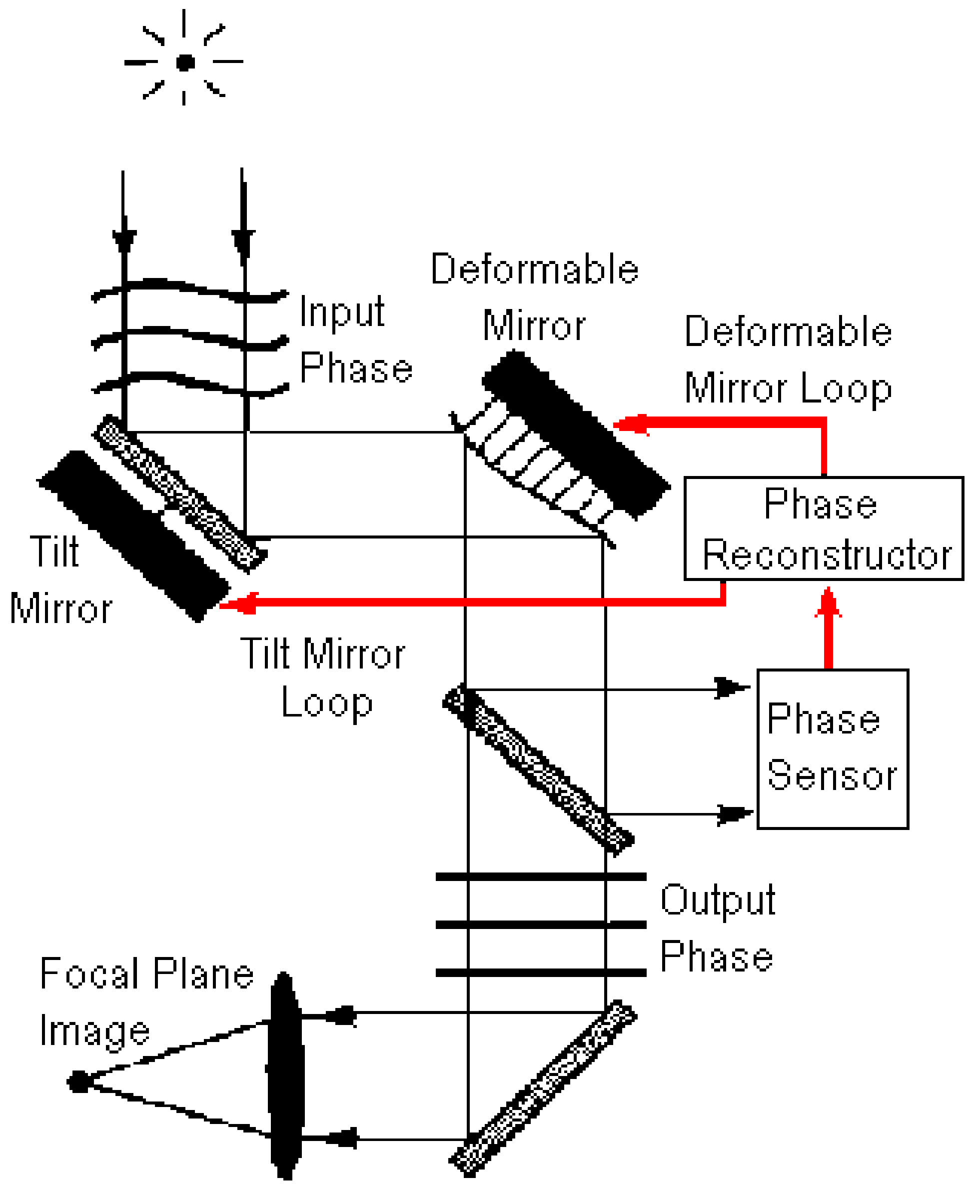
What is Adaptive Optics ?



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

5. Adaptive Optics

5.7 Software, algorithms & control

Wavefront reconstruction and control:
translating wavefront sensor signals to DM commands

- Response and control matrix
- Loop gain
- Zonal and Modal control

Transfer functions

Simulating AO systems for design and performance estimation

Telemetry

Practical considerations: computing power, data transfer

AO control

How should the AO system drive the DM from WFS measurements ?

“standard” solution (fast, linear):

- Measure/model how WFS measures DM commands
- If relationship is linear, this is stored as a “response matrix”
“response matrix” is inverted -> “control matrix” (this step usually includes some filtering – see next slides)
- WFS measurements x control matrix = DM commands

This could also be done by computing explicitly the wavefront:

WFS measurements -> wavefront -> DM commands

Good AO control now allows to separate WFS choice from DM choice:
example: Curvature WFS could run with a MEMs DM

Linear control of AO system: response and control matrix

Wavefront sensor response to DM commands is linear:

If DM command increased by factor x, WFS signal multiplied by x

WFS signal to sum of 2 DM commands = sum of the 2 WFS signals

→ Relationship can be written as matrix multiplication:

$A = M_{resp} B$

Assuming m actuators, n sensing elements

$A_{i=0...n-1}$: WFS signal vector (for example, x,y centroids for SH)

$B_{j=0...m-1}$: DM commands (can be voltages, displacements)

M_{resp}: m x n Response matrix (usually not a square matrix !)

AO control problem:

Given A (WFS measurement), and knowing M_{resp}, what is the DM command B which will produce the WFS signal -A ?

How to do this in a robust way, in the presence of noise, and with M_{resp} which is generally not inversible ?

Linear control of AO system: response and control matrix

Wavefront sensor response to DM commands is linear
→ DM commands to produce a given WFS signal is obtained by multiplication of A (WFS signal) by the control matrix M_{contr}

$B = M_{contr} A$

With M_{contr} the pseudo-inverse of $M_{resp} = M_{resp}^{+} = (M_{resp}^{T} M_{resp})^{-1} M_{resp}^{T}$

If M_{resp} is an inversible square matrix, $M_{contr} = M_{resp}^{-1}$

M_{contr} can be computed by Singular Value Decomposition (SVD) of M_{rest}

Singular Value Decomposition:

$M = U \Sigma V^{*}$

U: Unitary matrix

Σ: diagonal matrix (Eigenvalues a_i)

V: Unitary matrix, V^{*} its conjugate transpose ($=V^{T}$ if V real)

Pseudo-inverse :

$M^{+} = V \Sigma^{+} U^{*}$

With $\Sigma^{+} = 1/a$ if $|a|>0$, and 0 if $a=0$

Linear control of AO system: response and control matrix

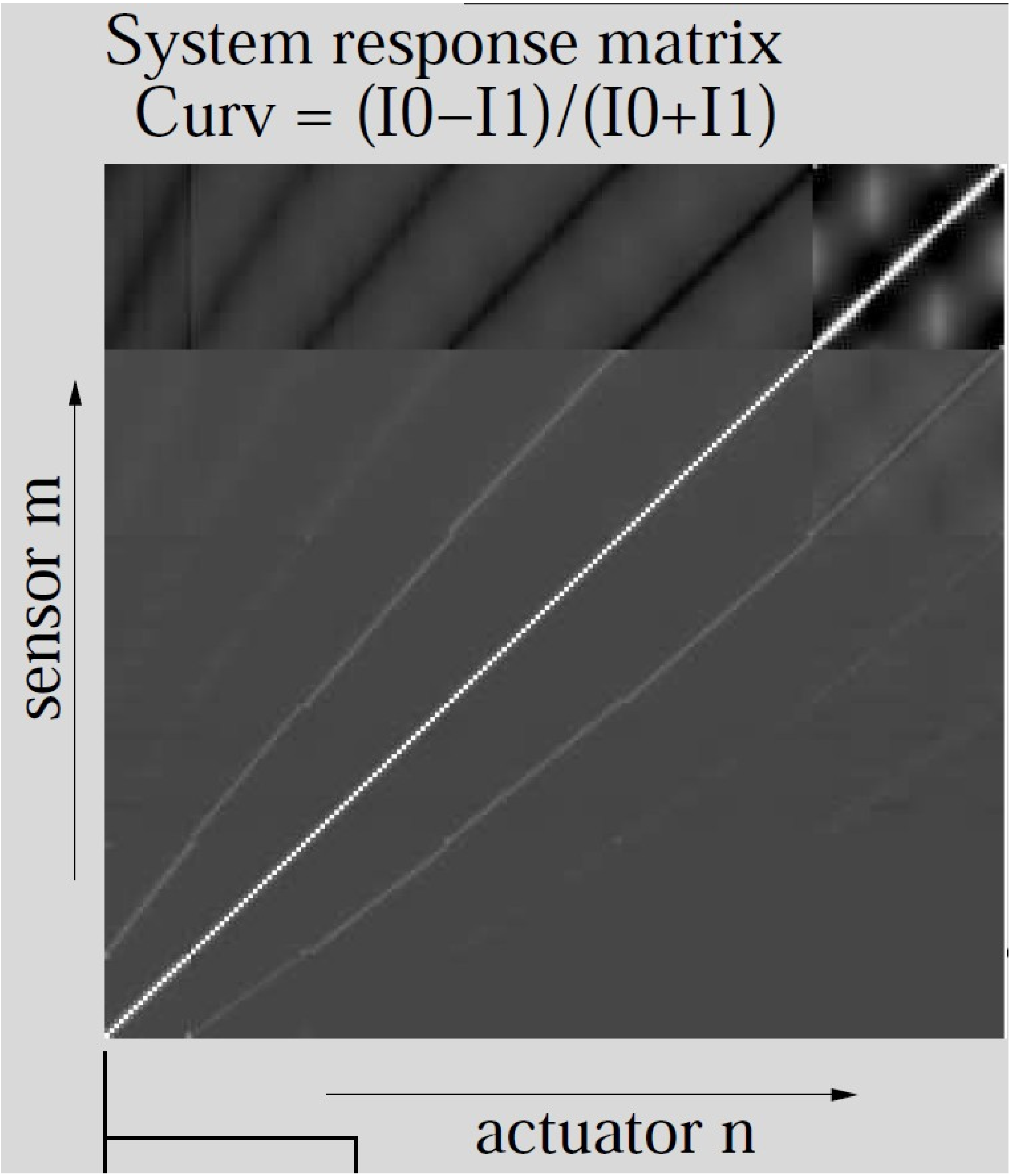
In practice:

- Although M_{resp} could be in theory computer, M_{resp} is usually measured by poking DM actuators and measuring the corresponding change in the WFS signal

- M_{resp} can be mesured quickly by driving simultaneously several actuators if M_{resp} is a sparse matrix (each DM actuator has an effect on a small number of sensors)

- M_{contr} is usually computed by SVD, and presence of noise in the measurement forces modes of M_{resp} with small eigenvalues to be discarded from the control loop (their eigeinvalue considered =0 in the pseudo-inverse computation)

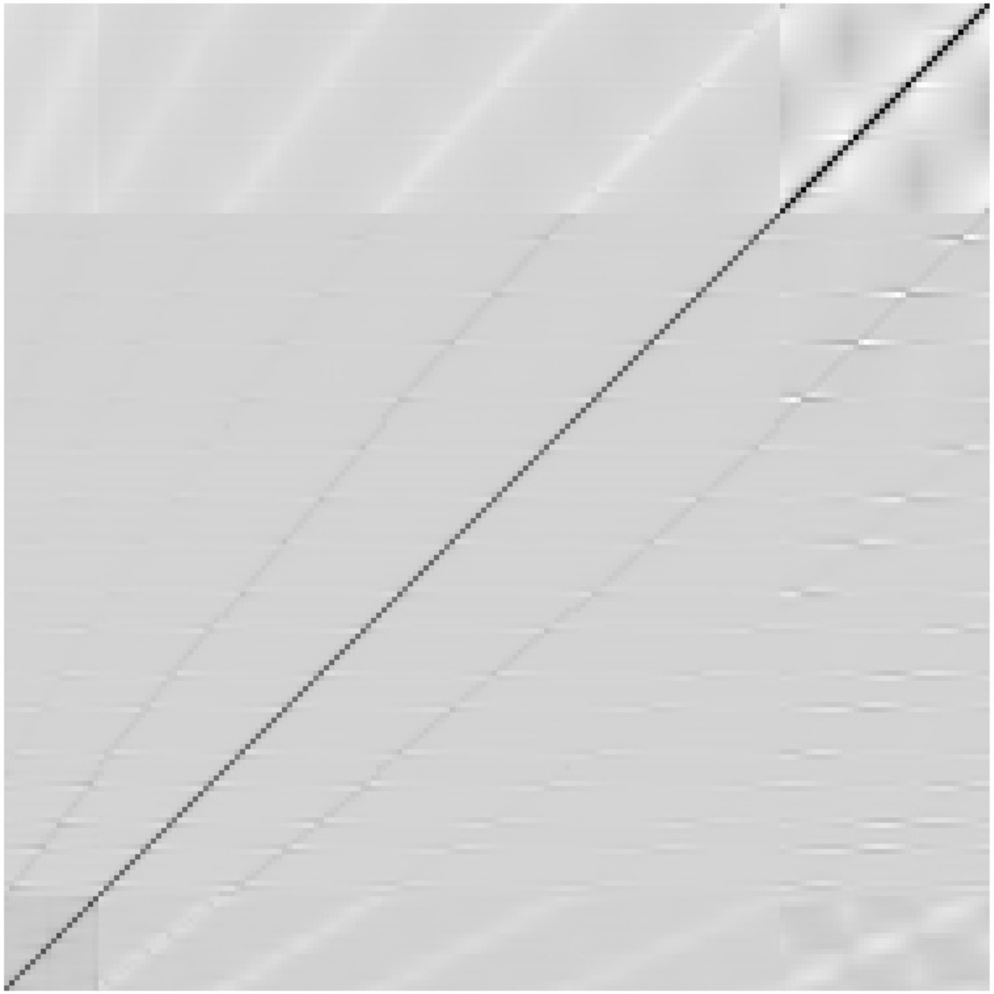
System response matrix: example (simulation)



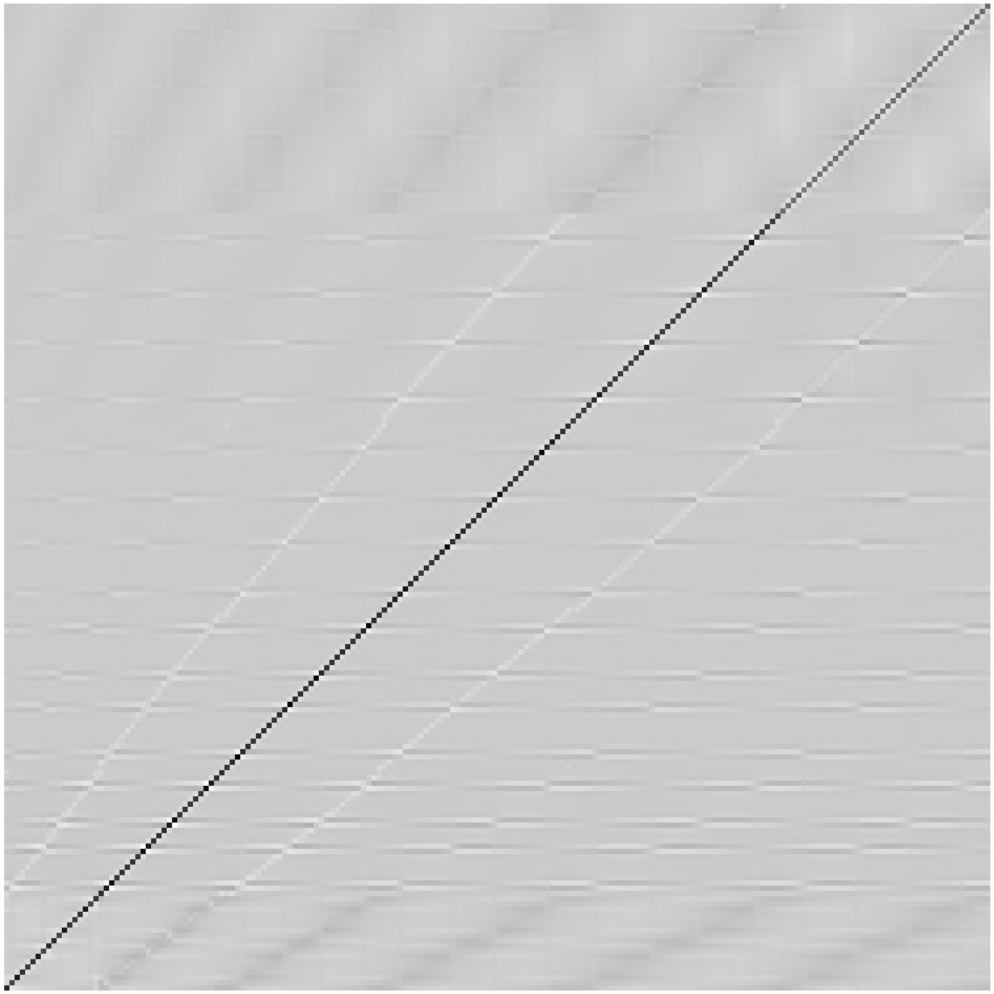
Measured response matrix includes system defects/imperfections, such as :
- alignment errors
- defective sensor(s)
- defective actuator(s)
- crosstalk

Mesuring response matrix is very good system diagnostics

System response and control matrix: example (simulation)



Response matrix



Control matrix

AO loop control: loop gain

At each step of the loop, offset dDM (= $-M_{contr}$ A) required to cancel WFS signal is computed. Ideally, with k the loop step (= time) :
$DM_k = DM_{k-1} + dDM$

Problem: with above equation, loop would likely be unstable

Effective time lag in the measurement is 1/sampling time

→ some temporal frequencies are amplified

Measurement is noisy, and several consecutive measurements should be averaged

Solution: use loop gain < 1:

$DM_k = DM_{k-1} + g\, dDM$
With $0<g<1$

Noisy WFS measurement (faint guide star) → small g

High quality WFS measurement (bright guide star) → large g

AO control: Modal control/filtering

Concept: Run AO loop at different speed for each mode, depending upon mode strength & WFS sensitivity for the mode
Gain becomes different for each mode

$M_{contr} = M_{resp}{}^{+} = V\, \Sigma^{+}\, U^{*}$
With $\Sigma^{+} = g_i/a_i$ if $|a_i|>0$, and 0 if $a_i=0$
Modal gains = g_i

Instead of thinking about AO control as relationship between individual sensors and actuators ("zonal" control), AO control is done mode per mode ("modal" control). Choice of modes is very important.

If $|a_i|$ is small (= WFS is not very sensitive to mode I), then
$1/a_i$ is large → noise can be amplified (noise/a_i is big)
If $|a_i|$ is small and corresponding mode in atmosphere is weak, then g_i should be small

AO control: Modal control/filtering

Modal control is very useful to:

- reject "bad modes" which can be produced by DM but not well sensed by WFS
- attenuate known vibrations
- powerful tool for system diagnostic

Modes poorly seen (noisy) by WFS & weak in the atmosphere should be prevented from feeding strong signals to DM. Powerful & well sensed mode should be rapidly driving the DM.

Modal control can continuously tune the system for optimal performance, adjusting gains g_i in real time (see next slide for transfer function description).

Transfer function $H_g(f)$ known as a function of g_i, and WFS signals measures WFS(f) = $H_g(f)$*Atm(f), with Atm(f) the input disturbance. Simplified description (without noise):

→ Atm(f) can be computed (= WFS(f)/$H_g(f)$)

→ WFS(f) can be estimated for other values of g_i

→ best g_i is adopted to minimize WFS(f)

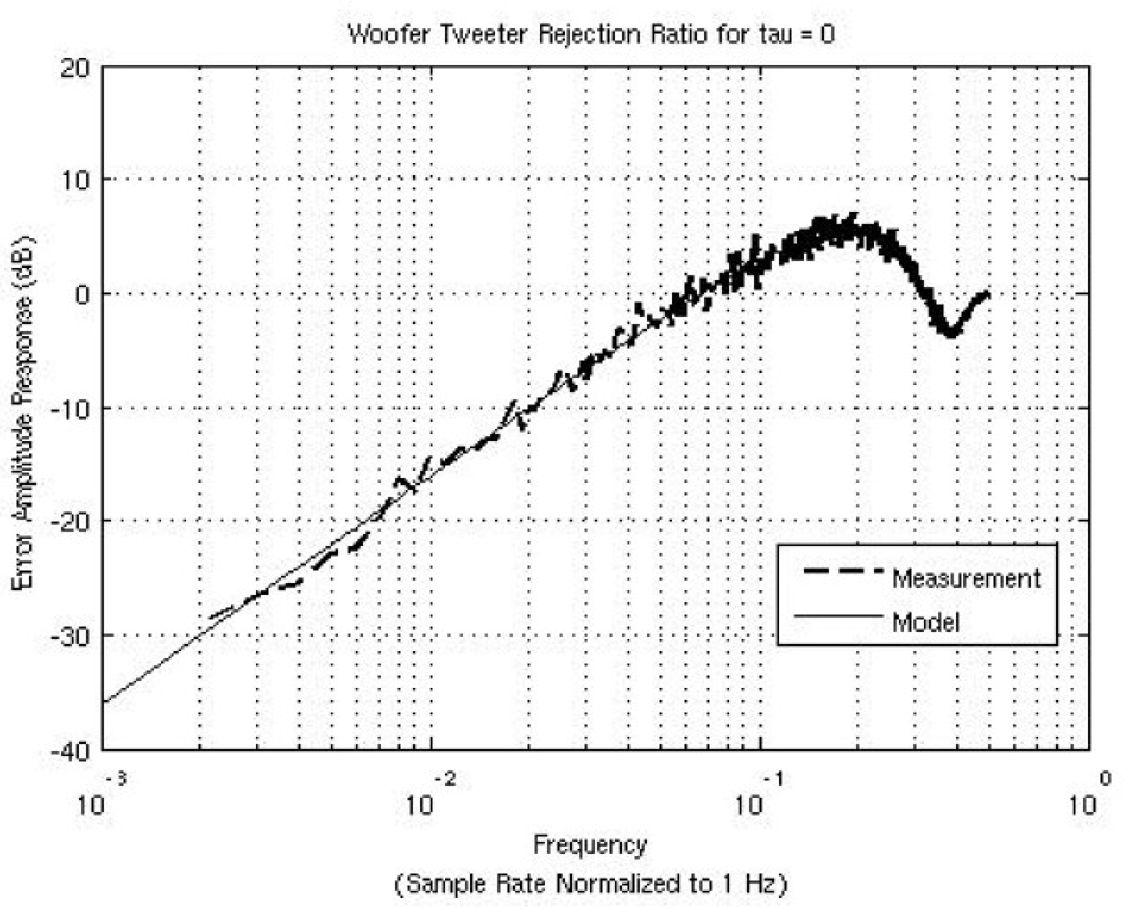
AO control: transfer function

AO control loop can be considered as a linear temporal filter. For each mode and each temporal frequency f, the AO system attenuates incoming errors by H(f), the AO error transfer function

H(f) < 1 : attenuation
H(f) > 1 : amplification

H(f) → 0 for f → 0 in a closed loop system

Notes:
- H(f) is complex :
    ampl = attenuation
    phase = delay
- analytical tools can express H(f) in amplitude and phase according to loop characteristics (gain, delay)



Hampton et al. (University of Victoria)

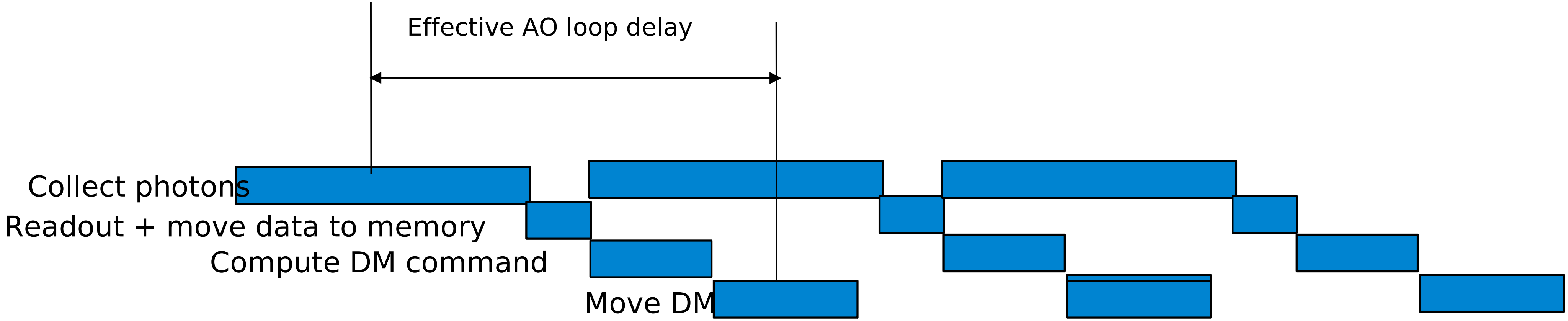
Optimizing AO control speed

→ 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 need to be fast

→ Clever, predictive control can help a lot: anything that could be predicted should be !



Realistic simulations of AO systems are extremely useful

AO simulations are relatively accurate, as input and outputs are well known:

- seeing properties are fairly well known (Kolmogorov layers)
- WFS behavior & properties are usually very well known
- Control algorithm identical in simulations & on the sky

AO simulations can investigate:

-> performance vs. # of actuators, DM type/geometry
-> loop instabilities & mode filtering
-> hardware trade-off:
    WFS detector readout noise
    DM hysteresis
    speed of electronics & computer
    Laser power for LGS
    On-axis vs. off-axis LGS
-> alignment tolerance

Telemetry is also very important

Recording WFS and DM data allows:

- seeing estimation & logging
- self-tuning of system
- diagnostics

If a strange behaviour is observed in the AO loop, it is very hard to identify it without being able to "play back" the time when it occurs.

Issues:

Disk space (2 kHz x 5000 single precision floats = 38MB/sec = 1 TB / night)

File management, archiving, sorting, searching