Adaptive Optics 101: Overview, Tech Review & Applications
Introduction and Motivation

Originally introduced in the 1950s as a concept for improving astronomical imaging by correcting atmospheric aberrations, it took nearly two decades for adaptive optics (AO) technology to catch up with theory and starlight to hit the first AO system[1]. Years later, major telescopes around the world are now equipped with this expensive imaging technology. While these AO-enabled telescopes were being developed, technological advances of the last decade in CCD cameras, frame grabbers and MEMS deformable mirrors have inspired innovative researchers to solve wavefront distortion problems in fields such as microscopy, retinal imaging and laser communication. These early adopters were rewarded with scientific breakthroughs in their respective fields. Now, with proven applications and mature, affordable components, AO is poised for widespread use in a myriad of optical fields.

A major strength of AO is its application versatility. Many of the world's major telescopes such as the European Southern Observatory in Chile and the Keck Observatory in Hawaii, rely on AO to remove wavefront distortion caused by atmospheric turbulence in order to provide clear images of stars and extra-solar planets. Biological researchers have integrated AO into microscopes to correct wavefront aberrations introduced by tissue and thus extracting vital information from biological specimens. Vision science researchers are using AO in their efforts to detect eye disease before its onset and begin earlier treatment[2]. Finally, laser applications such as laser beam shaping for free space communication and laser machining has been successfully demonstrated with AO.

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[1] "Adaptive Optics." *Wikipedia*. Wikimedia Foundation, 28 Aug. 2014. Web. 02 Sept. 2014.
[2] Yuhua Zhang, Siddharth Poonja, Austin Roorda, "MEMS based adaptive optics scanning laser ophthalmoscopy", Optics Letters; Vol. 31, No. 9, 2006

Adaptive Optics Fundamentals

Although AO technology has advanced since its conception, its three main components have remained constant: a wavefront sensor to measure distortion, a wavefront corrector to compensate for the distortion and a control system to calculate the required correction and necessary shape to apply to the corrector. Figure 1a shows a schematic diagram of the system with each of these elements.
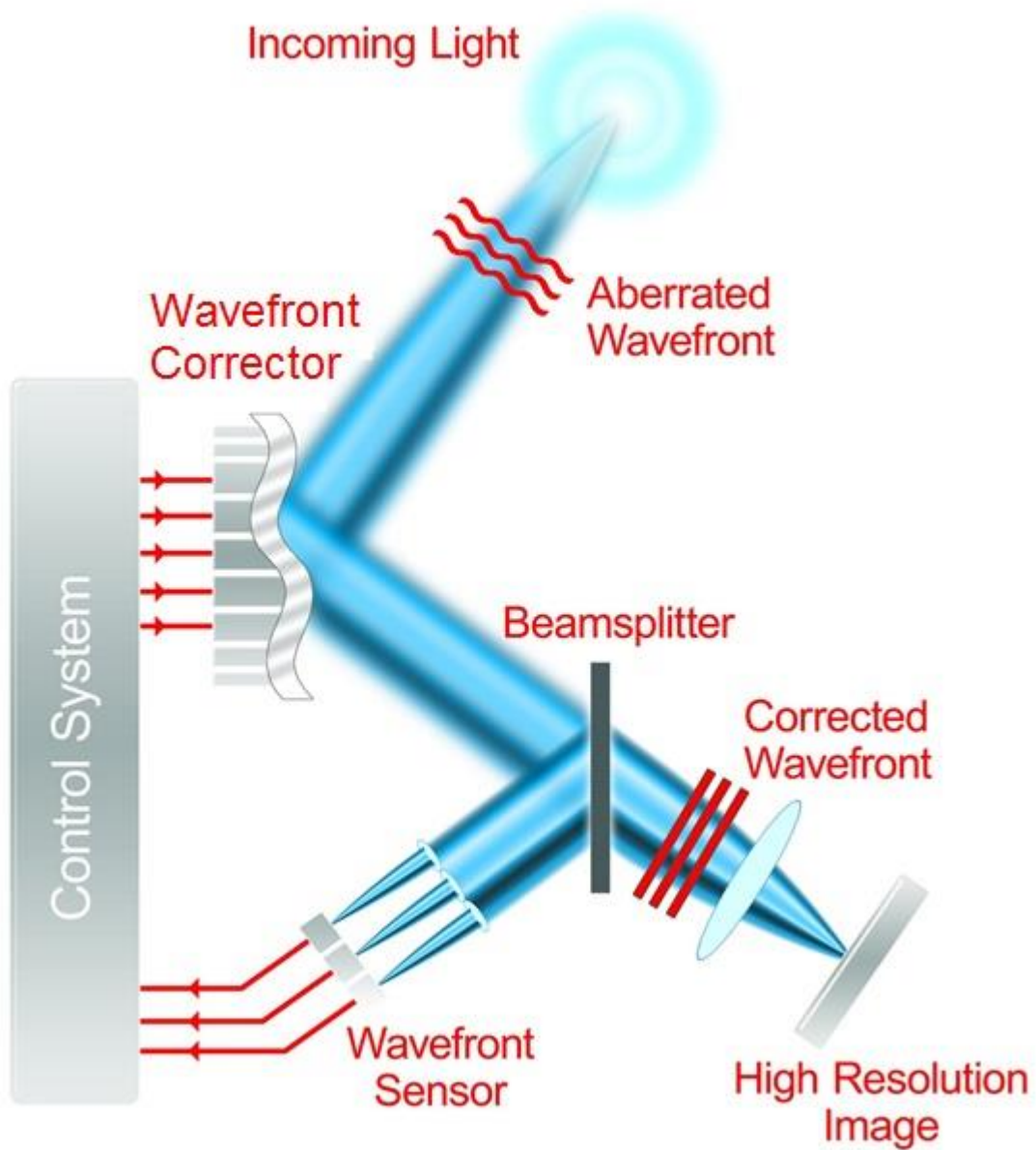

Figure 1a Traditional adaptive optics components and configuration. Adapted from C. Max, Center for Adaptive Optics

Wavefront Sensors and Controller

The most common wavefront sensor used is called a Shack-Hartmann Wavefront Sensor. This sensor splits light into a number of small beams using an array of miniature lenses (called lenslets). The light from each of these lenslets is focused onto a CCD camera. As the portion of the wavefront hitting the lenslet is aberrated, the focused spot on the CCD camera moves. Through simple geometry using the displacement of the focused spot and the focal length of the lenslet, the local tilt of the wavefront is calculated, as seen in Figure 1b. Shack-Hartman sensors are used most commonly given their simplicity and manufacturability. There are other techniques for wavefront sensing such as curvature and pyramid sensors but these are not as widely used. The control system is typically a computer running control algorithm software. Upon receiving wavefront information from the wavefront sensor, the controller calculates the appropriate shape to compensate the wavefront and sends that information to the wavefront corrector.
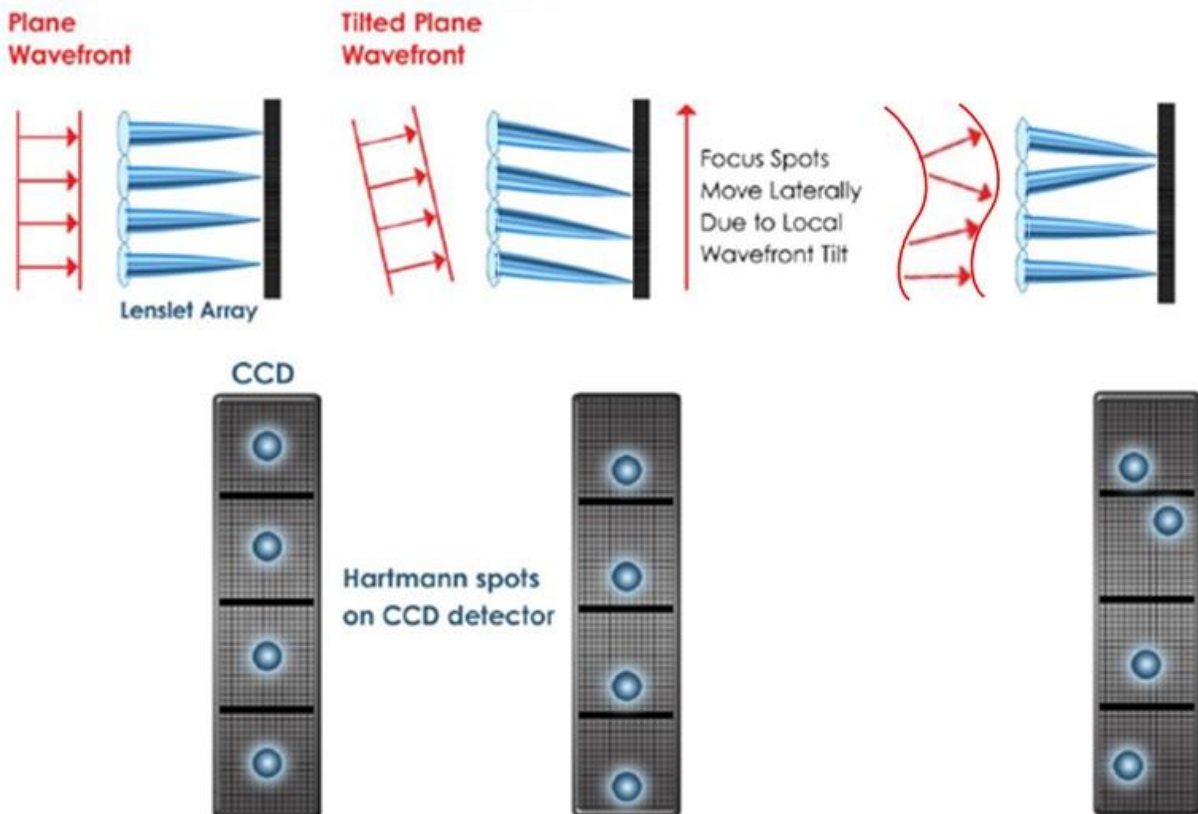

Figure 1. Depiction of fundamental theory of a Shack-Hartmann wavefront sensor. As the wavefront is aberrated, the focused spots due to the lenslet array shift, characterizing the wavefront. Credit: B.M. Levine, Jet Propulsion Laboratory.

Deformable Mirrors

After the aberration is measured, it needs to be corrected, which brings us to the true adaptive element in AO, the wavefront corrector. The most prevalent technology used for this function is a deformable mirror (DM), a thin, flexible reflective layer whose shape is controlled through a variety of mechanisms, based on different competing technologies. The selection criteria for a DM are application based. The fundamental specifications for DM systems are actuator count, inter-actuator coupling, speed, stoke and surface finish. The number of actuators in the mirror array and ranges from 19 actuators for an entry level membrane DM to over 4000 actuators for a MEMS DM used for extreme adaptive optics in astronomy[3]. Inter-actuator coupling along with resolution determines how complex a wavefront the deformable mirror can correct. Speed is based on the architecture and material properties of the DM. Stroke is a measure of maximum actuator deflection. Stroke and resolution present a significant tradeoff. Low resolution bimorph and ferromagnetic DMs can have a stroke as high as 50μm, but are not suitable for applications that call for correction of more than simple, low order aberrations. Most microscopic, vision science and laser shaping applications require 1 to 4μm of stroke, which is achievable with high resolution MEMS DMs. A cross sectional schematic of MEMS DMs can be seen in Figure 2.
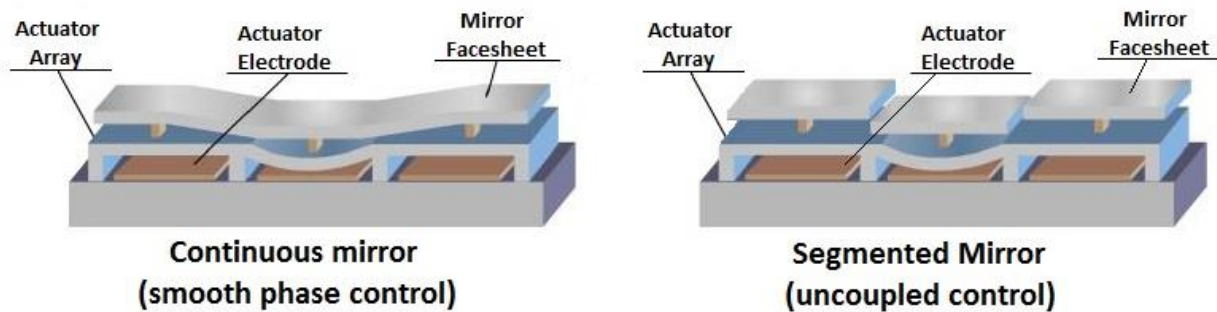

Figure 2. Overview of the elements of a MEMS deformable mirror with continuous and segmented facesheets. Credit: Boston Micromachines Corp.

MEMS deformable mirrors are commonly used in many AO applications given their versatility, maturity of technology and the high resolution wavefront correction that they afford. Using advanced, inexpensive manufacturing technology, MEMS DMs' performance strengths are inherent to micromachining:

1. Large actuator arrays create high resolution wavefront correction
2. Advanced microstructures allow minimal influence between adjacent actuators for high frequency surfaces
3. Optimized design enables rapid wavefront shaping for high speed applications

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[3] Steven Cornelissen, Paul Bierden, Thomas Bifano, "Development of a 4096 Element MEMS Continuous Membrane Deformable Mirror for High Contrast Astronomical Imaging", Proc. Of SPIE, Vol. 6306, 2006.

Bimorph deformable mirrors are made by creating a membrane surface by connecting a piezoelectric material with another material. Electrodes are patterned on the piezoelectric layer. A localized voltage is applied to the piezoelectric layer, thereby expanding one layer with respect to the next and creating a localized membrane curvature[4]. Bimorphs are capable of high stroke, but are not able to correct high order wavefront aberrations due to high coupling between adjacent pixels. The ability to put dielectric coatings on bimorphs makes them well-suited for high-energy laser applications.

Membrane deformable mirrors employ a simple membrane layer similar to a drum with an electrode pattern underneath. When electrodes are charged, the membrane deflects electrostatically[5]. The simple architecture makes for relatively inexpensive fabrication, but like bimorph DMs, membrane DMs have high interactuator coupling resulting in limited spatial frequency.

Ferromagnetic deformable mirrors have recently been developed for adaptive optics. These devices are capable of the high stroke of membrane DMs and have the low interactuator coupling of MEMS DMs, but are limited by their complex and expensive manufacturing process. As a result, they are limited to low actuator counts of 277 pixels which makes them viable for high amplitude, low resolution wavefront correction. However, the ferromagnetic nature of these devices limits frame rates to 2 kHz, making them impractical for many communications and astronomical applications.

Piezoelectric DMs were the first widely used for astronomy. These macroscale deformable mirrors are driven by individual piezoelectric stacks giving them the low interactuator coupling similar to MEMS and ferromagnetic DMs. Their large size, in the 100s of millimeters, and high pricing, in the hundreds of thousands to several millions of dollars, make piezoelectric impractical for many applications.

[4] "Deformable Mirror." *Wikipedia*. Wikimedia Foundation, 24 Aug. 2014. Web. 02 Sept. 2014.
[5] "Deformable Mirror." *Wikipedia*. Wikimedia Foundation, 24 Aug. 2014. Web. 02 Sept. 2014.

Adaptive Optics Applications

Vision Science

Leading vision scientists believe that someday the human retina will be a window into human health. The ability to resolve individual retina cells or photoreceptors and ocular blood flow through microscopic vasculature will allow scientists to monitor changes in patient health. This holds promise to noninvasively detect, diagnose and treat the leading eye pathologies such as glaucoma, diabetic retinopathy and age related macular degeneration. To date, ultra-high resolution images of the retina have not been achievable due to imperfections of the eye itself, causing wavefront distortions.

AO corrects the wavefront distortions introduced by the cornea and crystalline lens and has enabled increased contrast levels and unprecedented retinal resolution levels. The two primary techniques that employ AO for eye imaging are confocal scanning laser ophthalmoscopy (SLO) and optical coherence tomography (OCT). Confocal SLO works by focusing laser light on the retina and creating an image through scanning. Without AO, the best achievable resolution levels are in the 5-10 μm scale, which doesn't resolve individual cells that are about 3 μm. AO can achieve 1 μm resolution levels and can produce detailed images of photoreceptor cells, as seen in Figure 3. This image was created using a 140 actuator MEMS deformable mirror. In OCT, an interferometric imaging technique creates 3D scanned images. Figure 4 shows cross sectional images obtained with an adaptive optics spectral domain OCT (AO-SDOCT) system by Hammer, et. al, of Physical Sciences, Inc. with and without AO. The left image is with AO turned off,
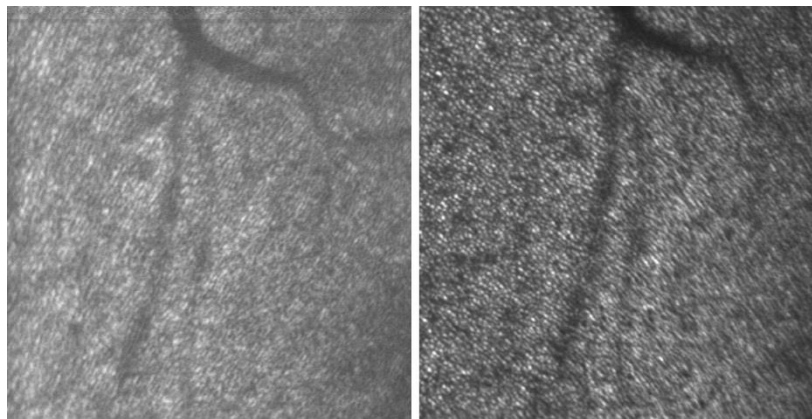
and the right image is with AO turned on. In the OCT images taken with adaptive optics, the external limiting membrane, shown by the arrow, is better resolved as are capillaries and structures in other retinal layers.

Figure 3. Adaptive Optics Scanning Laser Ophthalmoscope images. Left image is without adaptive optics (AO) correction. The right image shows the improvement in contrast and resolution with the use of AO. Credit: Images courtesy of Dr. Jennifer Sun and group at Beetham Eye Institute, Joslin Diabetes Center
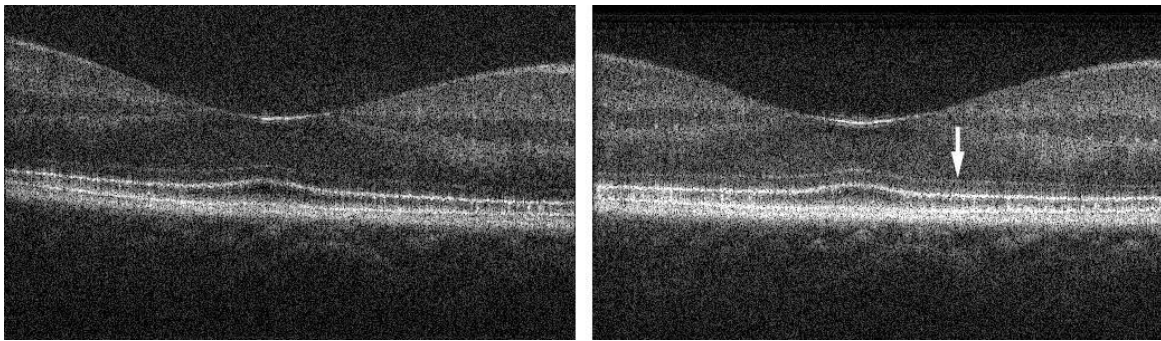
Figure 4. Adaptive optics spectral domain OCT (AO-SDOCT) cross sectional images with and without adaptive optics. The left image is with AO turned off, and the right image is with AO turned on. In the OCT images taken with adaptive optics, the external limiting membrane, shown by the arrow, is better resolved as are capillaries and structures in other retinal layers. Credit: D.X. Hammer, Physical Sciences Inc.

Clinical Vision Science

Ophthalmologists imaging the retina for disease diagnosis and prediction of response to disease treatment, such as diabetes, require a scientific instrument that integrates AO in order to achieve precise images. An Adaptive Optics Scanning Laser Ophthalmoscope (AOSLO) has the potential to replace or augment less direct methods of tracking disease states such as visual acuity (VA) and can resolve retinal structures and pathology that is valuable in both diagnosis and treatment. Providing cellular resolution in *in vivo* high-resolution imaging, its lateral resolution exceeds OCT systems today, enabling considerably well-defined images.

Dr. JK Sun and her team at the Beetham Eye Institute, Joslin Diabetes Center have quantified and applied an AOSLO for clinical studies[6]. Enabling capabilities include measures of cone physiology, detection of microaneurysms, small-vessel blood flow measurement and offset aperture imaging for enhanced feature detection. The AOSLO is capable of creating high resolution images necessary for vision scientists to improve visual outcomes of patients with diabetes.

Microscopy

In biological microscopy, *in vivo* imaging is critical since living tissue is much more relevant for studying cellular processes. A major obstacle is the amount of light than can illuminate the tissue without damaging the sample. AO increases not only resolution, but also signal strength and contrast ratio. These enhancements afforded by AO allow deep-tissue imaging *in vivo*.

Dr. Benjamin Potsaid, Research Scientist at the Center for Automation Technologies and Systems at Rensselaer Polytechnic Institute, found an opportunity to solve a problem present in all high-power microscopes. The tradeoff between magnification and field of view poses a constant challenge to researchers looking at larger samples under higher magnification. An existing solution uses a fast scanning microscope stage that patches together an image mosaic. However, for many samples, the moving mechanics disturbs the image. Another solution uses a fast scanning mirror instead of a moving stage. This

[6] Sun, Jennifer K., MD MPH. "*Diabetes Research, Care, Education & Resources*" Web. 11 Apr. 2014.

requires expensive and complex optics to overcome blurring caused by light passing through an off-axis optical path. Potsaid's team created the Adaptive Scanning Optical Microscope[7] (ASOM) to compensate for aberrations caused by optical imperfections and greatly reduce the cost of a high powered, wide field of view scanning microscope. Figure 5 shows air force target images without (a) and with (b) the use of the deformable mirror. The smallest lines are separated by 2 μm.
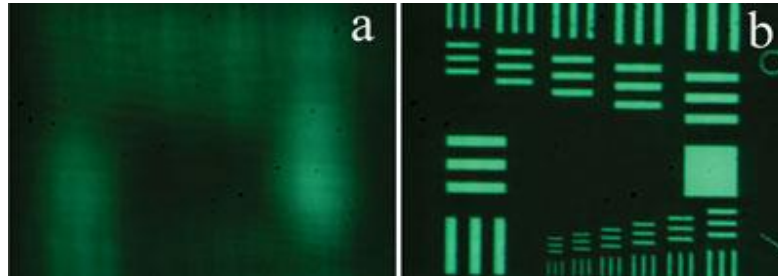

Figure 5. Image improvement shown using a standard air force target with the Adaptive Scanning Optical Microscope (ASOM). Credit: Potsaid, Rensalaer Polytechnic Institute and Thorlabs

Another major obstacle in biological imaging is acquiring images at greater depths for deep tissue *in vivo* imaging. Scattering media along with wavefront distortions in the optical path limits the imaging depth capability, which is a problem standard Multiphoton Microscopy faces. By using adaptive optics techniques, the wavefront distortions can be compensated for both the optical path aberrations and scattering media. Super Penetration Multi-Photon Microscopy (S-MPM) was pioneered by Dr. Meng Cui and his team at the Cui Lab at Howard Hughes Medical Institute,[8] and further researched by Boston University by focusing light through static and dynamic strongly scattering media. By using a fast MEMS spatial light modulator, images of 1 μm diameter fluorescent beads through 280 μm thick mouse skull reaching image depths of about 500 μm were achieved. SLMs are able to correct for both low order spherical aberrations and high order scattering effects. The optimized SLM phase improves imaging over a field of view of 10-20 μm for samples tested to date.

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[7] Benjamin Potsaid, Yves Bellouard, and John T. Wen, "Adaptive Scanning Optical Microscope (AOSM): A multidisciplinary optical microscope design for large field of view and high resolution imaging". Optical Express, Vol. 13, No. 17, 2005.
[8] J. Tang, R. N. Germain, and M. Cui Proceedings of the National Academy of Sciences of the United States of America, 109:8434-9(2012) doi:10.1073/pnas.1119590109
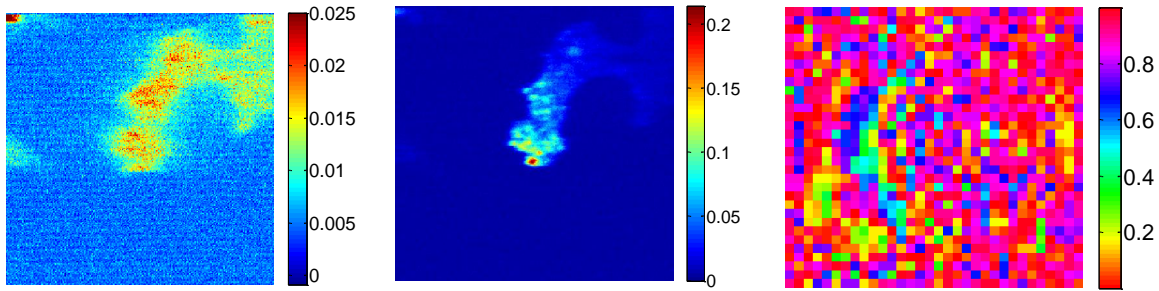
Figure 6   Imaging fluorescent beads through a thin strongly scattering medium (7.5 μm layer of titanium oxide paint (l_s* = 140 nm)) from left to right: Multi-Photon Microscope Image of beads, Superpenetration Multi-Photon Microscope Image of beads, and spatial light modulator phase map. Image Credit: Precision Engineering Research Lab, Boston University.

Laser Applications

A different push in AO has been in the field of long range laser communication. Free-space optical communication holds potential for a new method for data transmittal without the need for wires or fibers. There are a number of commercial systems that currently provide this, but they are limited to a range of ~1km. when sending data over longer distances, atmospheric turbulence will limit the achievable data rate. AO allows for the compensation of this atmospheric distortion and will provide a high-speed long range data link.

Lawrence Livermore National Laboratory led the Coherent Communications Imaging and Targeting program (CCIT) which analyzed horizontal path laser beam shaping using a 1020 element count SLM mirror. In the field test performed, they found the AO system achieved 8x signal improvements for a long range laser communication system. The conclusions of the program demonstrated the potential of large actuator count SLMs to replace conventional deformable mirrors for applications requiring high Strehl ratios and communications and imaging under conditions of strong turbulence[9].

Ultrafast lasers are useful in many applications within spectroscopy, photochemistry, laser processing and microscopy. However, to make the most use of such short laser pulses, a pulse compressor is needed to compensate for the dispersion induced by optical elements. Liquid crystal-based spatial light modulators (SLM)[10] are most commonly used in laser pulse compressors. Although a proven technology, liquid crystals have drawbacks including jitter and a limited fill factor.

Janelia Farm's Reto Fiolka addressed these obstacles by using a MEMS SLM for laser pulse shaping and the results established that the precision and stability of the device allowed close to perfect restoration of transform limited laser pulses. Fiolka concluded, "The tested

[9] Baker, K., Stappaerts, E., Gavel, D., Tucker, J., Silva, D., Wilks, S., Olivier, S., Olsen, J. Adaptive Compensation of Atmospheric Turbulence Utilizing an Interometric Wave-Front Sensor and a High-Resolution MEMS-Based Spatial Light Modulator. Lawrence Livermore National Laboratory. SPIE (2004)

[10] Lozovoy, V.V., Pastirk, I. & Dantus, M. Multiphoton intrapulse interference.IV. Ultrashort laserpulse spectral phase characterization and compensation. *Opt. Lett*. 29, 775-777 (2004).

device represents a promising alternative to liquid crystal displays, since the MEMS technology enables high fill factor, high efficiency and operation speed, exceptional phase stability and accuracy and can be used over a very broad wavelength spectrum."

Astronomy

A major restriction astronomers face is capturing high resolution and precise images due to atmospheric aberrations. Today, it has become more common for ground based telescopes to use adaptive optics to correct for atmospheric aberrations allowing successful, reliable and clearer images. Including precision optics, wavefront sensors and MEMS deformable mirrors, adaptive optics solutions are being used in major astronomy research projects worldwide.

Robo-AO is the first highly efficient, autonomous laser adaptive optics and science system operating on-sky. Currently deployed on the Palomar 60-inch telescope in Palomar, CA, the project is led by Principal Investigator Christoph Baranec, currently at the University of Hawaii with Software Lead Reed Riddle, Project Scientist Nicholas Law, Co-Investigator A. N. Ramaprakash, and students and collaborators from Caltech Optical Observatories collaborating with the Inter-University Center for Astronomy and Astrophysics. Using visible and infrared imaging cameras, the system's main parts include a laser guide star, an integrated AO and science camera system and a robotic control system[11]. Instead of the traditional manual procedure, Robo-AO automates the processes which allows an increase in efficiency allowing a higher count of observations to be made per night. Since the system is robotic, it can rapidly respond to new discoveries such as supernovae or repeatedly observe targets over time providing the ability to monitor weather on other planets in the solar system.
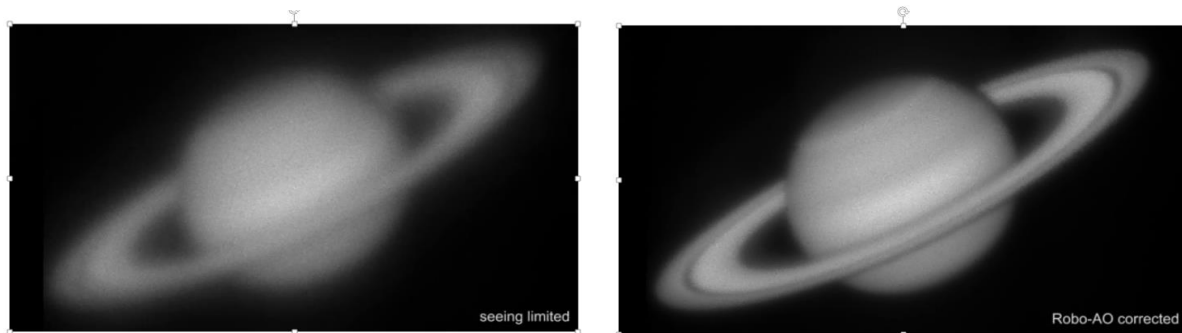

Figure 7. Uncorrected (left) and AO Corrected (right) images of Saturn with Robo-AO.
Image credit: Christoph Baranec, California Institute of Technology

[11] Christoph Baranec, Reed Riddle, A.N. Ramaprakash, Nicholas Law, Shriharsh Tendulkar, Shrinivas Kulkarni, Richard Dekany, Khanh Bui, Jack Davis, Jeff Zolkower, Jason Fucik, Mahesh Burse, Hillol Das, Pravin Chordia, Mansi Kasliwal, Eran Ofek, Timothy Morton and John Johnson "Robo-AO: An Autonomous Laser Adaptive Optics and Science System". ArXiv:1210.0532 [astro-ph.IM] Web. Oct 1 2012

Another telescope considered to be on the smaller scale that integrates AO into their system is KAPAO. This natural guide star adaptive optics system was developed for the Pomona College Table Mountain Observatory (TMO) 1-m telescope. The primary goals for applying adaptive optics techniques in KAPAO is to improve image resolutions by a factor of 5-10 and to serve as an on-sky test bed for evolving new wavefront sensing technologies[12]. KAPAO saw its first light during the summer of 2012, demonstrating the capability of the system to correct static and time-varying aberrations.

On a much larger scale, the Gemini Planet Imager (GPI) has had a boastful amount of success from adopting the AO practice. Led by Lawrence Livermore National Labs, GPI is deployed on one of the world's largest telescopes, the 8-meter Gemini South telescope, and is has recently detected light from extra-solar planets. With assistance from its advanced AO system and high actuator count MEMS deformable mirror, it has clarified planet images obscured by light from parent stars, atmospheric aberrations and optical imperfections in the imaging system. GPI's system will be able to see objects about ten million times fainter than their parent stars, allowing detection of warm planets up to one billion years old and measurements of polarization of light from other solar systems[13].
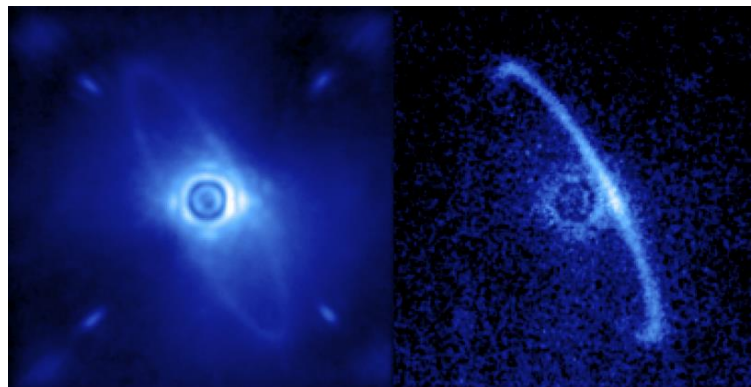

Figure 7. GPI's first light image of the light scattered by a disk of dust orbiting the young star HR4796A.
Image credit: Processing by Marshall Perrin, Space Telescope Science Institute

Direct imaging of exoplanets from a ground-based telescope can be limited due to numerous atmospheric constraints. Space telescopes on-orbit require wavefront control systems in order to identify enhanced observations without the concern for adjustments after launch. Kerri Cahoy, Boeing Assistant Professor of Aeronautics and Astronautics at MIT, and her team have built and developed a three-unit CubeSat called MicroMAS. Planned to launch in June 2014, MicroMAS is expected to provide observations and predictions of earth's weather conditions, climate records and other scientific objectives[14]. The goal of MicroMAS is to promote space imaging and free space communication applications using low cost, compact adaptive optics components.

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[12] "KAPAO: Pomona's Adaptive Optics Instrument". *Department of Physics and Astronomy*. Ponoma College, n.d. Web. 25 Apr. 2014

[13] "Gemini Planet Imager." *Gemini Planet Imager*. N.p., 7 Jan. 2014. Web. 03 Sept. 2014.

[14] "Space Systems Laboratory." *MIT*. MIT SSL, n.d. Web. 28 Apr. 2014.

AO Resources

There are a number of organizations dedicated to supporting AO research and education. These centers provide an excellent starting point for scientists and engineers seeking to integrate AO into their optical instrumentation. Based at the University of California, Santa Cruz, the Center for Adaptive Optics (CfAO) was founded in 1999 with a mission "to advance and disseminate the technology of adaptive optics in service to science, health care, industry and education". The University of Arizona hosts a similar center which focuses on astronomical imaging. Working in partnership with the Steward Observatory, the Center for Astronomical Adaptive Optics (CAOO) works to enhance the resolution capabilities of large ground-based telescopes.

Future of AO

Medical Advances

AO holds promise to change the way doctors diagnose diseases. Highly publicized research by Prof. Tien Wong, Director of The Retinal Vascular Imaging Centre, University of Melbourne, Australia has shown a link from retinal vasculature damage to coronary heart disease[15], stroke[16] and diabetes. His work uses new retinal imaging technology to predict diabetes, stroke, heart disease, hypertension and other risk factors. According to Wong, an increase in imaging resolution provided by AO may address a major limitation with the prediction of cardiovascular disease using imaging from standard retinal photography in its inability to detect subtle changes, on the scale of a few microns, between healthy and diseased vessels. "We know these changes exist," Wong says, "But are detectable only by averaging large populations and not in an individual." This will allow doctors to detect subtle changes in cell attrition and microvasculature on an individual patient to non-invasively diagnose the diseases that cause the most hospitalization and death worldwide.

Towards Commercialization

In the second half of the last century, inventive scientists developed a theory for a cumbersome, expensive optical correction technique that would someday be improved. Industrious engineers and early adopting researchers worked in parallel simultaneously refining technology while finding applications beyond astronomy in retinas, communication signals and cancer cells. This culmination of mature, affordable technology and proven applications has paved a path to commercialization. AO experts such as Benjamin Potsaid believe that in the next five years, adaptive optics will be an enabling technology in biological research, medical diagnostics and high precision laser manufacturing. In the five years that follow, Potsaid believes "AO will be a standard component in an optical engineer's toolbox just as polarizers and beam splitters are today."

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[15] Tien Y. Wong, Wayne Rosamond, Patricia P. Chang, David J. Couper, A. Richey Sharrett, Larry D. Hubbard, Aaron R. Folsom, Ronald Klein, "Retinopathy and risk of congestive heart failure". JAMA 2005; 293:63-69.

[16] Tien Yin Wong, Ronald Klein, A. Richey Sharett, David J. Couper, Barbara E. K. Klein, Duan-Ping Liao, Larry D. Hubbard, Thomas H. Mosley, "Cerebral white matter lesion, retinopathy and risk of clinical stroke: The Atherosclerosis Risk in the Communities Study". JAMA 2002;288:67-74