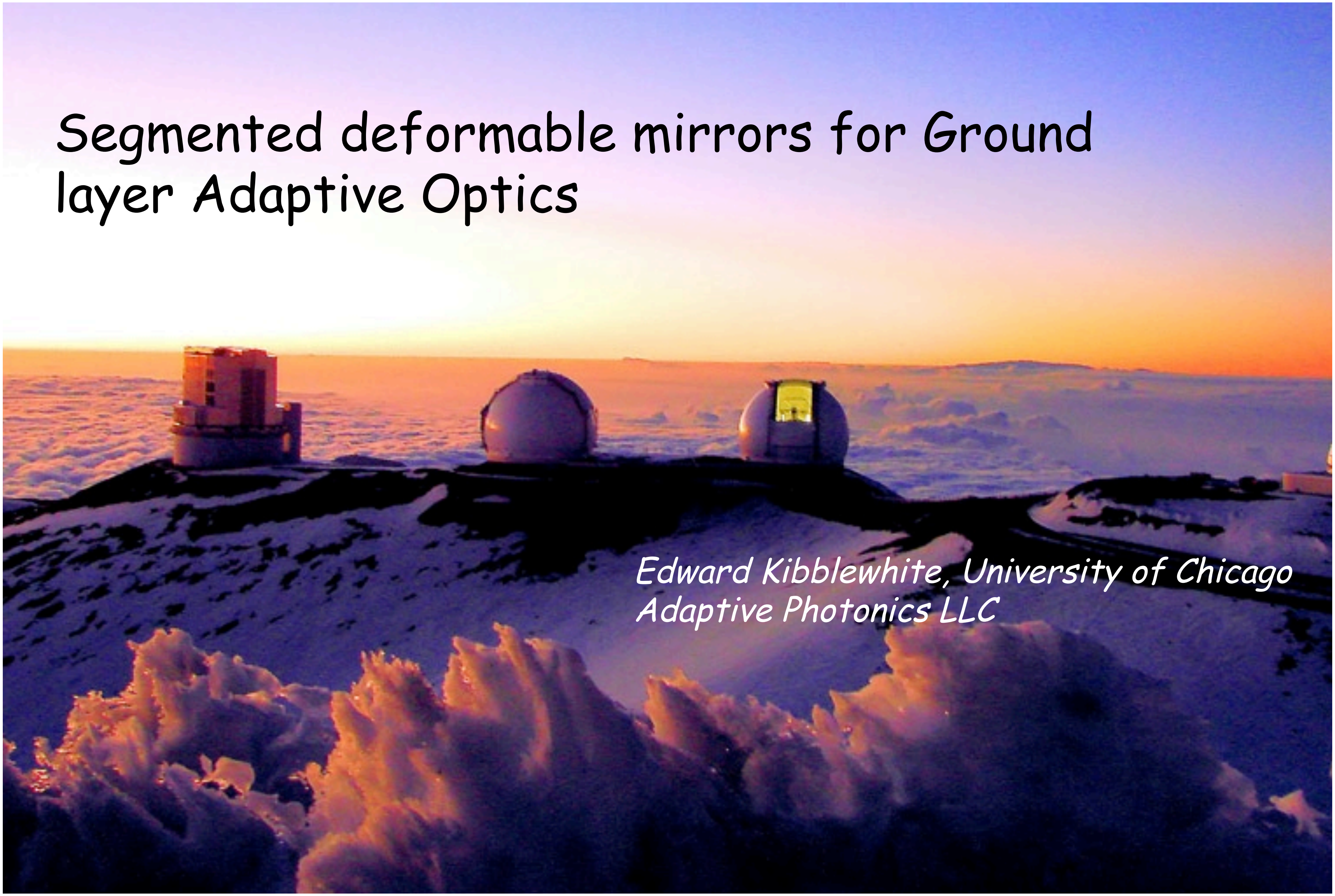
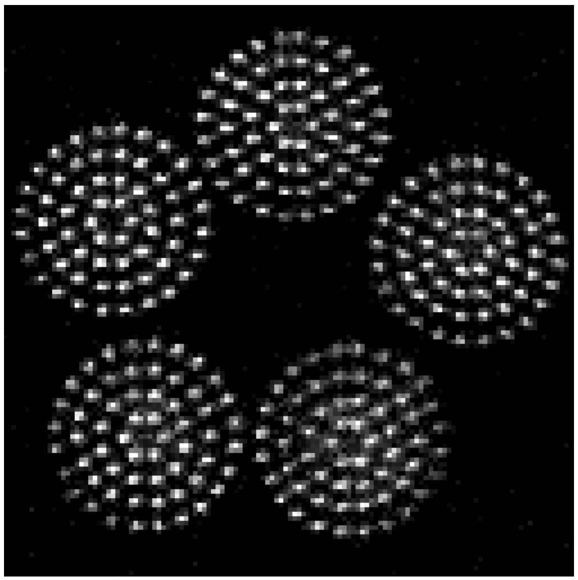
Segmented deformable mirrors for Ground layer Adaptive Optics

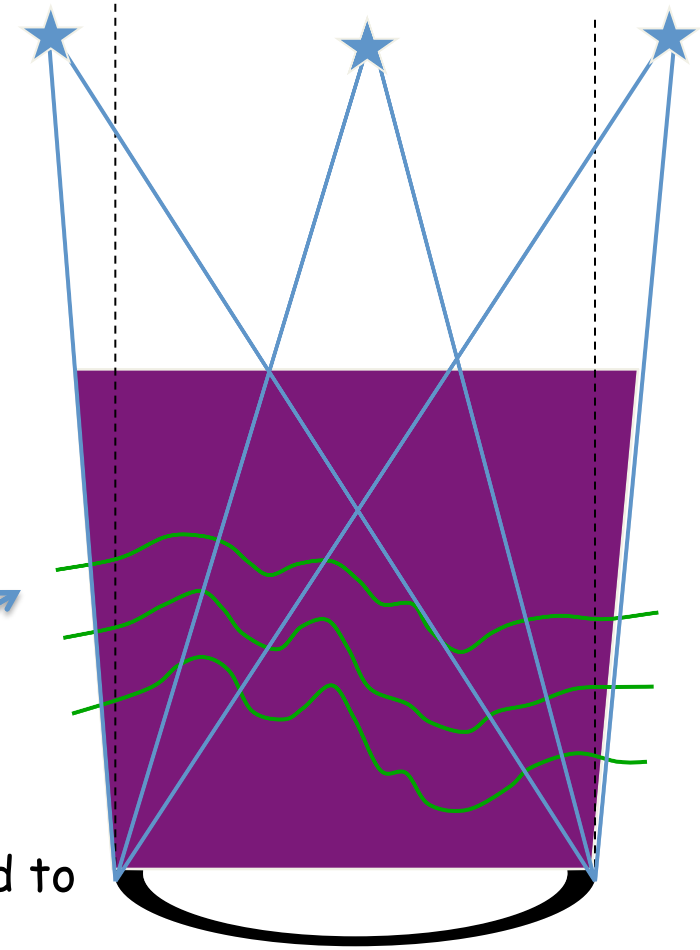


Edward Kibblewhite, University of Chicago
Adaptive Photonics LLC

Ground Layer AO

Shack Hartmann Images of 5 guide stars in Steward Observatory constellation





Slope data from all five beacons are averaged to Reduce effect of low altitude turbulence

Ideal Ground Layer Adaptive Optics

- GLAO EFFICIENCY DEPENDS ON THE SITE

- Median Seeing at Keck Observatory ≈0.63 arcsec
  - 0.21 arcsec telescope seeing
  - 0.45 arcsec in first 80m
  - 0.15 arcsec 80 – 500m
  - 0.33 arcsec in "free" atmosphere

- If we could remove ALL low altitude seeing we reduce seeing 0.63 arcsec -> 0.33 arcsec over a wide field of view

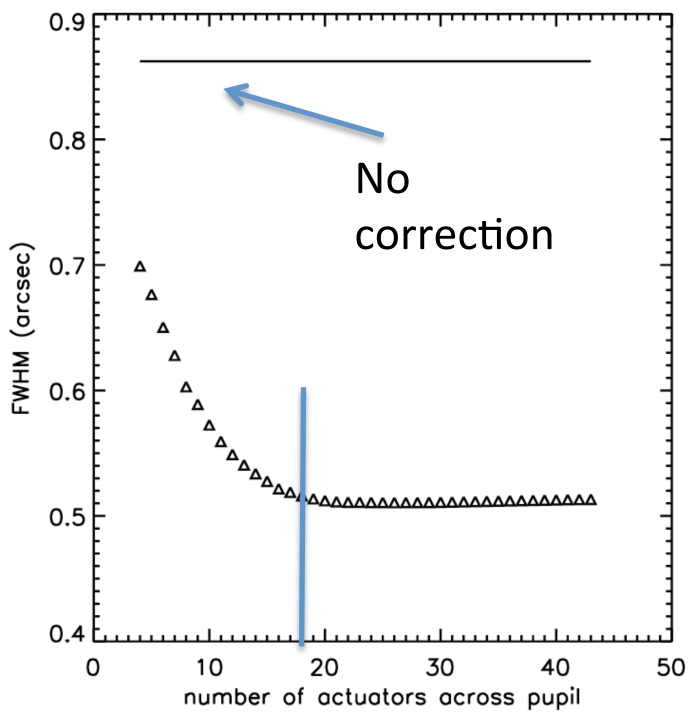
Challenges for GLAO

- Seeing improvement not very large (factor 2 at most, usually 1.5 in practice)
  - Survey figure of merit ≈ (Diameter of field/FWHM)
- Complex system
  - Deformable secondary mirror (?)
  - Multiple sodium lasers (?)
  - Multiple WFS (?)
- Expensive

QUESTIONS:

1. How many actuators do we actually need ?
2. Is there a better way to build the deformable mirror ? (Cheaper, Lighter, lower power etc.)
3. Do we actually need multiple sodium LGS?

Number of actuators needed for GLAO



*[Andersen et al PASP **118** 1574]*

- Various studies suggest modest number of degrees of freedom required
  - 95% optimum performance recovered with 314 actuators for Gemini for > 0.7 μm
    - 1 m diameter secondary

Current Deformable Secondary Mirror technology

- Thin (2mm) faceplate controlled by an array of force sensors floating below a reference plate
- Mature technology

- Lowest resonant frequency of plate ≈ 10 Hz
  - Requires active (high bandwidth force servos) + passive (air film) damping

  Complex interacting design

Most DSM built today have an actuator spacing ≈ 32 mm (≈1000 actuators over 1 m diameter secondary)

- Good for high order AO
- May be overkill for GLAO

Increasing actuator spacing for contactless thin faceplate technology is non trivial

- Increasing spacing from 30 mm to ≈60 mm requires
  - higher damping/actuator (to control resonances within faceplate)
  - thicker faceplates (to reduce gravity deformation)
  - larger actuator forces (to control thicker faceplates)
  - significant extra development (?)

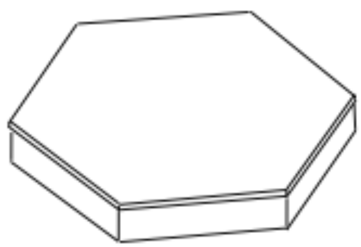
ADDITIONALY

- Faceplate stress scales as diameter^2/thickness
  - Bigger faceplates tend to be more fragile
- Overall weight tends to scale ≈ diameter^3

Alternative approach

- Use an array of segmented mirrors ("mini-ELT")
  - Effective segment diameter 1.4 to 1.7 a continuous plate actuator spacing for similar fitting error
  - ≈95% performance on 1 meter secondary with hexagon mirrors 9 cm side (161 segments have same correction as 316 DSM actuators)
- Advantages
  - Mirror production is straightforward
    - For Keck secondary astigmatism ≈ 3.7 μm, coma ≈ 0.11 μm
    - For TMT secondary astigmatism ≈ 6.6 μm, coma≈ 0.20μm
  - Directly scalable to ELT secondary diameters
  - Lower power, weight
- Disadvantages
  - Gaps between segments (≈400 μm) (although IR emissivity may be less due to hole in middle of segment)

Segmented deformable secondary mirror
built from small segments attached to structural support (reference surface provided by edge sensors) "mini ELT"



9 cm mirror segment
integrated with electronics

Large Adaptive Secondary mirror

Effective segment diameter
1.4 to 1.7 actuator spacing for similar fitting error
(depending on edge conditions)

≈95% performance on 1 meter secondary with hexagon mirrors 9 cm side

(161 segments have same correction as 316 DSM actuators)

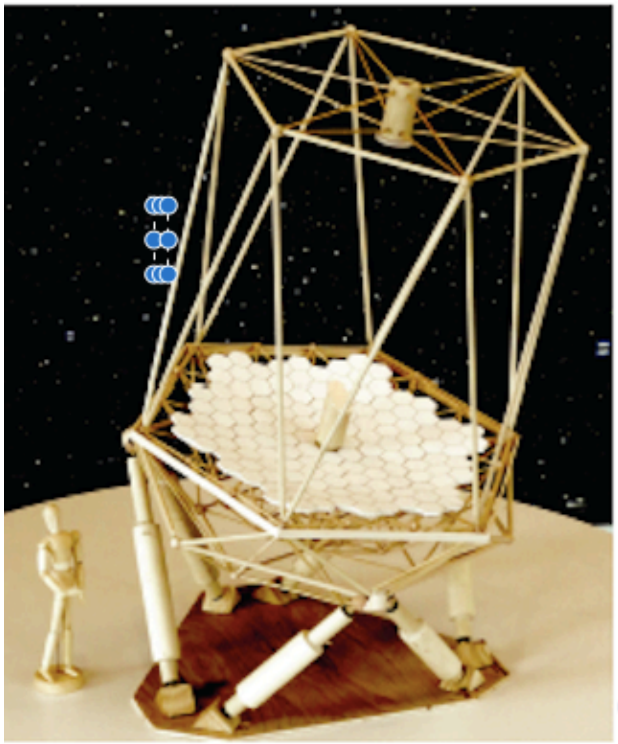
Based on Agile Segment Telescope Technology

- Historically no factor of two increase in size achieved without MAJOR technology change
  - Only way to break $D^{2.6}$ cost law
- 21st century technology drives us towards cheap mass production of components + clever computer control
  - CD disks, digital camera, automobiles (?) etc.
- ELTs will be the flagships of astronomers for key projects

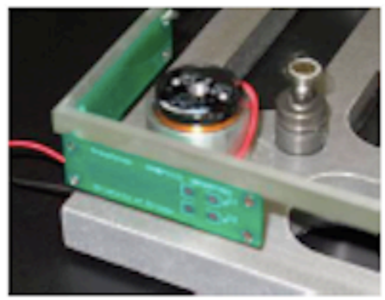
  BUT
- Critical need for access to large (12-15m) telescopes dedicated to various statistical survey and high risk projects: GOAL: $100K/sq.m

25m deep space tracking telescope

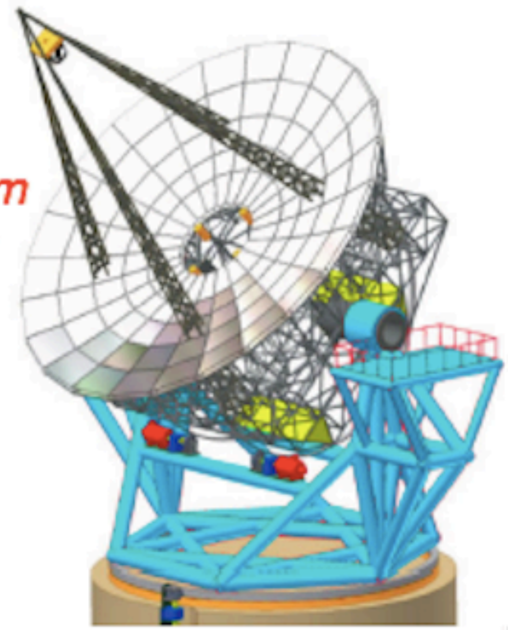
Adaptive wavefront control at the primary mirror



50% Strehl @ 1.2 μm in 1.4 arcsec seeing and 16th magnitude point source



actuator, edge sensor and damping support



2.4m telescope for GEO satellite imaging interferometric array

Advantages of Segmented Deformable Secondary Mirrors

- Ease of manufacture: Segment size ≈ 9 cm

Zernike	Keck	f1.6 12 m	TMT
c22	-4.05 μm	-4.55 μm	-6.54 μm
c31	203 nm	195 nm	97 nm

- Long Life high reflectivity coatings
  - ≈ 98 % reflectivity over wide wavelength range
- Hole in center can match secondary obstruction
  - lower emissivity [offsets ≈1 % loss due to gaps]

Lower weight, power consumption, cost.
Scalable technology

Forces to track wavefront are very small

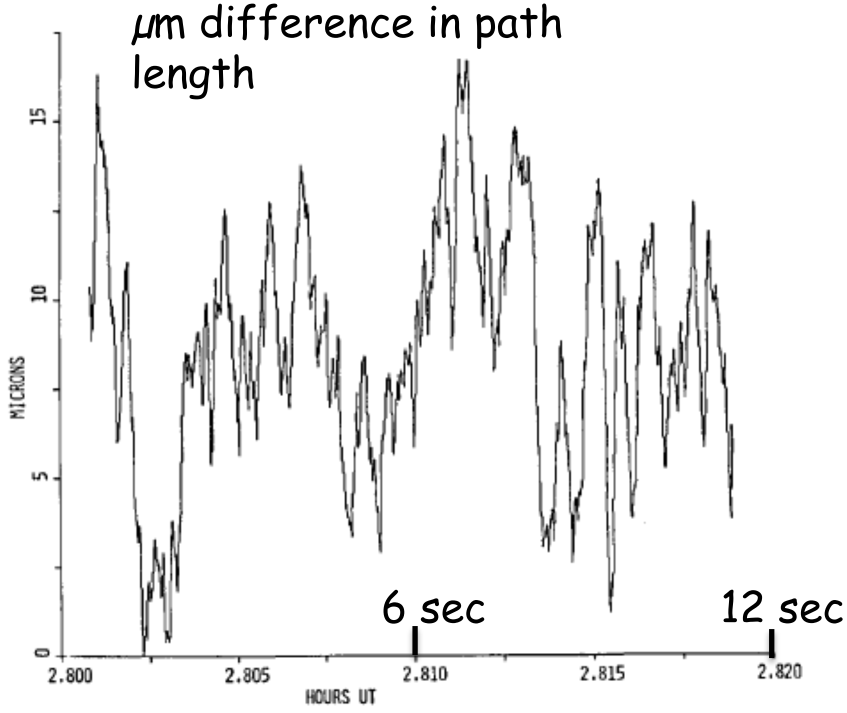


Fig. 3. Fringe position for α Aql, 6 Nov. 1986.

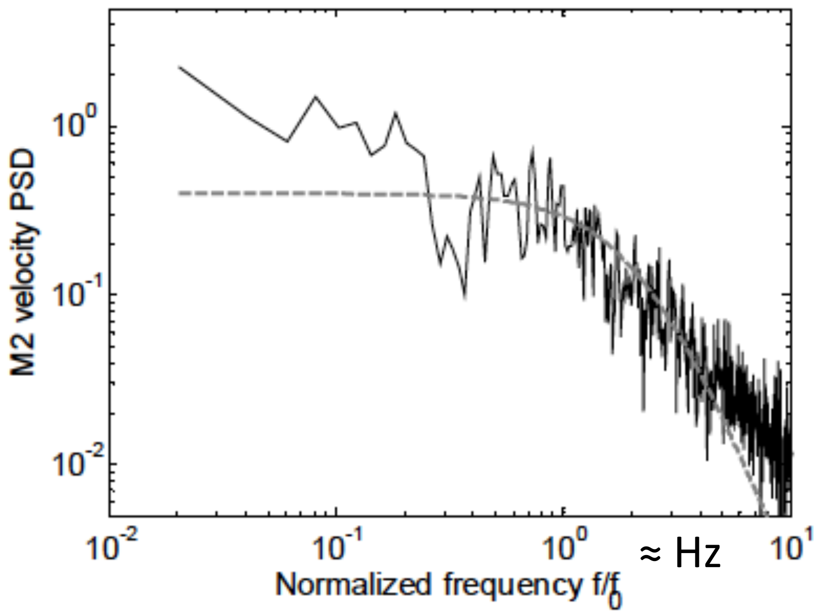
Correlation time constant
(time to move 1 rad)
$T_0 = 0.81 r_0 / v \approx 0.01$ s

rms fringe velocity ≈ 10 µm/s
rms acceleration ≈ 2 mm/s^2

NOTE: Even assuming movement of 1.47 $(D/r_0)^{5/6}$ rad% [rms wavefront difference between center and edge of primary] in T_0 gives rms acceleration ≈0.05 m/sec^2*

Path length variations between 10 cm apertures spaced 12 m apart [Mk3 Interferometer]

Wind Forces are more important

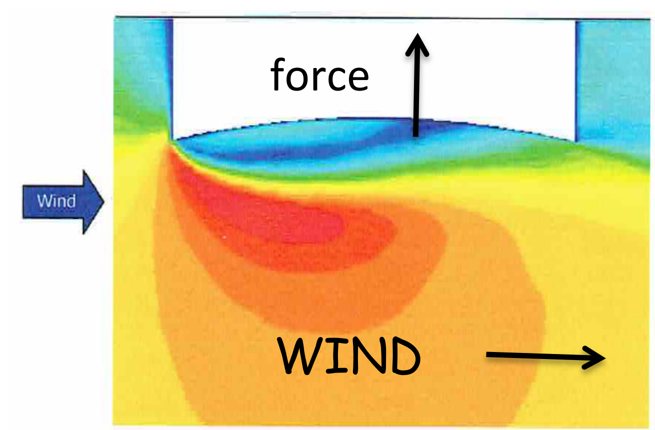


Gemini study found 40% outside wind speed at secondary

23% outside wind speed in buffeting

73% force normal to surface (Microgate LBT study)

For Outside wind velocity of 15 m/s
Low frequency wind force ≈ 10 Pa
Wind buffeting (≈ 1 Hz) ≈ 4 Pa
Worse case shear force across segment ≈0.03 N
[there is a force gradient across the secondary]



Summary of pressures

• Areal weight under gravity	150 Cos z Pa
• Static wind force DC – 1 Hz	5 Pa
• Wind buffeting $\geq$ 1Hz	2 Pa
• Wavefront compensation	<0.01 Pa

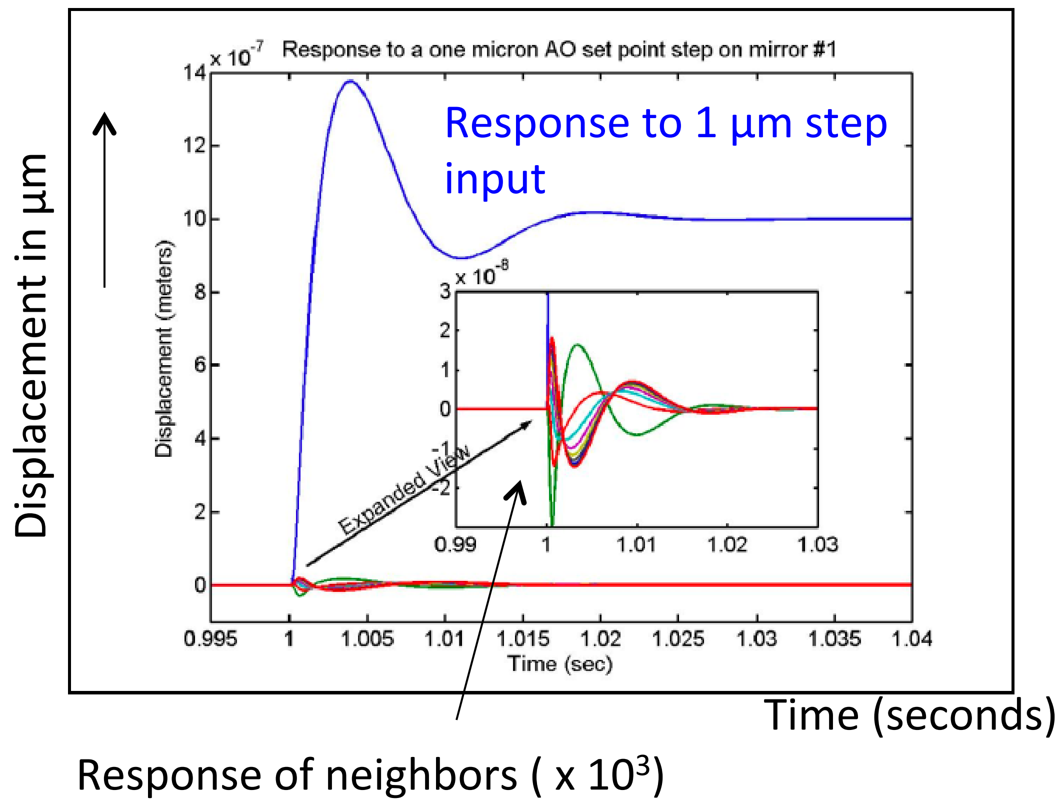
TECHNICAL CHALLENGES

Damping of structure

Development of small, low power, edge sensors

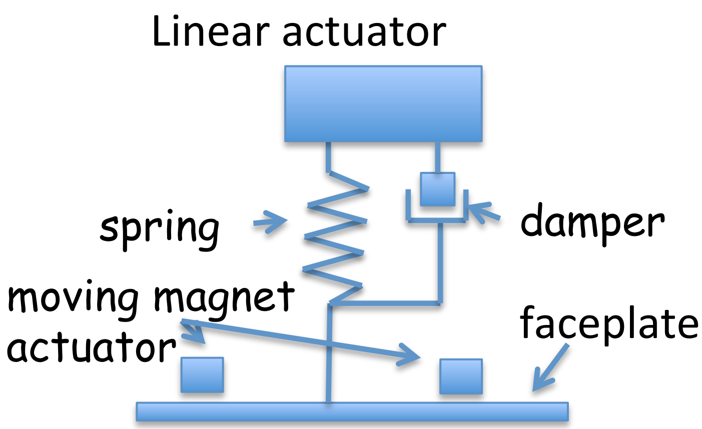
Tilt/piston position can be controlled on a compliant backing structure

RESULTS FROM SIMULATION

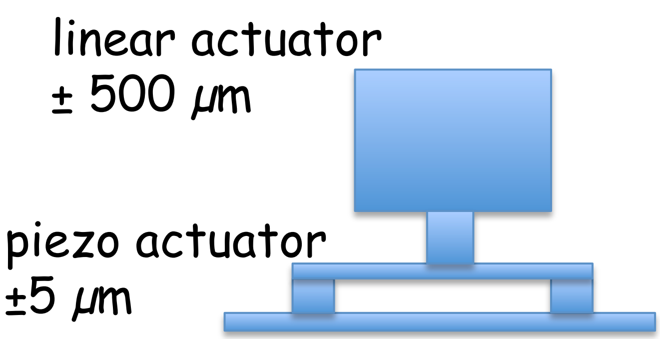


- Servo control bandwidth > Structure
- Tip-tilt interaction very small
- 1 µm step on one segment kicks neighbor by 15 nm

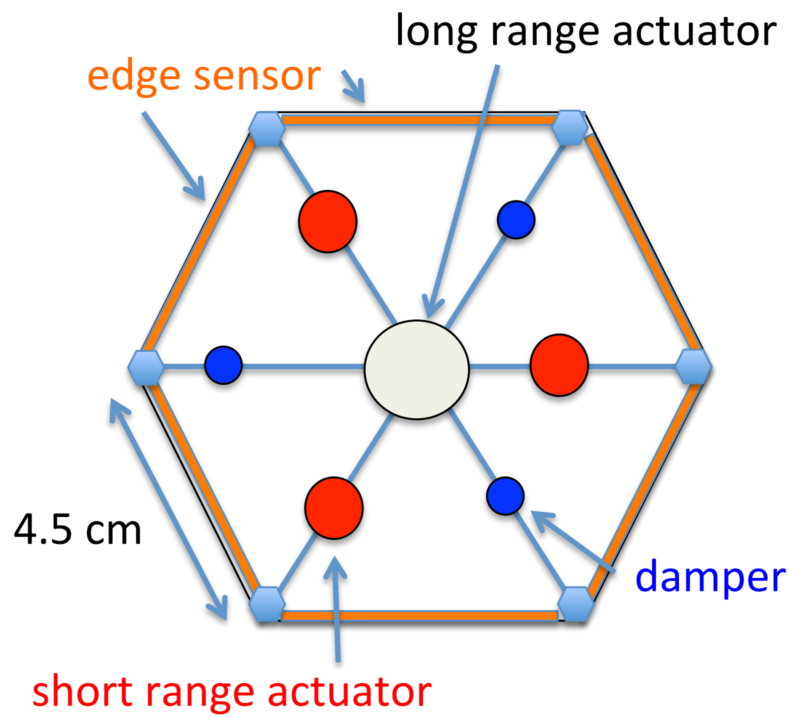
Hierarchical control system examples



Force actuator control



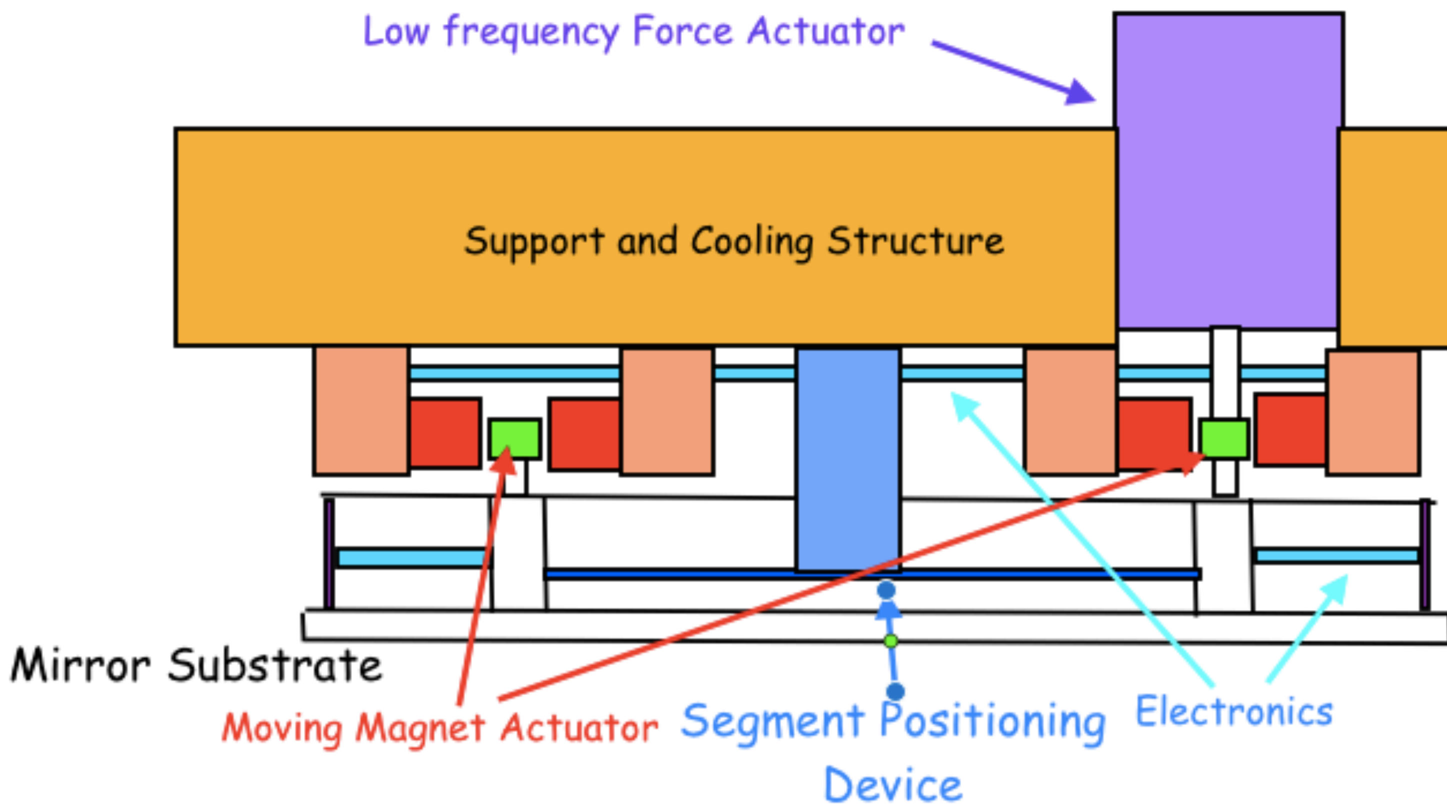
Position actuator control



power dissipation/segment ≈ 0.5 watt

Each segment can be individually removed

Schematic diagram of a segment

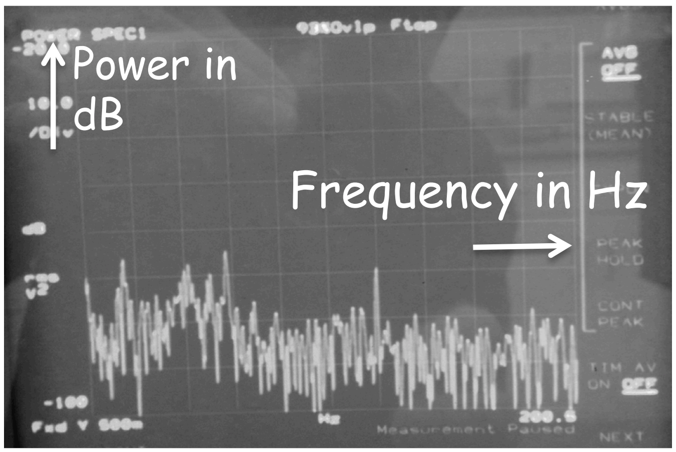


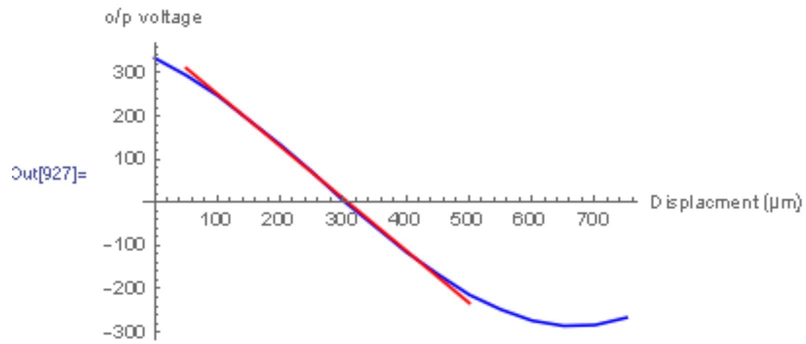
Adaptive Photonics edge sensor

Critical technology – small size, low power

- Analog version (300 mW power)

Power Spectrum





Frequency	Position Noise
60 Hz	0.5 nm
120 Hz	0.8 nm
60-2000 Hz	0.081 nm/√Hz

Next generation:

Linear range: ±0.35 mm

2 x 1 x 0.2 cm linear dimension

< 50 mW power/sensor

Bandwidth: 100 kHz

Noise < 0.3 nm/√Hz

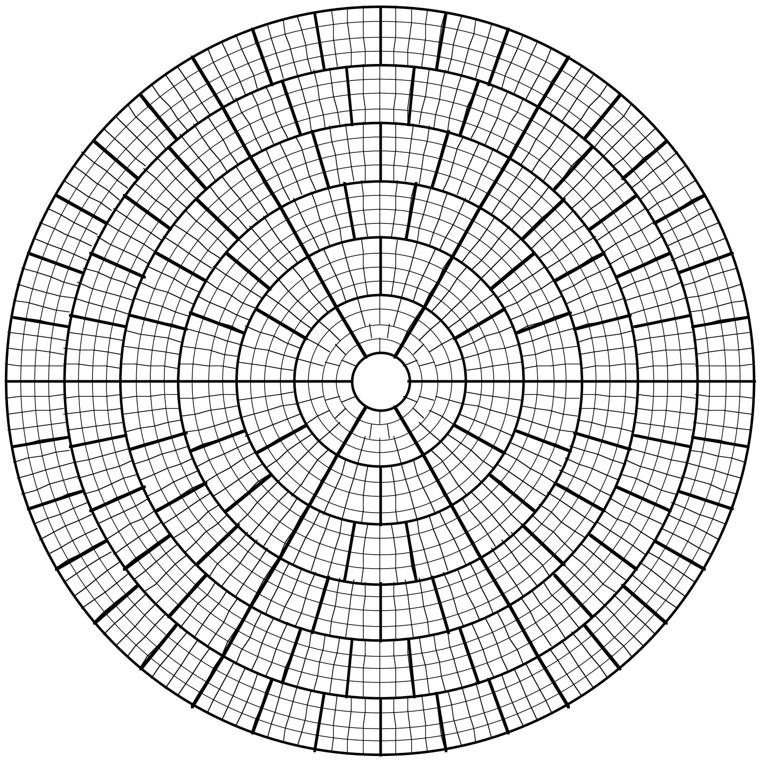
Summary of force actuator control

- Individual segments ≈ 50 cm^2 in area
- 80 gm. moving mass/segment (including electronics)
- 3 point support: 9 nm rms quilting
- Force requirements
  - Short range (3 kHz bandwidth) ≈ 0.02 N/actuator
  - Long range (10 Hz bandwidth) ≈ 0.3 N/actuator
- Total Power dissipation/segment

On segment	
Short range actuators	50 mW
Position sensors	300mW
Off segment	150 mW

For 1 m diameter secondary
Total Power < 150 watts
Total weight < 100 kg

Segmented Mirror technology for ELTs



- Trapezoidal segments may have advantages for ELTS
  - 24 different segments for 3.6 m secondary
  - assembled in rafts of 16 segments
  - 1992 segments 7 cm. across
  - 4000 degrees of freedom

CHALLENGE 3: Sampling the wavefront in GLAO

- Ideal system would use tomographic reconstruction of 3-D turbulence and average out the ground layer

- Most systems propose array of LGS/NGS and average out the effects of high altitude turbulence (often a dual use laser system)

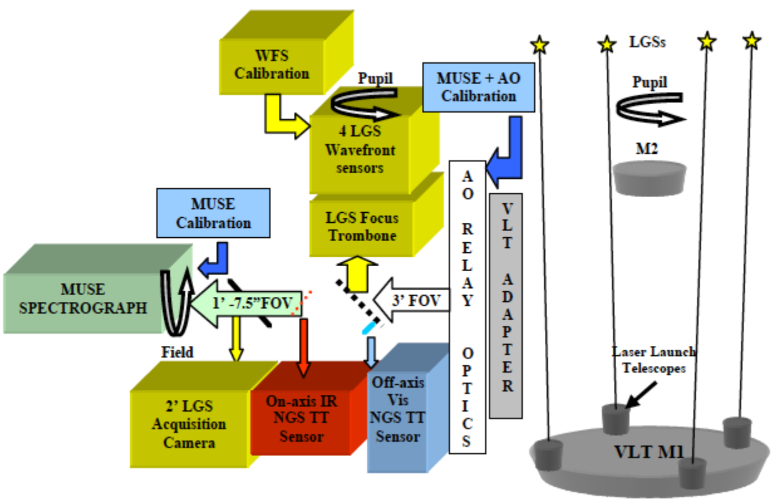
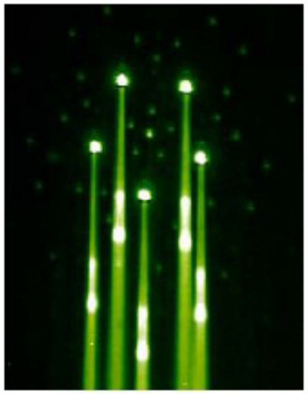
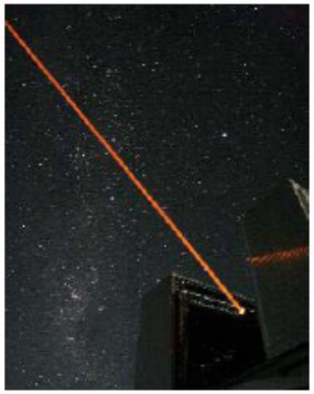
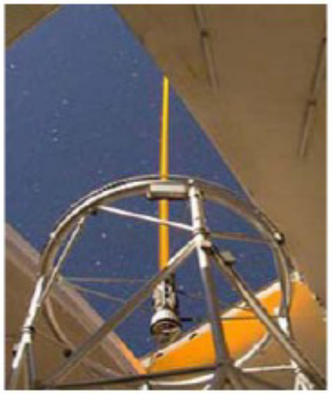


Figure 2: MUSE GLAO #1 and 2; GLAO#1: DM is at M2, GLAO#2: DM is in the AO relay optic

Possible laser approaches

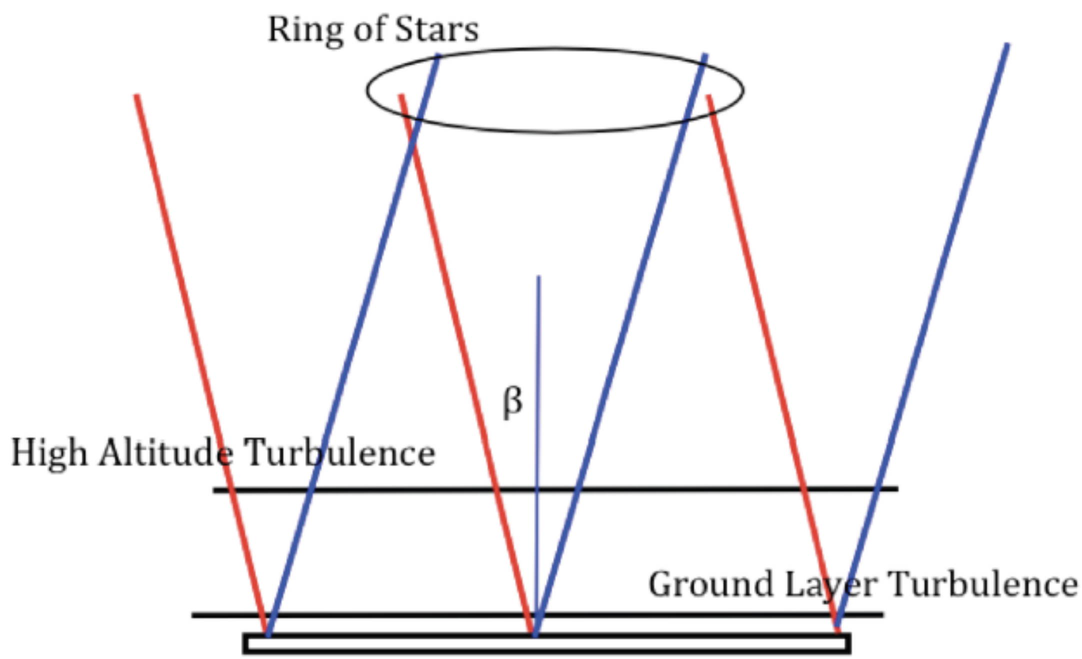
   

	SR-LGS	MR-LGS	S-LGS	MS-LGS
	Single Rayleigh LGS: gated at low altitude	Multiple Rayleigh stars, low or high altitude	Single Sodium	Multiple Sodium
On-axis performance	Medium	Medium	High	High
Homogenity	Medium	High	Low	High
Tech. Risk	Optics/ Detectors	Optics/ Detectors	Laser	Laser

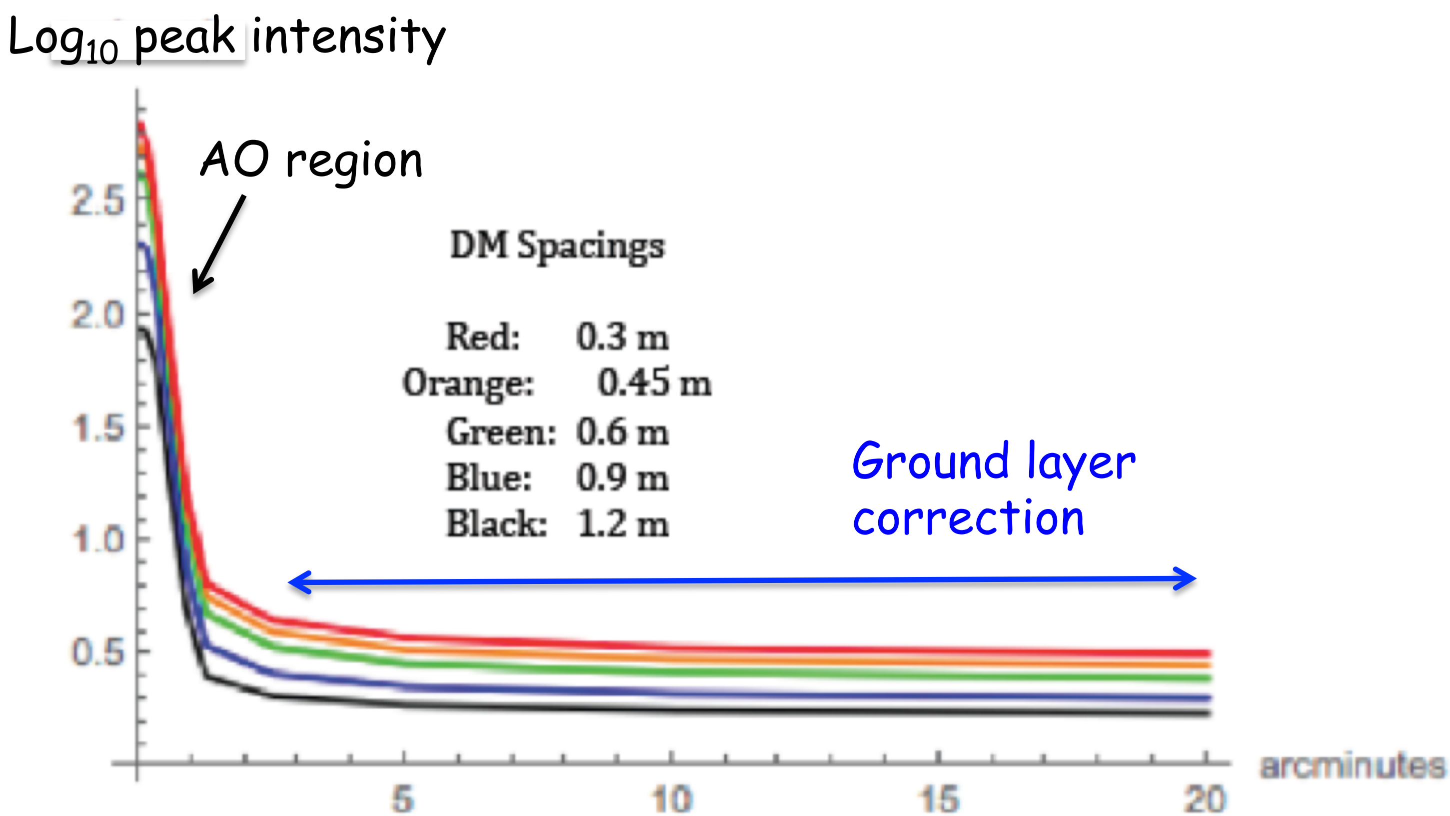
Concept study for 12 m telescope in China

Ideal GLAO system has dense packed ring of stars round edge of field of view
[12m China study with Lu Feng, CAS]

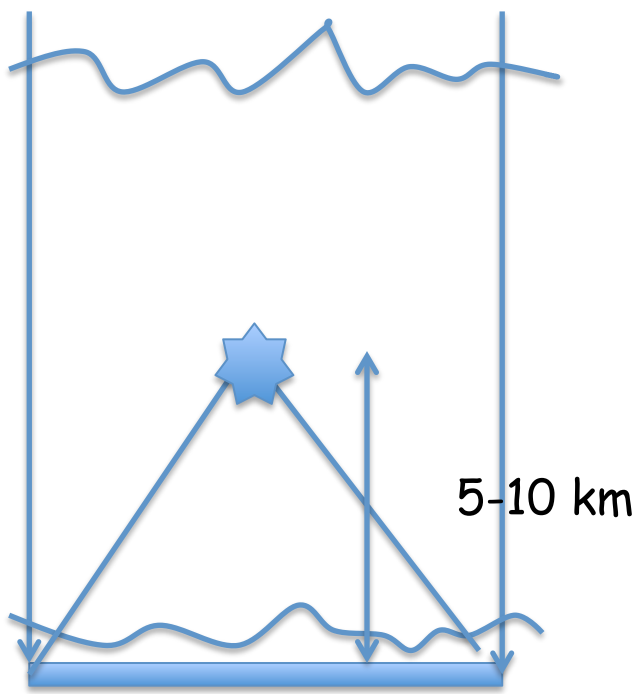
- Best correction
- Highest uniformity of psf
- Analytical approach *[Tokovinin PASP 116,941]*



Adjusting the radius of the beacons enables us to trade Strehl ratio with field of view

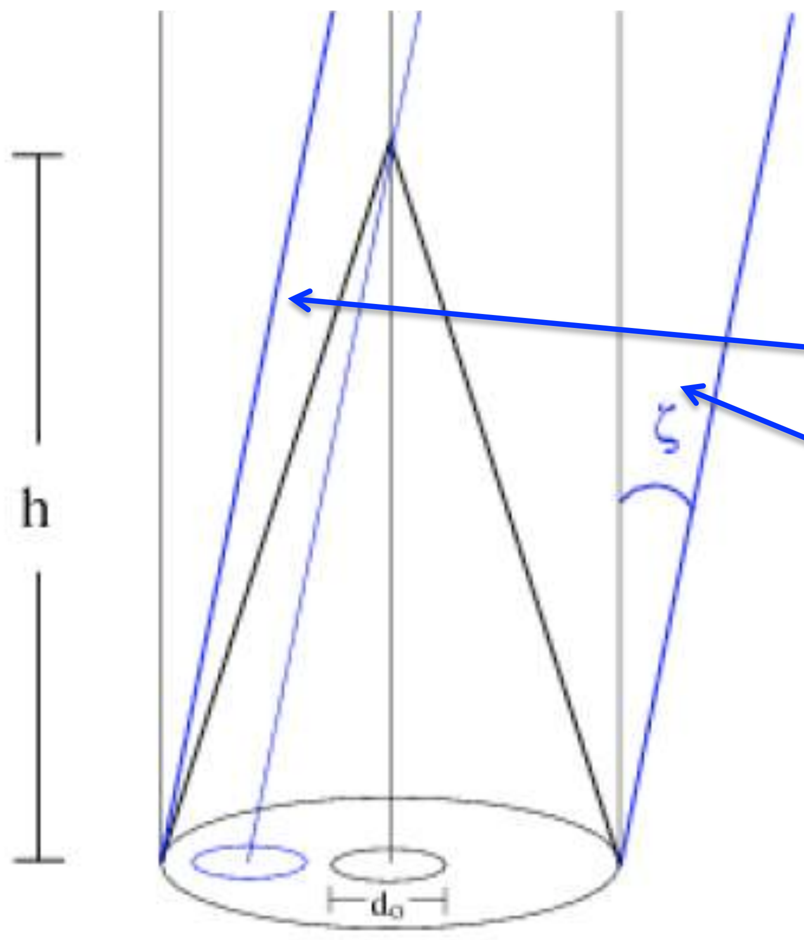


Use a Rayleigh Beacons for Ground layer AO



- Simplest laser beacons use Rayleigh scattering from air molecules
- Brightness high for short ranges
  - Inverse square law + high air density
- For large telescopes we ONLY sample turbulence near the ground, don't correct at all for high altitude turbulence
  - Can give partial correction foreground layer turbulence

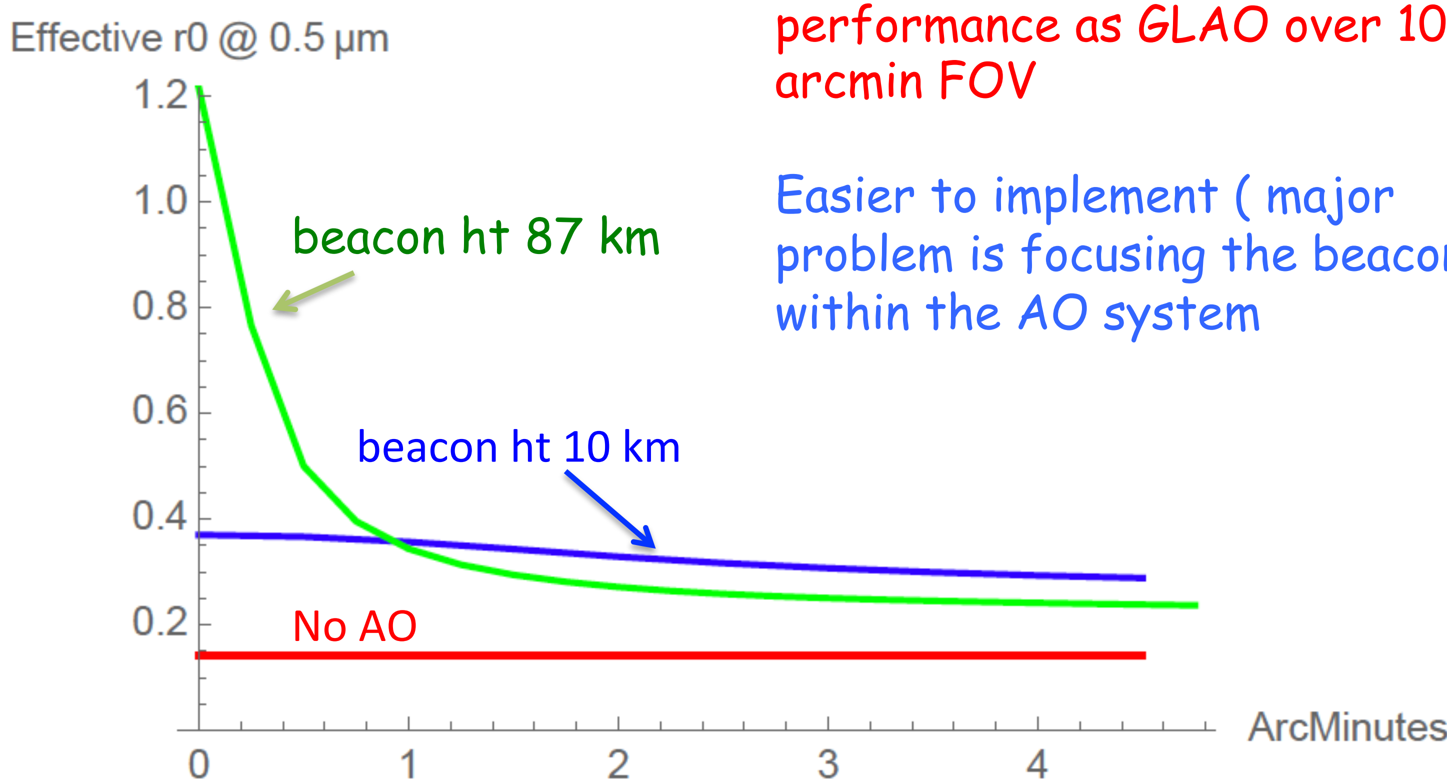
The Cone Effect reduces off-axis anisoplanatism



- Cone effect reduces on-axis Strehl Ratio
- At off axis angles some of the anisoplanatism is "Reduced "
- Phase wrapping means that other side is not as bad as you might think

- Cone effect rades Strehl ratio for FOV

Single laser beacon has a large field of view 10 km Rayleigh beacon observes same limiting flux in only 20% of the time(c.q. 50% for GLAO)



Single Rayleigh laser beacon has similar (or better) performance as GLAO over 10 arcmin FOV

Easier to implement (major problem is focusing the beacon within the AO system

Summary

- Highly segmented deformable secondary mirrors could be well suited for GLAO observing
- Uses lightweight mass produced optical fabrication (rms coma term ≈ 100 nm wavefront error)
- New inductive sensing technology reduces power, weight and complexity of edge sensing
- Significant reduction in overall power, weight and cost is possible
- Could be developed as secondary mirror on ELTs
- Test bed for adaptive primary mirror telescopes

END

CONCEPT:

Mass produced segments ≈ 30 cm x 1 cm thick preassembled into rafts (few sq m)

Segments controlled by voice coil actuators

High control b/w mitigates structure vibrations/ wind

High order atmospheric turbulence correction

Figure sensed using inductive edge sensors + laser wfs

Light weight Space Frame Structure

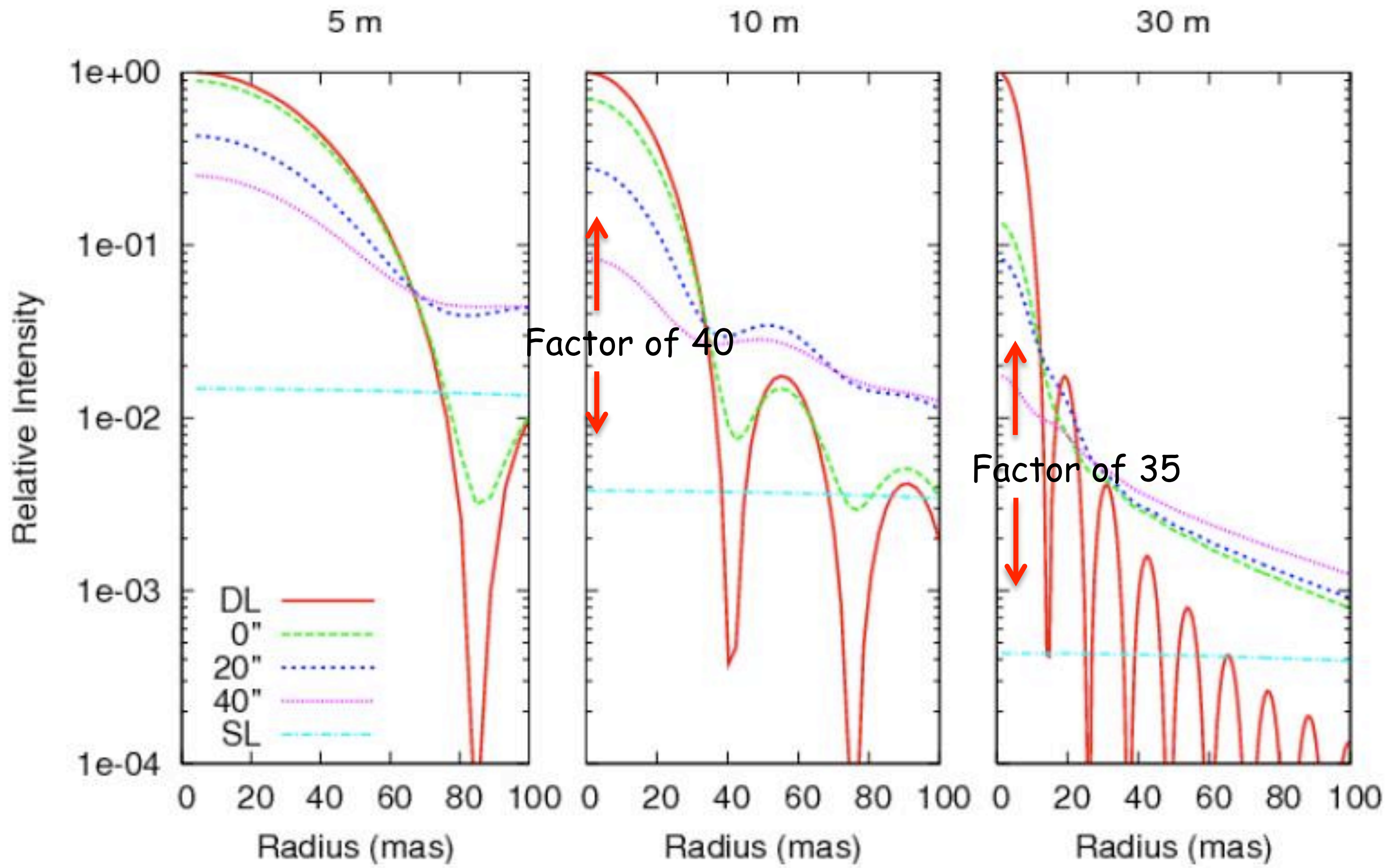
Failure tolerant control

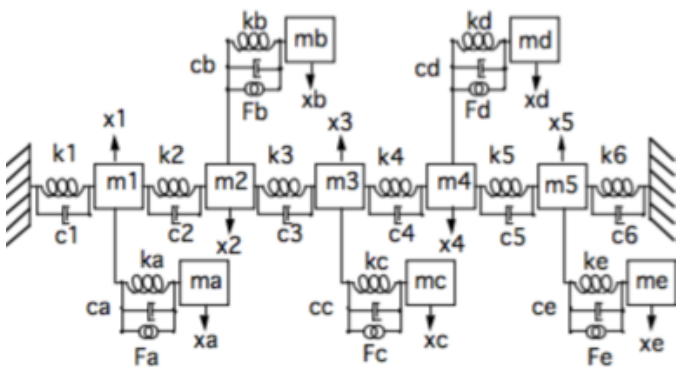
AIM: Diffraction limited performance at low cost

Single Beacon has ok correction over interesting FOV even for ELTS

Psf calculations after Britton

Factors of >30 in central intensity over 1 arcmin diameter FOV @ 1 μm

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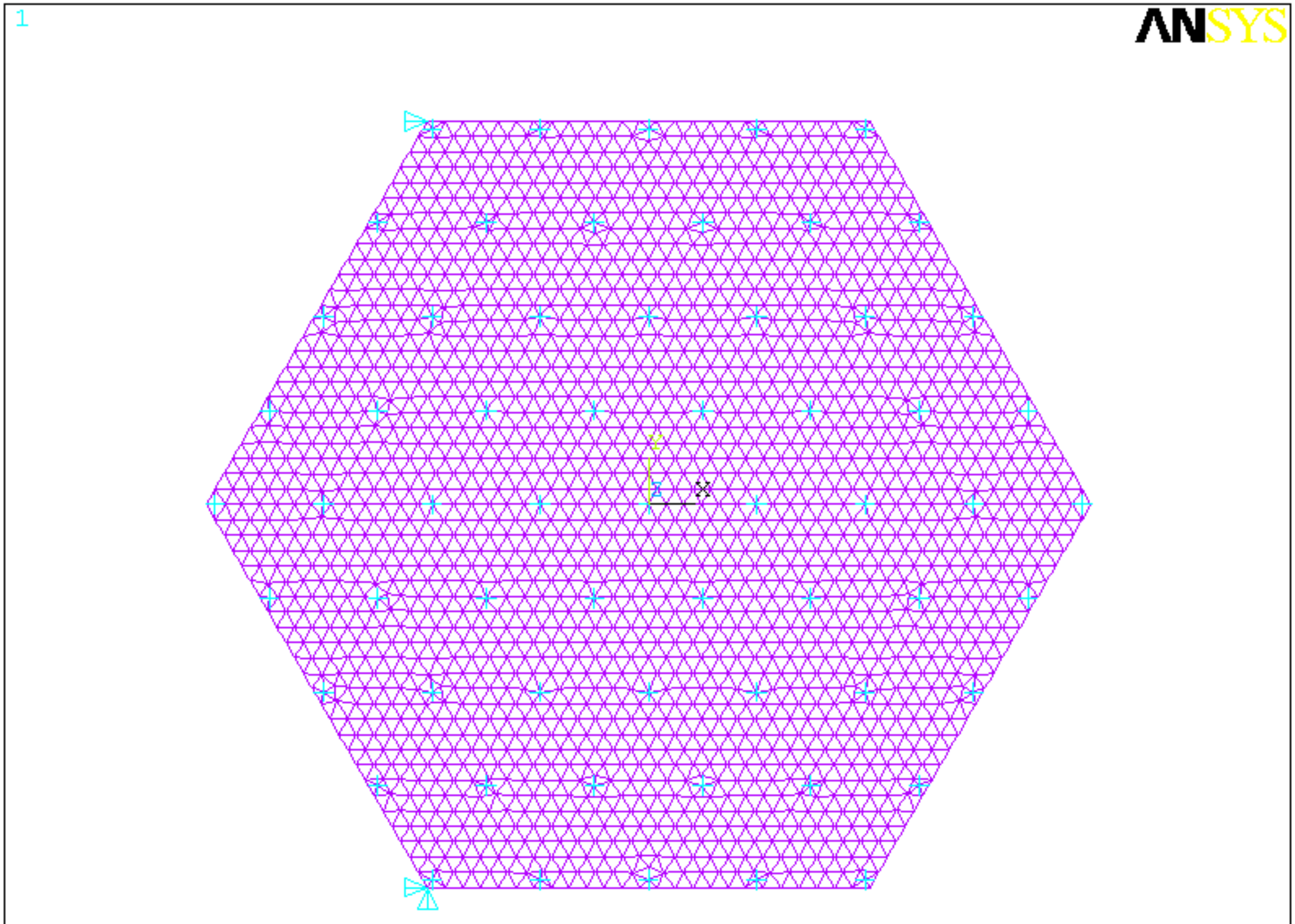
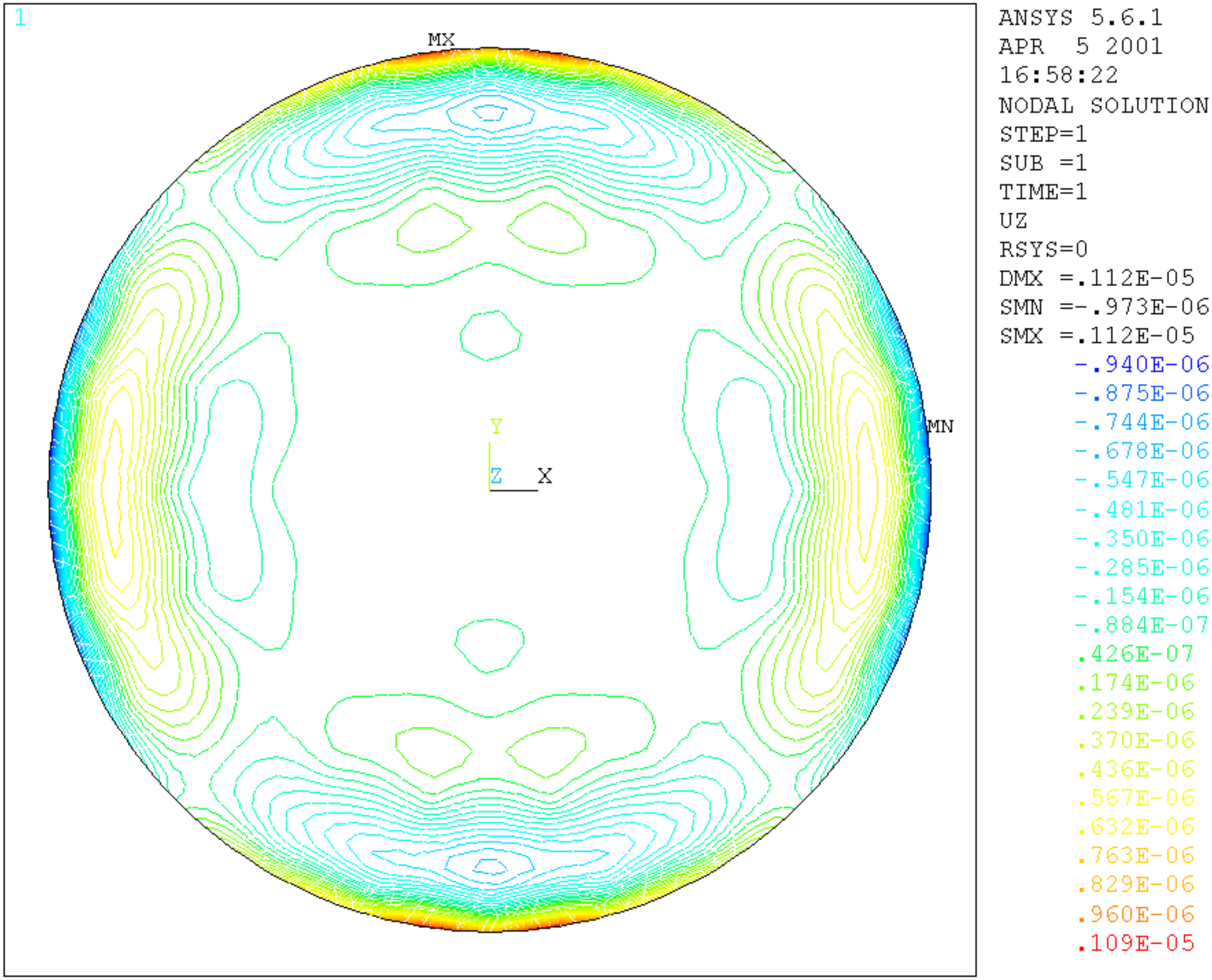


2.45m hex mirror, 2 cm thick, 61 points 2.5 cm in from edge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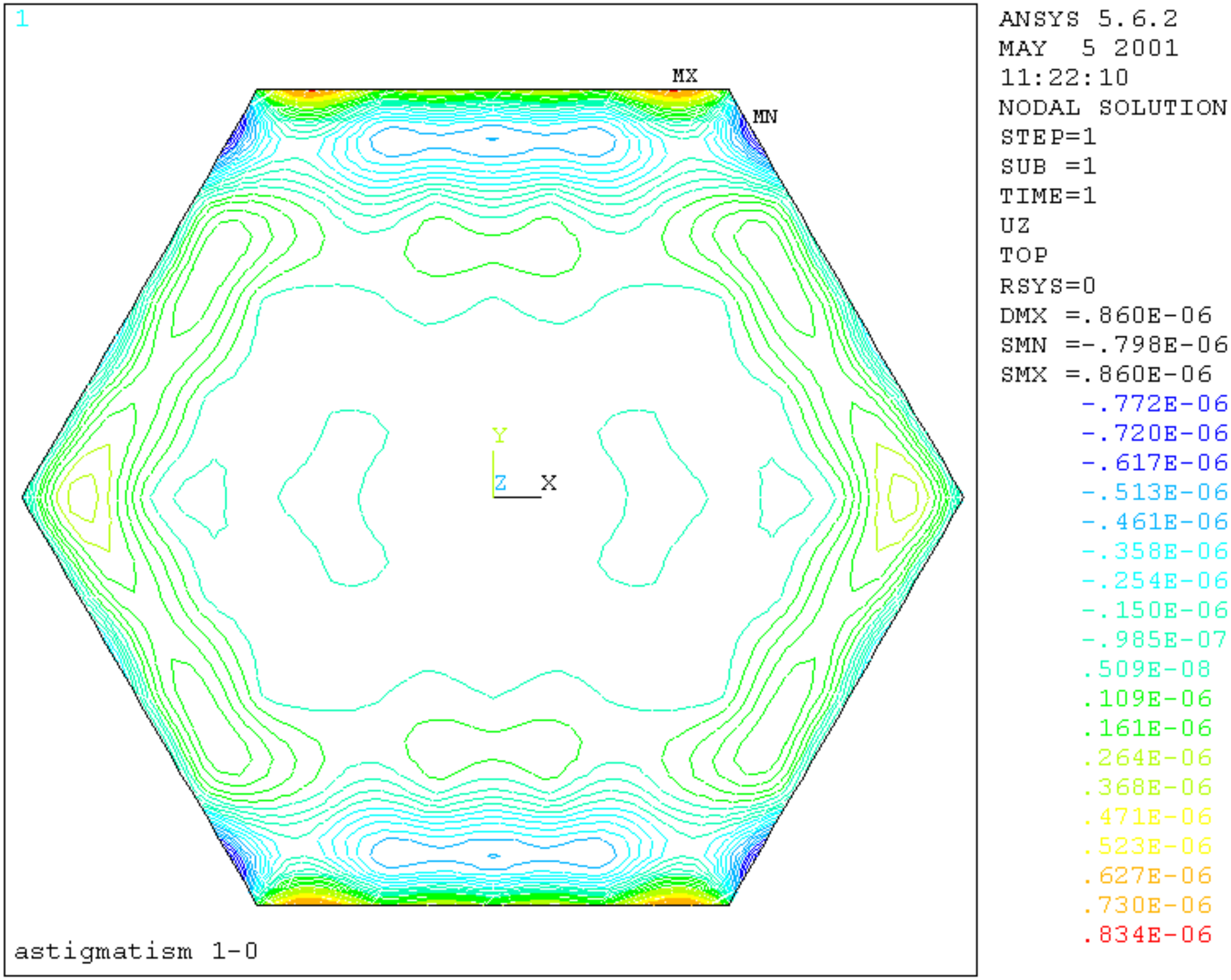

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Segment position can be controlled on a compliant backing structure