Adaptive Optics lectures

2. Adaptive optics

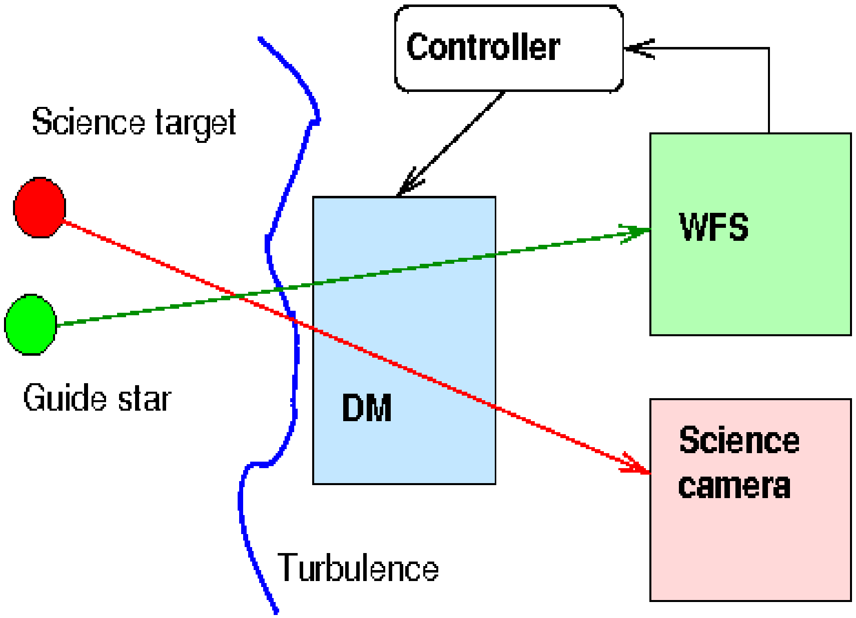
Invented in 1953 by H.Babcock

Andrei Tokovinin

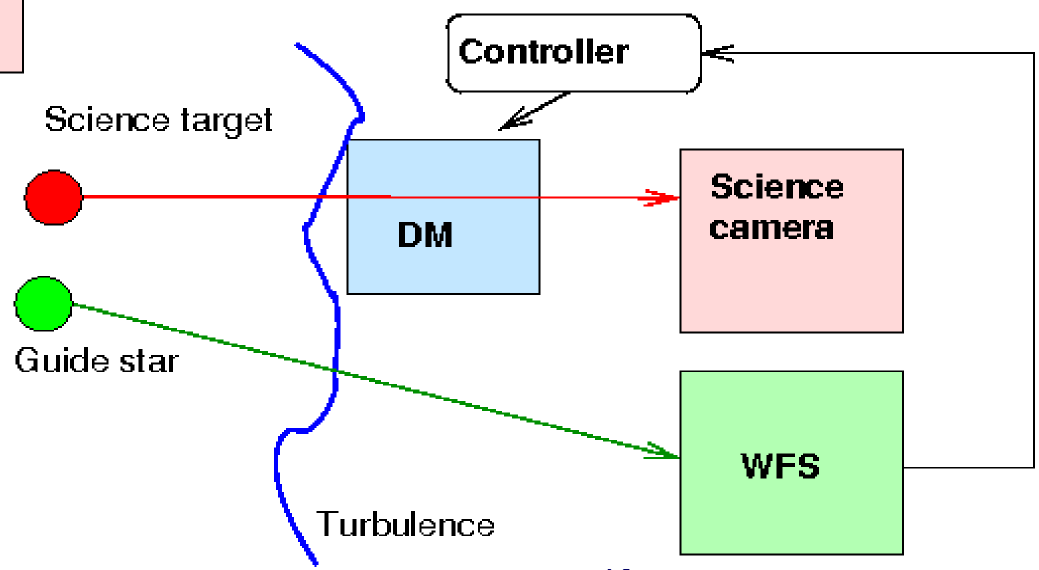
Plan

- General idea (open/closed loop)
- Wave-front sensing, its limitations
- Correctors (DMs)
- Control (spatial and temporal)
- Laser guide stars
- MCAO, MOAO, & GLAO
- AO engineering: system concept and error budget
- Non-astronomical AO

How it works?



Closed-loop servo system

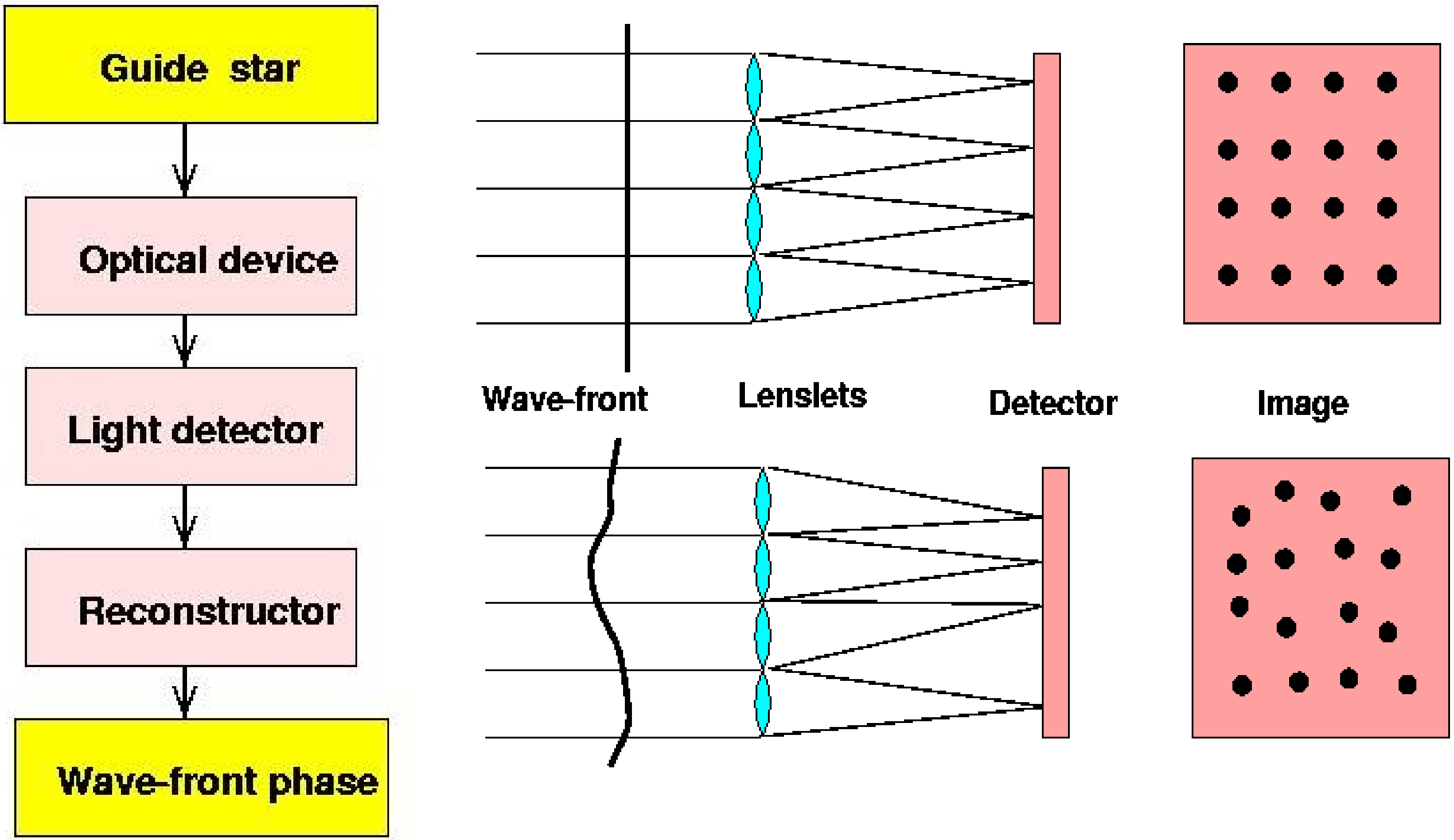


Open loop correction

Wavefront sensing

- Needs a light source to measure the wavefront: the guide star (GS), natural or laser
- GS must be bright (>10..100 photons per r_0 and τ_0 at imaging λ)
- GS must be close to the target (< θ_0), best the target itself
- WFS must use all available photons (be achromatic, unless LGS).

The Shack-Hartmann WFS



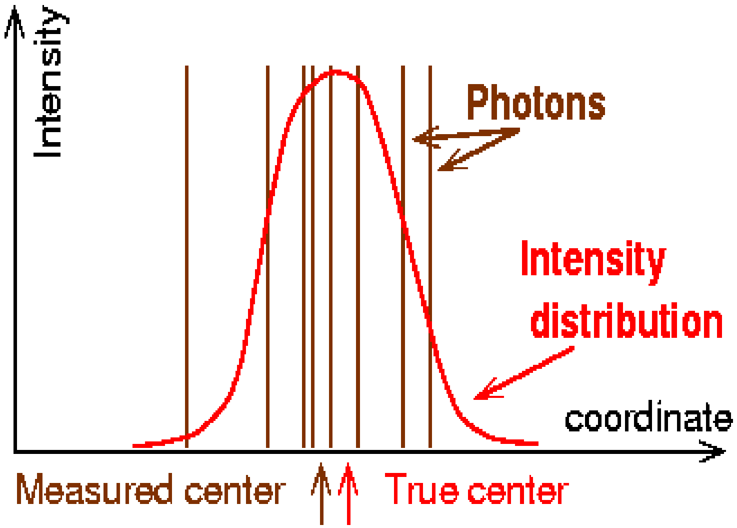
S-H parameters

- Sub-aperture size d (on the pupil), number of sub-apertures
- Spot size $\varepsilon = \max(\lambda/d, \lambda/r_0)$. λ– WFS wavelength
- Sampling: pixels per ε (>1 normally)
- Field (pixels per sub-aperture)
- Detector: noise, frame rate, delay

Spot centroiding

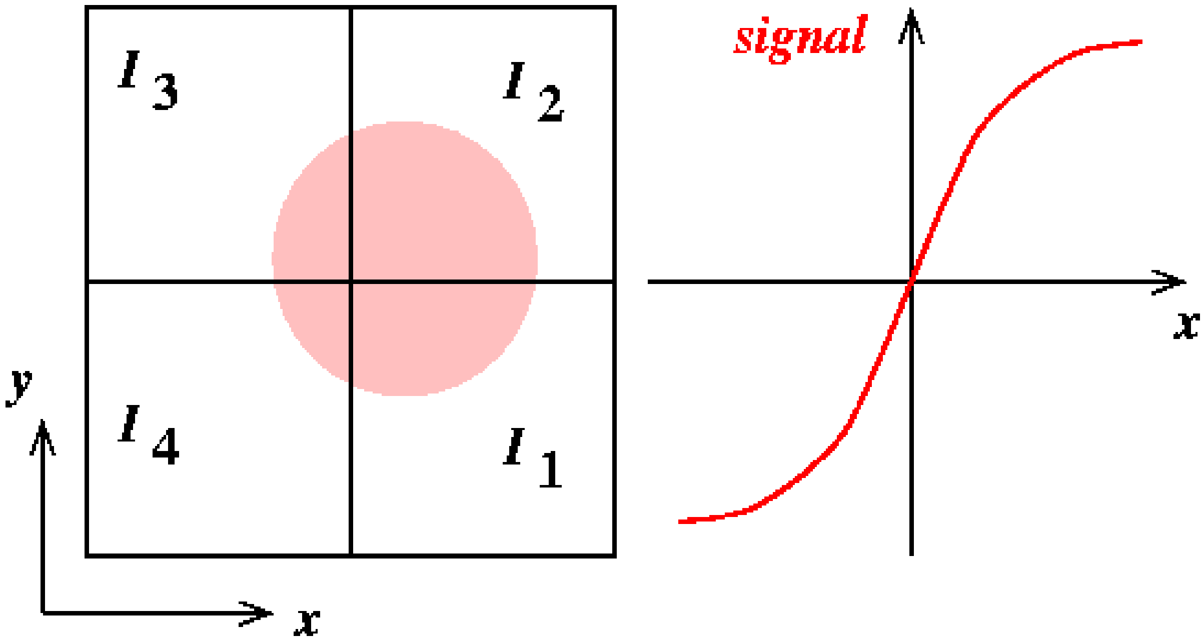
With N photons, the best accuracy is $\varepsilon/\sqrt{N}$. It does not depend on the field size (almost). When the readout noise is important, the error is larger, and the centroiding method matters.

1. Quad-cell
2. Simple centroid
3. Modified centroid (weighted)
4. Correlation



Centroids are never accurate!

Centroiding: quad cell



Pros:

- Fast
- Only 4 pixels

Cons:

- Non-linear
- Var. response
- Not optimum

$$x \approx \frac{\beta}{2}\frac{I_1+I_2-I_3-I_4}{I_1+I_2+I_3+I_4}, \quad y \approx \frac{\beta}{2}\frac{I_2+I_3-I_1-I_4}{I_1+I_2+I_3+I_4}.$$

Wavefront reconstruction

Spatial resolution: min. period 2d, aliasing!

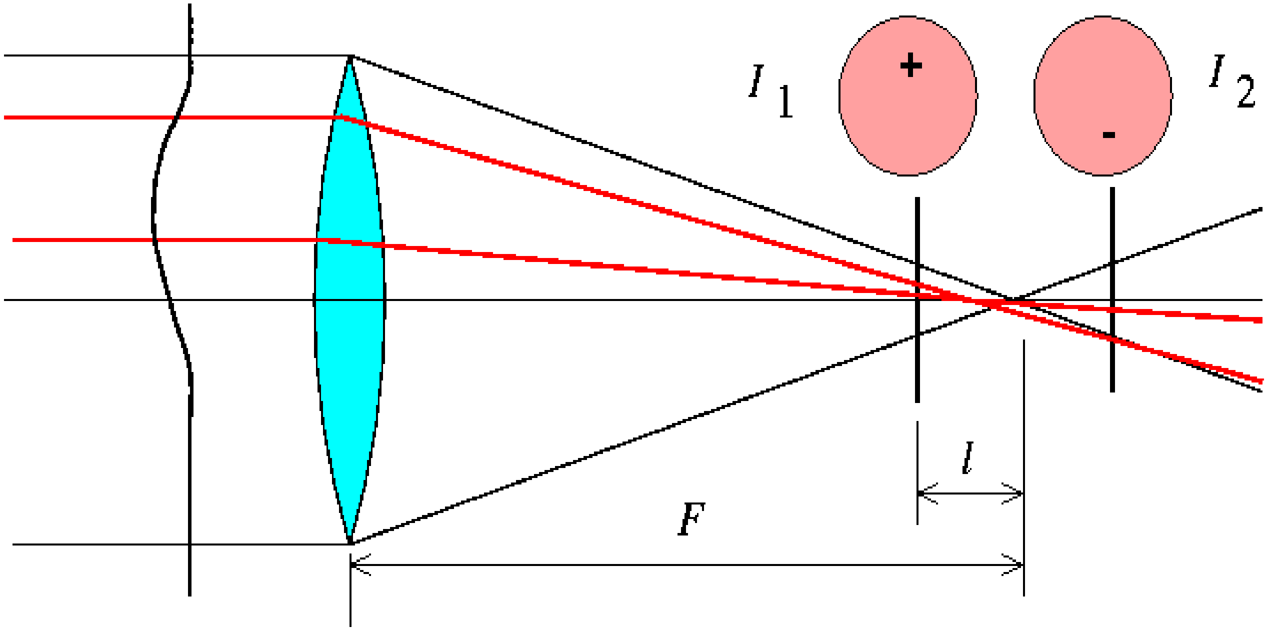
Phase is computed from integration of slopes

Higher order modes have larger slopes,
hence less noise

Noise on low-order modes increases as f^{-2} .

Different WFS flavors have different noise properties!

Curvature WFS
(F.Roddier)



Intensity in a defocused image is a proxy of wavefront curvature

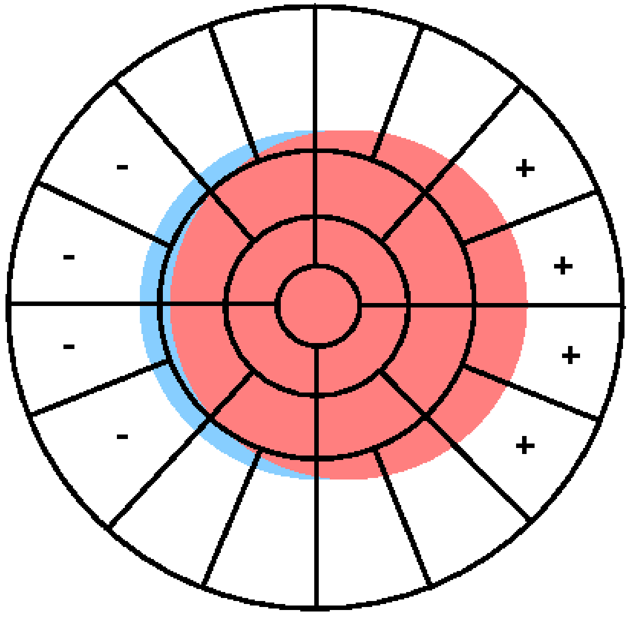
Difference between intra- and extra-focal to cancel scintillation

The amount of defocus defines resolution & sensitivity

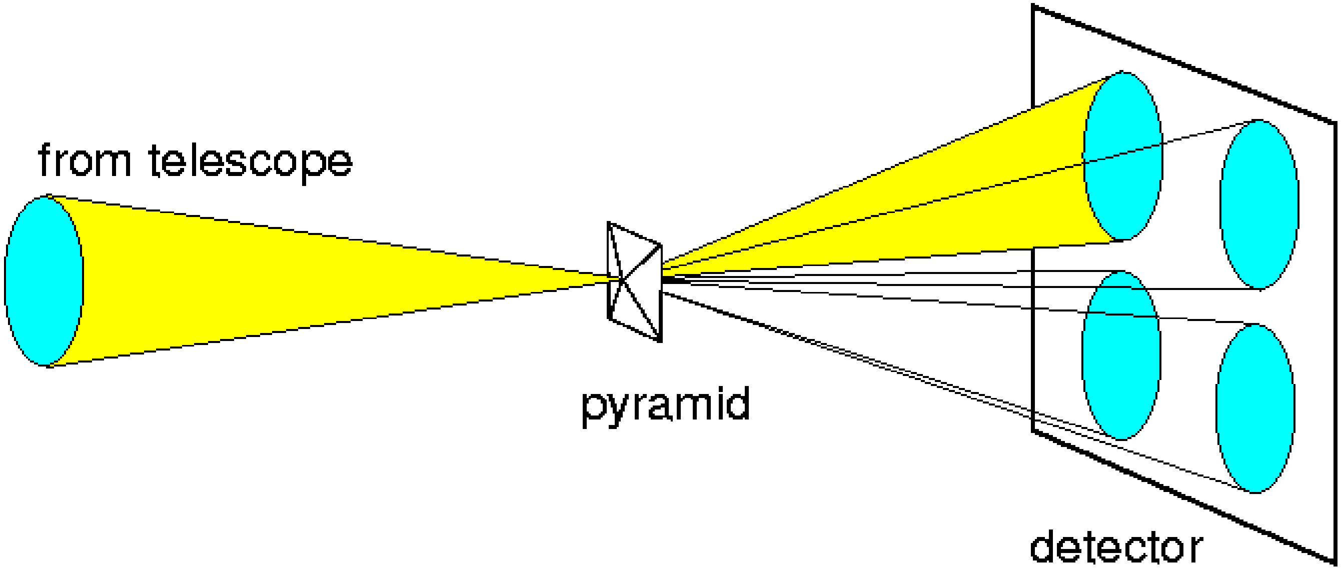
Non-linear CWFS (O.Guyon): extension of the idea

Curvature WFS: noise propagation

- Double integration: noise ~f $^{-4}$, large tip-tilt errors!
- Works well only as null sensor (in closed loop)



Pyramid (knife-edge) WFS



For a finite source, works like S-H with quad cell.

For point source partially corrected, works better.

Uses modulation to blur the source

Not suitable for open-loop systems!

Which WFS is better?

Shack-Hartmann	Pyramid
Standard	Novel
Accurate	Approximate
Noisy	Less noise
Many pixels	4 pixels/subaperture
Not flexible	Flexible

Other WFS concepts: curvature (incl. NLCWFS), interferometric, focal-plane. Gershberg-Saxton phase recovery, diversity,...

Deformable mirrors

- Piezo-stack (traditional). 3-5mm pitch, few μm stroke, fast

(Keck AO, GEMS, etc.). Xinetics → CILAS → ?

- Bimorph ("curvature"): stroke ~f^{-4} (large defocus!)
- Membrane (magnetic). Linear! ALPAO (France).
- Micro-machine (small, many actuators). Linear!
- Deformable secondaries (magnetic with feedback).

Spatial control: match WFS & DM

WFS signal x → wavefront → DM actuator commands v

$$x = A\,v$$

A = interaction matrix

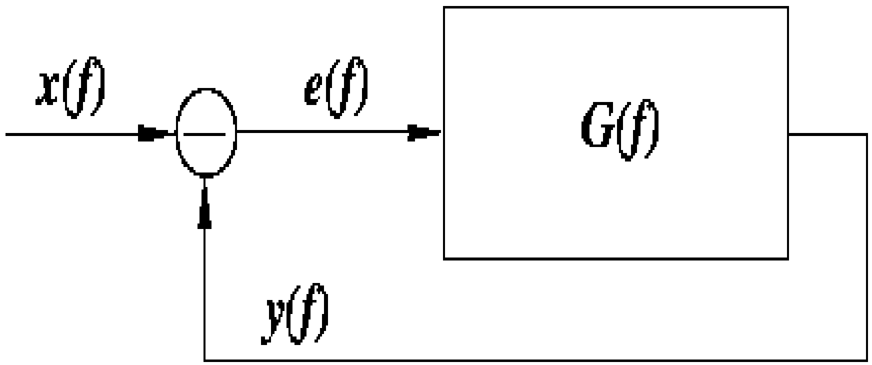
$$v = A^{-1}x$$

A^{-1} = control matrix

Use SVD decomposition to remove "weak" modes

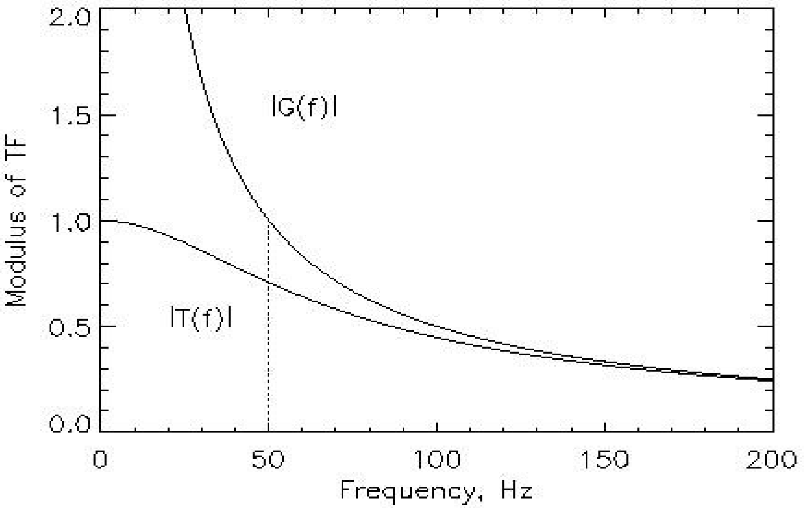
Deal with "unseen modes" (e.g. waffle)

Servo loop control



If we apply the correction too strong or too soon, the servo will become unstable!

$$\frac{G(f)}{1+G(f)}\tilde{x}(f) = \tilde{T}(f)\tilde{x}(f).$$



G(f)=g/if: integrator

|T(f)|= 1/[1 + (gf)²]

Error transfer function

Noise transfer function

Servo control 2.

- Digital loop: the 3-dB frequency is typically 1/10 of the loop frequency
- Delays matter (2-frame delay in SAM)
- Kalman filtering (or similar) to remove fixed frequencies
- Spatial predictive control (wavefront moves)

Laser guide stars

- LGS is needed to solve the sky coverage problem
- Creates more problems: laser, light pollution, restrictions on propagation
- Still needs tip-tilt NGS
- Cone effect
- Higher cost

Two types of LGS: Rayleigh and sodium

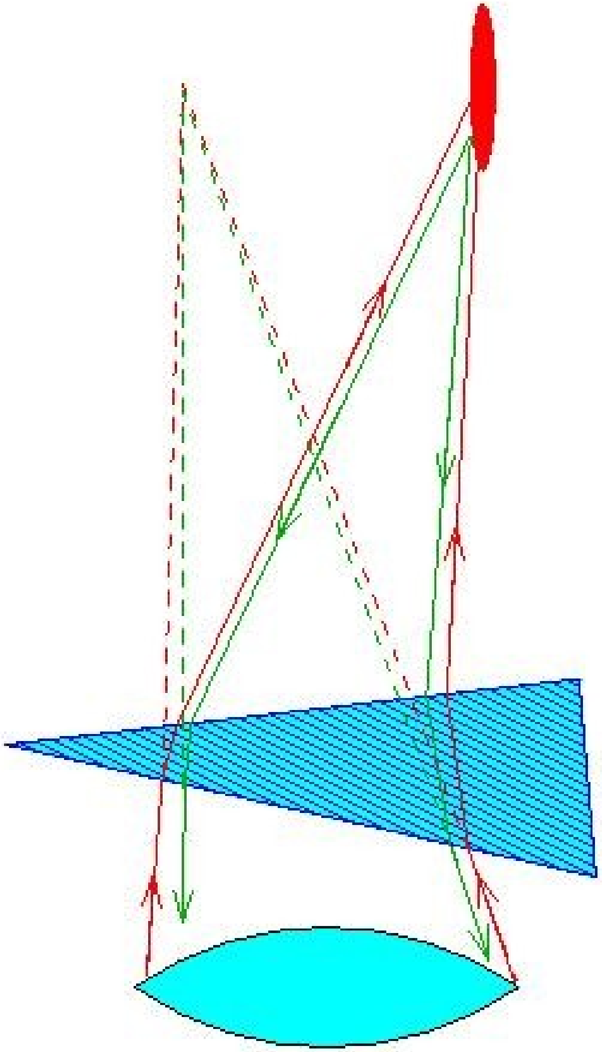
Why LGS need tip-tilt stars?

Up-tilt - Down-tilt = 0!

Several solutions to measure atmospheric tilts

But telescope shake remains.

Seismometer??

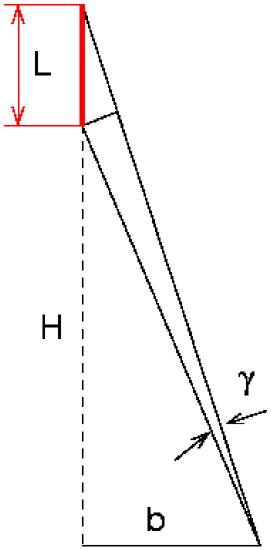


Rayleigh LGS

- Uses Rayleigh and aerosol backscattering. Needs air, max. height ~20km. Scattering $\sim\lambda^{-3}$ → “likes” blue/UV
- Pulsed laser and gated WFS to receive photons from (H,H+L) only.
- Large cone effect and spot elongation.

$\Upsilon=(Lb)/H^2$. “Dynamical refocus” (MMT)

- Not suitable for ELTs!



Rayleigh LGS: SOAR, MMT, LBT

Sodium LGS

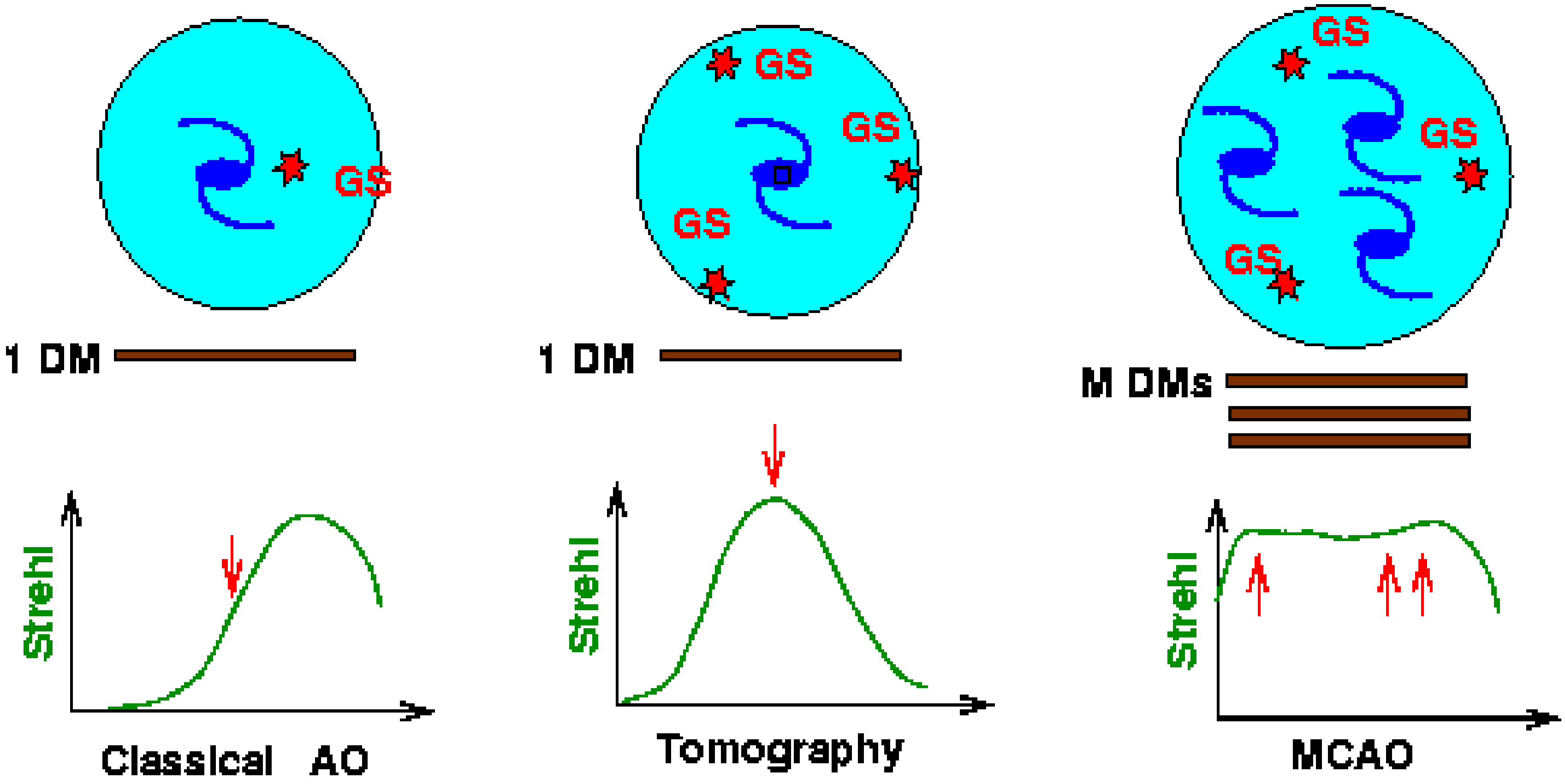
- Uses resonant scattering of D1 line from ~90km layer
- The laser must be tuned to D1 (589nm), polarization and spectrum matter → high cost, low laser reliability
- Variable Na layer (meteoritic origin), seasonal
- Not aircraft-safe
- Best (only!) choice for large apertures and ELTs

Sodium LGS: 2xKeck, 1xVLT, Gemini(N,S), Lick, all ELTs

Advanced AO concepts

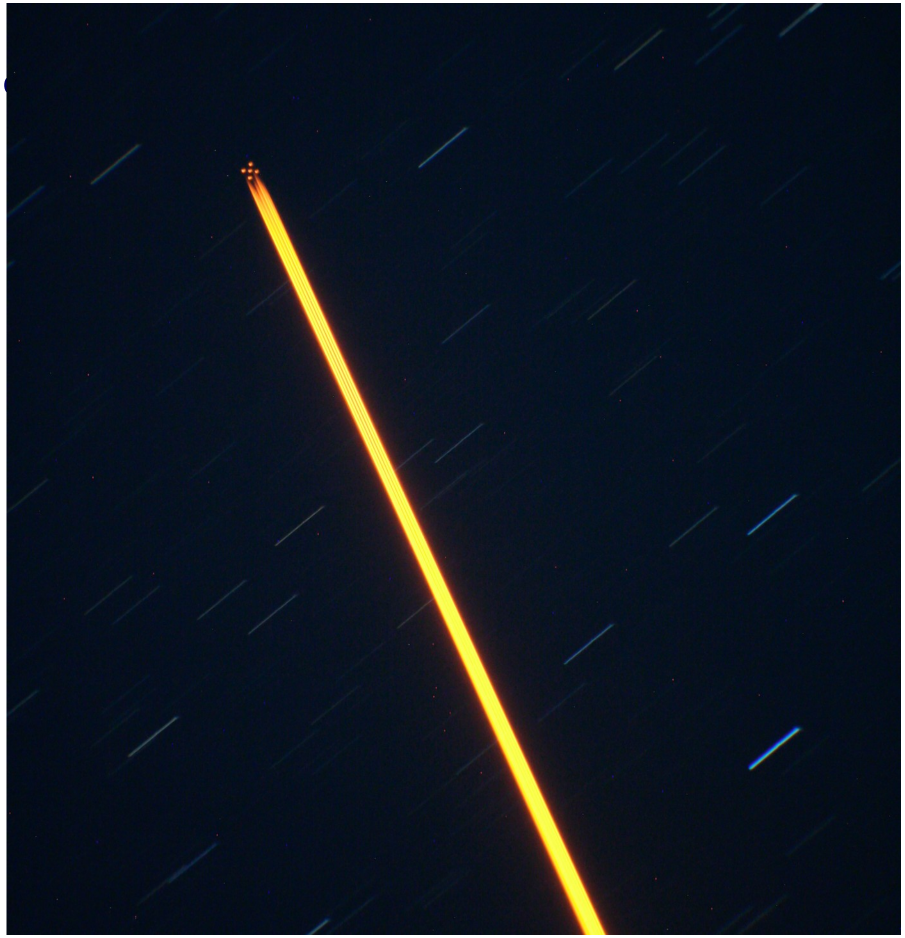
- Tomography: use several GS to reconstruct 3D phase
- Tomography helps to overcome the LGS cone effect
- Apply 3D correction: Multi-Conjugate AO (MCAO)
- Correct each target individually: Multi-Object AO (MOAO), open-loop only!
- Correct only the ground layer: GLAO

MCAO & tomography



Gemini MCAO (GEMS)

- 5 sodium LGSs, 50W nomina
- 5 S-H WFSs, 3 tip-tilt NGSs
- 3(2) DMs (0, 4.5, 9km)
- IR imager [GMOS]



Problems: laser, Na layer, fratricide, alignment, failed DM, aircraft, operation,...

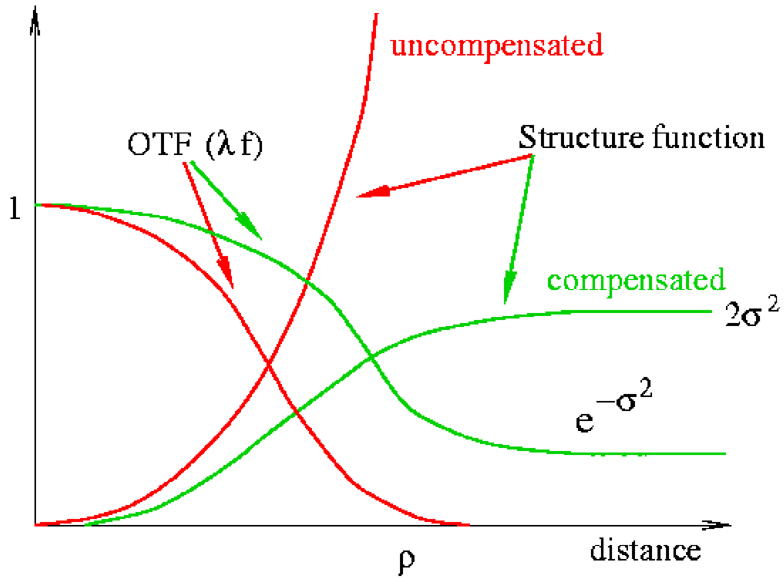
http://www.gemini.edu/sciops/instruments/gems/introduction-gems

How good is the AO correction?

Strehl ratio (central PSF intensity vs. ideal)

$$SR = \exp [-\langle \Delta\varphi^2 \rangle]$$

The correction is measured by the residual errors:



1. Fitting and aliasing (spatial res.)
2. Noise
3. Servo lag error
4. Anisoplanatism, cone effect, tilt

AO error budget

$\sigma^2_{fit} = 0.35\ (d/r_0)^{5/3}$

$\sigma^2_{lag} = (\tau_0\ f_{3dB})^{-5/3}$

$\sigma^2_{noise} = K\ N_{ph}^{-1/2}$

$\sigma^2_{iso} = (\theta/\theta_0)^{5/3}$

The terms are not exactly additive!

Phase error is proportional to λ^{-6} !

Designing an AO system

- Define goals of the instrument
- Technology constraints: available components
- Budget constraints
- Dimension the system (actuator & photon count)
- Balance the errors (error budget)
- Improve and iterate
- Formulate design requirements

Non-astronomical AO

- Defence: space watch (resolve spacecraft images)
- Defence: energy concentration (burn the enemy)
- Communication: optical signal transmission
- Medicine: eye diagnostic (view retina at high resolution)

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