Adaptive Optics

Wavefront correction

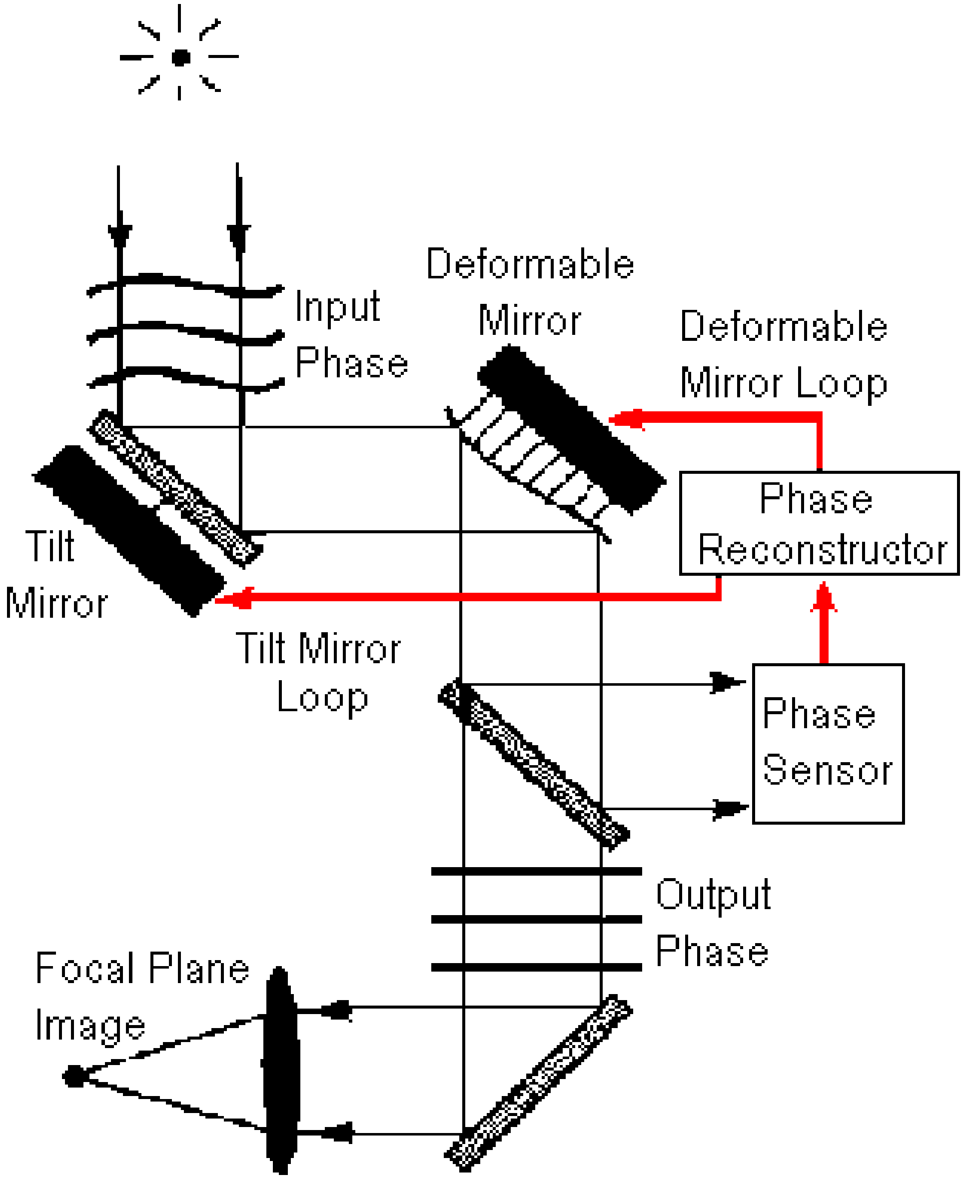
Fundamentals of wavefront correction

- Spatial sampling
- Speed

Hardware: Deformable mirror technologies

- magnetic force
- Piezo electric / electrostrictive
- Electrostatic force

What is Adaptive Optics ?



Main components of an AO system:

Guide star(s): provides light to measure wavefront aberrations, can be natural (star in the sky) or laser (spot created by laser)

Deformable mirror(s) (+ tip-tilt mirror): corrects aberrations

Wavefront sensor(s): measures aberrations

Computer, algorithms: converts wavefront sensor measurements into deformable mirror commands

Wavefront correction Fitting error

Assuming that the wavefront error is perfectly known, how well can the deformable mirror(s) correct it ?

Wavefront errors from atmospheric turbulence in sq. radian

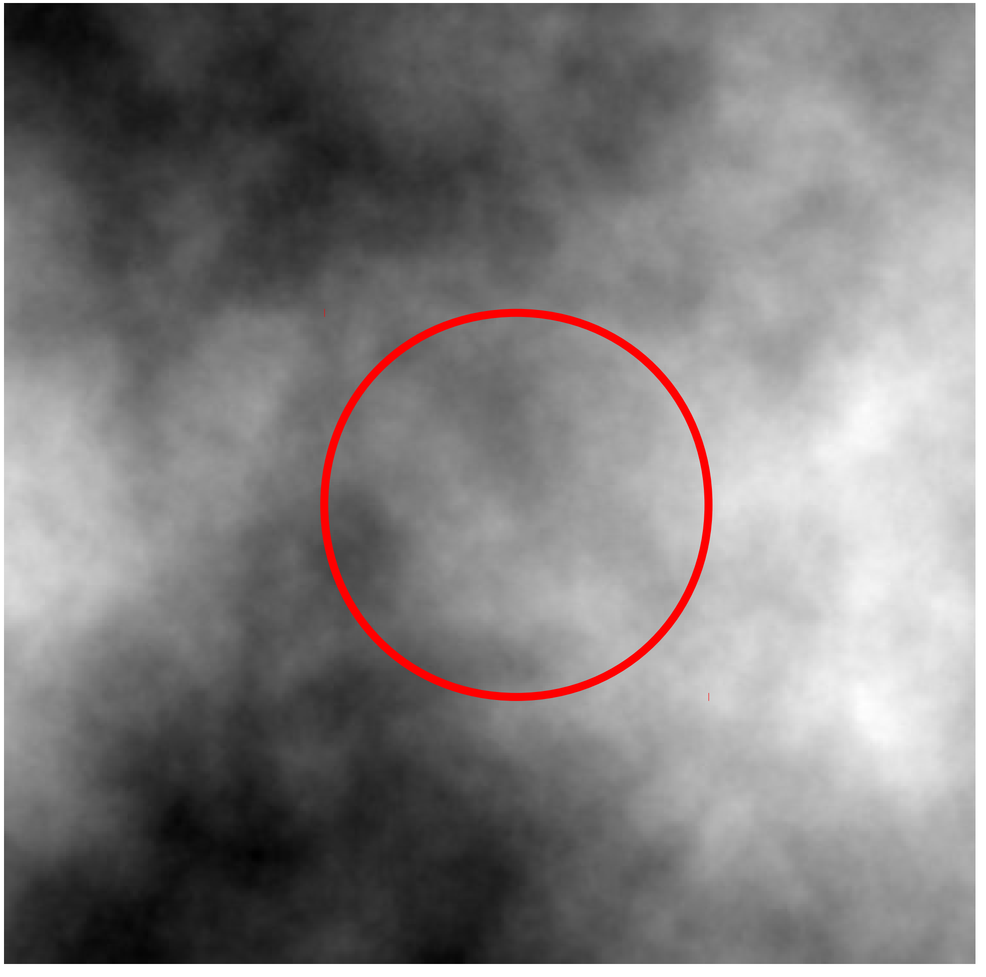
$$\sigma^2 = 1.03\ (D/r_0)^{5/3}$$

+ Vibrations, telescope guiding errors

+ Aberrations from optical elements (primary mirror, large number of small mirrors)

+ DM shape at rest

Kolmogorov turbulence



Fitting error: DM stroke

Need enough stroke on the actuators

$\sigma^2 = 1.03\ (D/r_0)^{5/3}$

(unit = radian)

Larger D -> more stroke needed

(also: faster system -> more stroke needed)

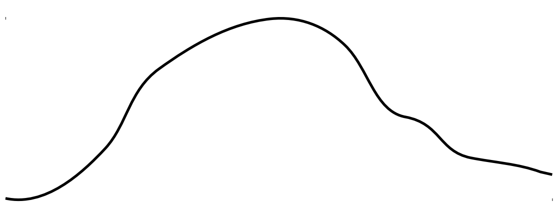
Most of the power is in tip-tilt:

It is helpful to have a dedicated tip-tilt mirror, or mount the DM on a tip-tilt mount

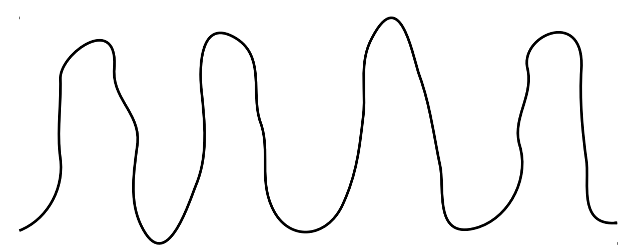
On many DMs, interactuator stroke < overall stroke

DM stroke needs to be looked at as a function of spatial frequency

eg: in a curvature DM, radius of curvature decreases as the number of actuators increases



Is easier than



Fitting error: number of actuators

Need enough actuators to fit the wavefront

D = telescope diameter, N = number of actuators
d = sqrt(D^2/N) = actuator size

If we assume each actuator does perfect piston correction (but no tip/tilt), WF error variance in sq. radian is:

$\sigma^2 = 1.03\ (d/r_0)^{5/3} = 1.03\ (D/r_0)^{5/3}\ N^{-5/6}$

If we assume continuous facesheet,

$\sigma^2 \sim 0.3\ (D/r_0)^{5/3}\ N^{-5/6}$

D = 8 m, r_0 = 0.8 m (0.2 m in visible = 0.8 m at 1.6 μm)
Diffraction limit requires ~ N = 24

In fact, exact DM geometry & influence functions are needed to estimate fitting error

Fitting error over a finite field of view

Need enough actuators to fit the wavefront for over a non-zero field of view

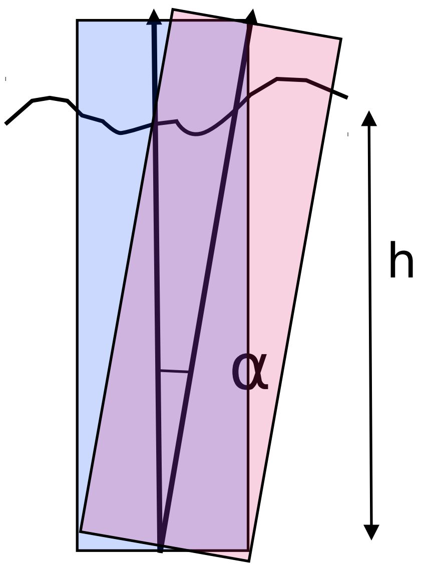
Two equivalent views of the problem:
- Wavefront changes across the field of view (MOAO)
- Several layers in the atmosphere need to be corrected (MCAO)

If we assume perfect on-axis correction,
and a single turbulent layer at altitude h,
the variance (sq. radian) is :

$\sigma^2 = 1.03\ (\alpha/\theta_0)^{5/3}$

Where α is the angle to the optical axis,
θ_0 is the isoplanatic angle:

$\theta_0 = 0.31\ (r_0/h)$



D = 8 m, r_0 = 0.8 m, h = 5 km $\rightarrow \theta_0 = 10''$

To go beyond the isoplanatic angle: more DMs needed (but no need for more actuators per DM).

Speed

Assuming perfect DMs and wavefront knowledge, how does performance decrease as the correction loop slows down ?

Assuming pure time delay t

$\sigma^2 = (t/t_0)^{5/3}$

t_0 = coherence time "Greenwood time delay"= 0.314 r_0/v

v = 10 m/s

r_0 = 0.15 m (visible)   0.8 m (K band)

t_0 = 4.71 ms (visible)   25 ms (K band)

Assuming that sampling frequency should be ~ 10x bandwidth

for "diffraction-limited" system (1 rad error in wavefront):
sampling frequency = 400 Hz for K band

for "extreme-AO" system (0.1 rad error):
sampling frequency = 6 kHz for K band

DM Requirements and issues

Stroke: how much can the DM surface move
Number of actuators
Speed: How fast does the DM respond, vibrations
Stability: Does the surface drift with time, are the actuator responses stable in time, sensitivity to temperature, humidity, pressure

Hysteresis
Backlash
Wavefront quality

- Shape when not driven
- Non-correctable surface errors

Heat output
Reliablility

<u>**Number of actuators should be very carefully chosen**</u>

Resist temptation of having more actuators than needed:
Systems with too many actuators are:
- not very sensitive (don't work well on faint stars)
- Harder to run at high speed
- demanding on hardware, more complex & costly
- less tolerant (alignment, detector readout noise...)

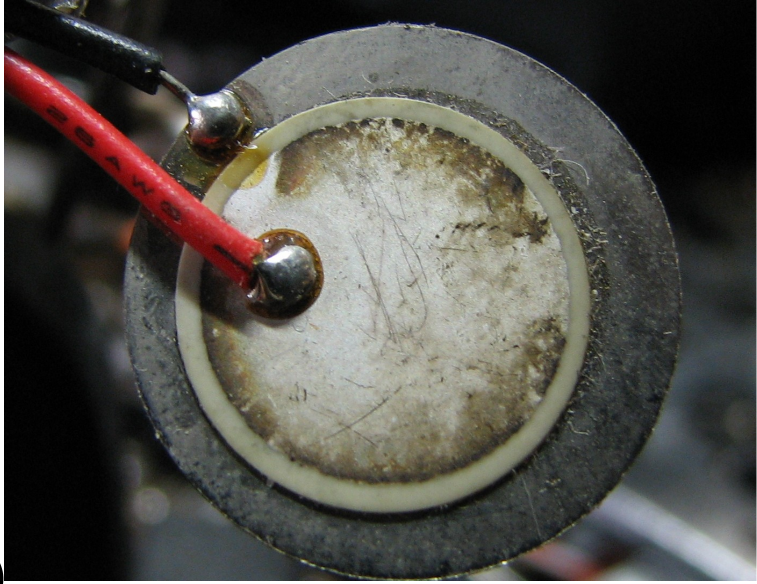
See also “noise propagation” section of this lecture

There is usually little motivation to have much more than ~1 actuator per r0.

Exception:
Extreme-AO, where actuator # is driven by the size of the high contrast “dark hole”

Piezoelectric effect

Coupling between electric field and mechanical strain



Applied electric field ↔ dimension

Relation is approximately linear, but:

- Hysteresis (~10%)
- Small drifts (temperature, exitation history)

Requires high voltage (typically > 100V)

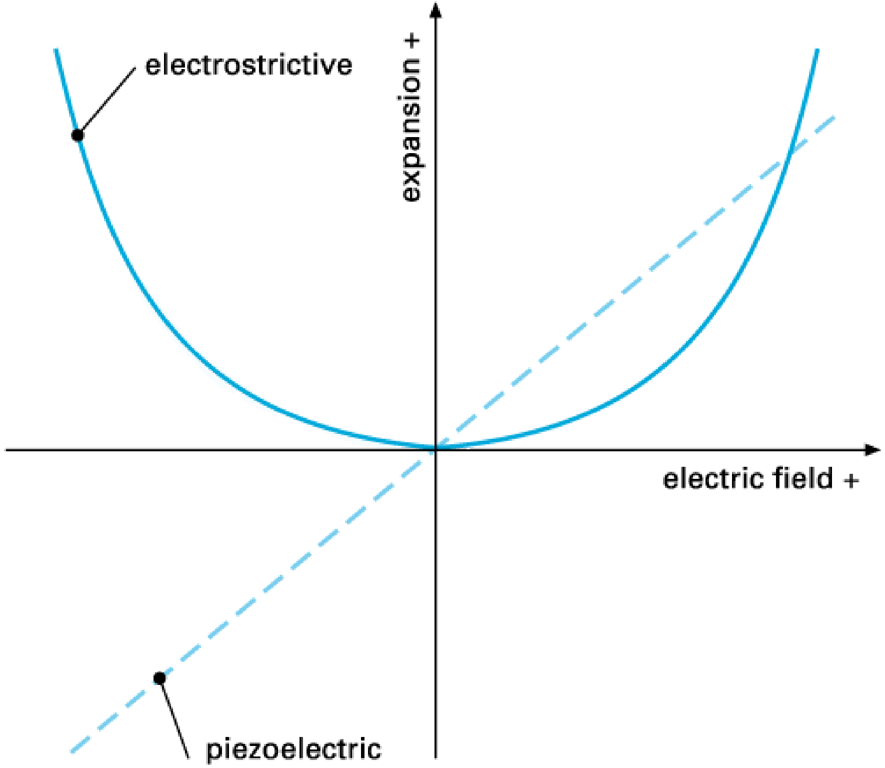
Bipolar (voltage can be positive or negative)

Electrostrictive materials

Quadratic relationship between Electric field and displacement

Smaller hysteresis, but more temperature dependance than piezoelectric materials.

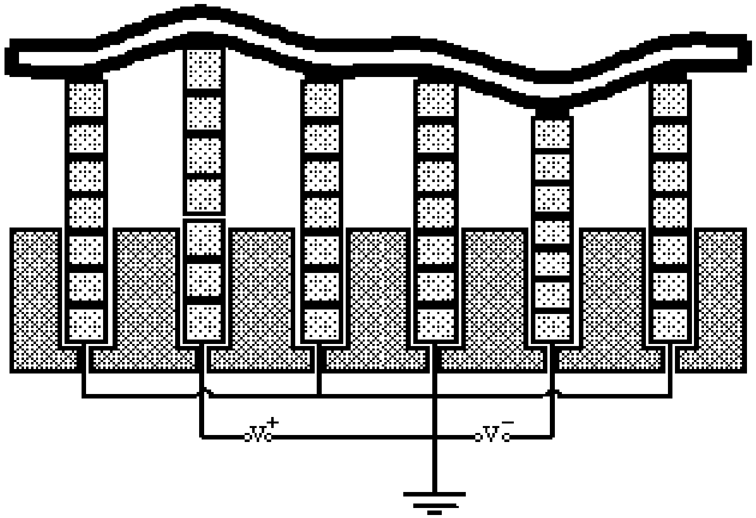
Higher capacitive load
→ requires higher currents

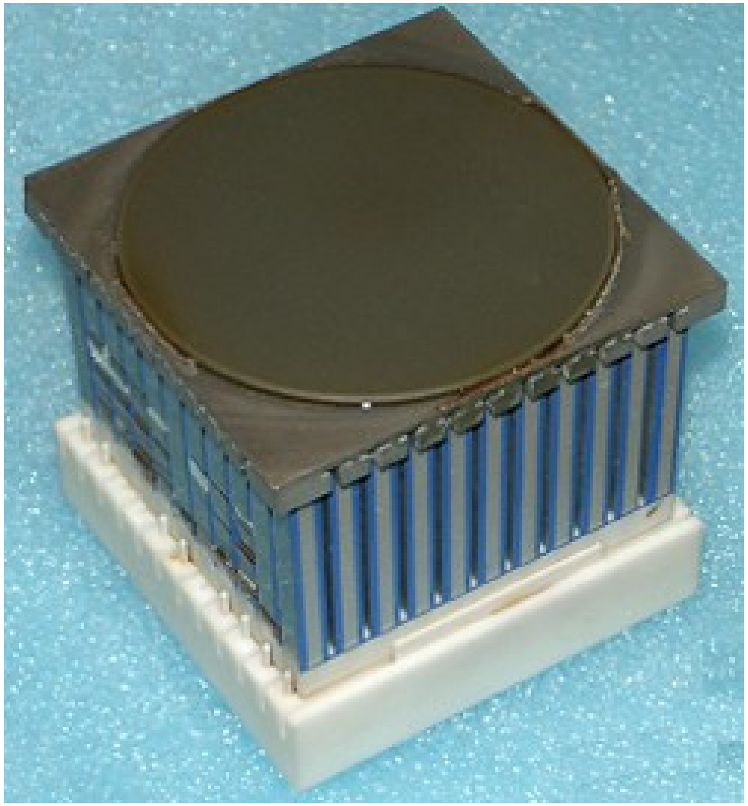


Piezo stack DM

Displacement is proportional to electric field
Large displacement = high electric field over long length of material

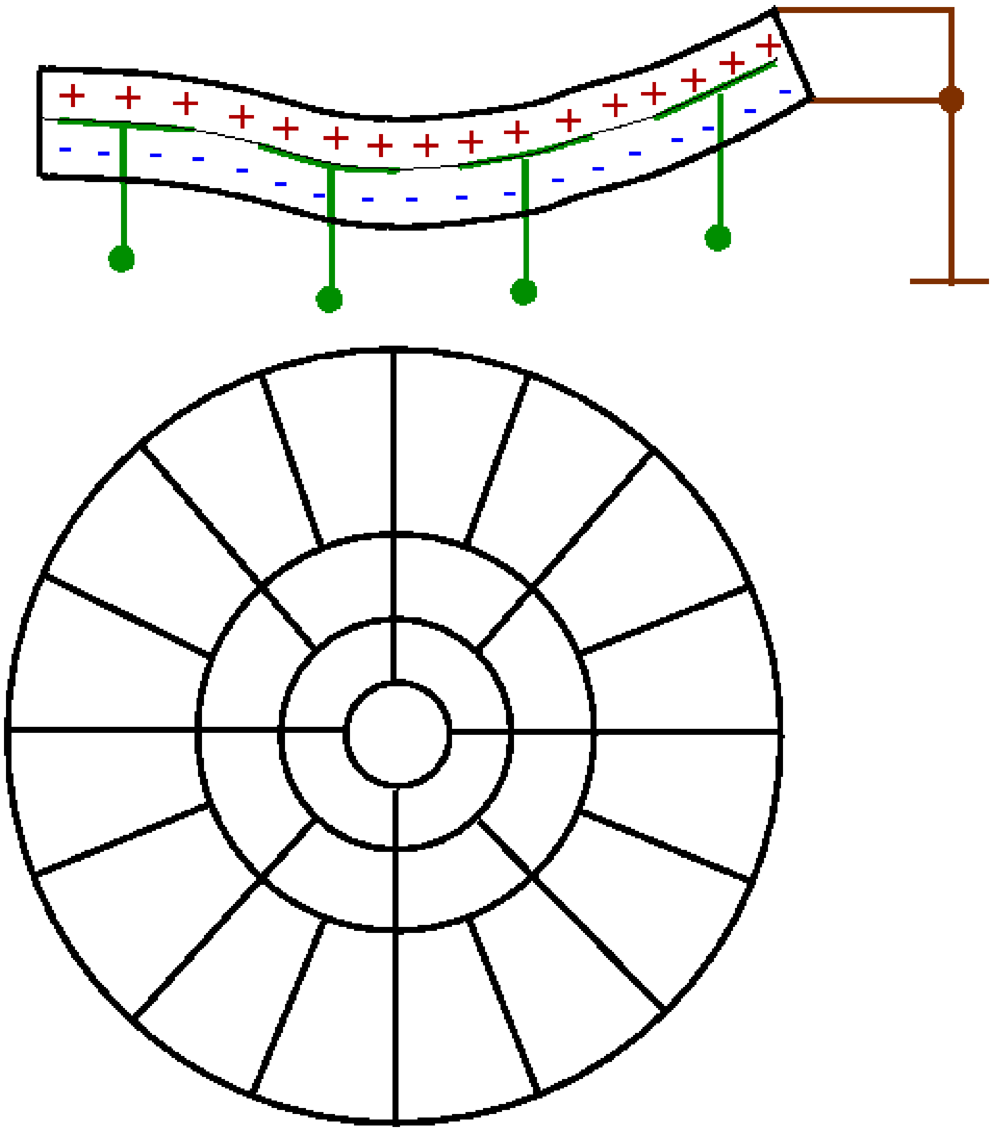
To avoid unreasonably high voltages, stack of piezo layers is used
Voltage is applied across each layer





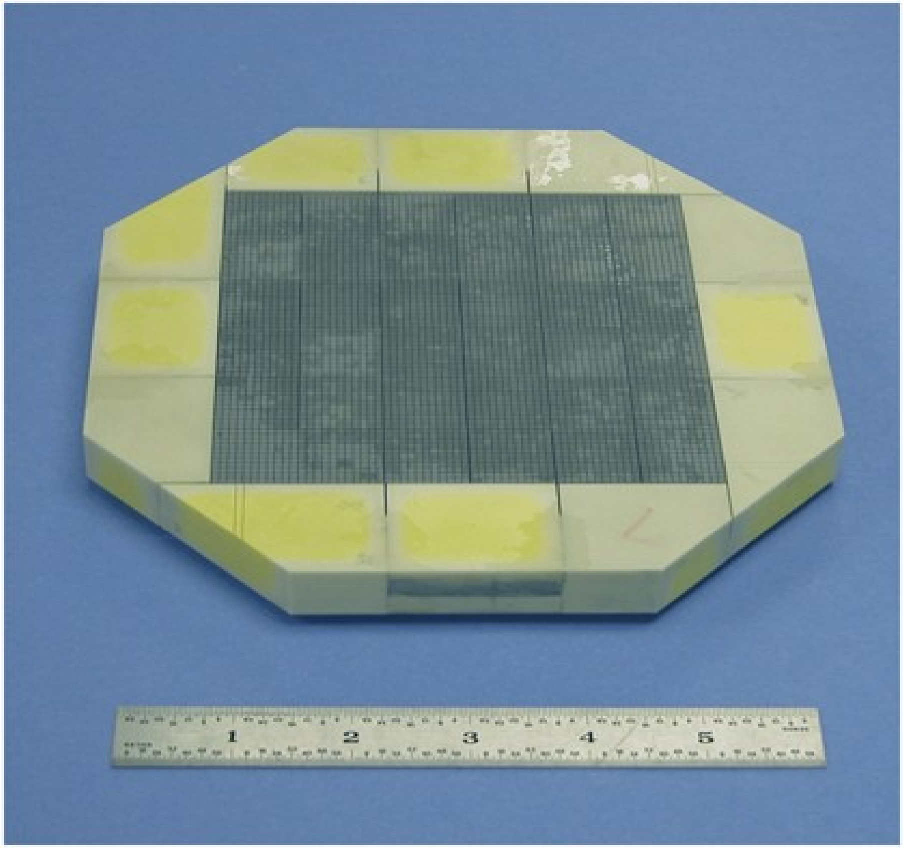
Piezo actuated mirror (Cilas)

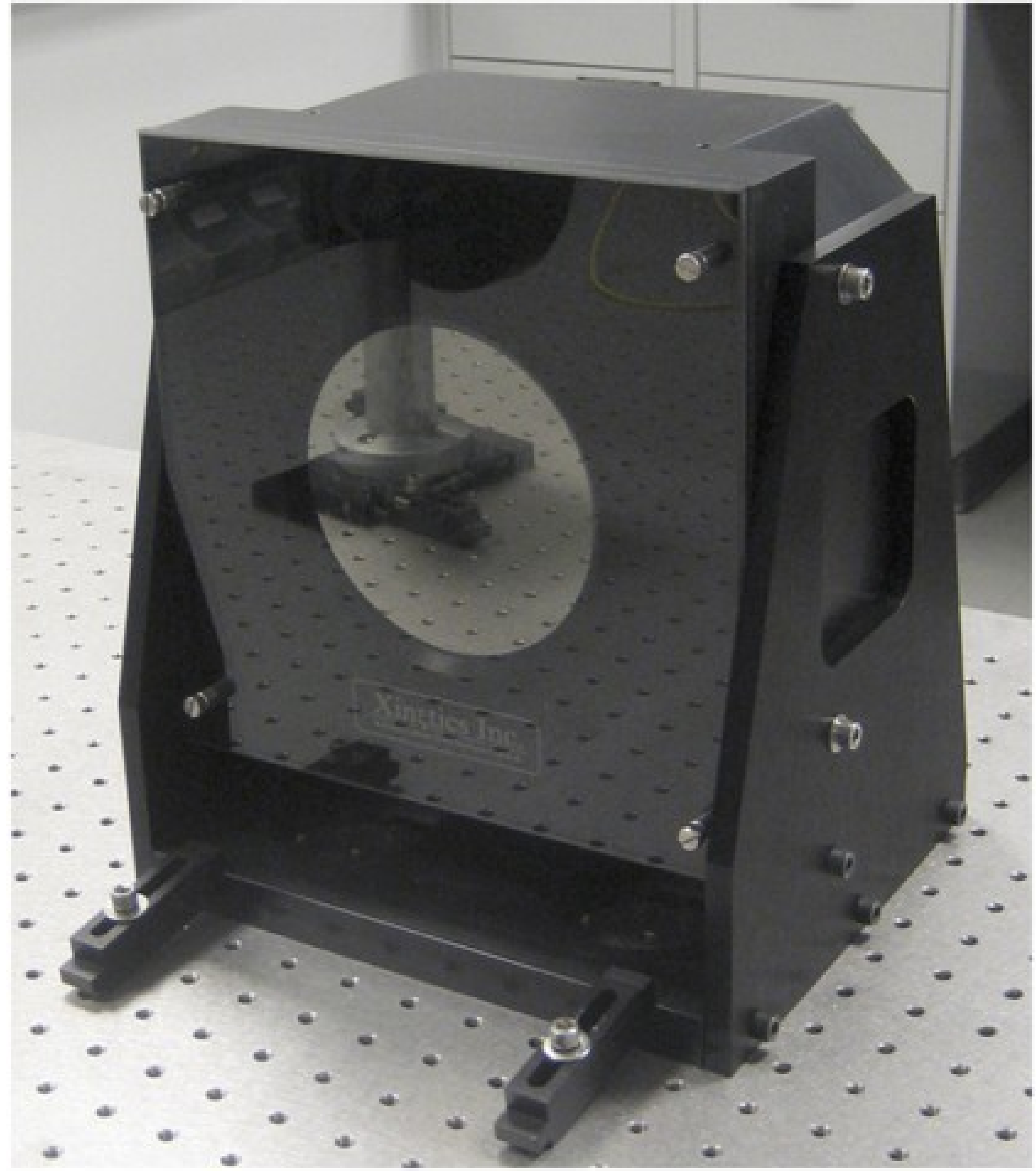
Bimorph DMs



Curvature DM made by IfA, University of Hawaii

Electrostrictive DM

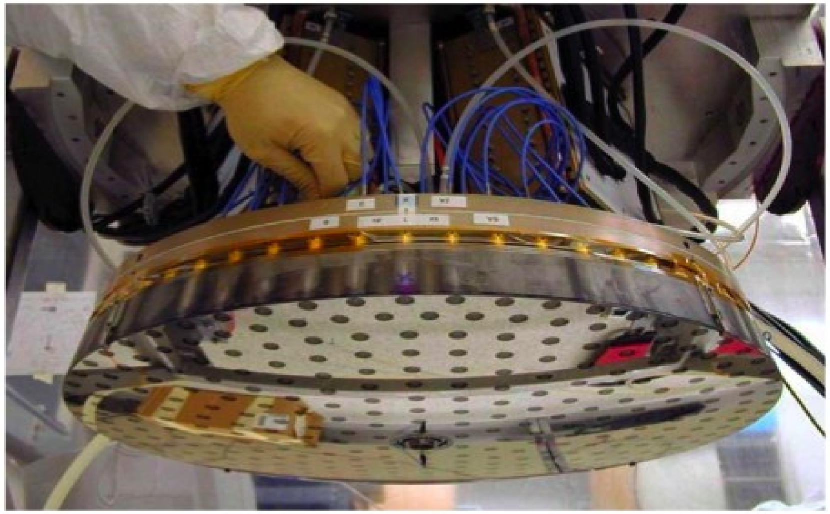


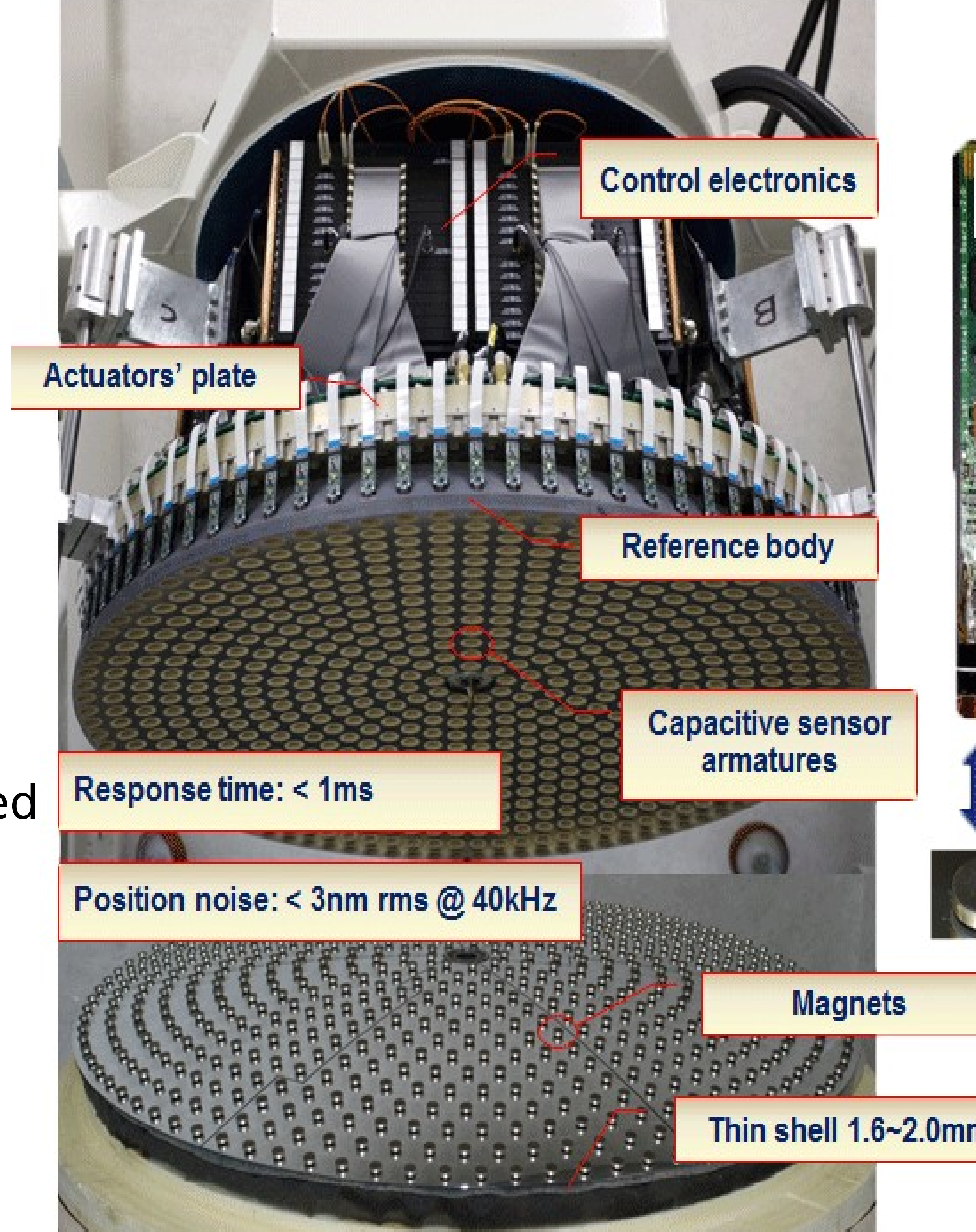


The 4356-actuator deformable mirror for PALM-3000 (Xinetics Inc.).

Magnetic force

Adaptive secondary Mirror



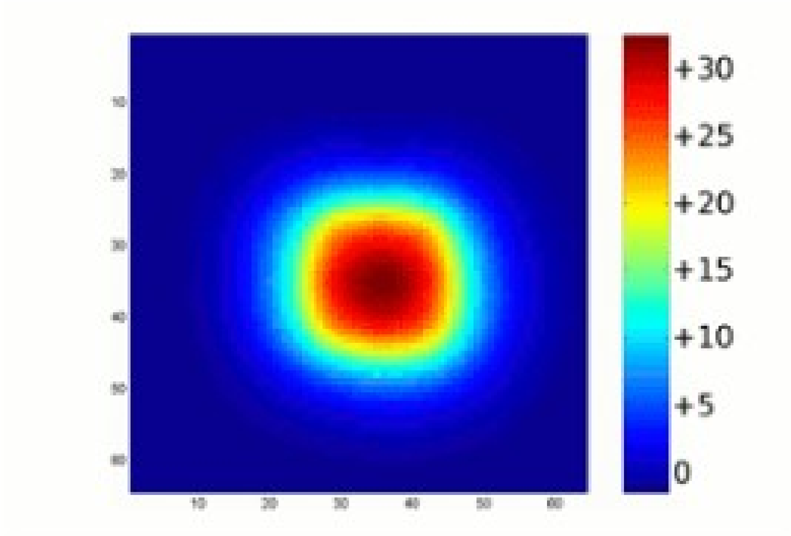


Thermal IR instruments need low thermal background
-> fewer warm optics

adaptive secondary mirror (MMT, LBT, Magellan)

Magnetic force

Small magnetic DMs
Key advantage is large stroke

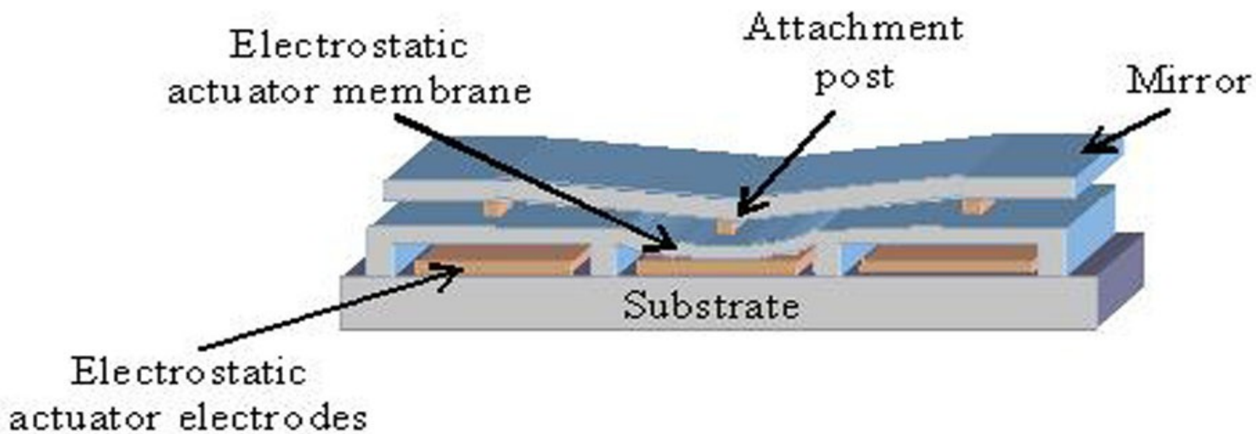


Typical stroke obtained while applying currents on 3x3 actuators (wavefront value, twice the mirror surface)

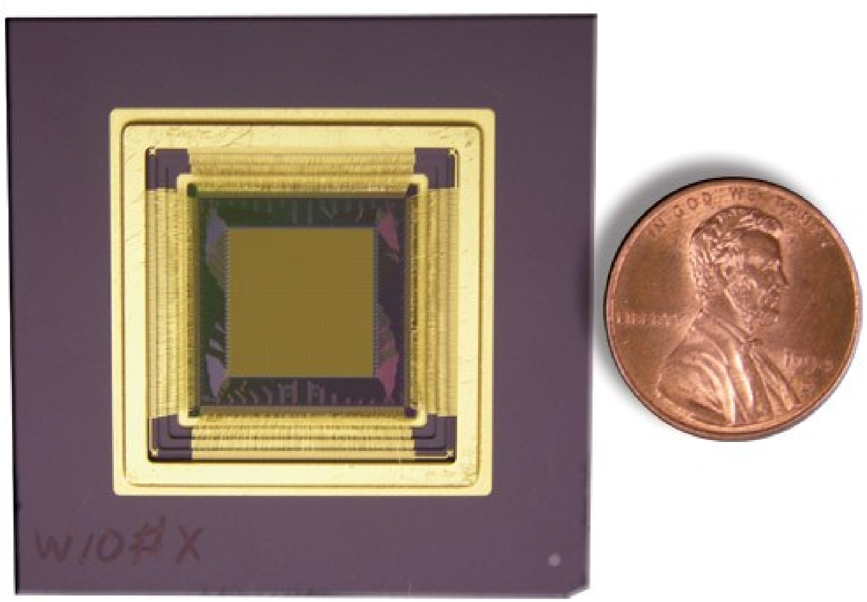
> 20 micron stroke
(high speed DM97, Alpao)

241 actuators magnetic DM
(Alpao)

Electrostatic DMs
large number of actuators in a small space



Small electrostatic MEMS mirror (Boston Micromachines, 1024 act)



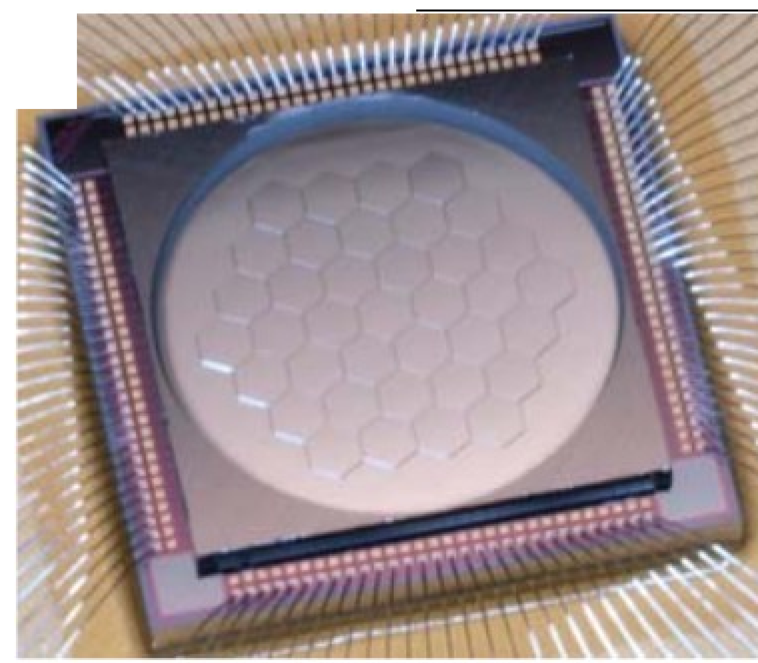


Figure 1. Photograph of an Iris AO PTT111-X deformable mirror.

Some more exotic concepts...

Thermal deformable mirror

uses thermal expansion to deform a mirror

very slow, difficult to calibrate, but can be very cheap

Liquid crystal

- Very high actuator count
- Compact
- Cheap
- Chromatic, polarization issues
- Speed can be a concern