Adaptive Optics Overview

Adapted from presentations by Prof. Claire Max, UC Santa Cruz
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With additional material from the MPE Garching AO group, ESO AO group, UCLA AO group, and GBT surface adjustment program

Neptune

Details of diffraction from circular aperture

1) Amplitude

\[ \text{somb}(r) = 2 J_1(\pi r) / (\pi r) \]

First zero at
\[ r = 1.22 \frac{\lambda}{D} \]

2) Intensity

Airy Pattern

\[ \text{somb}^2(r) \]

FWHM
\[ \frac{\lambda}{D} \]
Imaging through a perfect telescope

With no turbulence, FWHM is diffraction limit of telescope, $\theta \sim \lambda / D$

Example:
$$\lambda / D = 0.02 \text{ arc sec for } \lambda = 1 \mu m, D = 10 m$$

With turbulence, image size gets much larger (typically 0.5 - 2 arc sec)

Why is adaptive optics needed?

Turbulence in earth’s atmosphere makes stars twinkle

More importantly, turbulence spreads out light; makes it a blob rather than a point

Even the largest ground-based astronomical telescopes have no better resolution than an 8" telescope!
No atmosphere, no twinkle

Neptune at 1.6 μm: Keck AO exceeds resolution of Hubble Space Telescope

HST - NICMOS

Keck AO

2.4 meter telescope

10 meter telescope

(Two different dates and times)
Lesson: Keck in near IR has same resolution as Hubble in visible light.

**Uranus with Hubble Space Telescope and Keck AO**

- HST, Visible
- Keck AO, IR

**Neptune in infra-red light (1.65 microns)**

- Without adaptive optics
- With Keck adaptive optics

May 24, 1999

June 27, 1999
VLT NAOS AO first light

Cluster NGC 3603: IR AO on 8m ground-based telescope achieves same resolution as HST at 1/3 the wavelength

Hubble Space Telescope
WFPC2, \( \lambda = 800 \text{ nm} \)

NAOS AO on VLT
\( \lambda = 2.3 \text{ microns} \)

Adaptive optics makes it possible to find faint companions around bright stars

Two images from Palomar of a brown dwarf companion to GL 105

Credit: David Golimowski
**Images of a bright star, Arcturus**

Lick Observatory, 1 m telescope

- $\delta \sim 1 \text{ arc sec}$
- $\delta \sim \frac{\lambda}{D}$

Long exposure image  
Short exposure image  
Image with  
adaptive optics

Speckles (each is at diffraction limit of telescope)

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**What does it really look like?**

Speckles and the  
“Seeing disk”  
With AO

Images from the MPE Garching AO group  
http://www.mpe.mpg.de/ir/ALFA
Atmospheric perturbations cause distorted wavefronts

Rays not parallel

Plane Wave

Index of refraction variations

Distorted Wavefront

Optical consequences of turbulence

• Temperature fluctuations in small patches of air cause changes in index of refraction (like many little lenses)
• Light rays are refracted many times (by small amounts)
• When they reach telescope they are no longer parallel
• Hence rays can’t be focused to a point:
Turbulence arises in several places

- Stratosphere
- Tropopause
- Boundary layer

Heat sources within dome

Wind flow around dome

Local “Seeing” - Flow pattern around a telescope dome

Cartoon (M. Sarazin): wind is from left, strongest turbulence on right side of dome

Computational fluid dynamics simulation (D. de Young) reproduces features of cartoon
How does adaptive optics help? (cartoon approximation)

- Measure details of blurring from “guide star” near the object you want to observe
- Calculate (on a computer) the shape to apply to deformable mirror to correct blurring
- Light from both guide star and astronomical object is reflected from deformable mirror; distortions are removed

Schematic of adaptive optics system

Feedback loop: next cycle corrects the (small) errors of the last cycle
How a deformable mirror works (idealization)

BEFORE

Incoming Wave with Aberration

Deformable Mirror

AFTER

Corrected Wavefront

Deformable Mirror for real wavefronts
Characterize turbulence strength by quantity $r_0$

Wavefront of light

$\rightarrow r_0$ “Fried’s parameter”

Primary mirror of telescope

- “Coherence Length” $r_0$: distance over which optical phase distortion has mean square value of 1 rad$^2$ ($r_0 \sim 15 - 30$ cm at good observing sites)
- Easy to remember: $r_0 = 10$ cm $\leftrightarrow$ FWHM = 1” at $\lambda = 0.5$ μm

Real deformable mirrors have continuous surfaces

Piecewise linear fit

$\rightarrow r_0$ Phase $\Phi$

Primary mirror

- In practice, a small deformable mirror with a thin bendable face sheet is used
- Placed after the main telescope mirror
Most deformable mirrors today have thin glass face-sheets

- Glass face-sheet
- Light
- Cables leading to mirror's power supply (where voltage is applied)
- PZT or PMN actuators: get longer and shorter as voltage is changed

Deformable mirrors come in many sizes

- Range from 13 to > 900 actuators (degrees of freedom)

A couple of inches

About 12”
**Schematic of adaptive optics system**

Feedback loop: next cycle corrects the (small) errors of the last cycle.

**Shack-Hartmann wavefront sensor concept - measure subaperture tilts**

Pupil plane  Image plane
Shack-Hartmann wavefront sensor measures local “tilt” of wavefront

- Divide pupil into subapertures of size ~ \( r_0 \)
  - Number of subapertures \( \alpha (D / r_0)^2 \)

- Lenslet in each subaperture focuses incoming light to a spot on the wavefront sensor’s CCD detector

- Deviation of spot position from a perfectly square grid measures shape of incoming wavefront

- Wavefront reconstructor computer uses positions of spots to calculate voltages to send to deformable mirror
Curvature sensing - Computer simulation of curvature wavefront sensing

- AO loop open:
  (a) wavefront distortion.
  (b) intrafocal image.
  (c) extrafocal image
  (d) curvature signal at high resolution.
  (e) curvature signal binned into 60 subapertures.

* Simulation parameters: 0.60 arc sec seeing (at 500 nm), sensing wavelength = 700 nm (monochromatic), infrared image wavelength = 2.5 μm, out of focus distance = 25 cm, telescope focal length = 400 m, telescope diameter = 8 m with 14% obscuration from 1.12 m diameter secondary. Photon noise has not been simulated — all signals are “infinite” light level.

7/2/01
Typical optical design of AO system

Adaptive optics system is usually behind main telescope mirror

- Example: AO system at Lick Observatory’s 3 m telescope
Adaptive optics increases peak intensity of a point source

Lick Observatory

No AO  With AO

Intensity

No AO  With AO

AO produces point spread functions with a “core” and “halo”

Definition of “Strehl”: Ratio of peak intensity to that of “perfect” optical system

• When AO system performs well, more energy in core
• When AO system is stressed (poor seeing), halo contains larger fraction of energy (diameter ~ r₀)
• Ratio between core and halo varies during night
If there’s no close-by “real” star, create one with a laser

- Use a laser beam to create artificial “star” at altitude of 100 km in atmosphere
Laser “guide star” (or, here, guide stars)

Twin beams toward the Galactic center for AO with the Keck Interferometer

Photo credit Dan Birchall, UCLA

Galactic Center with Keck laser guide star

Keck laser guide star AO

Page 37
AO in the isoplanatic patch

Turbulence arises in several places

- Stratosphere
- Tropopause (10-12 km)
- Boundary layer (~1 km)
- Wind flow around dome
- Heat sources within dome
Multi-conjugate AO (MCAO)

Active optics: reflector surface errors

- Many telescopes have segmented surfaces: Keck, NGST, and radio telescopes are familiar examples
- Now deform the aperture to correct the phase errors
Zernike polynomials

- The Zernike polynomials are orthogonal on a unit disk
  - First, piston (up-down)
  - Then tilts (R-L, up-down)
  - Then bends with one half cycle across aperture
  - Then more and more cycles
- Orthogonality simplifies computations; Zernike for circular apertures

Image from Rocchini, Wikipedia commons

Surface improvement

Daytime Q-band aperture phase

230 μm rms

with thermal Zernikes applied

Blade = thermal + gravitational Zernike terms
Red = gravitational Zernike terms only

Block = thermal + gravitational Zernike terms
Red = gravitational Zernike terms only

NRAO