Adaptive Optics Kits

THORLABS

► **Kit Includes Deformable Mirror, Shack-Hartmann Wavefront Sensor, and All Necessary Optics / Hardware**

► **Up to 100 Hz Closed-Loop Operation**

► **Closed-Loop Operation via Stand-Alone Control Software**

Shack-Hartmann
Wavefront Sensor
15 Hz

Deformable Mirror
6x6 or 12x12 Array

Related Items

Shearing Interferometer

Shack-Hartmann Wavefront Sensor

MEMS-Based Deformable Mirrors
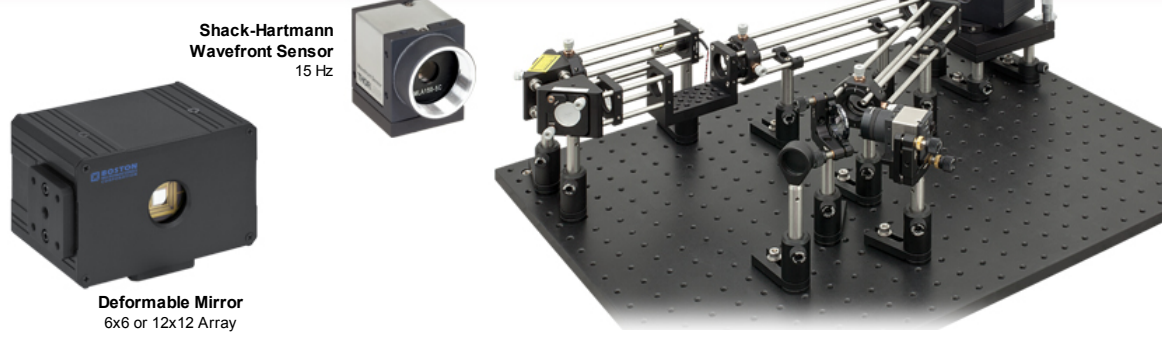
Piezoelectric Deformable Mirrors

| Overview | Specs | DM | WFS | Software | Components | AO Tutorial | Aberrations | Off-Axis Imaging | Publications | Documents | Feedback | Tag Cloud |

Features

- Complete Kit and Software for Out-of-the-Box Wavefront Measurement and Control
- Kit Includes (See the *Components* Tab for Details)
  - Continuous Deformable Mirror
  - 15 Hz CCD-Based Shack-Hartmann Wavefront Sensor
  - Laser Diode Module (635 nm)
  - All Imaging Optics and Associated Mounting Hardware
  - Fully Functional Stand-Alone Control Software for Windows
  - SDK for Custom Applications Authored by the End User
- Four Kits Available with the Following Options:
  - Aluminum- or Gold-Coated Deformable Mirror
  - 32- or 140-Actuator Deformable Mirror
  - 15 Hz CCD Shack-Hartmann Wavefront Sensor*

Thorlabs' adaptive optics kits are a complete adaptive optics imaging solution, including a deformable mirror, wavefront sensor, control software, and optomechanics for assembly. These miniature, precision wavefront control devices are useful for beam forming, microscopy, laser communications, and retinal imaging. To learn more how the wavefront sensor, deformable mirror, and software operate as a closed-loop system to correct wavefront distortion, please see the various tabs on this page or the Adaptive Optics 101 white paper.

Thorlabs now offers four variations of AO Kits. Choose from a gold- or aluminum-coated deformable mirror with 140 or 32 actuators. Each kit includes a 15 Hz CCD-based Shack-Hartmann wavefront sensor*. Details on all four AO Kit options are outlined in the various tabs on this page. A reflectivity plot for the gold and aluminum coatings is available on the DM tab.

Please consider sharing with us your adaptive optics applications by emailing technicalmarketing@thorlabs.com.

High-Speed Adaptive Optics Kits

Thorlabs is currently developing adaptive optics kits that use our High-Speed CMOS-Based Wavefront Sensor. For more information or to enquire about availability, please contact techsupport@thorlabs.com.

Related White Papers
Adaptive Optics 101	Linear Array Deformable Mirror	MEMS Optical Modulator
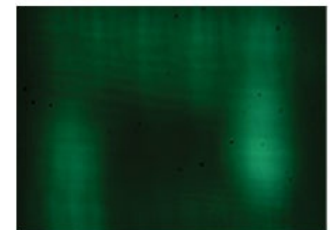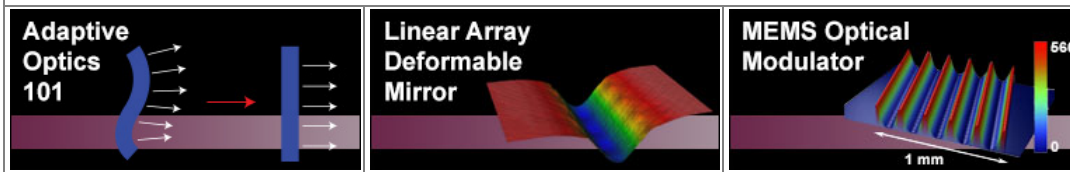
(a)
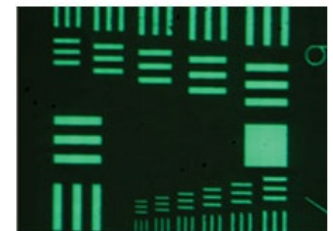
(b)

Air force target imaged using (a) a flat mirror (b) an optimized deformable mirror. The smallest lines are separated by 2 µm.

1

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Boston Micromachines Deformable Mirrors		
Deformable Mirror Type	Multi-DM Gold or Aluminum Coated Included in AOK1	Mini-DM Gold: DM32-35-UM01 Aluminum: DM32-35-UP01 Included in AOK2
Actuator Array	12 x 12	6 x 6
Actuator Stroke (Max.)	3.5 µm	
Actuator Pitch	400 µm	
Clear Aperture	4.4 mm x 4.4 mm	2.0 mm x 2.0 mm
Acceptance Angle	±18°	-
Mirror Coating (Click for Plot)	Gold (-UM01) or Aluminum (-UP01)	
Average Step Size	<1 nm	
Hysterisis	None	
Fill Factor	>99%	
Mechanical Response Time (10% - 90%)	<100 µs (~3.5 kHz)	
Surface Quality	<20 nm (RMS)	
Head Dimensions	4.5" x 2.95" x 2.8" (114.3 mm x 74.9 mm x 71.1 mm)	
Driver		
Frame Rate (Max.)	8 kHz (34 kHz Bursts)	
Resolution	14 Bit	
Driver Dimensions	9.0" x 7.0" x 2.5" (229 mm x 178 mm x 64 mm)	4.0" x 5.25" x 1.25" (102 mm x 133 mm x 32 mm)
Computer Interface	USB 2.0	

Thorlabs Shack-Hartmann Wavefront Sensors	
Wavefront Sensor Type	CCD-based Sensor (WFS150-5C) Included in AOK1 and AOK2
Camera	
Frame Rate (Max)	15 Hz[a]
Sensor Type	CCD
Aperture Size (Max)	5.95 mm x 4.76 mm
Camera Resolution (Max)	1280 x 1024 Pixels (Selectable)
Pixel Size	4.65 x 4.65 µm
Shutter	Global
Exposure Range	77 µs - 66 ms
Microlens Array	
Wavelength Range	300 - 1100 nm
Lenslet Pitch	150 µm
Lenslet Diameter	Ø146 µm
Number of Lenslets (Max)	39 x 31 (selectable)
Effective Focal Length	3.7 mm
Substrate	Fused Silica (Quartz)
Coating	Chrome Mask
Performance	
Wavefront Accuracy @ 633 nm	λ/15 rms
Wavelength Sensitivity @ 633 nm	λ/50 rms
Wavefront Dynamic Range @ 633 nm	>100λ
Local Radius of Curvature	>7.4 mm
Image Digitization	8 Bit
General / Physical	
Optical Input Connector	C-Mount
Physical Size (H x W x D)	34 mm x 32 mm x 48.3 mm
Power Supply	<1.5 W via USB

a. For the configurations used in the AO Kit, the frame rates will be nominally 8 Hz for the CCD sensor. This PC hardware-dependent speed is achieved without graphical display, assumes a 5th order Zernike fit at the specified camera resolution, and minimum exposure time.

6 x 6 or 12 x 12 MEMS Deformable Mirror

- 6 x 6 (Mini-DM) or 12 x 12 (Multi-DM) Actuator Models Available
- 3.5 µm Maximum Actuator Displacement
- High-Speed Operation up to 3.5 kHz
- 400 µm Center-to-Center Actuator Spacing
- Low Inter-Actuator Coupling Result in High Spatial Resolution
- Zero Hysteresis Actuator Displacement
- 14-Bit Drive Electronics Yield Sub-Nanometer Repeatability
- Compact Driver Electronics with Built-In High Voltage Power Supply Suitable for Benchtop or OEM Integration
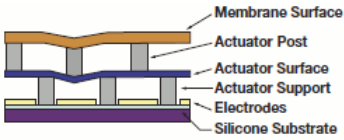
Included Deformable Mirror			
Item #	Actuator Array	Mirror	Coating
AOK1-UM01	12 x 12	Multi DM	Gold
AOK1-UP01		Multi DM	Aluminum
AOK2-UM01	6 x 6	DM32-35-UM01	Gold
AOK2-UP01		DM32-35-UP01	Aluminum

Through our partnership with Boston Micromachines Corporation (BMC), Thorlabs is pleased to offer BMC's Mini- and Multi- Deformable Micro-electro-mechanical (MEMS) based mirrors as part of our adaptive optics kits. These deformable mirrors (DMs) are ideal for advanced optical wavefront control; they can correct monochromatic aberrations (spherical, coma, astigmatism, field curvature, or distortion) in a highly distorted incident wavefront. MEMS deformable mirrors are currently the most widely used technology in wavefront shaping applications given their versatility, maturity of technology, and the high resolution wavefront correction capabilities they provide.

Our Deformable Mirrors, fabricated using polysilicon surface micromachining fabrication methods, offer sophisticated aberration compensation in easy-to-use packages. The mirror consists of a mirror membrane that is deformed by either 32 electrostatic actuators (i.e., a 6 x 6 actuator array with four inactive corner actuators for the Mini-DM) or 140 electrostatic actuators (i.e., a 12 x 12 actuator array with four inactive corner actuators for the Multi-DM). These actuators provide 3.5 µm of stroke (over 11 waves at 632.8 nm) with zero hysteresis.

Mirrors are available with a Gold (-M01) or Aluminum (-P01) reflective coating. Each is packaged with a protective 6° wedged window that has a broadband AR coating for the 400 - 1100 nm range. See the coating curve graphs below for details.

BMC's Mini- and Multi-DMs are also available separately. Click here for more information.

MEMS Deformable Mirror Structure
Click to Enlarge
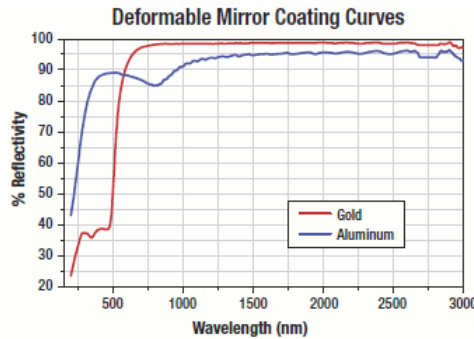
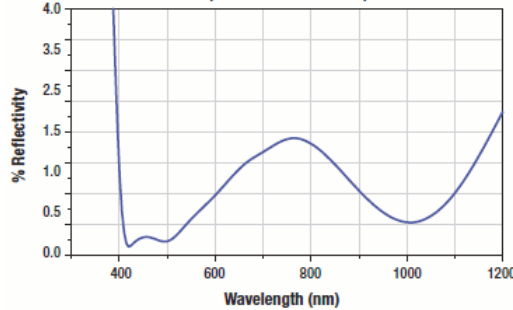Click to Enlarge
Typical Reflectivity Plots for Aluminum- and Gold-Coated Surfaces of the Deformable Mirror (Without the Protective Window) at 45° AOI.

Click to Enlarge

Click to Enlarge
AR Coating Curve for the Protective 6° Wedged Window

Shack-Hartmann Wavefront Sensor

- High-Sensitivity Model: CCS-Based, up to λ/50 RMS (WFS150-5C)*
- Wavelength Range: 300 - 1100 nm
- Real-Time Wavefront and Intensity Distribution Measurements
- Nearly Diffraction-Limited Spot Size
- For CW and Pulsed Light Sources
- Flexible Data Export Options (Text or Excel)
- Live Data Readout via TCP/IP

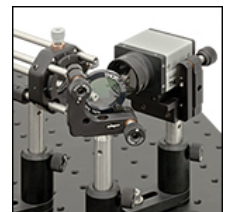| Item # Prefix	Wavefront Sensor Included
AOK1	1.3 Megapixel, λ/50 Sensitivity Model
AOK2	WFS150-5C

Thorlabs AO Kit includes the WFS150-5C CCD wavefront sensor. These Shack-Hartmann wavefront sensors can detect distortions in the wavefront which can then be corrected by the deformable mirror.

1.3 Megapixel CCD Sensor
Our WFS150-5C 1.3 Megapixel wavefront sensor has a higher wavefront sensitivy of up to λ/50 RMS due to the increased spatial resolution of the CCD sensor (4.65 µm pixel pitch). This sensor operates at a frame rate of 15 Hz, and is included with the AOK1 and AOK2 AO Kits.

See the Specs tab for complete specifications.

*Thorlabs is currently developing adaptive optics kits that use our High-Speed CMOS-Based Wavefront Sensor. For more information or to enquire about availability, please contact techsupport@thorlabs.com.

Click to Enlarge
λ/50 High-Sensitivity Wavefront Sensor

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Application Software

For out-of-the-box operation, the AO Kit comes with a fully functional, stand-alone, Windows XP and 7-compatible program for immediate operation of the instrument. This software is capable of minimizing wavefront aberrations by analyzing the signals from the Shack-Hartmann wavefront sensor and generating a voltage set that is applied to the deformable mirror. Users can also monitor the deformable mirror actuator control voltages, wavefront corrections, and intensity distribution in real time. Since the application software provides full control of the AO Kit, it is an excellent tool for research and development or developing educational packages based on adaptive optics. A software development kit is also included for custom applications (see below).
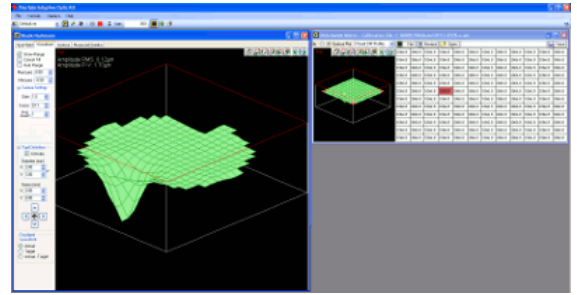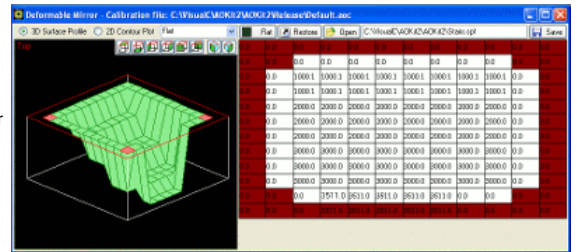

Click to Enlarge

Deformable Mirror Control

- Real-Time Representation of the Deformable Mirror Actuator Displacements (Based on Voltages Applied to the Mirror)
- Spreadsheet-Like Numerical Interface Provides User-Input of Actuator Deflections
- Save/Recall Mirror Surface Maps

The deformable mirror control shows a graphical plot of the DM surface shape as well a spreadsheet-like numerical interface that allows the user to input actuator deflections (in nanometers). The actuator deflection values may be changed individually or in selected groups. The actual shape of the DM will differ slightly due to a small influence of adjacent actuators.

Specific mirror shapes can be loaded and saved from this window, allowing the creation of a library of unique and specialized mirror shapes that can be later recalled at the click of a button.
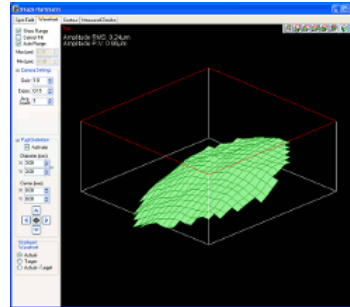

Click to Enlarge
Deformable Mirror Control
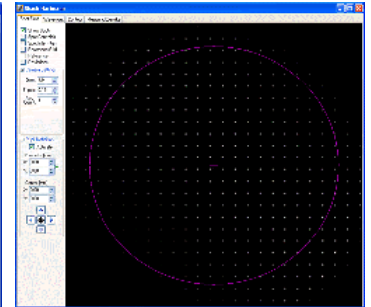
Shack-Hartmann Control

- Four Tab Displays
  - Wavefront Sensor Spot Field Measured Directly from the Sensor
  - Wavefront Plot (See Example at Right)
  - Contour Wavefront Plot
  - Measured Zernike Coefficients
- Wavefront Plot is Scalable / Rotatable
- Easily Access Wavefront Sensor and Display Control Settings in Each Tab Display
- Display Measured, Reference, or Difference Wavefront Plots
- Min/Max Threshold Eliminate 'Flickering' Active/Inactive WFS Spots
- User-Controllable Spot Centroid and Reference Spot Indicators (See Example to the Right)

In the spot field window (above, far right), the camera's exposure time and gain can be controlled. A pupil control allows the user to analyze the wavefront data within a user-defined circular pupil. The camera image of the spots (white spots in inset), spot centroid locations (red X's), reference locations (yellow X's), deviations (white lines between red and yellow X's), and intensity levels may easily be displayed in the spot field window.

In addition to the camera controls mentioned above, when viewing the wavefront, the user has the option to display the measured wavefront, target (reference) wavefront, or the difference between these two wavefronts. There are predefined view angles for the wavefront plot, or it can be continuously adjusted by the user.
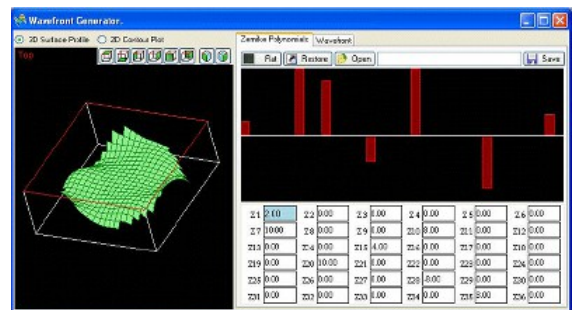

Click to Enlarge
Shack-Hartmann Wavefront

Click to Enlarge
Shack-Hartmann Spot Field

Zernike Wavefront Function Generator

- User-Controllable Reference Wavefront
- User-Defined Zernike Sampling Pupil Size and Position
- User-Defined Reference Using First 36 Zernike Terms
- User-Captured Reference Wavefront
- 3D Surface Plot or 2D Contour Plot Display

The Wavefront Generator control enables the user to create a reference wavefront by combining the first 36 Zernike polynomials in the spreadsheet-like grid. A graphical display of the created wavefront, along with the minimum, maximum, and peak-to-peak wavefront deviations are provided.

The wavefront generator control window also allows the user to capture the current measured wavefront and set it as the reference wavefront. Reference wavefronts can be saved and later recalled by the user.

Click to Enlarge
Zernike Function Generator

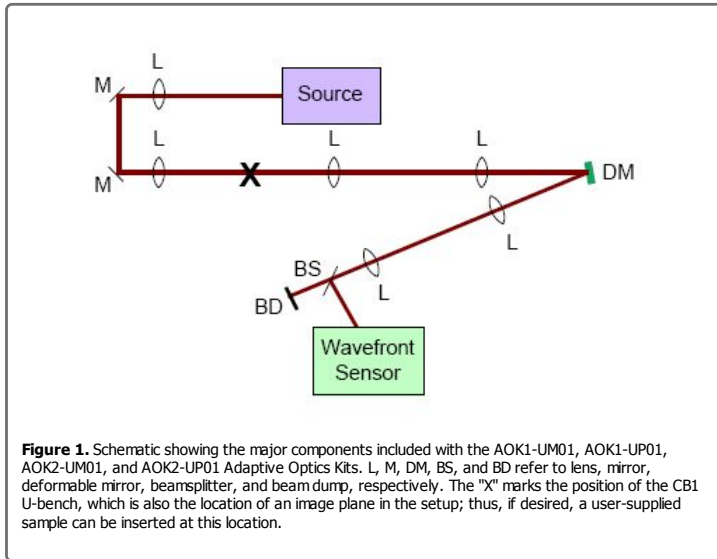## Software Development Kit

The Adaptive Optics Kit includes a Software Development Kit (SDK) in the form of a flexible, cross-platform-compatible Dynamic Link Library (DLL) ideal for user-authored applications. The kit additionally includes full-featured Windows application software with easy-to-use Graphical User Interface (GUI) for full system control right out of the box. The SDK is designed to be a conduit for easy integration of AO instrumentation, control, and arithmetic functions into a user system. The application software provides immediate interaction with the AO Kit Deformable Mirror and Shack-Hartmann Wavefront Sensor. This software is ideal for research, development, and educational applications. Additionally, the demo software provides pop-up tooltips containing detailed information pertaining to specific function calls dispatched by the associated GUI control.

SDK Memory Management

A unique aspect to the SDK is its versatile memory structure. We provide an SDK that is compatible with a broad range of programming environments, including C-based languages, Visual Basic, LabVIEW, and any other language capable of interfacing with standard DLL's. These languages allocate data memory using different methods. In order to maximize performance and cross-platform compatibility, the SDK employs a flexible memory structure that allows it to transparently use either its own or user software-allocated data space.

In addition to the WFS150-5C high-resolution CCD Shack-Hartmann Wavefront Sensor, your choice of an Aluminum- or Gold-Coated Mini- or Multi-DM deformable mirror, and control software (Windows XP and 7 Compatible), these adaptive optics kits also include a source, all collimation/imaging optics, and all mounting hardware necessary to build the layout depicted in the schematic below. Please note that a breadboard is not included.

AO Kit Components		
Item	**Qty.**	**Photo**
WFS150-5C CCD-Based Wavefront Sensor	1	
Deformable Mirror	1	
Light Source		
CPS180 Collimated Laser Module	1	
LDS5 5V DC Regulated Power Supply	1	
Optics		
LA1608-A or LA1068-B 75 mm Focal Length Plano-Convex Lens*	6	
BB1-E02 or BB1-E03 Broadband Dielectric Mirror*	2	
NE20A Mounted Ø1" Absorptive Neutral Density Filter	1	
NE10A Mounted Ø1" Absorptive Neutral Density Filter	1	
BP108 Pellicle Beamsplitter	1	

Figure 1. Schematic showing the major components included with the AOK1-UM01, AOK1-UP01, AOK2-UM01, and AOK2-UP01 Adaptive Optics Kits. L, M, DM, BS, and BD refer to lens, mirror, deformable mirror, beamsplitter, and beam dump, respectively. The "X" marks the position of the CB1 U-bench, which is also the location of an image plane in the setup; thus, if desired, a user-supplied sample can be inserted at this location.
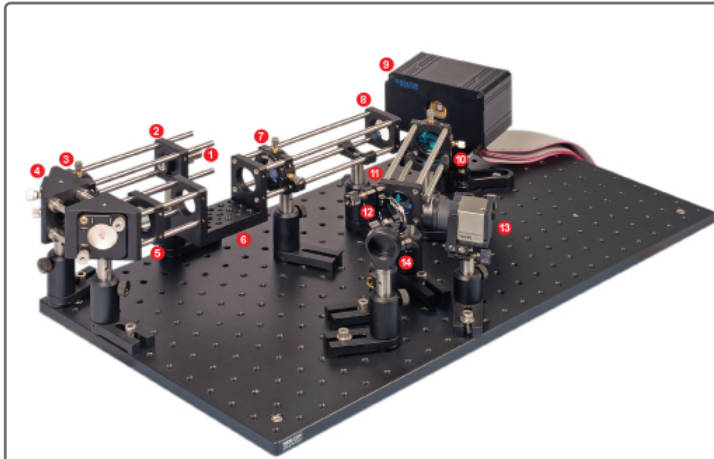
Figures 2 and 3 below are photographs showing two different views of an assembled AOK1-UP01 AO Kit. The cage components are divided into three pre-aligned pieces that need to be arranged on a user-supplied breadboard: two sections of preassembled cage components are used together to image a beam waist onto the DM surface and a third preassembled cage system is used to image a beam waist onto the Shack-Hartmann wavefront sensor.

If you are not familiar with Thorlabs' 30 mm cage assemblies, they consist of cage-compatible components that are interconnected with cage rods. Each cage component features four tapped holes with center-to-center spacings of 30 mm, and they are joined together into a cage system using Ø6 mm rigid steel cage rods of varying lengths. For this setup, cage rods with lengths of 1", 1.5", 3", and 6" were used. The reason for building a cage system is to ensure that the optical components housed inside the cage system have a common optical axis.

Figure 2. A photograph of an AOK1-UM01 Adaptive Optics kit. Please note that the breadboard is not included with the purchase of an AO kit. The key components, which will be discussed in the text below, are numbered.

The first two preassembled cage sections consist of the laser diode source, four 75 mm focal length lenses, two cage-compatible turning mirrors, and a U-shaped bench. The CPS180 Laser Diode Module (labeled #1 in Fig. 2), which outputs ~1 mW of light at 635 nm, is housed inside a CP02 Cage Plate (#2 in Fig. 2) using an AD11F Ø11 mm-to-SM1 Adapter. Light exiting the module is centered within the cage system and on the surface of the DM using the adjustment knobs on the two KCB1 Right-Angle Cage-Compatible Kinematic Mounts (the first of which is labeled as #4 in Fig. 2), which house BB1-E03 Broadband Dielectric Mirrors; these mirrors have an antireflection coating for the 750 - 1100 nm range. A CPA1 alignment plate, which locates a small through-hole at the exact center of a cage assembly, is used to assist with this alignment. Please note that with the purchase of AOK1-UP01 or AOK2-UP01, the two BB1-E03 mirrors are replaced by two BB1-E02 mirrors, which have an antireflection coating for the 400-750 nm range.

Two LA1608-B 75 mm focal length lenses (the first of which is housed in the HPT1 Translating Lens Mount labeled as #2 in Fig. 2 and the second of which is housed in the CP02 Cage Plate labeled as #3 in Fig. 2) are used to image a beam waist at the center of the CB1 30 mm Cage System U bench (represented by an X in Fig. 1 and labeled as #6 in Fig. 2 above). A sample can be placed in this image plane. Please note that the LA1608-B lenses used for the AOK1-UM01 and AOK2-UM01 are replaced by LA1608-A lenses with the purchase of an AOK1-UP01 or AOK2-UP01 adaptive optics kit. In either case, the first lens is placed ~94 mm from the source (since the collimation optic built into the laser diode module source has a focal length of ~19 mm), and the second lens is placed in the optical path so that it is ~150 mm after the first lens. Then, during the alignment process done at Thorlabs, fine adjustments are made to the lens locations by using an SI050 Shearing Interferometer to ensure the laser beam is collimated.

Then, two more LA1608-B lenses (one is housed in the HPT1 mount labeled as #7 in Fig. 2 and the other in the CP02 mount labeled as #8 in the figure) are used to image a beam waist onto the DM (#9); by having a beam waist at the DM surface, the range of actuation needed to correct for any aberrations is minimized. All of these components are connected using ER Cage Rods to build a cage system, which ensures that a common optical axis is maintained. Since both KCB1 turning mirror mounts are internally threaded, four ERSCA Adapters must be used to connect them with cage rods. These adapters are visible in the foreground of Fig. 3.

The DM is mounted onto a DM-KM1 Kinematic Mount (available only with this kit), which in turn is mounted on four TR2 Posts and secured to the breadboard using four UPH1 Post Holders. The DM is placed on the breadboard such that it is located 75 mm after the fourth lens and so that the reflected beam makes as shallow of an angle as possible. In this case, the angle of reflection is ~35°.

The third preassembled cage section consists of two more 75 mm focal length lenses, which are once again housed using an HPT1 Translating Lens Mount (#10 in Fig. 2) and a CP02 Cage Plate (#11 in Fig. 2). Two CP02B Cage Plate Adapters, which are mounted onto TR3 Posts and secured to the breadboard using UPH2 Universal Post Holders, are placed approximately 1/3 and 2/3 of the way between the lenses to support the weight of the cage components. These lenses are used to place the DM in a plane that is conjugate with the Shack-Hartmann lenslet array, thereby enabling the AO kit software to optimize the position of the DM actuators. This section of cage components is placed on the breadboard so that the first lens is located 75 mm after the DM.

After exiting the third cage subassembly, a 92:8 pellicle beamsplitter (#12 in Fig. 2) is used to direct a small portion of the light to the last major component of the AO kit, the WFS150-5C Shack-Hartmann Wavefront Sensor (#13). The sensor is placed on a 1.6" x 1.0" Kinematic Platform Mount. The kinematic mount is threaded onto a TR3 Post (Ø1/2" x 1.5" tall) and secured to the breadboard with a UPH2 Universal Post Holder. To attenuate the amount of light entering the Shack-Hartmann wavefront sensor, NE10A and NE20A Ø1" Mounted Neutral Density Filters, which have an optical density of 1.0 and 2.0, respectively, are used. Since the sensor itself features internal C-mount threading and the ND filter is housed inside a 0.3" long SM1 (1.035"-40) lens tube, an SM1A9 C-Mount to SM1 Adapter is necessary to mate the ND filter to the front of the WFS150C.

The portion of light transmitted by the beamsplitter can be blocked by a beam block (#14) that is constructed from an SM1A7 Alignment blank that has been threaded into an LMR1 Lens Mount and onto a TR3 Post. The post can be secured to the breadboard using a UPH2 Universal Post Holder. Alternatively, the beam block can be removed and the light can be launched into an application.

Mechanics		
DM-KM1 Kinematic Mount (Sold in Kit Only)	1	
KCB1 Right-Angle Kinematic 30 mm Cage Mount	2	
CXY1 30 mm Cage-Compatible XY Translation Mount	3	
CP02 Threaded 30 mm Cage Plate	4	
CP02B Cage Plate Adapter	4	
CB1 30 mm Cage System U Bench	1	
LMR1 Lens Mount for Ø1" Optics	1	
AD11F SM1 Adapter for Ø11 mm Collimators	1	
SM1A9 C-Mount to SM1 Adapter	1	
KM100BP Pellicle Kinematic Mount	1	
Kinematic Prism Mount	1	
UPH2 2" High Universal Post Holder	10	
TR3 Ø1/2" x 3" Post	10	
ER1 Ø6 mm x 1" Cage Rod	4	
ER1.5 Ø6 mm x 1.5" Cage Rod	4	
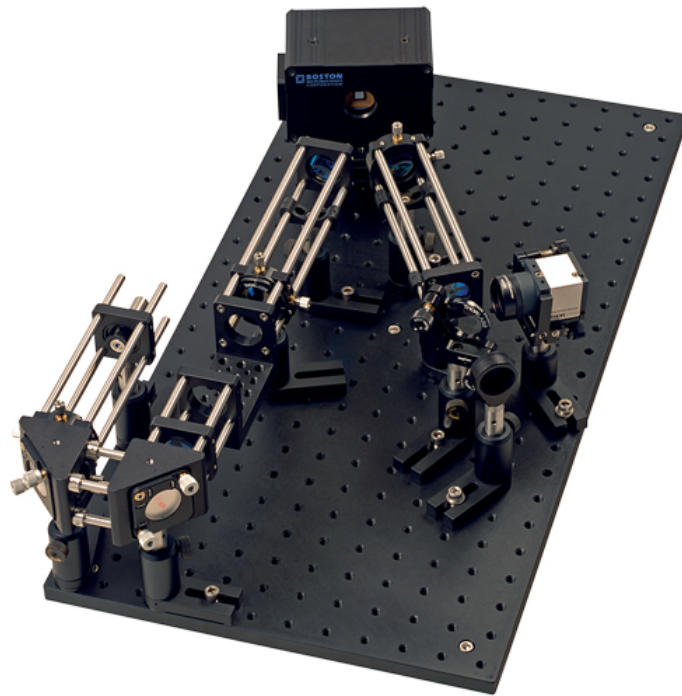
Figure 3. A photograph showing an alternative view of a preassembled Adaptive Optics Kit. Please note that a breadboard is not included with the AO Kit.

ER3 Ø6 mm x 3" Cage Rod	4	
ER6 Ø6 mm x 6" Cage Rod	12	
ERSCA ER Rod Adapter	4	
UPH1 Universal Post Holder	4	
TR2 Ø1/2" x 2" Post	4	
Alignment Tools		
CPA1 30 mm Cage System Alignment Plate	1	
SM1A7 SM1 Alignment Disk	1	

*Kits with an aluminum-coated Deformable Mirror contain the LA1608-A and BB1-E02, while kits with a gold coated mirror include the LA1608-B and BB1-E03.

A Note about the Optics Included with the Adaptive Optics Kits:
The AOKx-UM01 and AOKx-UP01 AO Kits include the exact same optical and mechanical components, with a few exceptions which are detailed in the table below.

| Components Included with Each AO Kit				
AO Kit Item #	**Wavefront Sensor**	**Deformable Mirror**	**Wavelength-Dependent Components**	
			Lenses	**Mirrors**
AOK1-UM01	WFS150-5C	Multi DM	LA1608-A	BB1-E02
AOK1-UP01	WFS150-5C	Multi DM	LA1608-B	BB1-E03
AOK2-UM01	WFS150-5C	DM32-35-UM01	LA1608-A	BB1-E02
AOK2-UP01	WFS150-5C	DM32-35-UP01	LA1608-B	BB1-E03

Introduction:

Adaptive optics (AO) is a rapidly growing multidisciplinary field encompassing physics, chemistry, electronics, and computer science. AO systems are used to correct (shape) the wavefront of a beam of light. Historically, these systems have their roots in the international astronomy and US defense communities. Astronomers realized that if they could compensate for the aberrations caused by atmospheric turbulence, they would be able to generate high resolution astronomical images; with sharper images comes an additional gain in contrast, which is also advantageous for astronomers since it means that they can detect fainter objects that would otherwise go unnoticed. While astronomers were trying to overcome the blurring effects of atmospheric turbulence, defense contractors were interested in ensuring that photons from their high-power lasers would be correctly pointed so as to destroy strategic targets. More recently, due to advancements in the sophistication and simplicity of AO components, researchers have utilized these systems to make breakthroughs in the areas of femtosecond pulse shaping, microscopy, laser communication, vision correction, and retinal imaging. Although dramatically different fields, all of these areas benefit from an AO system due to undesirable time-varying effects.

Typically, an AO system is comprised from three components: (1) a wavefront sensor, which measures these wavefront deviations, (2) a deformable mirror, which can change shape in order to modify a highly distorted optical wavefront, and (3) real-time control software, which uses the information collected by the wavefront sensor to calculate the appropriate shape that the deformable mirror should assume in order to compensate for the distorted wavefront. Together, these three components operate in a closed-loop fashion. By this, we mean that any changes caused by the AO system can also be detected by that system. In principle, this closed-loop system is fundamentally simple; it measures the phase as a function of the position of the optical wavefront under consideration, determines its aberration, computes a correction, reshapes the deformable mirror, observes the consequence of that correction, and then repeats this process over and over again as necessary if the phase aberration varies with time. Via this procedure, the AO system is able to improve optical resolution of an image by removing aberrations from the wavefront of the light being imaged.
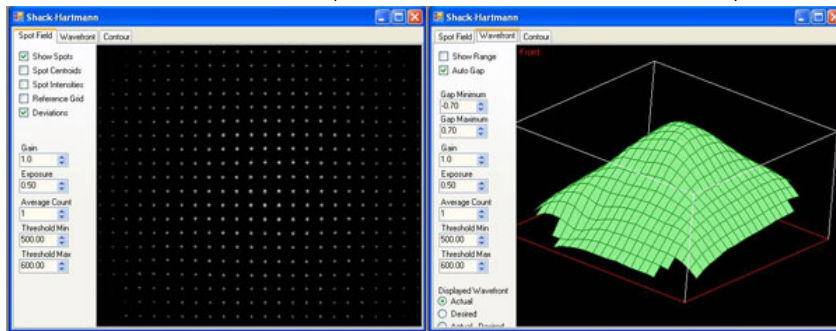
The Wavefront Sensor:

The role of the wavefront sensor in an adaptive optics system is to measure the wavefront deviations from a reference wavefront. There are three basic configurations of wavefront sensors available: Shack-Hartmann wavefront sensors, shearing interferometers, and curvature sensors. Each has its own advantages in terms of noise, accuracy, sensitivity, and ease of interfacing it with the control software and deformable mirror. Of these, the Shack-Hartmann wavefront sensor has been the most widely used.

A Shack-Hartmann wavefront sensor uses a lenslet array to divide an incoming beam into a bunch of smaller beams, each of which is imaged onto a CCD camera, which is placed at the focal plane of the lenslet array. If a uniform plane wave is incident on a Shack-Hartmann wavefront sensor (refer to Fig. 1), a focused spot is formed along the optical axis of each lenslet, yielding a regularly spaced grid of spots in the focal plane. However, if a distorted wavefront (i.e., any non-flat wavefront) is used, the focal spots will be displaced from the optical axis of each lenslet. The amount of shift of each spot's centroid is proportional to the local slope (i.e., tilt) of the wavefront at the location of that lenslet. The wavefront phase can then be reconstructed (within a constant) from the spot displacement information obtained (see Fig. 2).
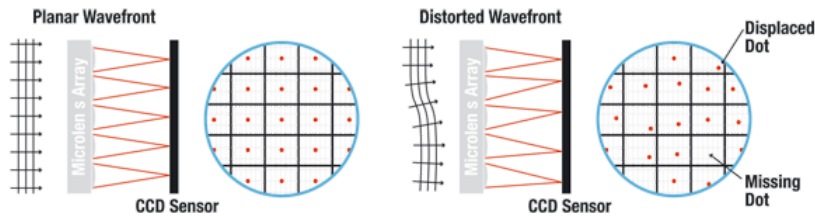
Figure 1. When a planar wavefront is incident on the Shack-Hartmann wavefront sensor's microlens array, the light imaged on the CCD sensor will display a regularly spaced grid of spots. If, however, the wavefront is aberrated, individual spots will be displaced from the optical axis of each lenslet; if the displacement is large enough, the image spot may even appear to be missing. This information is used to calculate the shape of the wavefront that was incident on the microlens array.
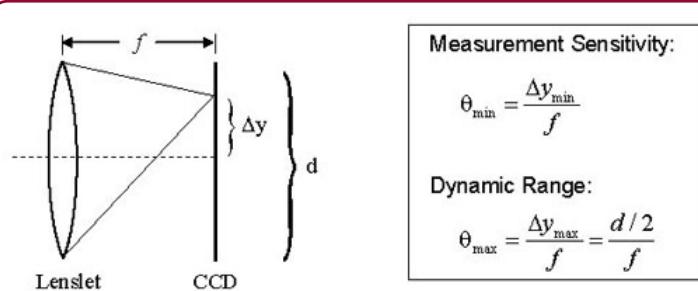

Figure 2. Two Shack-Hartmann wavefront sensor screen captures are shown: the spot field (left-hand frame) and the calculated wavefront based on that spot field information (right-hand frame).

The four parameters that greatly affect th performance of a given Shack-Hartmann wavefront sensor are the number of lenslets (or lenslet diameter, which typically ranges from $\sim 100 - 600$ μm), dynamic range, measurement sensitivity, and the focal length of the lenslet array (typical values range from a few millimeters to about 30 mm). The number of lenslets restricts the maximum number of Zernike coefficients that a reconstruction algorithm can reliably calculate; studies have found that the maximum number of coefficients that can be used to represent the original wavefront is approximately the same as the number of lenslets. When selecting the number of lenslets needed, one must take into account the amount of distortion s/he is trying to model (i.e., how many Zernike coefficients are needed to effectively represent the true wave aberration). When it comes to measurement sensitivity θ_{min} and dynamic range θ_{max}, these are competing specifications (see Fig. 3 below). The former determines the minimum phase that can be detected while the latter determines the maximum phase that can be measured.

A Shack-Hartmann sensor's measurement accuracy (i.e., the minimum wavefront slope that can be measured reliably) depends on its ability to precisely measure the displacement of a focused spot with respect to a reference position, which is located along the optical axis of the lenslet. A conventional algorithm will fail to determine the correct centroid of a spot if it partially overlaps another spot or if the focal spot of a lenslet falls outside of the area of the sensor assigned to detect it (i.e., spot crossover). Special algorithms can be implemented to overcome these problems, but they limit the dynamic range of the sensor (i.e., the maximum wavefront slope that can be measured reliably). The dynamic range of a system can be increased by using a lenslet with either a larger diameter or a shorter focal length. However, the lenslet diameter is tied to the needed number of Zernike coefficients; therefore, the only other way to increase the dynamic range is to shorten the focal length of the lenslet, but this in turn, decreases the

measurement sensitivity. Ideally, choose the longest focal length lens that meets both the dynamic range and measurement sensitivity requirements.

The Shack-Hartmann wavefront sensor is capable of providing information about the intensity profile as well as the calculated wavefront. Be careful not to confuse these. The left-hand frame of Fig. 4 shows a sample intensity profile, whereas the right-hand frame shows the corresponding wavefront profile. It is possible to obtain the same intensity profile from various wavefuncton distributions.

Measurement Sensitivity:

$$\theta_{min} = \frac{\Delta y_{min}}{f}$$

Dynamic Range:

$$\theta_{max} = \frac{\Delta y_{max}}{f} = \frac{d/2}{f}$$

Figure 3. Dynamic range and measurement sensitivity are competing properties of a Shack-Hartmann wavefront sensor. Here, f, Δy, and d represent the focal length of the lenslet, the spot displacement, and the lenslet diameter, respectively. The equations provided for the measurement sensitivity θ_{min} and the dynamic range θ_{max} are obtained using the small angle approximation. θ_{min} is the minimum wavefront slope that can be measured by the wavefront sensor. The minimum detectable spot displacement Δy_{min} depends on the pixel size of the photodetector, the accuracy of the centroid algorithm, and the signal to noise ratio of the sensor. θ_{max} is the maximum wavefront slope that can be measured by the wavefront sensor and corresponds to a spot displacement of Δy_{max}, which is equal to half of the lenslet diameter. Therefore, increasing the sensitivity will decrease the dynamic range and vice versa.
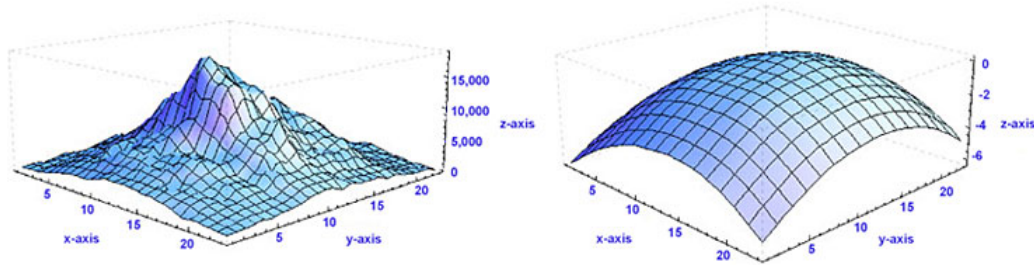
Figure 4. Several pieces of information are provided by the Shack-Hartmann wavefront sensor, including information about the total power at each lenslet and the calculated wavefront distribution present. Here, the left-hand frame shows a sample intensity profile, while the right-hand frame shows the corresponding wavefront.

The Deformable Mirror:
The deformable mirror (DM) changes shape in response to position commands in order to compensate for the aberrations measured by the Shack-Hartmann wavefront sensor (refer to the Types of Aberrations tab to learn more about the aberrations that the DM can correct). Ideally, it will assume a surface shape that is conjugate to the aberration profile (see Fig. 5). In many cases, the surface profile is controlled by an underlying array of actuators that move in and out in response to an applied voltage. Deformable mirrors come in several different varieties, but the two most popular categories are segmented and continuous (see Fig. 6). Segmented mirrors are comprised from individual flat segments that can either move up and down (if each segment is controlled by just one actuator) or have tip, tilt, and piston motion (if each segment is controlled by three actuators). These mirrors are typically used in holography and for spatial light modulators. Advantages of this configuration include the ability to manufacture the segments to tight tolerances, elimination of coupling between adjacent segments of the DM since each acts independently, and the number of degrees of freedom per segment. However, on the down side, the regularly spaced gaps between the segments act like a diffraction pattern, thereby introducing diffractive modes into the beam. In addition, segmented mirrors require more actuators than continuous mirrors to compensate for a given incoming distorted wavefront. To address the optical problems with segmented DMs, continuous faceplate DMs (such as those included in our AO Kits) were fabricated. They offer a higher fill factor (i.e., the percentage of the mirror that is actually reflective) than their segmented counterparts. However, their drawback is that the actuators are mechanically coupled. Therefore, when one actuator moves, there is some finite response along the entire surface of the mirror. The 2D shape of the surface caused by displacing one actuator is called the influence function for that actuator. Typically, adjacent actuators of a continuous DM are displaced by 10-20% of the actuation height; this percentage is known as the actuator coupling. Note that segmented DMs exhibit zero coupling but that isn't necessarily desirable.
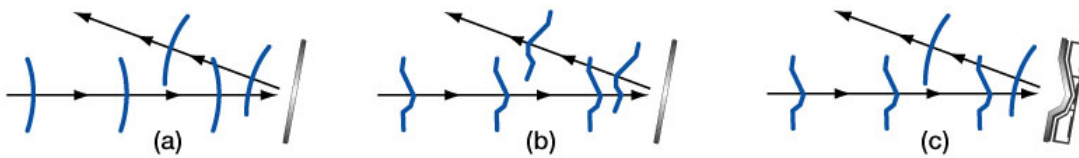
Figure 5. The aberration compensation capabilities of a flat and MEMS deformable mirror are compared. (a) If an unabberated wavefront is incident on a flat mirror surface, the reflected wavefront will remain unabberated. (b) A flat mirror is not able to compensate for any deformations in the wavefront; therefore, an incoming highly aberrated wavefront will retain its aberrations upon reflection. (c) A MEMS deformable mirror is able to modify its surface profile to compensate for aberrations; the DM assumes the appropriate conjugate shape to modify the highly aberrated incident wavefront so that it is unaberrated upon reflection.
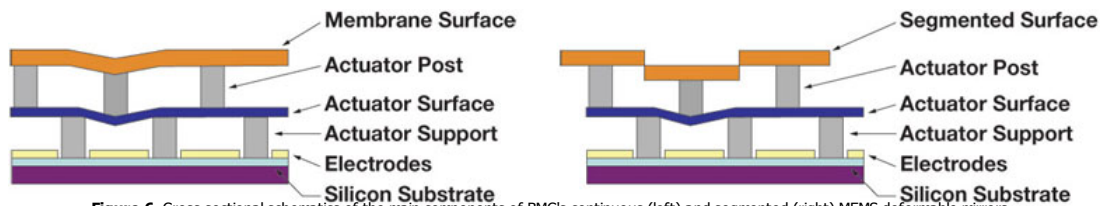
Figure 6. Cross sectional schematics of the main components of BMC's continuous (left) and segmented (right) MEMS deformable mirrors.

The range of wavefronts that can be corrected by a particular DM is limited by the actuator stroke and resolution, the number and distribution of actuators, and the model used to determine the appropriate control signals for the DM; the first two are physical limitations of the DM itself, whereas the last one is a limitation of the control software. The actuator stroke is another term for the dynamic range (i.e., the maximum displacement) of the DM actuators and is typically measured in microns. Inadequate actuator stroke leads to poor performance and can prevent the convergence of the control loop. The number of actuators determines the number of degrees of freedom that the mirror can correct for. Although many different actuator arrays have been proposed, including square, triangular, and hexagonal, most DMs are built with square actuator arrays, which are easy to position on a Cartesian coordinate system and map easily to the square detector arrays on the wavefront sensors. To fit the square array on a circular aperture, the corner actuators are sometimes removed (e.g., the deformable mirror included with the AOK1-UM01 or AOK1-UP01 has a 12 x 12 actuator configuration but only 140 actuators since the corner ones are not used). Although more actuators can be placed within a given area using some of the other configurations, the additional fabrication complexity usually does not warrant that choice.

Figure 7 (left frame) shows a screen shot of a cross formed on the 12 x 12 actuator array of the DM included with the adaptive optics kit. To create this screen shot, the voltages applied to the middle two rows and middle two columns of actuators were set to cause full deflection of the mirror membrane. In addition to the software screen shot depicting the DM surface, quasi-dark field illumination was used to obtain a photograph of the actual DM surface when programmed to these settings (see Fig. 7, right frame)

The Control Software:
In an adaptive optics setup, the control software is the vital link between the wavefront sensor and the deformable mirror. It converts the wavefront sensor's electrical signals, which are proportional to the slope of the wavefront, into compensating voltage commands that are sent to each actuator of the DM. The closed-loop bandwidth of the adaptive optics system is directly related to the speed and accuracy with which this computation is done, but in general, these calculations must occur on a shorter time scale than the aberration fluctuations.

In essence, the control software uses the spot field deviations to reconstructs the phase of the beam (in this case, using Zernike polynomials) and then sends conjugate commands to the DM. A least-squares fitting routine is applied to the calculated wavefront phase in order to determine the effective Zernike polynomial data outputted for the end user. Although not the only form possible, Zernike polynomials provide a unique and convenient way to describe the phase of a beam. These polynomials form an orthogonal basis set over a unit circle with different terms representing the amount of focus, tilt, astigmatism, comma, et cetera; the polynomials are normalized so that the maximum of each term (except the piston term) is +1, the minimum is −1, and the average over the surface is always zero. Furthermore, no two aberrations ever add up to a third, thereby leaving no doubt about the type of aberration that is present.
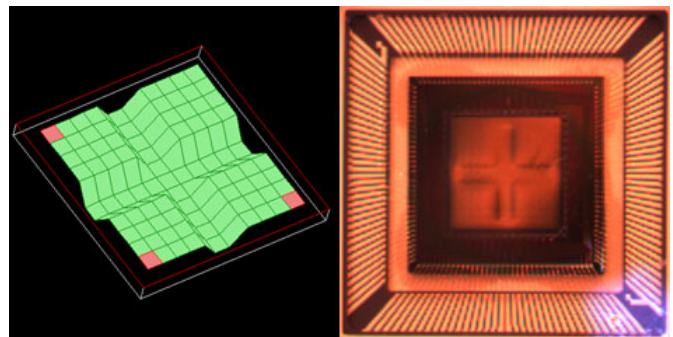
Figure 7. A cross-like pattern is created on the DM surface by applying the voltages necessary for maximum deflection of the 44 actuators that comprise the middle two rows and middle two columns of the array. The frame on the left shows a screen shot of the AO kit software depicting the DM surface, whereas the frame on the right, which was obtained through quasi-dark field illumination, shows the actual DM surface when programmed to these settings. Note that the white light source used for illumination is visible in the lower right-hand corner of the photograph.

Introduction
Off-axis scanning is frequently used in many imaging techniques including Optical Coherence Tomography (OCT), Confocal Microscopy, and Adaptive Scanning Optical Microscopy (ASOM). Without adaptive optics, images obtained using these techniques will suffer from the off-axis aberrations discussed in the Aberrations tab, thereby requiring one to choose between resolution and field of view. However, by using a deformable mirror, this tradeoff is overcome. To learn more about how a deformable mirror works and its role in an adaptive optics system, please see the AO Tutorial tab.

An Example: ASOM
As an example, consider Thorlabs' Adaptive Scanning Optical Microscope (ASOM), which is shown in Fig. 1 at the right and combines a high-speed steering mirror, large aperture scan lens, and micro-electro-mechanical (MEMS) deformable mirror to provide a large field of view (Ø40 mm) while preserving resolving power (1.5 µm over the entire field of view) and a high image acquisition rate (30 fps). As the imaged area on the sample is changed (by changing the orientation of the fast steering mirror), the deformable mirror is used to correct the off-axis aberrations introduced by the scan lens, thus maintaining the diffraction-limited 1.5 µm resolution across the extended composite field of view.

ASOM works by taking a sequence of small spatially separated images in rapid succession and then assembling them to form a large composite image. Although mosaic construction has been used in the past to expand the field of view while preserving resolution, it necessitated the use of a moving stage. In contrast, the ASOM uses a high speed 2D mirror, a specially designed scanner lens assembly, a deformable mirror, and additional imaging optics to overcome this tradeoff.

Figure 2 shows a schematic of the ASOM scanner lens assembly (SLA). Unlike a traditional microscope objective, which must image onto a flat surface, the ASOM allows for a curved image field (i.e., the natural image field shape for a lens – refer to the Field Curvature Section under the Aberrations tab), thereby greatly simplifying the optical design and number of lens elements necessary. The figure shows four different scan angle positions. The blue lines represent on-axis scanning, whereas the green, red, and yellow lines correspond to various off-axis scan angles. For each scan angle illustrated, the wavefront distortion as a function of linear displacement from the central position on the image tile of the wavefront sensor is given.
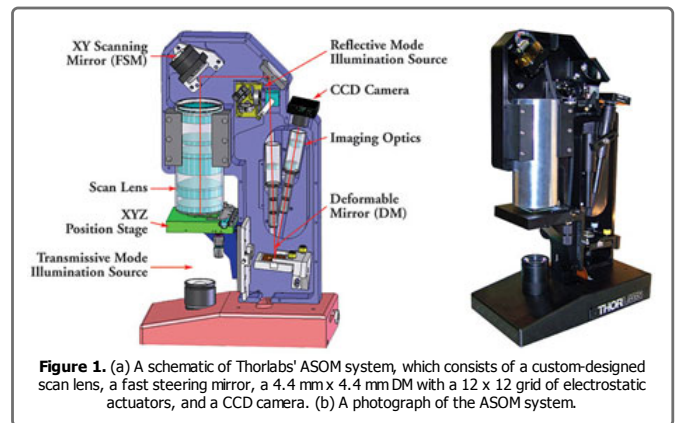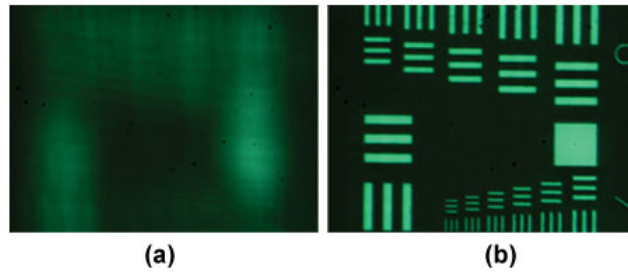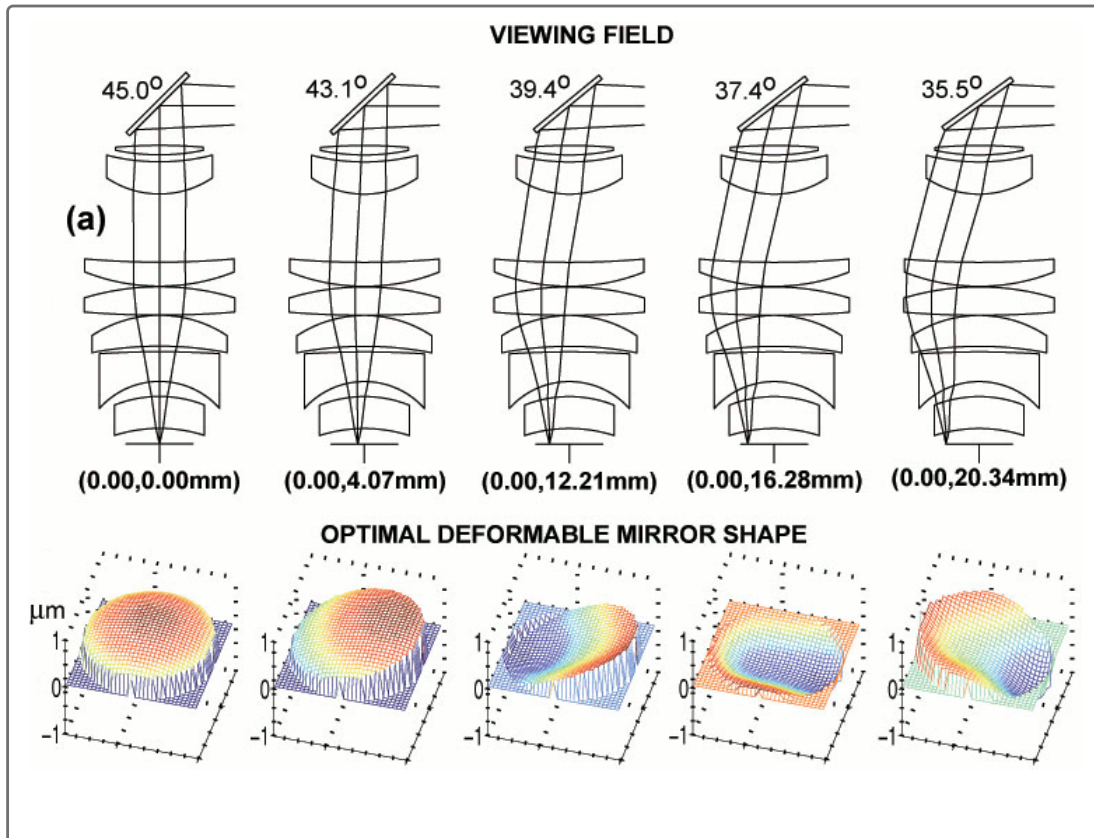

Figure 1. (a) A schematic of Thorlabs' ASOM system, which consists of a custom-designed scan lens, a fast steering mirror, a 4.4 mm x 4.4 mm DM with a 12 x 12 grid of electrostatic actuators, and a CCD camera. (b) A photograph of the ASOM system.
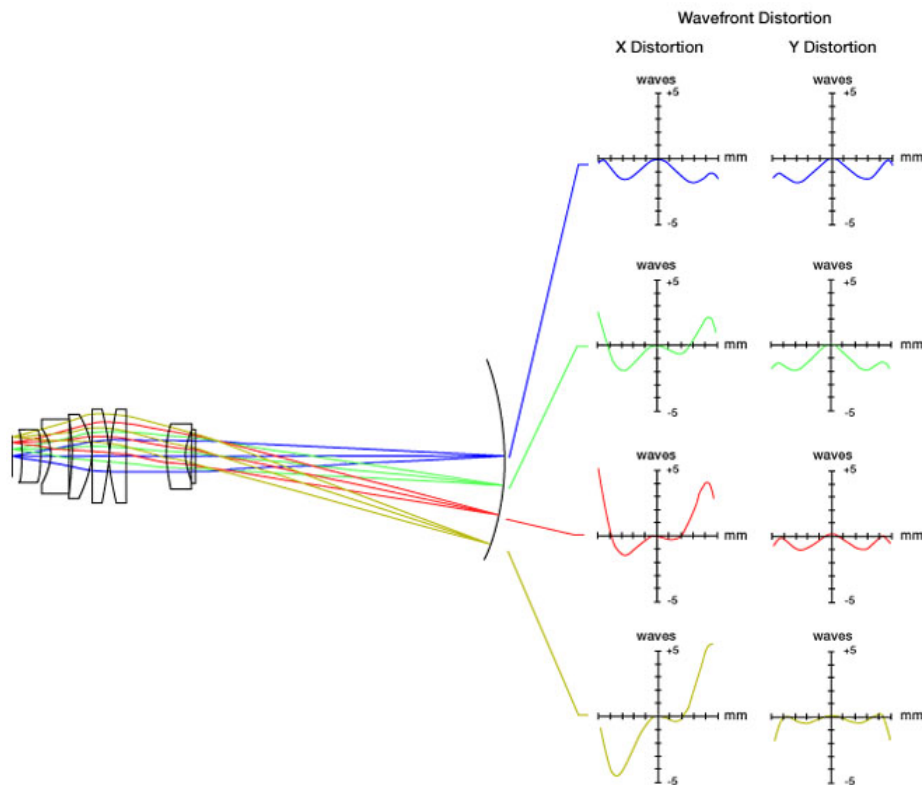
Figure 2. Adaptive Scanning Optical Microscopy (ASOM) utilizes a curved image field, thereby greatly simplifying the scanner lens assembly shown. The blue, green, red, and yellow rays represent various off-axis scan angles (0˚, 2˚, 4˚, and 6˚, respectively). For each angle, the corresponding wavefront distortion is shown. The graphs show the distortion (in waves) as a function of position on the wavefront sensor tile. Regardless of scan angle, notice that no waves of distortion are present at the exact center of each image tile. Please note that for this figure, the term "distortion" is meant to encompass all types of aberrations.

Although the large aperture scan lens and overall system layout are specifically designed to deal with field curvature, all other off-axis aberrations, such as coma and astigmatism (see the Aberrations tab for a detailed discussion), are still present in the ASOM system. These aberrations are compensated for at each individual field position throughout the scanner's range by a deformable mirror. Figure 3 shows the optimal DM shape for a given angular position of the high speed steering mirror.

VIEWING FIELD

45.0°	43.1°	39.4°	37.4°	35.5°

(a)

(0.00,0.00mm)	(0.00,4.07mm)	(0.00,12.21mm)	(0.00,16.28mm)	(0.00,20.34mm)

OPTIMAL DEFORMABLE MIRROR SHAPE

Figure 4. Air force target imaged using (a) a flat mirror (b) an optimized deformable mirror. The smallest lines are separated by 2 μm.

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