lasers through the atmosphere for directed energy & laser comm.

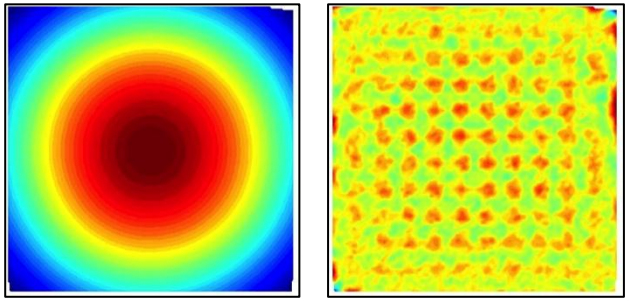
AOX High Energy Laser (HEL) SPA Deformable Mirrors

New Developments in DMs for Directed Energy

- HEL SPA deformable mirrors combine woofer & tweeter functionality
  - Low spatial frequency excursion up to 81 µm PV
  - High spatial frequency correction with 285 to 420 actuators at 5mm spacing
  - Closed loop surface figure <15 nm rms
- Customizable VLA Optical Coating
  - Stress Balanced Coating Process Eliminates Coating Stress Effects on Mirror Figure
- <2°C temperature rise under 5 kW/cm2 for 30s
- Adaptive mirrors suitable for extreme thermal environments since thermal errors are highly correctable by the actuators
- Mirrors fabricated with 7.5cm x 7.5cm clear apertures combined with piston/tip/tilt IWC functionality
- Performance under HEL thermal loading to be validated later this year



5 kW/cm^2 incident power
Thermal distortion after 30 sec



Predicted SFE
113nm rms

Corrected SFE
0.32nm rms

AOX Thermally Managed Deformable Mirrors

New Developments in DMs for High Thermal Loads

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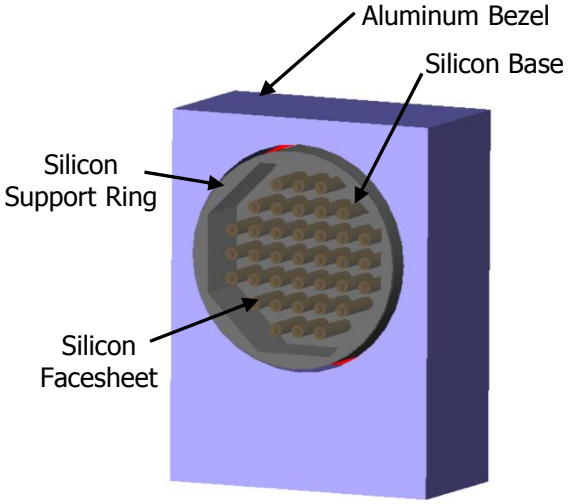
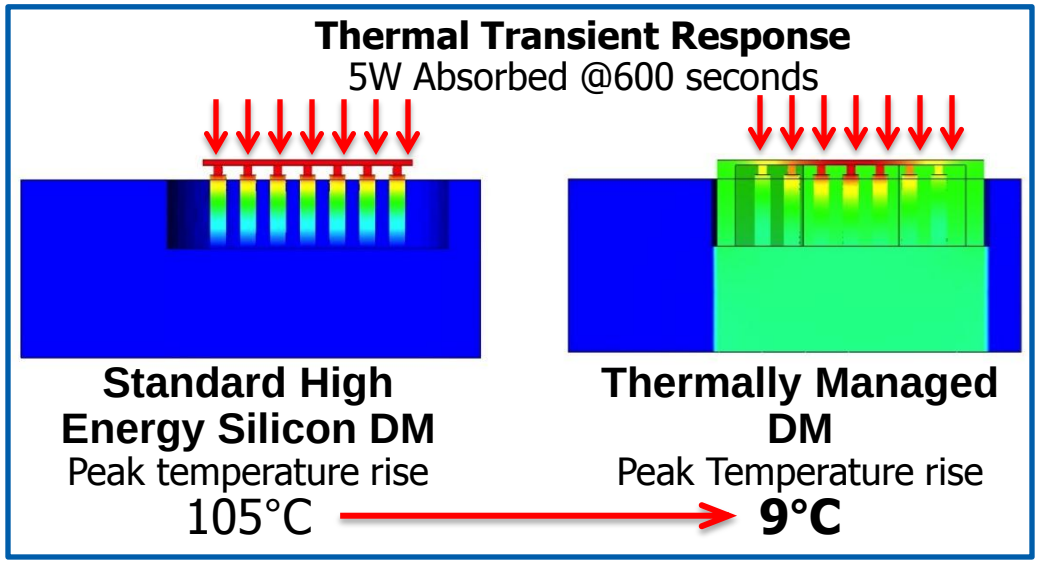
- Thermally managed deformable mirrors allow for steady state thermal loading
- Standard high energy silicon deformable mirrors have insufficient thermal mass in the facesheet to handle extreme flux loading over very long runtimes
- Thermally managed DMs can reduce steady state temperature rise by order of magnitude compared to standard high energy silicon DMs
- Thermal management can be either fully passive, or simple indirect cooling can be implemented to further enhance performance

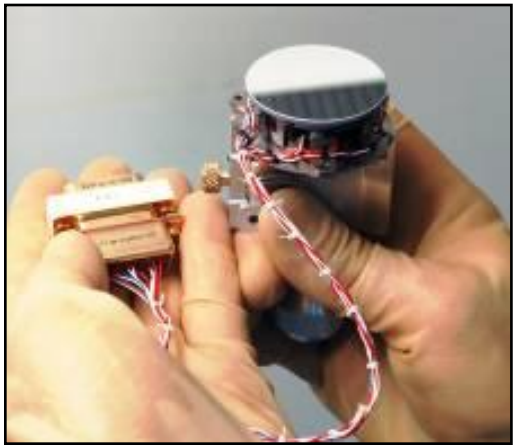




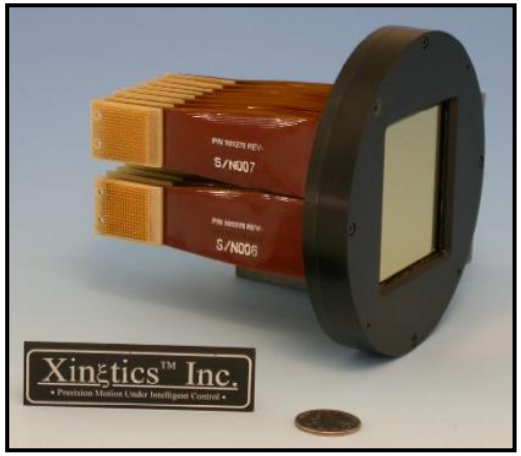
Deformable Mirrors for Space Imaging Systems

The Hubble Space Telescope
Circa 1991

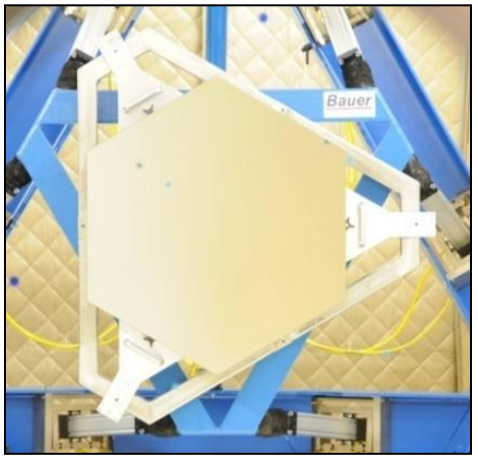
- Many space telescopes have had optical problems after launch – only HST has been corrected on orbit
  - "Control loop" closed by astronaut servicing
- Active Optics: Mirrors that can be reshaped after launch; and the Wavefront Sensing and Control system to command them
  - *Reduce mission risk*
    - Correct any optical problem that might arise
    - Enable testing to spec during system assembly and integration
  - *Reduce mission cost*
    - Reduce mission mass
    - Relax fabrication and assembly tolerances
    - Speed up Integration and Test phase



Articulating Fold Mirror
WF/PC II Precision alignment



Modular Deformable Mirrors
Coronagraph imaging



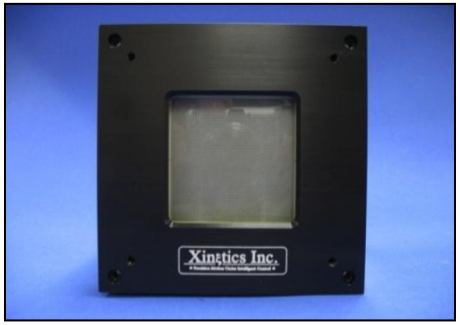
Lumens Hybrid Deformable Mirror
Lightweight segmented primary mirrors

AOX High Density Module Deformable Mirrors

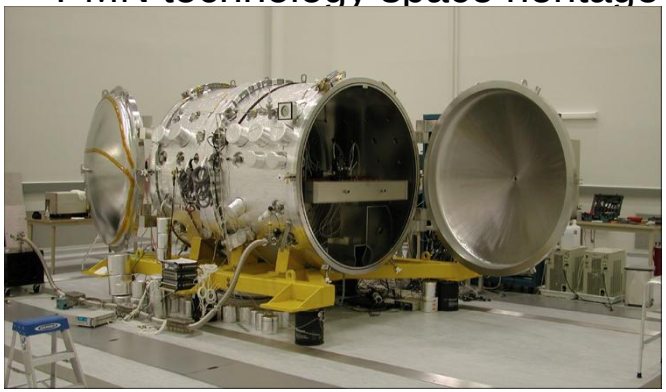
New Developments in DMs for High Contrast Imaging

- 1.0mm spacing modular deformable mirrors provide extreme spatial frequency correction & angstrom level control
  - 1.0mm actuator modules with 0.5 µm stroke available in 32x32 and 48x48 arrays
  - Scaling to mirrors with 4096 channels and greater achieved by bonding multiple modules together into larger arrays
  - Mirror surface polished to λ/100 rms
  - Surface figure (open loop) stable to 0.01nm rms for long durations (> month) with 100% actuator functionality
- AOX module DMs have enabled 10^{-9} contrast imaging for future planet finding missions
- Module mirror technology at TRL-6 based on successful protoflight random vibration testing performed by JPL last year
- PMN technology space heritage at TRL-9 on Hubble WF/PC-2

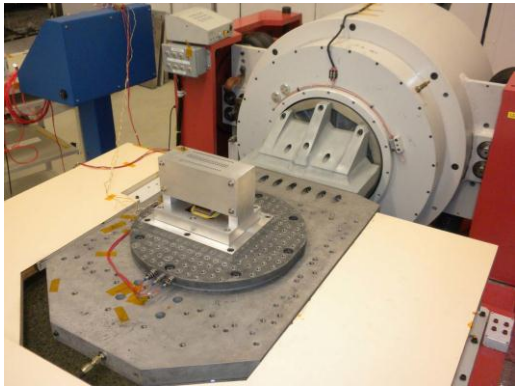
1024 Channel DM 32X32 module



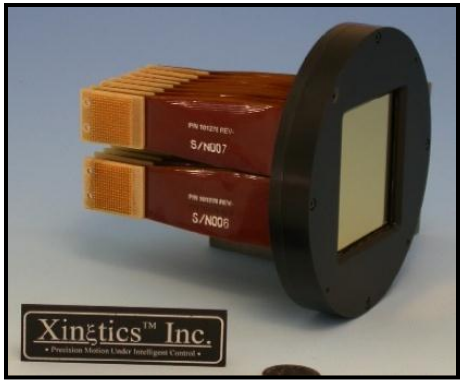
2304 Channel DM 48X48 module



JPL's High Contrast Imaging Testbed



Random vibration testing in 3 axes

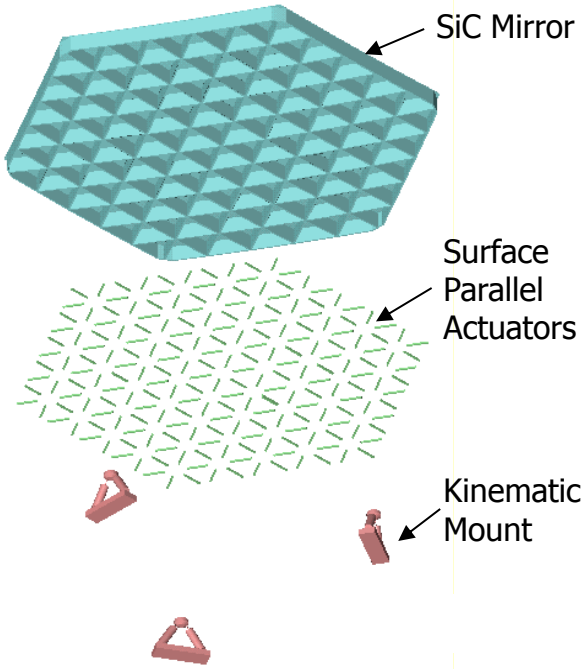


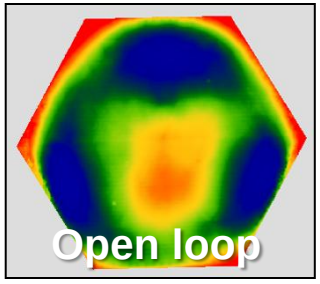
4096 Channel DM
2x2 Array of 32x32 Modules

Active Hybrid Mirror (AHM) for Large Apertures

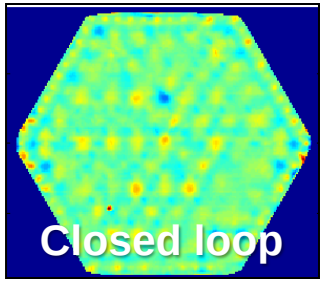
… Ultra-lightweight mirrors for large space apertures

- Lightweight SiC substrates
  - SiC provides high stiffness and dimensional stability
  - Remarkably low areal densities 10-12 kg/m²
  - Apertures up to 1.35m demonstrated, scalable to 2m
- Surface Parallel Actuation
  - Discrete PMN actuators integrated into SiC rib structure
  - Surface parallel actuation eliminates need for reaction structure
  - Mirrors with up to 342 actuators demonstrated
- Optical Surface
  - Nanolaminate optical replication enables production on 6 week centers
  - Direct optical polishing enables better optical figure and finish suitable for UV applications
- Hybrid mirrors suitable for active primary, secondary, or large grazing incidence mirrors
- Replicated hybrid mirror technology compatible with SiC, graphite epoxy and glass substrates
- Active hybrid mirrors can correct for gravity, thermal errors and other system errors allowing for relaxed tolerances
- Technology demonstrated to TRL-6





SFE RMS = 0.386 µm



SFE RMS = 0.021 µm

Rapid production fabrication and low area density of Active Hybrid Mirrors address the needs of future large segmented apertures

AOX Woofer/Tweeter SiC Active Hybrid Mirrors

New Developments in Lightweight DMs for larger apertures

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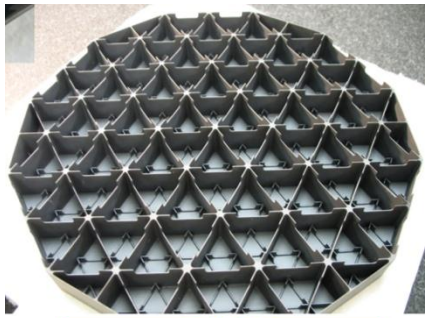
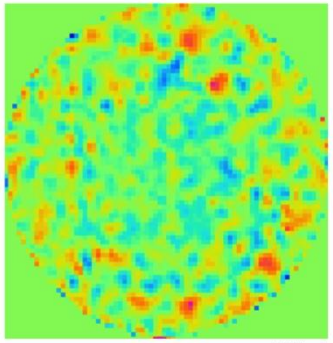
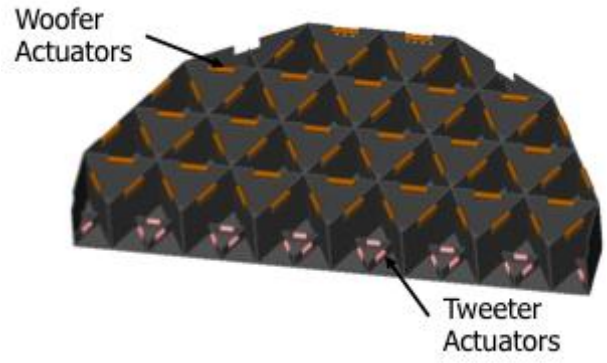
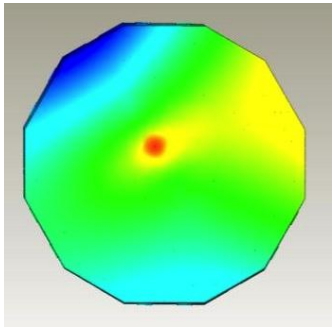
- Direct polished SiC hybrid mirror with surface parallel figure control actuators in main ribs and cathedral ribs for large stroke DM for high energy laser application
- Global Control Actuators positioned in the major rib structure
  - Actuator influence function extends over the entire optical surface for large amplitude low spatial frequency correction – 40µm PV excursion
- Fine Control Actuators positioned in the short, cathedral rib structure
  - Actuator influence only over local zone for high spatial frequency correction
- Direct polished SiC achieves exceptional closed loop optical performance with relaxed optical polishing tolerances reducing cost and schedule
- SiC active hybrid mirrors offer exceptional performance for application with high thermal loads
- Active SiC hybird mirrors suitable for active secondary mirror applications



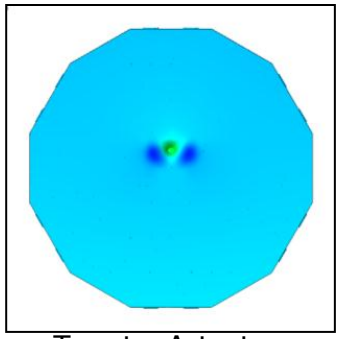


Closed Loop SFE RMS = 4.9 nm





Woofer Actuator
Influence Function

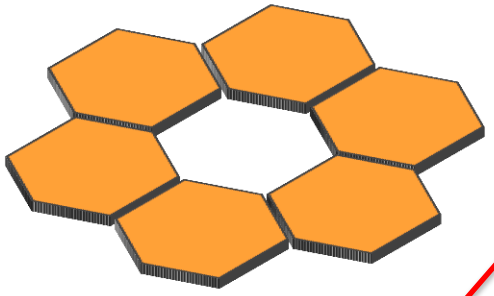


Tweeter Actuator
Influence Function

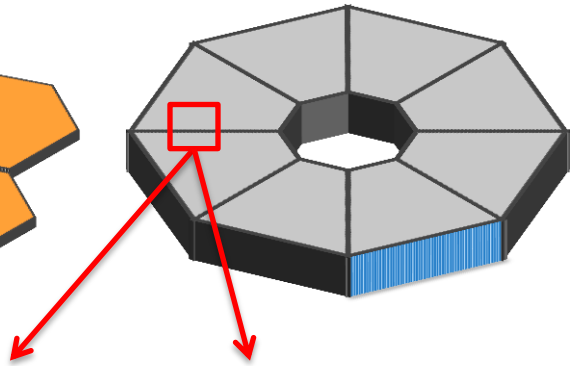
Scaling SiC Mirrors for Large Apertures
Segmented vs Bonded Monolith Mirrors

- AOX SiC manufacturing capability limited to 1.8-2.0m based on size of current infrastructure
- Large apertures with segmented mirrors
  - Segmented mirrors enable scaling to much larger apertures than monolithic mirrors with existing production capabilities by increasing the number of segments
  - Have to deal with phasing segments
- Large bonded monolithic mirrors
  - SiC parts can be joined together to form larger monolithic substrates reducing cost and risk of scaling infrastructure
  - Leverages SiC strength, stiffness and production manufacturability to enable ultra-lightweight substrates
  - Large 1 – 2m SiC substrates to be joined using either established brazing or SiC slip bonding techniques
- SiC Slip Bonding
  - Parts bonded with SiC slip in prefired state before final firing
  - Bonded substrate is polishable across bond joint
  - SiC bonding can be scaled to ~2m using existing furnaces
- Brazing SiC
  - Brazing occurs at a lower temperature than final SiC firing
  - Active fugitive braze materials enable multi-step braze assembly
  - Large braze ovens much less expensive to scale than large high temp SiC furnaces

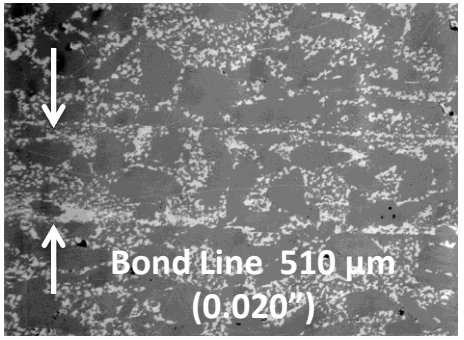
Segmented Mirror



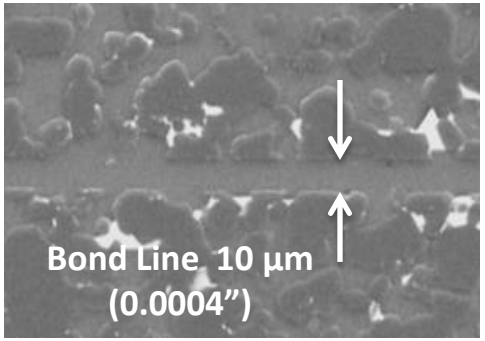
Bonded Monolithic Mirror

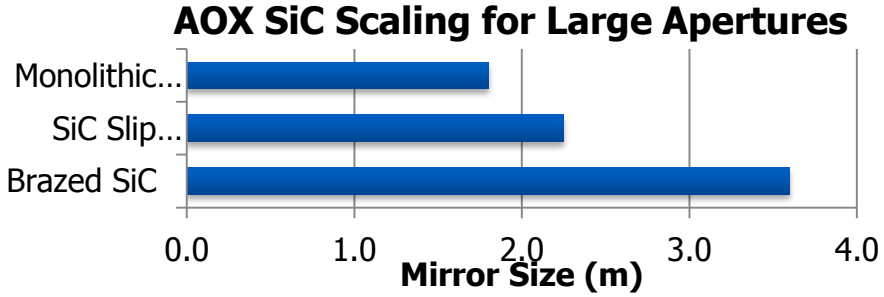


SiC Slip Bonding



Active Fugitive Braze





Summary

- Merging of AOA and Xinetics into AOX brings together decades of wavefront sensing and control expertise with decades of deformable mirror leadership
- AOX has delivered over 300 DM systems
- AOX DMs are operational in applications from Directed Energy to Astronomy for over 18 years
- AOX continues to develop new DM technologies to address various needs such as:
  - Higher bandwidth
  - More stroke
  - More actuators
  - Smaller spacing
  - Increased performance with reduced size, weight and power
- AOX continues to raise the TRL of DMs

AOX inventing and maturing active optics technology to enable a new generation of high-performance optical systems


NORTHROP GRUMMAN