Main challenges / error budget terms in astronomical AO systems

Fundamental wavefront error budget terms :

1 Fitting error

2 Speed

3 Limited # of photons

These 3 fundamental errors usually need to be traded against each other

4 AO guide "star" size & structure, sky background

5 Non-common path errors

- chromaticity
- cone effect (LGS) & anisoplanetism

6 Calibration, nasty "practical" things

- vibrations, instabilities between control loops
- DM hysteresis / poor calibration (generally not too serious in closed loop)

Useful references:

Adaptive Optics in Astronomy (2004), by Francois Roddier (Editor), Cambridge University Press

Adaptive Optics for Astronomical Telescopes (1998), by John W. Hardy, Oxford University Press

Wavefront error budget

Wavefront error σ is in radian in all equations.

Wavefront variance σ^2 is additive (no correlation between different sources), and the wavefront error budget is built by adding σ^2 terms.

Wavefront error (m) = $\lambda \times \sigma/(2\pi)$

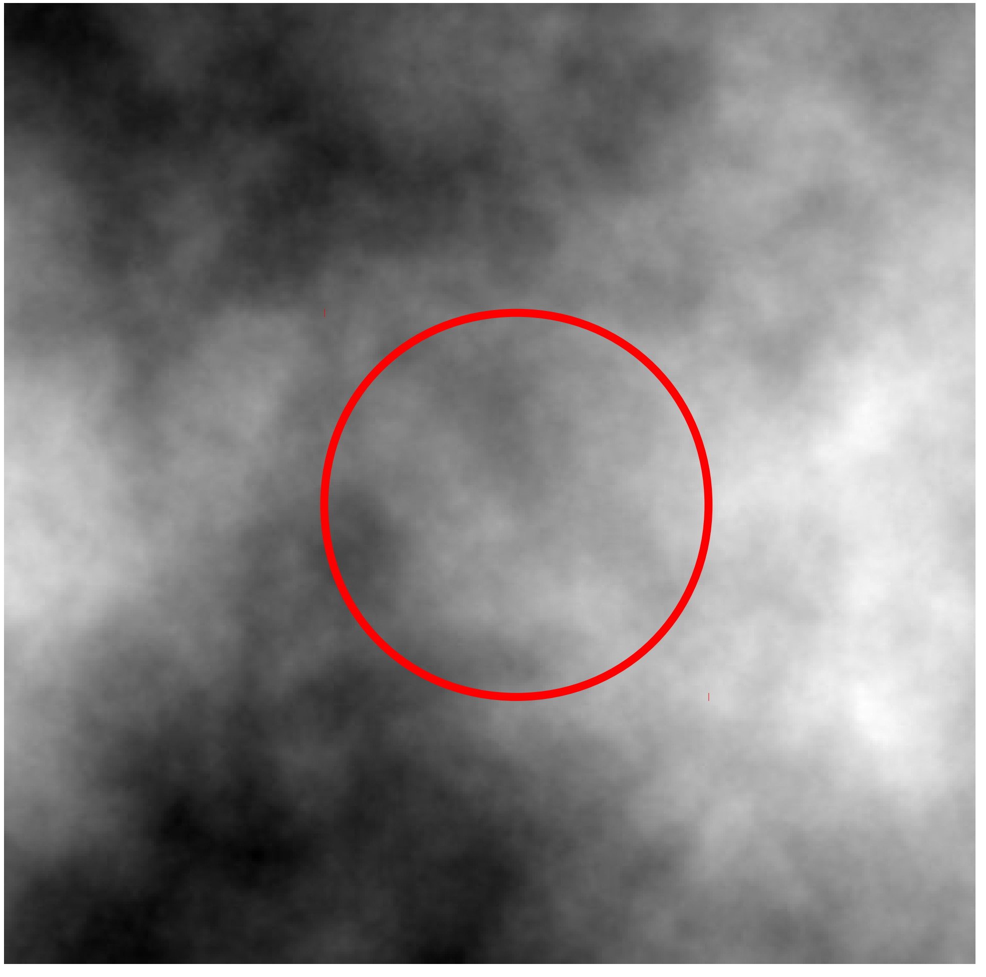
Strehl ratio ~ $e^{-\sigma^2}$
(Marechal approximation, valid for Strehl ratio higher than ~0.3)

Useful references:
Adaptive Optics in Astronomy (2004), by Francois Roddier (Editor), Cambridge University Press
Adaptive Optics for Astronomical Telescopes (1998), by John W. Hardy, Oxford University Press

1. Fitting error

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

Kolmogorov turbulence



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

1. Fitting error

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)

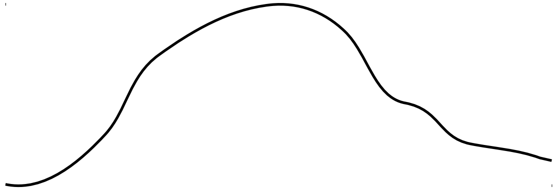
Most of the power is in tip-tilt:

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

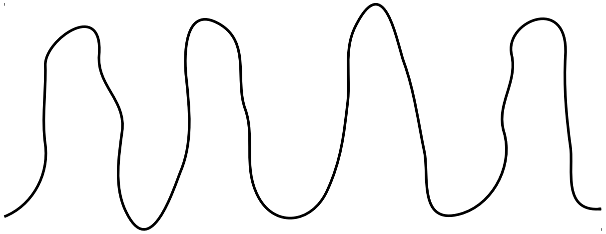
On many DMs, interactuator stroke < overall stroke

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



1. Fitting error

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

1. Fitting error & 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)

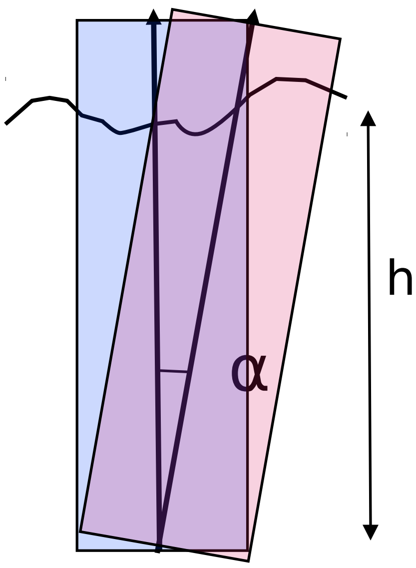
If we assume perfect on-axis correction, and a single turbulent layer at altitude h, the variance (sq. radian) is :

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

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 $\rightarrow$ θ_0 = 10”

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

2. 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

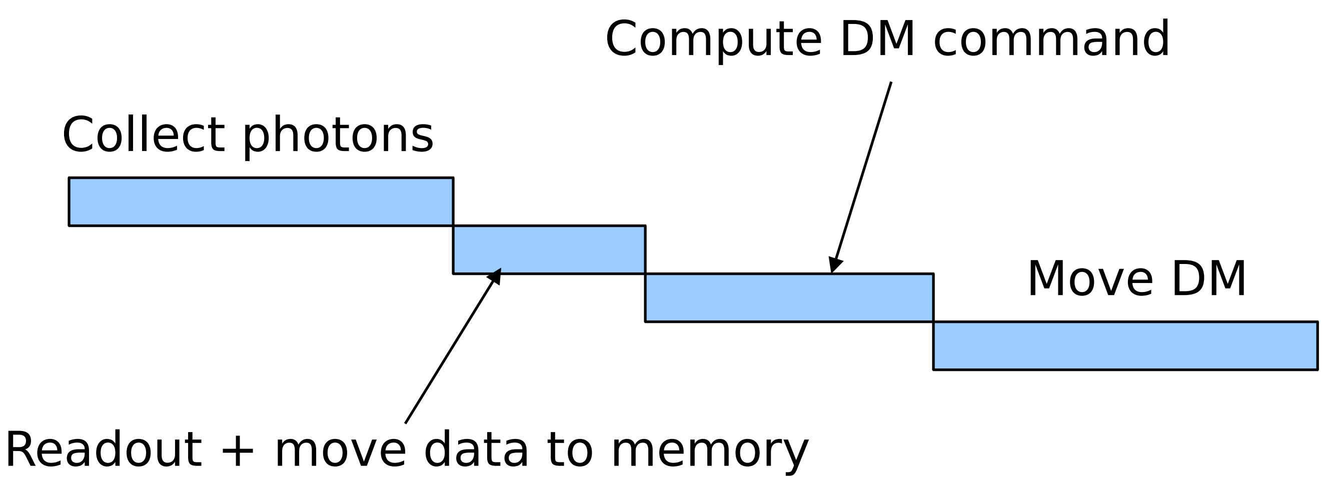
for "diffraction-limited" system (1 rad error in wavefront):
sampling frequency = 400 Hz for K band

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

-> High speed means fewer photons / sample
need high SNR in WFS (optimal use of photons)

-> need fast hardware (see below)
- DM: good time response, low vibration
- Detector: fast readout / low readout noise
- computer, software & electronics

-> Clever, predictive control can help a lot
"anything that could be predicted should be !"



3. Limited # of photons from stars (per unit of time)

With a fixed finite photon arrival rate, how well can I measure the wavefront (speed vs. SNR) ?

Longer WFS "exposure time" -> better SNR but more time lag

m_V=15 -> 400 ph/ms on 8m pupil in 0.5 µm band (20% efficiency)

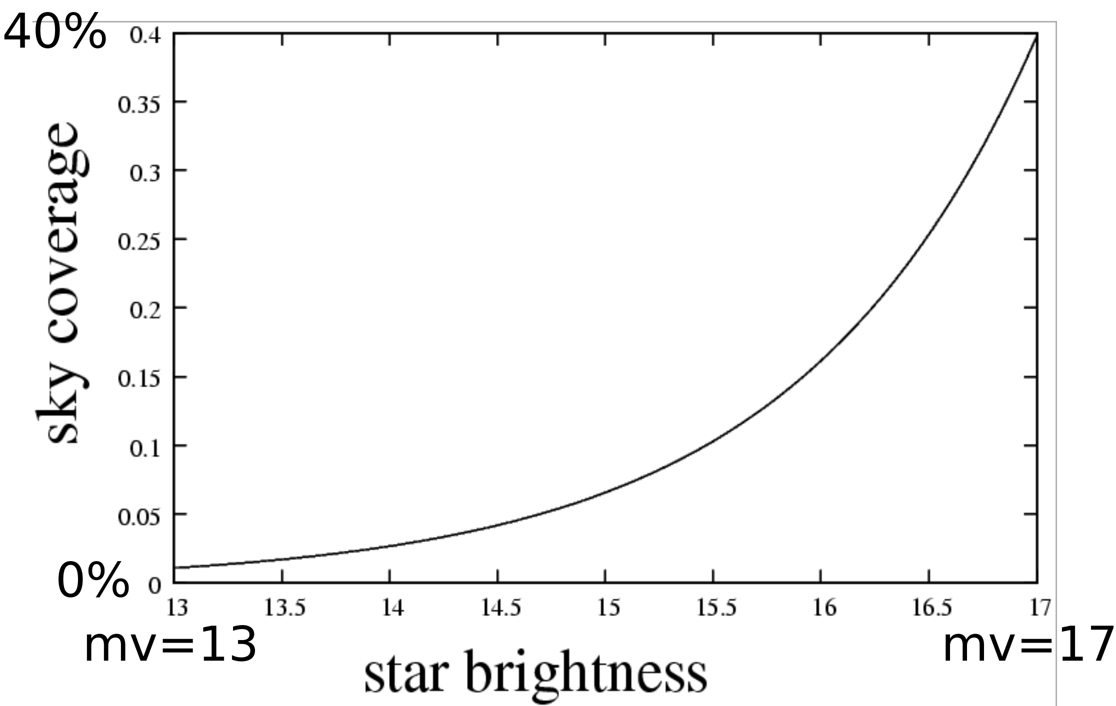
Example 1: **General purpose NGS system**

Goal: achieve diffraction limited performance over much of the sky

Star brighter than m_V density ~ 9e-4 exp(0.9 m_V) per sq. deg (galactic pole)

ref: Parenti & Sasiela, 1994

Within a 20" radius:



m_V=8 -> 2.5e5 ph/ms on 8m pupil in 0.5 µm band
& 20% efficiency

Example 2: Extreme-AO system
Goal: Achieve exquisite wavefront correction on selected bright stars

Running speed = 5 kHz (see speed section before)
2000 actuators

25 photons / actuators / sampling time
6 photon / pixel if 2x2 Shack Hartmann cells are used
with no readout noise, ~ 0.2 rad phase error per actuator
at best.

Limited # of photons will push system design into:

-> high efficiency WFS: good at converting OPD error into signal
(if possible, choose shorter wavelength)

-> high throughput (fewer optics), good detector (low readout noise)

-> WFS which works in broad band for NGS

-> bright laser for LGS, small angular size LGS

-> multiple guide stars

4. AO guide "star" size & structure, sky background

Extended targets means lower WFS efficiency and/or WFS failure

This problem is very WFS-dependent (some WFSs cannot deal with extended sources)

- Laser guide star is typically 1" or more, and elongated
- NGS: atmospheric refraction can be serious
  -> Atmospheric Dispersion Compensator (ADC) is often essential in the WFS
- frequent problem in Solar system observations
- double stars can be a problem

Sky background:

for faint guide stars, moonlight is a concern

5. Non-common path errors

- anisoplanatism (also discussed earlier in fitting error)

  Due to angular separation between guide star and science target, guide star WF is different from science WF

  -> minimize distance between guide star & science field

  -> use several guide stars & perform tomographic rec.

  -> if FOV is needed, use several guide stars (NGS or LGS)

- chromaticity

  AO correction is optimal for WFS wavelength, not for science wavelength (non negligible for Extreme-AO)

- cone effect (for LGS)

  -> tomographic reconstruction

- instrumental non-common path errors

  Due to optics in WFS only or in science camera only

  -> may need to be measured (for example, phase diversity daytime calibration) and offset to AO loop

6. Calibration, nasty “practical” things

- vibrations
  - -> good mechanical design
  - -> beware of cryocoolers (pumps), fans

- DM hysteresis / poor calibration (generally not too serious in closed loop)

- instabilities between control loops

Just because the AO system works in the lab, doesn't mean that it will work when it is on the telescope

Physical environment can be quite different (temperature, humidity, pressure, gravity orientation change, vibration environment)

Input wavefront may not be what is expected (telescope vibration, larger than expected telescope wavefront error)

Science wavelength choice:
IR is "easy", visible is "very very hard"

Things that get worse as lambda gets small:

- r_0 gets small: more actuators needed

  r_0 goes as $\lambda^{6/5}$ -> N goes as $\lambda^{-12/5}$

- speed gets high ($\tau_0 = 0.314\ r_0/v$) -> τ_0 goes as $\lambda^{6/5}$
- anisoplanatism gets small (FOV, sky coverage go down)

  θ_0 goes as $\lambda^{6/5}$

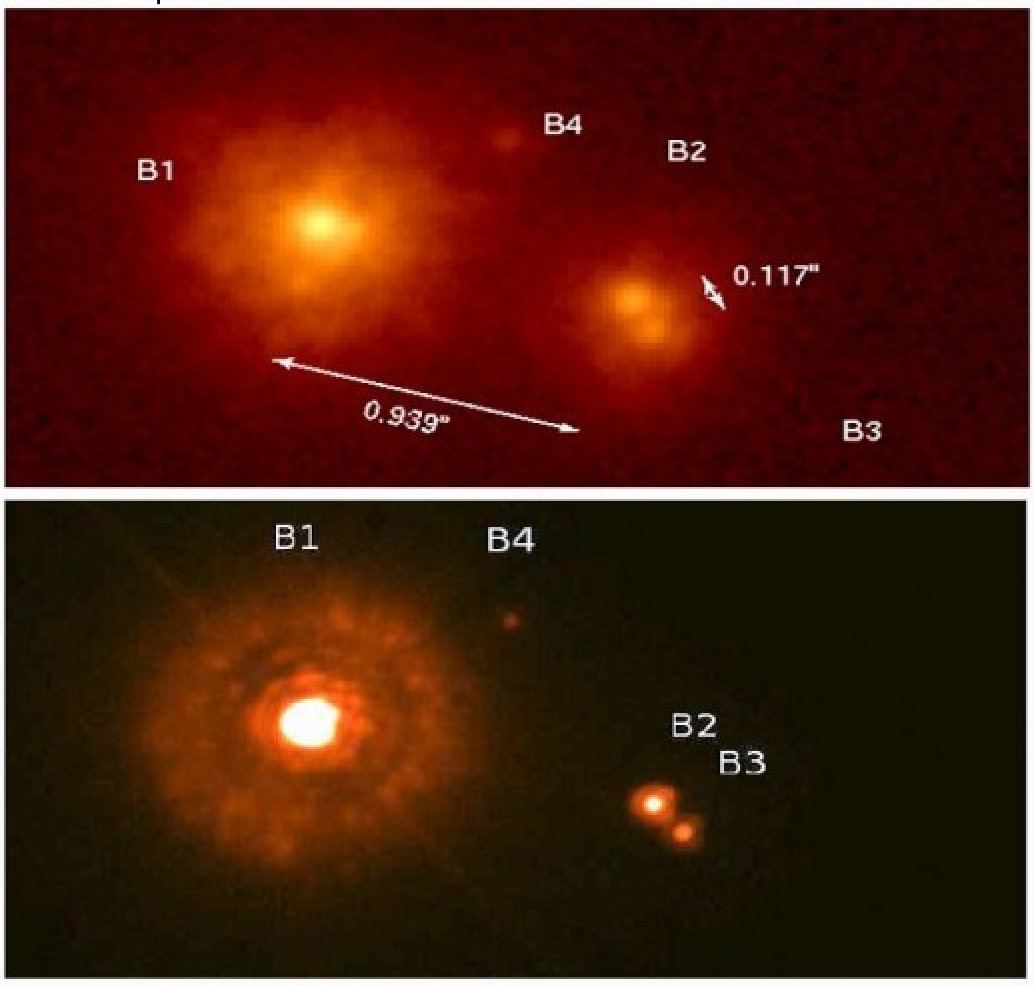
- chromaticity gets worse (refraction index of air varies more in visible than near-IR), ADC is needed
- instrumental non-common path errors get more serious

But diffraction limit is small in visible

Atmospheric refraction

Visible AO imaging

Trapezium inside Orion Nebula



Gemini Telescope (8m), near-IR AO

Magellan (6.5m)+ visible AO

Number of actuators should be very carefully chosen

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”

PSF quality: metric**S**

PSF quality metrics are driven by the science goals, and different metrics are used for different science goals/instruments/AO systems.

Example or PSF quality metrics:

- Full Width at Half Maximum (FWHM)
- Encircled energy (50 % of light in 0.xx” diameter)
- Strehl ratio
- astrometric accuracy
- photometric accuracy
- PSF contrast (for Extreme-AO)
- Correction radius (for Extreme-AO)
- residual jitter (for Extreme-AO + coronagraphy)