INTRODUCTION TO ADAPTIVE OPTICS AND ITS HISTORY

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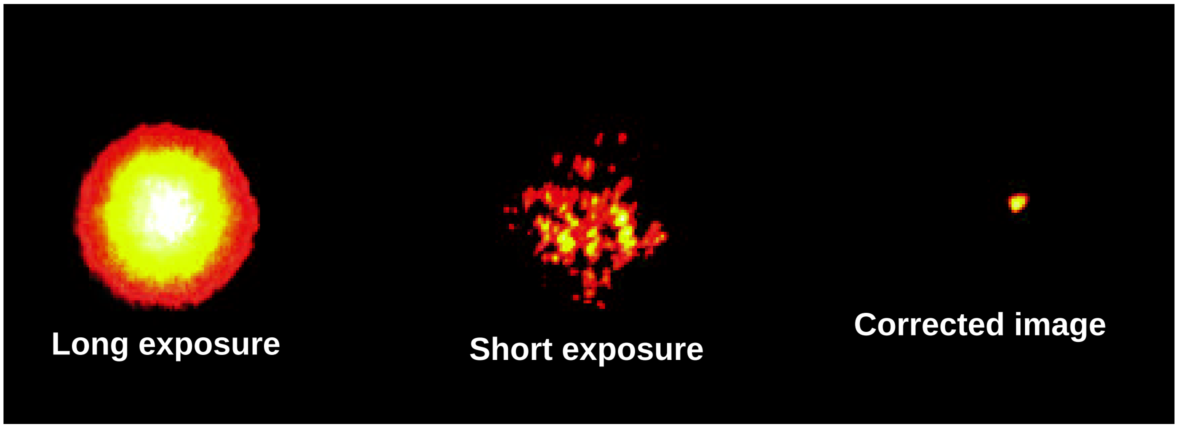
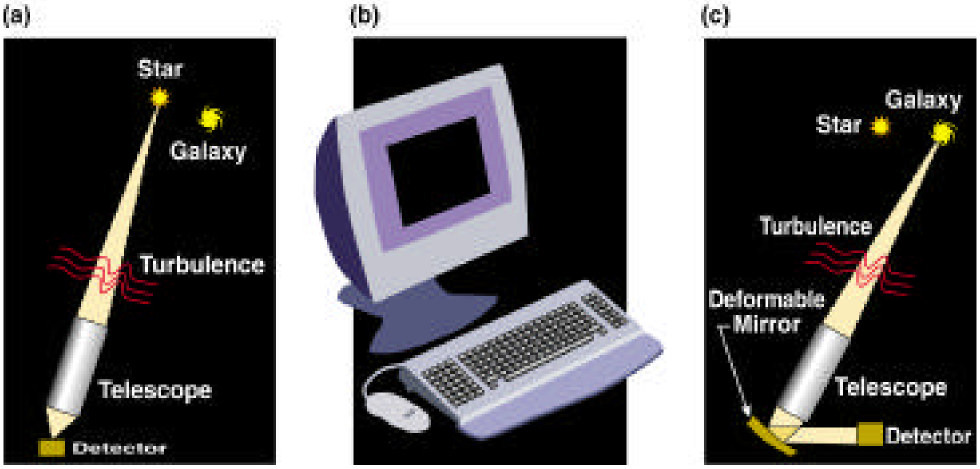
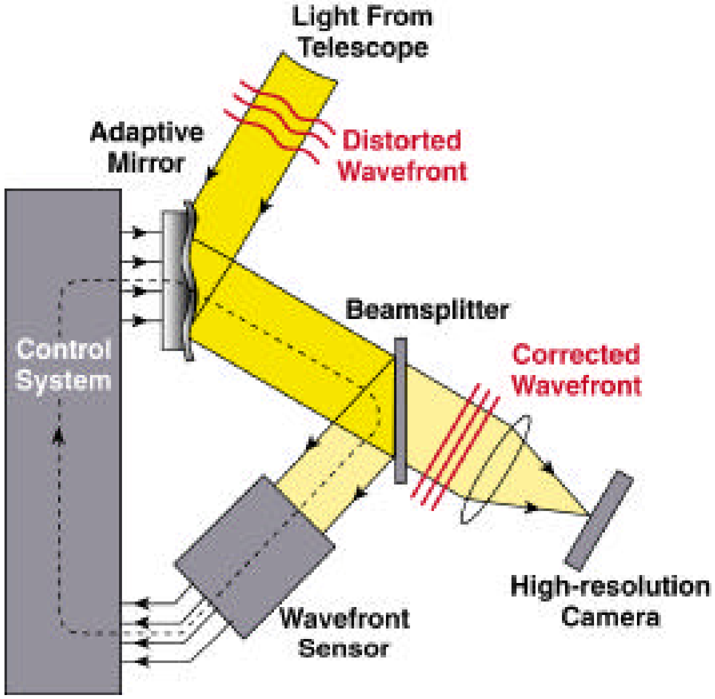
1. Why is adaptive optics needed? Turbulence in the Earth's atmosphere limits the performance of ground-based astronomical telescopes. In addition to making a star twinkle, turbulence spreads out the light from a star so that it appears as a fuzzy blob when viewed through a telescope. This blurring effect is so strong that even the largest ground-based telescopes, the two 10-m Keck Telescopes in Hawaii, have no better spatial resolution than a modest 8-inch backyard telescope! One of the major motivations for launching telescopes into space is to overcome this blurring due to the Earth's atmosphere, so that images will have higher spatial resolution than has been possible to date from the ground. The Figure below illustrates the blurring effect of the atmosphere in a long-exposure image (left) and a short "snapshot" image (center). When the effects of turbulence in the Earth's atmosphere are corrected, this distant star would look like the image on the right. *Image credit: Lawrence Livermore National Laboratory and NSF Center for Adaptive Optics.* Graphic can be obtained at the Center for Adaptive Optics, University of California at Santa Cruz, (831) 459-5592 or cfao@ucolick.org.

Bright Star (Arcturus) Observed with Lick Observatory's 1-m Telescope:



2. How adaptive optics works. Adaptive optics technology can correct for the blurring caused by the Earth's atmosphere, and can make Earth-bound telescopes "see" almost as clearly as if they were in space. The principles behind adaptive optics technology are illustrated in the Figure below. Assume that you wish to observe a faint galaxy. The first step is to find a relatively bright star close to the galaxy. a) Light from both this "guide star" and the galaxy passes through the telescope's optics. The star's light is sent to a special high-speed camera, called a "wavefront sensor," that can measure hundreds of times a second how the star's light is distorted by the turbulence. b) This information is sent to a fast computer, which calculates the shape to apply to a special "deformable mirror" (usually placed behind the main mirror of the telescope). This mirror cancels out the distortions due to turbulence. c) Light from both the "guide star" and the galaxy is reflected off the deformable mirror. Both are now sharpened because the distortions due to turbulence have been removed.





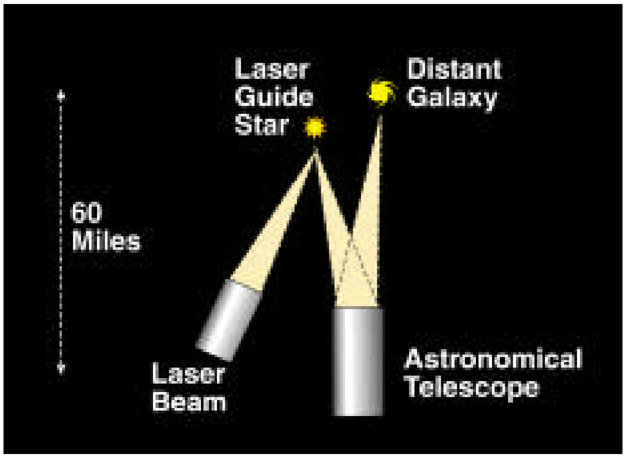
In practice, the process described schematically in the above Figure is a continuous one, and involves a "feedback loop" or "control system" that is always sending small corrections to the shape of the deformable mirror. This is illustrated in the Figure at left.

Image credits: Lawrence Livermore National Laboratory and NSF Center for Adaptive Optics. Graphics can be obtained at the Center for Adaptive Optics, University of California at Santa Cruz, (831) 459-5592 or cfao@ucolick.org.

3. The role of laser guide stars. Until the past few years, astronomical adaptive optics relied exclusively on the presence of a bright star positioned on the sky very close to the astronomical object being observed. Typically, for infrared observations this "guide star" must lie within about 30 seconds of arc of the astronomical target. (One second of arc corresponds to a dime viewed from a distance of about 2 kilometers.) For visible-light observations the "guide star" must be within about 10 seconds of arc. These limitations are quite severe, and mean that the fraction of objects in the sky that are favored with a suitable guide star is a few percent or less.

Of course astronomers would like to be able to look anywhere in the sky, not just at those lucky locations that have a bright guide star very nearby. To accomplish this, a laser can be used to make an "artificial star" almost anywhere in the sky.

The concept of "laser guide stars" was suggested in the early 1980's in both the military and astronomical communities. A laser beam is mounted on the telescope and pointed at the object to be observed. One concept is shown in the Figure on the left below. In this "sodium laser guide star" concept, the laser light is tuned to a yellow color (similar to the color of low-pressure sodium street lights) that excites a layer of sodium atoms about 60 miles up in the atmosphere. The sodium atoms glow in a small spot on the sky, making an "artificial star" that can be used to measure atmospheric turbulence. This concept is currently implemented on the ALFA system at Calar Alto in Spain, and at the Lick Observatory in California (Figure below right).



An alternative laser scheme that has been successfully implemented on an Air Force 1.5 m telescope at the Starfire Optical Range by Robert Fugate uses a pulsed green laser focused at an altitude of about 15 km. The green laser light scatters from molecules in the air, and the detector measuring the turbulence is timed so as to observe the scattered laser light at just the time when a laser pulse has traveled up and back from the desired 15-km altitude. This concept is called a "Rayleigh beacon" (named after the type of scattering from air molecules), and is currently being implemented for astronomy at the Mt. Wilson 100-inch telescope by Laird Thompson (University of Illinois).

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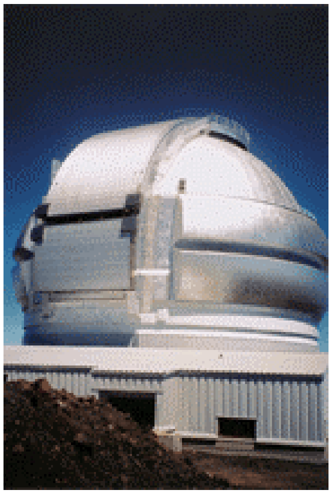
4. The heritage of adaptive optics technology. Adaptive optics development contains threads from both the astronomical and military communities. The concept was first proposed in a 1953 paper by astronomer Horace Babcock (then at Mt. Wilson and Palomar Observatories, now renamed The Carnegie Observatories). However 1950's technologies were not ready to deal with the exacting requirements needed for a successful adaptive optics system. In the late 1960's and early 1970's, the military and aerospace communities built the first significant adaptive optics systems, and began a sustained effort that has now led to very sophisticated Air Foce systems at the Starfire Optical Range in Albuquerque NM (contact: Robert Fugate) and at the Advanced Electro- Optical Facility on Maui in Hawaii (contact: Paul Kervin). Luis Alvarez's research group at DOE's Lawrence Berkeley Laboratory performed one of the first astronomy experiments, in which they built a simple deformable mirror that corrected only in one dimension but demonstrated that it could sharpen the image of a star. Early theoretical work on the capabilities and limitations of adaptive optics systems was done by Freeman Dyson (Institute for Advanced Study), Francois Roddier (University of Hawaii), and John Hardy (Itek Corporation, now retired).

Today the technical emphases of military and astronomical adaptive optics systems are rather different. Military applications typically need high adaptive optics performance, operate at visible wavelengths, require very rapid response times for their turbulence measurements, and utilize bright objects as "guide stars." In contrast, astronomical systems are limited by the fact that bright natural stars are rare. Until laser guide stars are in broad use, astronomical systems must operate with guide stars that are fainter. As a consequence, their response times are slower (in order to take longer exposures and gather more light during turbulence measurements), they choose to operate at infrared wavelengths (because these are easier for obtaining good performance), and the objects being imaged are fainter (requiring long time-exposures to obtain clear images or spectra).

Today's adaptive optics systems include the two Air Force facilities mentioned above (3-m class telescopes at the Starfire Optical Range in Albuquerque and the Advanced Electro-Optical Facility on Maui), and about half a dozen 3 -5 m class astronomical telescopes around the world. The newest additions are systems for the new generation of 8 - 10 m astronomical telescopes: the Keck I and II Telescopes and the Gemini North Telescope, all atop the Mauna Kea volcano in Hawaii.

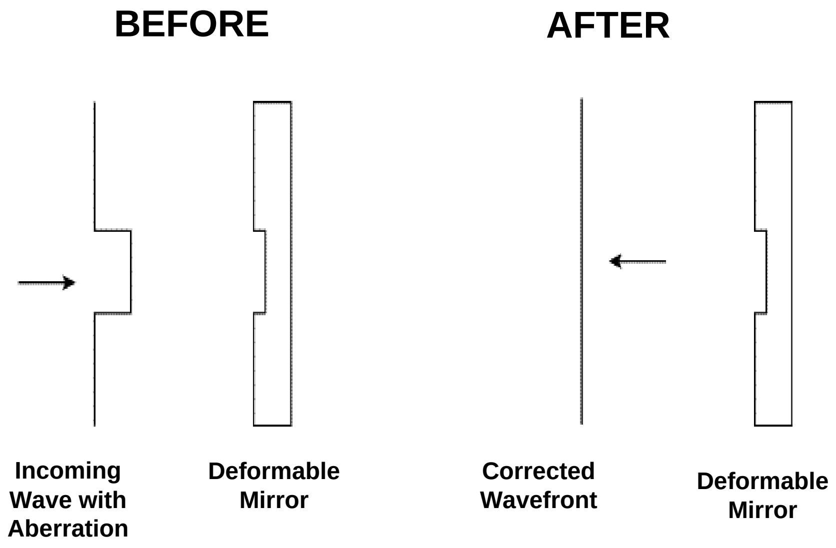
Keck I and II Telescopes
Image credit: W. M. Keck Observatory



Gemini North Telescope
Image Credit: Gemini Observatory

5. Key components of an adaptive optics system. The most distinctive components of an adaptive optics system are the "deformable mirror" which actually makes the optical corrections, and the "wavefront sensor" which measures the turbulence hundreds of times a second. These are connected together by a high-speed computer.

Today, deformable mirrors for astronomy are usually made of a very thin sheet of glass with a diameter of several inches. Attached to the back of the glass are various kinds of "actuators" -- devices which expand or contract in length in response to a voltage signal, bending the thin sheet of glass locally. The schematic below illustrates in very simplified form how such a deformable mirror is able to correct a distorted beam of light from a star, by straightening out its wavefront. Light is incident on the mirror from the left, and is reflected moving back to the left. If the deformable mirror has a depression that is half the depth of the initial distortion in the wavefront's shape, then by the time the light has reflected from the mirror and gone back the other way, the rest of the wavefront will have caught up with the "notched" section and the wavefront will be flat, or perfect. *Image credit: Lawrence Livermore National Laboratory and NSF Center for Adaptive Optics.* Graphics can be obtained at the Center for Adaptive Optics, University of California at Santa Cruz, (831) 459-5592 or cfao@ucolick.org.

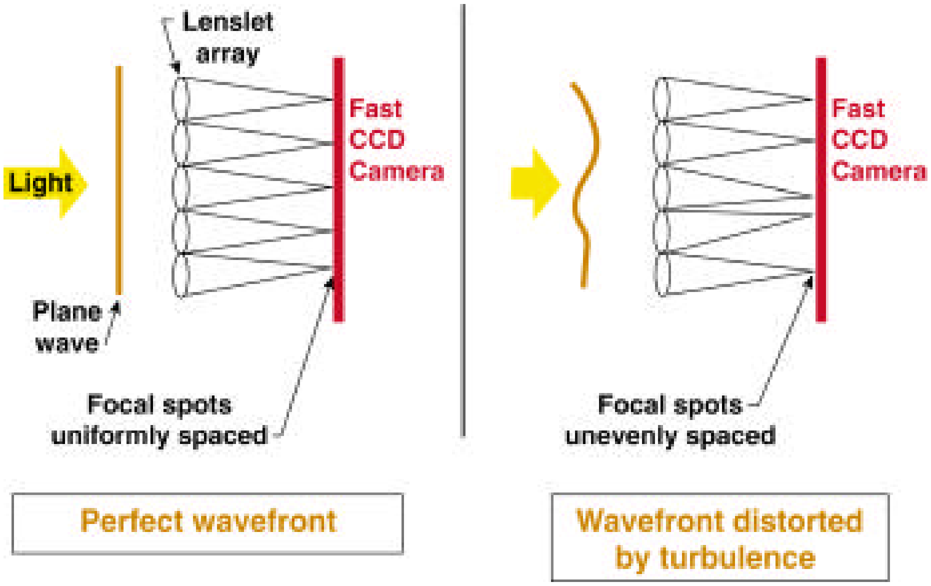


The Figure below illustrates a range of mirrors made by Xinetics Inc. (Devens, MA). *Image credit: Xinetics Inc.,* www.tiac.net/users/xinetics.

Future deformable mirror technology will involve mirrors that are both much larger and much smaller than those of today. Smaller mirrors are being developed using smaller piezo-electric actuators (Xinetics Inc.), using MEMS (micro-electro-mechanical) devices, and using LCD's (liquid crystal displays). Larger deformable mirrors that will replace the telescope secondary mirror are being developed by Roger Angel (Univ. of Arizona) and at Osservatorio Astrofisico di Arcetri, Italy.

The second key component of an adaptive optics system is a "wavefront sensor." For astronomy and for military applications, these sensors must measure turbulence hundreds to thousands of times a second. The detector doing this work is typically a fast charge coupled device (CCD), similar to those used at slower speeds in today's videocameras, or else a set of avalanche photodiodes (APDs). (For a technical introduction to avalanche photodiodes see "Avalanche Photodiodes: A User's Guide", at opto.perkinelmer.com/library/papers/tp5.htm.)

The arrangement of optics in front of the detector varies, depending on the wavefront sensing scheme being used. The two main schemes used for astronomy today are "curvature sensing" (www.ifa.hawaii.edu/ao/system/curv.html), developed at the University of Hawaii by Francois Roddier, and Shack-Hartmann wavefront sensing. The general idea of the latter is shown in the Figure below.



Light from a natural guide star or a laser guide star is incident on the wavefront sensor from the left (yellow arrows). The light is focused by a two-dimensional array of tiny lenslets onto a fast CCD camera (cross-section shown in red). In the absence of atmospheric turbulence, a "perfect" wavefront from a distant star would be flat, and could be focused to a point by the telescope optics. The wavefront sensor's lensets would focus this light to an evenly spaced checkerboard array of spots on the CCD camera. Turbulence introduces variable distortions to the wavefront, which cause the array of spots on the CCD detector to be irregularly spaced, and to dance around rapidly on the detector as the turbulence in the air changes with time. Using rapid measurements of the exact position of all the spots on the CCD detector, the computer can reconstruct the shape of the incident wavefront, and hence can derive what signals need to be sent to the deformable mirror in order to make the wavefront flat again.

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6. How does adaptive optics on today's largest telescopes compare with space telescopes?

Adaptive optics on the new generation of 8-10 m ground-based telescopes is nicely complementary to the capabilities of the 2.4 m diameter Hubble Space Telescope.

1) Hubble has very broad wavelength coverage, whereas today's astronomical adaptive optics systems on 8 - 10 m telescopes are designed to work only when observing in infrared light. Hubble has clear superiority for observations using ultra-violet and visible light, which cannot be done on today's largest telescopes even with adaptive optics.

2) Today, Hubble's infrared camera (NICMOS) is no longer operational. Ground-based adaptive optics systems on 8 - 10 m telescopes are thus the "only game in town" for high-resolution infrared observations. The Keck II Telescope's adaptive optics system currently yields spatial resolution in the infrared (e.g. 0.04 seconds of arc) comparable to the resolution which Hubble achieves in visible light (see www2.keck.hawaii.edu:3636/realpublic/ao/aolight.html).

3) NASA plans to revive Hubble's NICMOS infrared camera by the end of 2001. At that time, there will be high-spatial-resolution infrared capabilities both on the ground and in space. How will these compare?

Hubble will have the following advantages, relative to ground-based 8 - 10 m telescopes with adaptive optics observing in infrared light:

- Hubble will be able to "see" virtually the whole sky (it isn't limited by the need to have a very close guide star).
- Hubble will be able to measure the exact brightness of an astronomical object much more precisely (because it doesn't have to correct the rapid time-variations of turbulence).
- Hubble's ability to obtain spectra on extremely faint objects (such as the most distant galaxies) will be superior to the capabilities of ground-based telescopes (because the latter are afflicted with background "glows" from the Earth's atmosphere).

On the other hand, 8 - 10 m ground-based telescopes with adaptive optics will have several advantages over Hubble:

- The much larger diameter of ground-based telescopes will allow them to obtain three to four times better spatial resolution than Hubble at near-infrared wavelengths.
- Ground-based telescopes will be more sensitive than Hubble at wavelengths longer than about 2 microns, and will be able to obtain images at wavelengths longer than those detectable by Hubble.
- Ground-based telescopes will have extremely capable adaptive optics spectrographs that are too heavy and too large to be fitted into the Hubble telescope.

Thus we foresee a healthy "give and take" between ground-based and space telescopes.

7. Acknowledgement.

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