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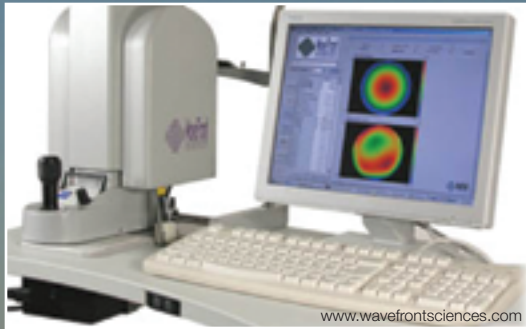
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ADAPTIVE OPTICS: ASTR

Alan Greenaway

Most people associate adaptive optics with astronomy because of its well-known role in bolstering the imaging power of telescopes and correcting for atmospheric distortion. But the field also has a growing number of applications in ophthalmology, biomedicine and industrial processes. And adaptive optic systems are increasingly being integrated into commercial products, including cameras, CD players and large TV screens.



Aerial view at sunrise on Mauna Kea with the Gemini North telescope (large silver dome) on the foreground ridge. Other observatories can be seen in the background.

ASTRONOMY and *BEYOND*

Adaptive optics (AO) has its roots in astronomy, and the fundamental concepts of the field are best demonstrated in that context. Due to the mixture of air of varying temperatures above astronomical telescopes, spatially variable density changes perturb the wavefront from the ideal plane-wave form it has above the atmosphere. The effect is to spread the

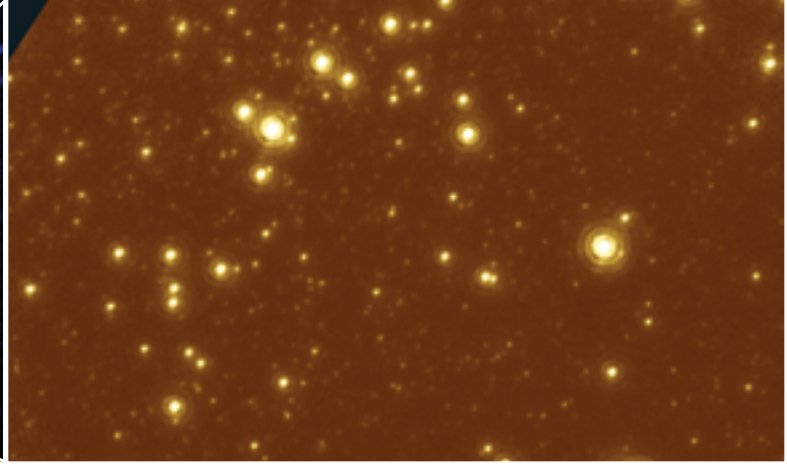
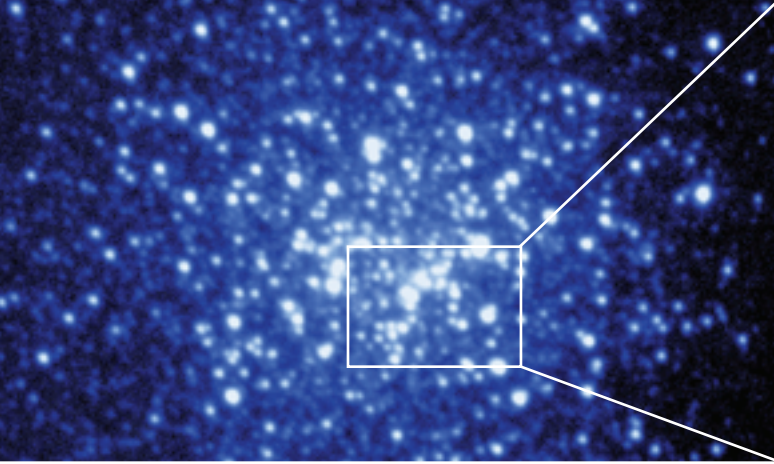
light, reducing both angular resolution and brightness in a stellar image.

Adaptive optics mitigate these effects. If the effects of turbulence go uncorrected, the resolution achieved at visible wavelengths by the largest telescope is equivalent to the theoretical performance of a telescope with a diameter equal to the Fried parameter, r_0 , with a value between 10 and 20 cm, depending on

atmospheric “seeing” conditions. Thus, using the well-known (albeit somewhat arbitrary) Rayleigh criterion, the linear image resolution scales in a large astronomical telescope falls by:

$$\alpha = 1.22 \frac{\lambda}{D} \rightarrow 1.22 \frac{\lambda}{r_0},$$

where D is the telescope diameter and λ the wavelength of observation.



Because the detail in a 2D image scales theoretically with mirror diameter squared, the loss of information is enormous. In addition, if the same photon flux is concentrated in a smaller image, the image is much brighter, leading to better image contrast and shorter exposure times.

Given the number of multi-million-dollar telescopes with mirror diameters exceeding 8 m, AO's contribution to astronomy is clear: It enables much higher-resolution images of much higher brightness, giving images with thousands of times the structural information content recorded in a fraction of the recording time otherwise needed.

Researchers have been using signal processing methods to improve image resolution in atmospherically degraded images since the 1970s. However, such approaches are very inefficient photometrically and have poor dynamic range. The first person to propose real-time correction using AO was Babcock in 1953. However, much of this technology remained classified by the government until 1978, when the U.S. Air Force disclosed it for the first time.

For applications of AO relevant to military programs as well as astronomy, the equipment into which AO must be fitted is very high cost, and performance considerations often supersede those of cost. Added to this—at least in the astronomy context—is the fact that each telescope has an individual design, and thus the AO system must be tailored to the instrument.

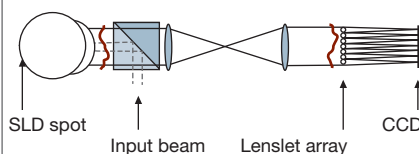
An AO system consists of three basic building blocks:

- ▶ A wavefront sensor (WFS) to measure the shape of the incident wavefront;

These pictures from Gemini North (Hawaii) show infrared images without (left) and with (right) adaptive optics. The AO-corrected image corresponds to the center of the left-hand image (boxed area). Note the diffraction rings in the corrected image.

Gemini Observatory, US National Science Foundation, and University of Hawaii Institute for Astronomy

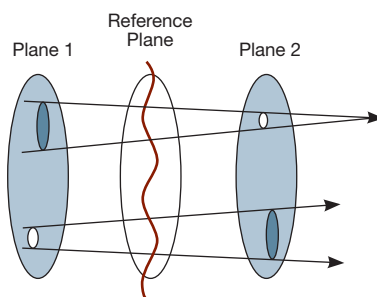
[Shack-Hartmann Sensor]



Light from a laser or SLD (superluminescent diode) is focused by the eye to a point on the retina. The reflected light emerges from the pupil as an aberrated wavefront and travels from the eye through a set of lenses onto a lenslet array.

From Center for Visual Science, Univ. of Rochester

[Phase-Diversity Sensing]



As the test wavefront propagates in space (from left to right in the illustration), converging (diverging) regions give rise to increasing (decreasing) intensity. Thus, the local wavefront curvature can be assessed by measuring the intensity difference on the plane symmetrically placed about the reference plane, in which the wavefront is to be determined. Aberration modes such as defocus, spherical aberration, etc. are easily detected.

- ▶ A wavefront modulator (WFM) to control the wavefront shape and;
- ▶ A control loop that commands the WFM in response to the measurements from the WFS.

Commercial and ophthalmologic applications

More recent applications of AO are popping up in consumer goods in the form of the autofocus devices in cameras and CD and DVD players, as well as large TV displays based on micro-machined mirror systems—although the individuals who developed these products may not recognize that they are adaptive optical systems.

Adaptive-optical zoom lenses and focus-adjustment mechanisms that were initially developed for planetary exploration vehicles can now be exploited in mobile-phone camera systems. Wavefront sensors based on the Shack-Hartmann sensor, which is widely used in astronomy, are now being adapted for metrology applications to measure the flatness of silicon wafers through distortions in the light beam reflected from the wafer surface. This enables researchers to make the best use of expensively produced wafers for circuit manufacture.

Many of the medical applications of applied optics are driven by ophthalmic needs. Wavefront sensors can be used to evaluate optical aberrations in the human eye before, during and after a patient undergoes corneal laser surgery. (The sensors perform this function so well, in fact, that they detect fluctuations caused by the variation in the tear film.) Conceptually, this is similar to the astronomy application, because a reference source used by the wavefront sensors is generated by laser

scatter or laser-induced fluorescence of a weak but focused laser spot on the retina.

Other ophthalmic studies have shown that retinal images, recorded after eye aberrations had been corrected, can reveal individual photoreceptors (rods and cones) and, in the latter case, the color-sensitivity of each receiver. Some have speculated that AO will one day enable “super” vision by addressing these receptors. For example, the wavefront distortion of the fore-optics of each eye could be used to create contact lenses tailored to individuals.

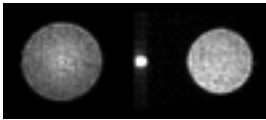
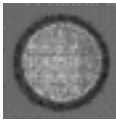
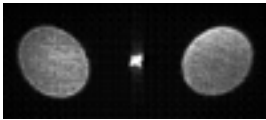
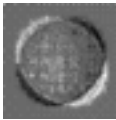
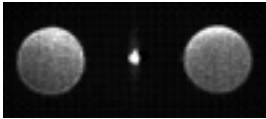
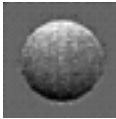
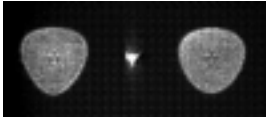
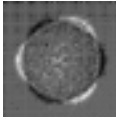
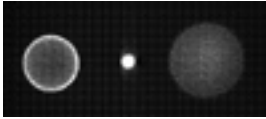
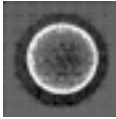
Meanwhile, the use of wavefront sensors for contact-lens quality control in one-off and volume manufacturing is already a reality. However, development in this area is ongoing in order to assess the more demanding requirements for intra-ocular devices and hybrid diffractive/refractive lenses.

Beyond ophthalmology, wavefront sensors have a useful role in normal laboratory optics. Even to the most inexperienced student, the correct orientation of lenses becomes readily apparent when the aberrations are assessed. With AO, the measurement of in-focus conditions can be achieved with about 100 times the accuracy achievable by an unaided observer, leading to a ranging capability.

Biomedicine and metrology

Wavefront sensing technology offers great promise as a non-contact, accurate and rapid measurement tool in the biomedical field. For example, it can play a role in protecting the long-term functionality of prosthetic joints. The wear, and thus usable lifetime, of such joints is closely linked to the form and surface finish on them. Because these joints have a limited lifetime and can only be replaced a few times, it is critical that they be designed well, particularly for younger recipients, who will be dependent on them for the rest of their lives. Accurate and computer-controlled polishing machines and new polishing techniques can improve the functionality of these important artefacts, and wavefront sensing can be used to measure the surface form in-situ so that the alignment between artefact

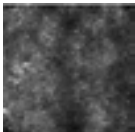
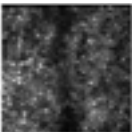
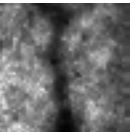
[Phase Diverse Measurements]

Phase Diversity Image	Difference
(a) 	
(b) 	
(c) 	
(d) 	
(e) 	

Graphic representation of the most common types of optical aberration. Little experience is required to recognize these in the laboratory: (a) defocus; (b) astigmatism; (c) coma; (d) trefoil; (e) spherical aberration.

From Blanchard P.M. et al. Appl. Opt. 39 6649-55

[Adaptive Compensation for Retinal Images]

(a) 	(b) 	(c) 
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— 10 arc min

(a) One of the best images that could be obtained when only defocus and astigmatism were corrected. (b) Adaptive optics are used to correct all of the eye's aberrations. This image distinctly resolves individual photoreceptors. (c) Further improved image obtained by averaging many images together.

From Roorda & Williams, 1999

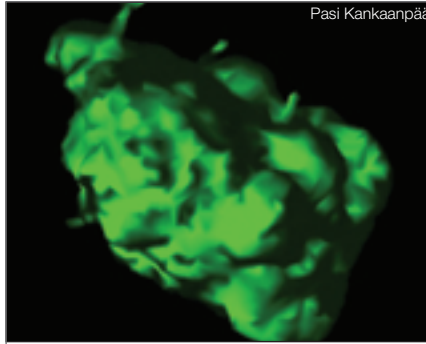
and tool is not disrupted during the measurement process.

Some metrology applications of wavefront sensing that are currently under investigation are the assessment of thin and not-so-thin laminate structures (number and thickness of layers and the form of the layer interfaces), pulse-by-pulse measurement of laser-beam quality (important in laser-machining applications) and particle-flow analysis.

Wavefront sensing is also emerging as a new tool in fluid-flow studies, where scientists are looking to track the movement of tracer particles through particle imaging velocimetry (PIV). The assessment of these tracers—in the mixing of fuel in reciprocating engines, for example, or of spray droplets in the food-processing industry—offers potentially large gains in process efficiency. In the case of the engine, an efficiency savings of up to 30 percent could be achieved if the perfect fuel mixture was achieved.

Previous approaches to PIV rely on stereo vision from two viewpoints with angles of up to 30 degrees (one viewpoint is hard enough to achieve), holographic imaging (which is subject to vibration) or imaging through arrays of small holes (photometrically inefficient). The small sources to be tracked emit spherical wavefronts, and the curvature of the wavefront received depends inversely on the square of the range to the source. AO wavefront sensors can measure curvature to $\lambda/1000$ accuracy and offer the potential to track the range of small source with sub-nm accuracy in high-resolution microscopy, with the lateral position of that source determined either from an image centroid or from the wavefront slope.

Measurement of the wavefront curvature does not need more than a single viewpoint, does not require coherent interferometry (thus, vibration is less important), can be photometrically efficient and, most important, can be used with fluorescent tracer particles. PIV using a wavefront sensing approach from a single point of view is easier and cheaper to implement than existing methods, and preliminary measurements have demonstrated an accuracy in



AO is being applied to improve a traditional technique in microscopy—the through-focal series, which is required to obtain an understanding of 3D structures and interactions within a living cell.

position determination that is only a few times inferior to current techniques. If the ease of implementation is maintained as the accuracy and volumetric capability of the wavefront sensing approach is improved, this technique could have a substantial impact on our daily existence.

In laboratory life science, the imaging of live cells is transforming our understanding of biological processes. Not only can a complete AO system be used to measure and correct the optical aberrations within the confocal scanning microscopes used in *in vitro* live-cell imaging, corrections can be applied for the optical distortions due to overlaying parts of the cells being imaged.

This is particularly useful when imaging processes close to a membrane, where three-dimensional curvature can lead to substantial degradation of image quality. This is an area of considerable challenge. Research on anisoplanatic applications in astronomy (i.e., attempts to increase the field of view by compensating for the atmospheric turbulence encountered along different lines of sight) and biomedical applications are progressing simultaneously.

On a more prosaic level, AO is being applied to improve a traditional technique in microscopy—the through-focal series, which is required to obtain an understanding of three-dimensional structures and interactions within a living cell. The through-focal series is also sometimes used to locate features of interest. It is generally obtained using a physical translation of either the specimen or the microscope in order to refocus on different specimen depths. In many circumstances, the mechanically implemented through-focal series is well-suited for identifying regions of interest and for the study of processes involving long time scales.

Increasingly, however, scientists are discovering that there are many processes for which short-time-scale phenomena hold the key. Areas of interest include the folding of protein structures, the mechanisms by which viruses attack membranes, the transportation of materials through cell membranes and the dynam-

ics of microtubules. Here, by providing rapid electronically controlled refocusing, AO can offer a high-speed alternative approach that is commensurate with the observation of processes occurring on millisecond time scales.

As the magnification required to elucidate the science increases, the electronic refocusing is degraded by other aberrations (particularly spherical aberration), the correction of which must be subsumed within the focus control. Further, electronic refocusing is liable to lead to a change in image magnification that must be corrected but that does not occur in the traditional through-focus series. Fortunately, it is simple to correct both the focus and the spherical aberration with AO, although the implementation of such corrections in an open-loop system requires a different control approach than that normally used in adaptive optics.

Data-collection techniques developed for phase diversity wavefront sensing provide a mechanism for simultaneous in-focus imaging of multiple specimen depths on a single detector plane. Developed for AO applications in high-speed jets and terrestrial imaging, these techniques can be used in live-cell imaging and modified to provide telecentric, multi-focus imag-

ing—in other words, equal magnification at all object distances.

Advances in wavefront control

Many recent developments in wavefront modulators are taking place outside the normal adaptive optics community. This is particularly true of liquid crystal spatial light modulators (SLMs), where the phase of an input beam is modulated through the same principles that are exploited in the displays found in laptops and TV screens. The application of an electric field leads to a rotation of the birefringent molecules, and this causes a change in the refractive index for one polarization. In displays, the resultant rotation in the beam polarization is used to modulate the beam intensity by passing it through a polarizer.

With AO or beam-steering applications, the polarizer can be removed and the phase modulation in the selected polarization can be exploited directly. Many adaptive optics applications require the use of unpolarized beams; the identical phase shift can be applied to orthogonal polarizations by using the SLM in reflective mode with a quarter-wave plate between the SLM and the reflective surface. Double passage of the wave plate rotates the polarization axes by 90 degrees so that both polarizations see the same single-pass phase retardance.

In many cases, adaptive optics systems operate through modal rather than zonal modifications of the wavefront. That is, rather than modifying the wavefront through a series of spatially restricted regions (zones), the required wavefront phase change is represented through a sum of polynomials defined over the whole wavefront. In most cases, the polynomials used are the Zernike polynomials, which form an orthogonal set and, for the lower-order polynomials at least, match well to the Seidel aberrations.

Thus, focus control can be affected through a single mode rather than a large number of spatially distinct pixels. For this reason, researchers have developed modally controlled wavefront modulators and wavefront sensors. These devices are ideal for applications such as focus

control because, as with their mechanically controlled counterparts, only a single degree of freedom is required to be controlled in operation. This simplicity is attractive for modal operation.

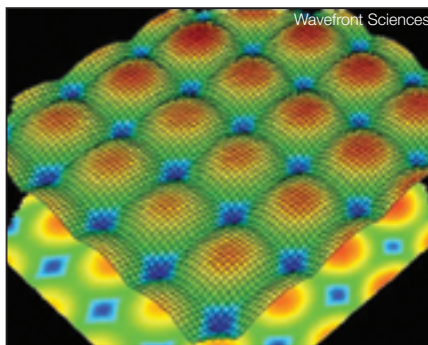
It is well known that there is a Fourier transform relationship between the temporal properties of a laser pulse and the spectral phase properties of the pulse. Control of the spectral phase is thus key to achieving the shortest-duration pulses. The implementation of wavefront modulators in dispersed beams offers another mechanism for optimizing the beam pulse time-history. Even for percussion laser drilling, cutting and forming applications, the control of spatial and/or temporal properties offers significant potential benefit. Intra-cavity wavefront control through use of deformable (and in some cases cooled) cavity mirrors also provides a means to compensate for thermal lensing within the cavity and thermal blooming in atmospheric transmission.

Future outlook

Moving forward, developments of wavefront modulator technologies suitable for AO applications will likely be driven by consumer display and data storage applications. The “off-the-shelf” devices are attractive vehicles for further developments, particularly in the commercial and biomedical areas, where the security of a reliable supply chain is at least as important as performance.

These new applications are paving the way for other opportunities within adaptive optics—in the correction of distortions in wide-field imaging applications such as live-cell imaging, for example, or imaging through turbulent media for manufacturing processes (e.g., in furnaces and chemical reactors’ vessels). Several laboratories now concentrate on the development of low-cost “black-box” components with simple interfaces.

The manipulation of laser beams and laser pulses is an area with high commercial potential that has not yet been fully exploited. By improving control of the beam shape and the temporal pulse profile, researchers may be able to create



Recent studies on compact wavefront sensors indicate that they can make high-accuracy measurements in large format—limited only by the detector technology.

“designer pulses” suitable for applications in which the precisely controlled use of ablative laser machining is required.

For the time being, however, there will likely be a continued requirement for the conventional wavefront modulators based on mirror technologies, especially those capable of handling high power. Thus, the use of membrane mirrors (including bi-morph mirror designs) will persist for these applications.

Used as an alternative to interferometric and other conventional metrology techniques, on the other hand, wavefront sensing seems likely to continue to expand, particularly for measuring complex optical systems rather than simple, bas-relief surface features. However, penetration of wavefront sensing metrology into this market will be incremental rather than rapid: The interferometer will remain the gold standard with which wavefront sensors will be compared for a long time.

Recent studies on compact wavefront sensors indicate that they can make high-accuracy measurements in large format—limited only by the detector technology. Researchers have also been exploring the innate ability of some sensors to measure discontinuous (and potentially rough) surfaces, to measure shape using

incoherent radiation and to measure 3-D positional information using both laser-illuminated and self-luminous objects.

Future developments in AO will continue to derive inspiration from the big-science areas of astronomy, laser devices and laser fusion, where adaptive optics will remain driven by requirements and specifications beyond those of most commercial and laboratory applications. Indeed, the most fruitful near-term developments will likely be in those areas, such as anisoplanatic imaging, where both the big-science and commercial or laboratory stakeholders have a mutual interest. ▲

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[References and Resources]

- >> Tutorial on adaptive optics: www.aoainc.com/technologies/adaptiveandmicrooptics/aostutorial.html
- >> Center for Adaptive Optics, an NSF Science and Technology Center: <http://cfao.ucoick.org/>
- >> European Southern Observatory: Introduction to Active and Adaptive Optics: www.eso.org/projects/aot/introduction.html
- >> Canada-France-Hawaii Telescope: Introduction to AO site: www.cfht.hawaii.edu/Instruments/Imaging/AOB/local_tutorial.html
- >> Wavefront Sciences, Inc. (For ophthalmic and other applications) www.wavefrontsciences.com/products.htm
- >> The published proceedings of the series of International Workshops on Adaptive Optics in Industry and Medicine are a good for an overview of the subject.
- >> 2nd International Workshop on Adaptive Optics in Industry and Medicine, Durham, England, July 1999, G.D. Love, ed., World Scientific, 1999
- >> 3rd International Workshop on Adaptive Optics in Industry and Medicine, Albuquerque, N.M., July 2001, Eds Restaino S. et al., eds., Starline Printing 2002.
- >> 4th International Workshop on Adaptive Optics in Industry and Medicine, Muenster, Germany, October 2003, Ed Wittrock U., ed., Springer Proceedings in Physics, **102**, 2006.
- >> 5th International Workshop on Adaptive Optics in Industry and Medicine, Beijing, China, Aug-Sept 2005, SPIE **6018**, 2006.
- >> *Lincoln Laboratory Journal*, **5** (1992) April Special Issue on Adaptive Optics. This article provides a good introduction to the state of adaptive optics at the time that it was declassified by the USAF.