Adaptive Optics
Taming Atmospheric Turbulence

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For more than three centuries, the Earth's atmosphere has frustrated astronomers. The layer of gases that we breathe also distorts the images formed by telescopes. This means that conventional telescopes of more than a few centimeters in diameter cannot reach the resolution limit set by their optics.

To Isaac Newton the problem was clear, and in 1704 he realized the effects of atmospheric turbulence on image formation. Just as heat waves shimmering above a hot patch of ground can distort our view, the image of a distant object formed by a telescope is distorted by the temperature variations in the intervening atmosphere. Therefore, light entering the telescope is traveling in slightly different directions at different places on the entrance aperture.

The image size and quality depends on a statistical measure of the spatial frequency of the turbulence called the coherence length, or r_0, typically about 10 cm at a good site. Hence, even at a good site the resolution of a big telescope, 4 or 8 m in diameter, will be similar to that of a 10-cm-diameter telescope; the image will never get any sharper than the atmosphere allows. With atmospheric turbulence it is as if the big single aperture of a telescope were replaced by an array of small telescopes of aperture r_0, with each telescope jiggling independently of all the others, so that all the separate point images almost never coincide. The rate at which the telescopes are jiggling is given by another statistical parameter called the coherence time, usually on the order of 1 ms. So, the image is blurred by tremors only a hand's width in size, whose motions are varying a thousand times a second!

A far-out proposal

One remedy that Newton proposed was to get as far above the atmosphere as possible. This is why modern astronomical telescopes are built on mountain peaks, flown on balloons and aircraft, or like the Hubble Space Telescope, placed in orbit around the Earth.

Because the Space Telescope is outside the atmosphere it realizes the full resolution of its 2.4-m aperture and is yielding revolutionary results in astrophysics. Still, it is only one telescope and observations can be done only at a limited rate. It is also much smaller than the new generation of 8- and 10-m class telescopes like the Keck I and II, Gemini, the Very Large Telescope (VLT), Subaru and the proposed Next Generation Space Telescope. Fifteen years ago astronomers could only dream of such telescopes, but today there are at least 10 in use or under construction. If the full resolution of such large apertures could be realized, it would be a major advance in the science of astronomy.

Fortunately, the technology exists to make this possible.

In 1953, Horace Babcock proposed an instrument that would measure the atmospheric distortions in real time and correct them using a fast, refigurable optical component.[1] Although the technology available then was not adequate to the task, the basic concepts, supported by contemporary technologies, have finally evolved into the current field of adaptive optics.

Fixing the image

A large number of adaptive optical systems are in use in both the defense and the astronomical communities. They are generally of the form shown in Figure 1. A large reflective telescope is imaging a distant pointlike object above the atmosphere. Although the light arriving at the telescope should be nearly a plane wave, it is instead highly distorted by passage through many localized air masses of varying temperatures (and varying indices of refraction).

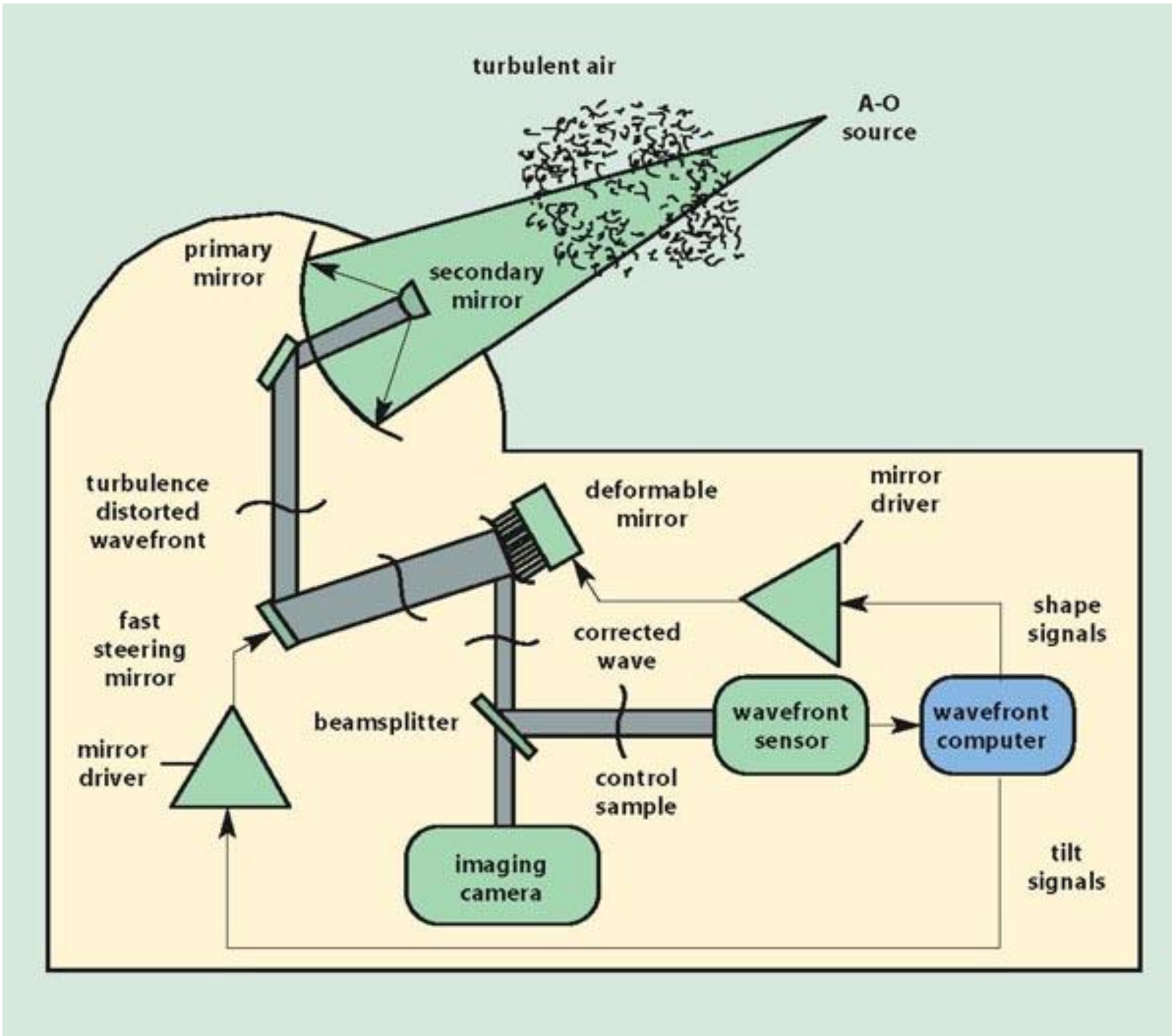

Figure 1. *Schematic of an adaptive-optics system.*

This aberrated wavefront is divided using a beamsplitter and sent to the main imaging camera (or other detection instrument such as an imaging spectrometer) and a wavefront sensor that controls some device to correct the wavefront phase. The wavefront sensor optically analyzes the beam sample and generates signals that are used by a very high speed processor to compute estimates of both the overall wavefront jitter or tilt and of the higher order wavefront-shape information. These signals are then used to form an optical feedback loop that tries to keep the incoming beam flat, yielding a corrected, high-resolution image in the camera focal plane. The tilt signals drive a fast-steering mirror to hold the object in the center of the image field; the shape signals are applied to an advanced component called a deformable mirror. This device is often a glass face sheet bonded to a two-dimensional array of piezoelectric transducers or, as in the bimorph mirror, a continuous bimorph structure of glass and piezoelectric material. Recently, micromachining technology has been used to produce membrane mirrors with electrostatic actuators. These devices are not as robust as their glass counterparts, but they are significantly less expensive and have the possibility of being mass-produced. In all these mirrors the transducers deform the face sheet so that it exactly cancels the atmospheric distortion. Another type of phase controlling device uses an array of liquid crystals with a refractive index that can be controlled by an applied voltage. However, these devices are generally too slow for atmospheric adaptive optics, and their spectral transmission is limited.

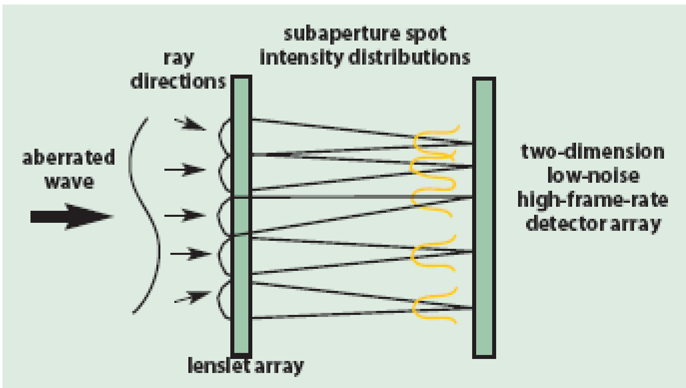

Figure 2. *Operating principle of a Shack-Hartmann wavefront sensor.*

A key component in this system is the wavefront sensor. Many types have been developed and a typical approach is shown in Figure 2, which is a Hartmann sensor, derived from the classical technique for figuring telescope primaries. The aberrated wave enters from the left. The fact that the wavefront is curved means that localized parts of the beam are traveling in slightly different directions in different places, as shown by the ray arrows (Newton's Rays of Light, which pass through diverse parts of the aperture).

These rays strike an array of lenslets whose diameter is chosen to match the dimension r_0 at the telescope primary. The lenslets break up the main aperture into subapertures, and behind each subaperture a focal spot forms. The local ray direction determines the position of each subaperture focal spot so that if a detector array is used to measure all the spot locations, the shape (and tilt) of the input beam can be calculated and used to correct the beam. However, as the atmosphere randomly perturbs the wavefront phase, how are we to know how to correct the wavefront? The adaptive optics system, and specifically the wavefront reconstructor, requires a calibration source outside the atmosphere with known initial phase that can be used to simultaneously measure the effect of the atmosphere on the wavefront. A nearby star could be used, but these are generally too faint and cannot be used if the source is moving.

Solving the source problem

Babcock pointed out that an adaptive-optics system needs a fairly bright source to operate effectively, which limited the range of astronomical objects that could be profitably studied. This remained a significant difficulty until 1981, when Julius Feinleib of Adaptive Optics Associates proposed creating a source artificially by projecting a high-power laser in the desired direction and utilizing the molecular backscatter from the high-altitude portions of the beam to drive the system.[2] An example of a laser guide star is shown in Figure 3.

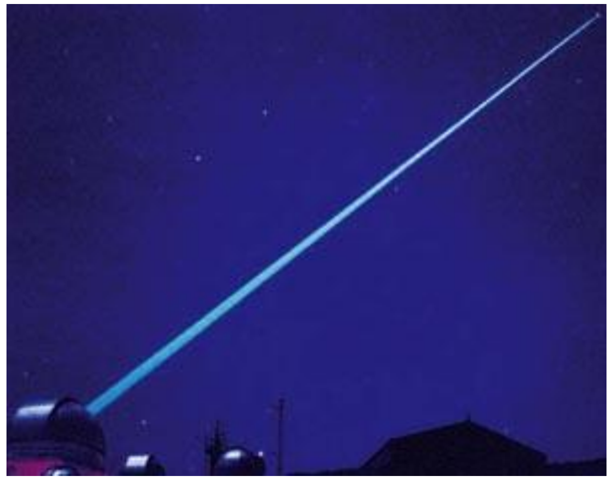

__Figure 3.__ A laser guide star in operation at Starfire Optical Range.

The idea was classified immediately and thereafter developed secretly by the defense community. In 1985, it was independently proposed in the open literature by Foy and Labeyrie.[3] Ultimately, the defense work was declassified and the technique has come to be known as the laser-guide-star approach,[2] which has vastly expanded the utility of adaptive optics and is an area of much research. In 1993, Babcock and Feinleib were awarded the Rank Prize for their contributions to adaptive optics.

State of the art

Advances in electronic imaging and computing power have now made it possible to implement the Hartmann approach to wavefront sensing in a small, table-top package; manufacturers include Adaptive Optics Associates, Inc., Wavefront Sciences, Inc., and CILAS in France. Figures 4 and 5 show Adaptive Optics' WaveScope wavefront sensor and its computer interface. By including some simple electronic boards in the system's computer, the device can also control deformable mirrors made by Xinetics, OKO Technologies, CILAS and Boston Micro-Machines. With the increase in computing speed it is now even possible to perform all the calculations for atmospheric adaptive optics with Pentium processors, freeing adaptive optics systems from the need for dedicated signal processing cards. This useof standard components to make an adaptive optics system shows that the technologies are reaching maturity. An example of the flattening of a Xinetics mirror using the WaveScope wavefront sensor to measure the mirror's figure, and calculate the reconstructor to control the actuators, is shown in Figure 6. The interferograms were calculated with the WaveScope wavefront sensor from Hartmann spot data. The left hand image shows the surface figure when the actuators are set at their midrange, and the right hand image shows the figure after flattening.

__Figure 4.__ Adaptive Optics Associates' WaveScope wavefront sensor.

Adaptive optical systems are in use or under development at a large number of locations worldwide. The largest operational system is at the US Air Force's Phillips Laboratory, which has released diffraction-limited, laser guide star driven results for visible wavelengths using a meter-class telescope. Raytheon has delivered the AEOS (Advanced Electro-Optical System) to the Phillips Laboratory's site on Mt. Haleakala, Hawaii. The system is used on a 3.67-m telescope and has a 941-actuator mirror.

There are also many adaptive optics systems being built for astronomy. Practically all of the new, 8-m class telescopes will have adaptive optics and systems are being retrofitted to many 4-m class instruments. Examples of systems in regular use for astronomical research are those built by the University of Hawaii for the Canada France Hawaii Telescope and ALFA, built by Adaptive Optics for the Max Planck Institute for Astronomy's Calar Alto Telescope. The ALFA[4] system (Figure 7) has a laser guide star, a fast, sensitive camera that takes 1000 frames per second, and a 97-actuator deformable mirror. Further dissemination of the technology by government labs such as the Phillips Lab, Jet Propulsion Laboratory, Lawrence Livermore and the MIT Lincoln Laboratory, as well as companies such as Adaptive Optics Associates, is bringing adaptive optics into common use.

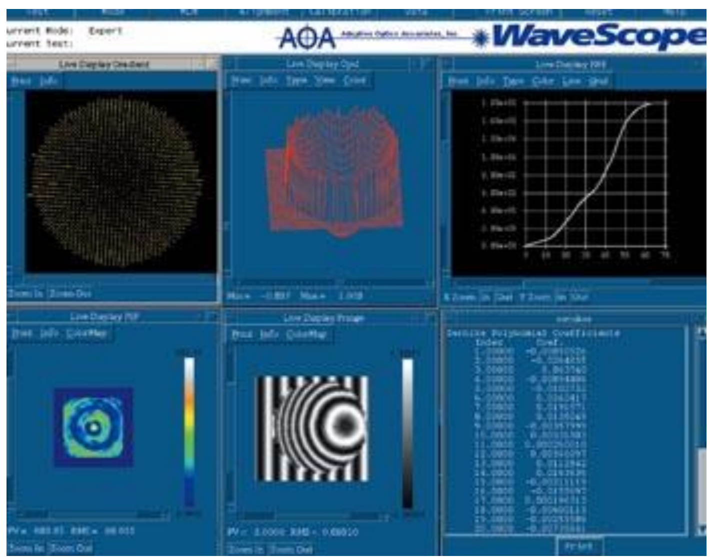

Figure 5. *The user interface for the WaveScope wavefront sensor. The current window shows some of the display and data reduction options available with the Zernike decomposition of the measured wavefront.*

The US military's interest in secure optical communications, long-range sensors and theater and ballistic missile defense systems is also driving new innovations in adaptive optics and wavefront sensing.

What's next?

Adaptive optics is finding many new applications outside defense and astronomy. The optical trains of high-power lasers used for materials processing, such as isotope separation, accumulate wavefront errors because of small thermal distortions in each of many optical elements; this could easily be corrected by adaptive optics. Another application is found in the growing field of laser communications. This uses a coded infrared laser to communicate between line-of-sight points. The turbulence and scintillation along the path through the atmosphere can be severe, and adaptive optics is used to limit the loss of data and channel fading.[5]

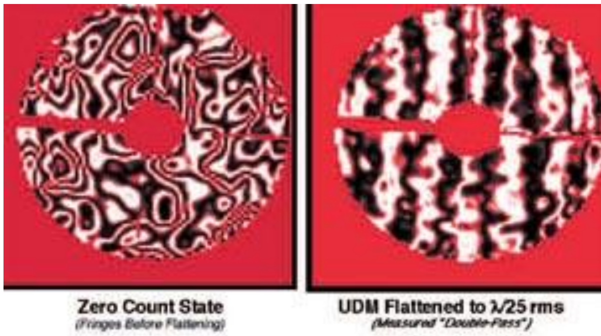

Figure 6. *Flattening of a Xinetics deformable mirror using the WaveScope wavefront sensor with its adaptive optics option.*

In the medical field retinal photography can be improved by compensation for the turbulence induced by intraocular fluid circulation, and eye surgeons can use a wavefront sensor to measure the shape of a patient's cornea during procedures like laser keratectomy. In ophthalmology both Visx and Zeiss Humphrey have developed Hartmann sensor-based instruments to measure the optical prescription of a patient's eye.

Wavefront sensors are also being used in optical testing and manufacturing. The shape of optical components can be measured as they are manufactured. Applications range from the measurement of telescope mirror figure to the control of the alignment of coupling lenses to the optical fibers used in telecommunications. A particularly successful use of a wavefront sensor for optical testing is on the Hubble Space Telescope repair mission, which was aided by an ultrahigh-accuracy wavefront sensor built by Adaptive Optics. The sensor, called the Aberrated Beam Analyzer (ABA), was used to test the Corrective Optics Space Telescope Axial Replacement (COSTAR) and Wide Field/Planetary Camera (WF PC) II systems prior to launch. The sensor uses an advanced variant of the Hartmann technique to achieve absolute accuracies of better than λ/100 rms, and long-term repeatability as high as λ/2000 rms.[6,7] It was so successful that the instrument has become the benchmark for testing all Hubble Space Telescope Instruments.

Figure 7. *The ALFA adaptive optics system installed on the Max Planck Institute for Astronomy's telescope in Calar-Alto, Spain.*

Thinking big

Astronomical research has always spurred the development of adaptive optics, and even as advanced systems are being installed on the new 8-m telescopes, astronomers and engineers are looking to the future. The next step, or perhaps leap, in telescope construction will be to Extremely Large Telescopes (ELTs) with apertures between 25 and 100 m in diameter, and the development of multiconjugate adaptive optics, where the turbulence of different atmospheric layers is measured with separate laser beacons and wavefront sensors. Such enormous apertures will probably be made up of many individual telescopes of between 1 and 5 m in diameter, each with its own adaptive optics system and laser guide star.[8] The separate mirrors will be aligned so they act as a single large unit. This alignment itself will require a wavefront sensor, and it presents similar challenges to those encountered in aligning the mirrors of today's large segmented telescopes like the Keck and Hobby Eberly. Once aligned, the parallel adaptive optics systems will correct the images. All the technology to implement adaptive optics on an ELT already exists; it is just a matter of scale.

Conclusion

Adaptive optics is advancing in two very different directions: it is finding applications in medicine and in the manufacture of consumer items; and also the defense and astronomy communities continue to develop bigger systems.

The component technologies required for adaptive optics are already having an impact far outside the field. High-speed machine-vision cameras are now commercially available, supported by real-time processing needed for fast, automated inspection and control. Many consumer cameras have electronic image stabilization, and the microoptics technologies developed for Hartmann sensing are creating applications in laser diode array control, conditioned light generation and advanced displays.

Adaptive optical systems demand detectors with high quantum efficiency, noise levels below 100 electrons per pixel, and speeds of thousands of frames per second. Computation rates in excess of 10 G-OPS sustained are in current use, and deformable mirrors having hundreds of actuators are in service. Until recently these systems have cost millions of dollars per installation, but the commercialization of fast computers and cameras is reducing this cost dramatically.

As technology advances, detectors will become quieter, larger and faster, processors more powerful, and mirrors with thousands of actuators will become feasible. Large systems are now being built to correct the apertures of today's 8-and 10-m class telescopes. One day, many such systems in parallel will correct the images formed by 100-m diameter telescopes.

Today, adaptive optics are in regular use on a number of astronomical telescopes. In a few years, they will become a universal part of astronomical optics, and we will finally have one up on Sir Isaac.

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