Fundamentals of Adaptive Optics

Lab session – Thales Course

Part 1 – Introduction

Adaptive optics (AO) is a technology used to improve the performance of optical systems by reducing the effects of rapidly changing optical distortion. It is used in astronomical telescopes and laser communication systems to remove the effects of atmospheric distortion, and in retinal imaging systems to reduce the impact of ocular aberrations. Adaptive optics works by measuring the distortions in a wavefront and compensating for them in real time with a spatial phase modulator such as a deformable mirror. AO was first envisioned by Horace W. Babcock in 1953, but did not come into common usage until advances in computer technology during the 1990's made the technique practical.

When light from a star or another astronomical object enters the Earth's atmosphere, turbulence (introduced, for example, by different temperature layers and different wind speeds interacting) distort and move the image in various ways. Images produced by any telescope larger than a about 30 centimeters are blurred by these distortions. For example, an 8-10 m telescope (like the VLT or Keck) can produce AO-corrected images with an angular resolution of 30-60 milli-arcsecond resolution at infrared wavelengths, while the resolution without correction is of the order of 1 arcsecond (see Fig. 1).

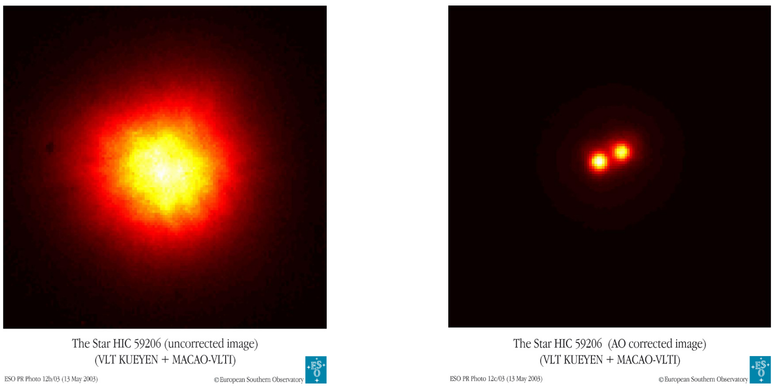

Figure 1: Effect of adaptive optics correction on the double star HIC 59206 observed by the VLT – source : wikimedia commons.

1.1 Calculate the ideal resolution (diffraction limited) at $\lambda = 500$ nm for an 8-m diameter telescope. For practical purposes, on good astronomical sites, the Fried parameter r_0 is about 20 cm. Remind what the Fried parameter is and calculate the corresponding resolution in microradians and in arcseconds. By how many is divided the resolution considering the perturbations of the atmosphere?

In order to perform adaptive optics correction, the shape of the incoming wavefronts must be measured as a function of position in the telescope aperture plane. Typically the circular telescope aperture is split up into an array of pixels in a wavefront sensor, either using an array of small lenslets (a Shack–Hartmann wavefront sensor), or using a curvature or pyramid sensor which operates on images of the telescope aperture. The mean wavefront perturbation in each pixel is calculated. This pixelated map of the wavefronts is fed into the deformable mirror and used to correct the wavefront errors introduced by the atmosphere. It is not necessary for the shape or size of the astronomical object to be known – even Solar System objects which are not point-like can be used in a Shack–Hartmann wavefront sensor, and time-varying structure on the surface of the Sun is commonly used for adaptive optics at solar telescopes. The deformable mirror corrects incoming light so that the images appear sharp.

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.

Part 2 – Equipment

The Thorlabs AO Kit includes:

- Laser Diode Module (635 nm)
- Shack-Hartmann Wavefront Sensor WFS20 from Thorlabs
- Continuous Surface Deformable Mirror from Boston Micromachines (BMC) DM140
- All Imaging Optics and Associated Mounting Hardware
- Fully Functional Stand-Alone Control Software for Windows AOKit from Thorlabs

Shack-Hartman Wavefront sensor (WFS)

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. 2), 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

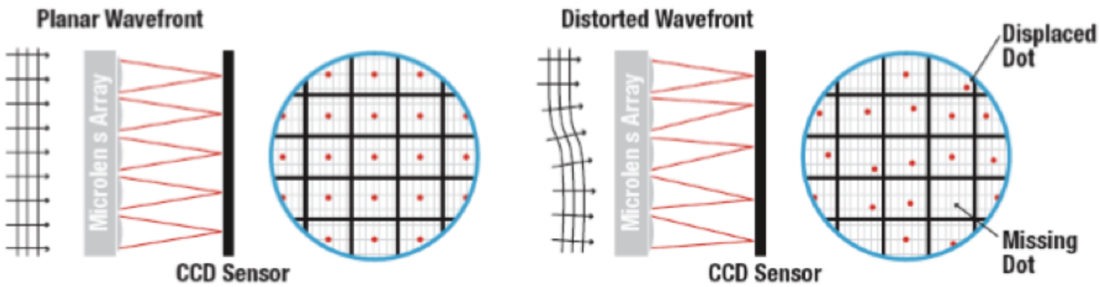

Figure 2: When a planar wavefront is incident on the Shack-Hartmann wavefront sensor's microlens array, the light imaged on the CCD sensor will display a regularly spaced grid of spots. If, however, the wavefront is aberrated, individual spots will be displaced from the optical axis of each lenslet; 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.

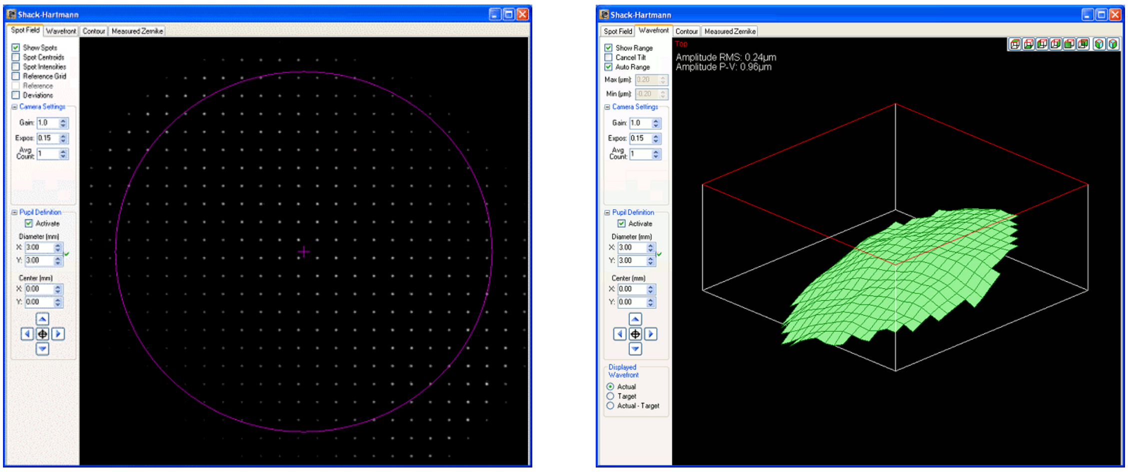

Figure 3: Two Shack-Hartmann wavefront sensor screen captures are shown: the spot field (left-hand frame) and the calculated wavefront based on that spot field information (right-hand frame).

wavefront phase can then be reconstructed (within a constant) from the spot displacement information obtained (see Fig. 3).

The four parameters that greatly affect the performance of a given Shack-Hartmann wavefront sensor are the number of lenslets (or lenslet diameter, which typically ranges from $\sim 100-600\ \mu$m), 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 they are 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. 4 to the right). The former determines the minimum phase that can be detected while the latter

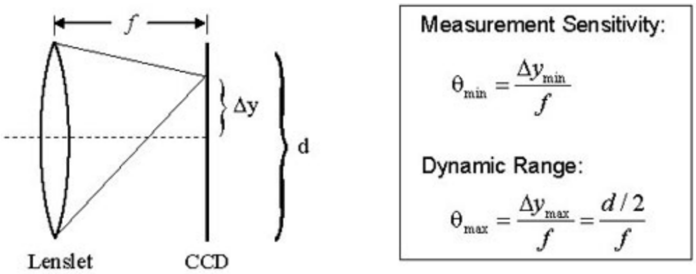

Figure 4: Dynamic range and measurement sensitivity are competing properties of a Shack-Hartmann wavefront sensor. Here, f, Δy, and d represent the focal length of the lenslet, the spot displacement, and the lenslet diameter, respectively. The equations provided for the measurement sensitivity θ_{min} 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.

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 ofthe 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.

This setup is equipped with a WFS20 wavefront sensor (see Fig. 5):

- CMOS-Based Sensor 7.20 mm × 5.40 mm (1440×1080 5-μm square pixels)
- 47×35 Lenslet array
- Sensitivity up to $\lambda/200$
- Large-Aperture Sensor with 11.26 mm Square Area
- Wavelength Range: 300 – 1100 nm
- Real-Time Wavefront and Intensity Distribution Measurements
- Nearly Diffraction-Limited Spot Size
- For CW and Pulsed Light Sources
- USB Connection for PC Operation
- Flexible Data Export Options (Text or Excel)
- Live Data Readout via TCP/IP

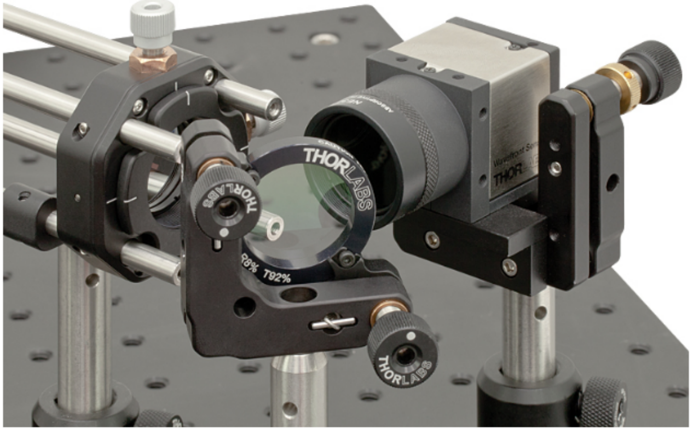

Figure 5: Thorlabs AO kit WFS20 CMOS-Based Sensor 7.20 mm × 5.40 mm.

Deformable mirror (DM)

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. Ideally, it will assume a surface shape that is conjugate to the aberration profile (see Fig. 6). 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. 7). 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, the 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 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.

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

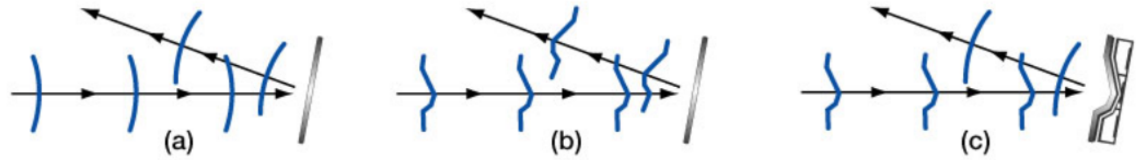

Figure 6: The aberration compensation capabilities of a flat and MEMS deformable mirror are compared. (a) If an unabberated wavefront is incident on a flat mirror surface, the reflected wavefront will remain unabberated. (b) A flat mirror is not able to compensate for any deformations in the wavefront; 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.

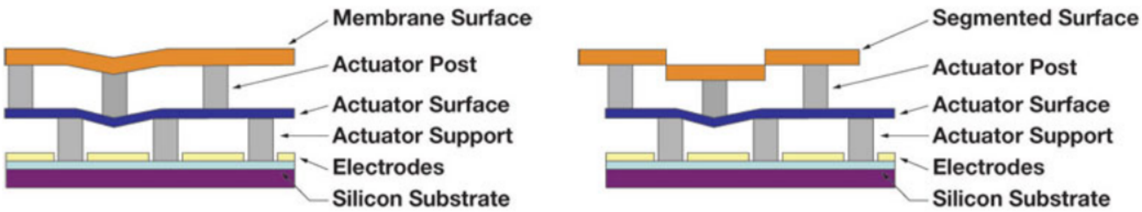

Figure 7: Cross sectional schematics of the main components of BMC's continuous (left) and segmented (right) MEMS deformable mirrors.

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 (here, the DM has a 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. Fig. 8 (left frame) shows a screen shot of a cross formed on the 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. 8, right frame).

To facilitate installation and setup, each package includes the deformable mirror, driver, and control software. These mirrors are capable of changing shape in order to correct a highly distorted incident wavefront. Micro-electro-mechanical (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 that they afford. These versatile DMs, which are fabricated using polysilicon surface micromachining fabrication methods, offer sophisticated aberration compensation in easy-

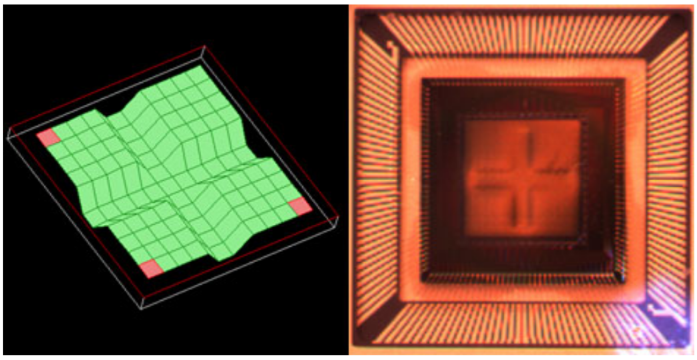

Figure 8: A cross-like pattern is created on the DM surface by applying the voltages necessary for maximum deflection of the 44 actuators that comprise the middle two rows and middle two columns of the array. The frame on the left shows a screen shot of the AO kit software depicting the DM surface, whereas 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.

Figure 9: BMC MEMS Multi-DM with its drivers electronics.

to-use packages. The mirror consists of a membrane that is deformed by 140 electrostatic actuators (i.e., a 12 actuator array with four inactive corner actuators), each of which can be individually controlled. These actuators provide 3.5 μm stroke over a compact area. Unlike piezoelectric deformable mirrors, the electrostatic actuation used with BMC's mirrors ensures deformation without hysteresis.

Boston MEMS multi-DM features (see Fig. 9) :

- Multi-DM: 12 Actuator Array (140 Active), size 4.4×4.4 mm^2
- 3.5 μm Maximum Actuator Displacement
- Zero Hysteresis
- Sub-Nanometer Repeatability (Average Step Size < 1 nm)
- Low Inter-Actuator Coupling of $\sim$ 13% Results in High Spatial Resolution
- Gold-Coated
- Protective Window with 6° Wedge and Broadband Antireflection Coating for 400 – 1100 nm
- Set of drivers electronics.

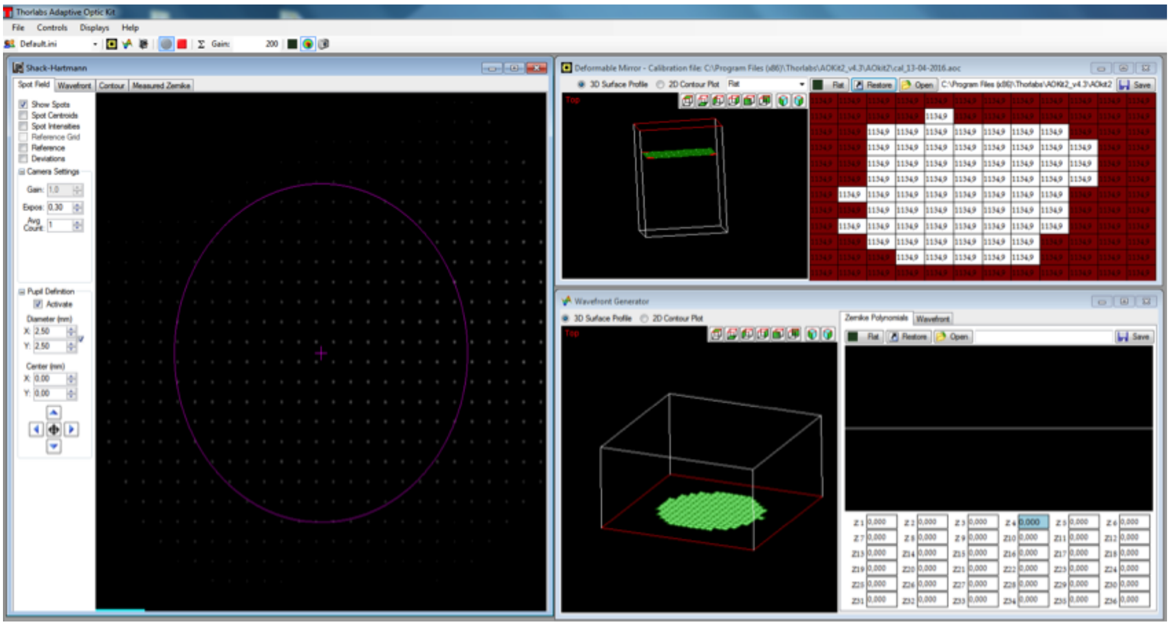

Figure 10: Control Software AOKit.

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, etc. 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.

Part 3 – Optical alignments

Your main goal for this lab is to get familiar with the 3 main elements of an AO system: the wavefront sensor, the deformable and the real time control system. The AO kit has been assembled and tested prior to the lab. It is in fully functioning order.

The first two preassembled cage sections of the AO kit consist of the laser diode source, four 75 mm focal length lenses, two turning mirrors, and a U-shaped bench. The 635 nm Laser Diode Module (labeled as 1 in Fig. 2), which outputs ~ 0.3 mW of light at

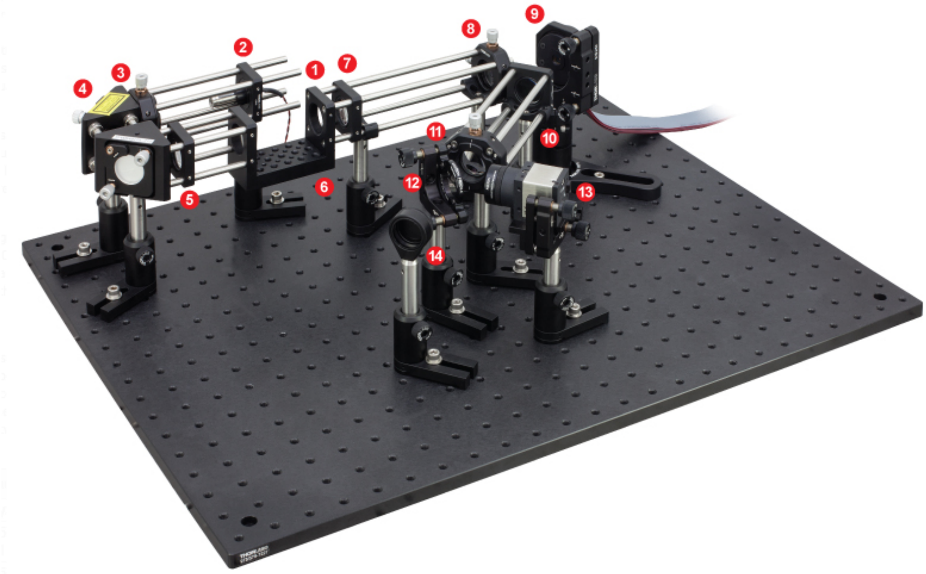

Figure 11: Schematic showing the major components included within the AO Kit.

635 nm, is housed inside a CP02 Cage Plate (2 in Fig. 2). Light exiting the module is directed to two KCB1 Right-Angle Cage-Compatible Kinematic Mounts (the first of which is labeled as 4 in Fig. 2), which house PF10-03-M01 Gold-Coated Mirrors; these mirrors offer an average reflectance of > 96% from 800 nm to 20 μm.

The AO kit uses two LA1608-B 75 mm focal length lenses (the first of which is housed in the CXY1 Translating Lens Mount labeled as 3 in Fig. 2 and the second of which is housed in the CP02 Cage Plate labeled as 5 in Fig. 2) that are used to image a beam waist at the center of the CB1 30 mm Cage System U-Bench (labeled as 6 in Fig. 2 to the right). A sample can be placed in this image plane. Then, two more LA1608-B lenses (one is housed in the CXY1 mount labeled as 8 in Fig. 2 and the other in the CP02 mount labeled as 7 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.

The DM reflects the beam through a shallow angle of $\sim 35°$ into the third preassembled cage section. This section contains two more 75 mm focal length lenses, which are once again housed using a CP02 Cage Plate (10 in Fig. 2) and a CXY1 Translating Lens Mount (11 in Fig. 2). 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.

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 WFS (13). The portion of light transmitted by the beamsplitter is focused by an achromatic lens (14) and imaged on a small CMOS camera DCC1545M (1280×1024 pixels) via a $\times 10$ microscope objective in order to characterize the Point Spread Function of the system.

3.1 Switch on the laser diode power supply. Check the alignment and the lenses positions to ensure the quality of the beam: it must be collimated after L2. L3 should be placed at ~ 141 mm from L2; check beam aligment. L4 should produce a collimated beam. The DM should be placed at ~ 73 mm from L4 and centered on the collimated beam.

3.2 L5 and L6 should be aligned at a 35° angle from the direction of L3 and L4, given that L5 should be placed at a distance of ~ 67 mm from the DM. The beam should be centered and collimated after L6.

3.3 The WFS must be placed at ~ 75 mm from L6, taking into account the pellicle beam-splitter to insure pupil conjugation. Explain why pupil conjugation is crucial in a AO setup. Otherwise, what happens if we apply an important tilt on the deformable mirror? Make a scheme to answer clearly to this question. Measure DM and L5, calculate the position of the image of the mirror by L5 and L6. Make sure that the WFS is at the right distance from L6.

3.4 Adjust the tilt of the WFS. Eventually, the sofware should display a wavefront with a peak to valley (PV) smaller then 1 μm. Check the centering of the WFS.

3.5 Start the Thorcam software and adjust the position of the microscope objective and the CMOS camera (the exposure time should be pretty small) to see the PSF in the best focus plane.

3.6 When zero voltage is applied on each actuator, the wavefront distortion measured by the wavefront sensor is related to the mirror shape and the setup in general. We can see the effect of the wavefront distortion on the PSF. According to the WFS, what is the main wavefront distortion in the setup? Is it obvious on the PSF? Would it be a problem on a real AO setup once the loop is closed?

3.7 What is the largest coefficient in the Zernike polynomials decomposition? Is it coherent with the shape of the wavefront and the PSF?

Part 4 – Study of the Deformable Mirror

The DM window is setup to have an edit box corresponding to an actuator and can be used to manually change the surface of the mirror. This is done by editing the individual actuators and assigning a value to each of them (from 0 to 3649.5). A profile of the resulting surface can be seen in the graph to the left of the edit box array.

4.1 Click on an actuator to modify the assigned voltage. Observe simultaneously the PSF spot, the WFS signal and the measured wavefront and suggest an explanation for your observations.

4.2 Check, for some values, the linearity of the wavefront distortion according to the actuator input.

4.3 What is the largest wavefront distortion caused by the actuator, you can measure with the wavefront sensor? Explain where this limitation comes from.

4.4 Modify the shape of the mirror using several actuators while observing simultaneously the wavefront sensor camera, the measured wavefront and the image spot. Does the response seem to be linear according to a linear combination of the tensions of the actuators? Is it important in a closed loop system?

Part 5 – Construction of the interaction matrix

What voltages should be applied to the mirror in order to compensate the displacements of the image spots of the lenslets caused by a wavefront distortion? We first answer the inverse question : we apply known values on each actuator and we calculate and memorize in the interaction matrix the displacements of the image spots of the Shack-Hartmann camera. The construction of the interaction matrix is made by clicking on the gearing icon. The software drives each actuator one by one, by pushing it then by pulling it (Push/Pull experiment).

5.1 Comment the form and the relative amplitude of theses deformations.

Part 6 – Working in closed loop

The loop is closed by clicking on the Σ icon. The assignment is a flat wavefront unless specified otherwise.

6.1 Start the closed loop and observe simultaneously the improvement of the PSF and the wavefront residual error. Inst

6.2 Discuss the role of the gain in terms of stability.

6.3 Try using the loop with different calibration files. What happens if you change the values of the start stroke and end stroke offsets?

The wavefront generator provide an easy means of setting a user-defined reference wavefront. It offers two means to achieve this. The first is to allow the user the ability to define a Zernike based reference wavefront and the second is to allow the user to capture a given wavefront at the WFS. The control system will attempt to adjust the DM surface to match the shape created by the wavefront generator.

6.4 Observe the effect of Zernike aberrations on the PSF and the wavefront.

6.5 The system can now be used in applications. A sample can be placed midway between L2 and L3. Try compensating for two lenses with respective focus lengths +500 mm and −500 mm. Comment the results

6.6 Calculate the focus lengths with a wavefront measurement.

6.7 Try compensating for the aberrations introduced by a low quality glass plate.

6.8 Move the glass plate around the position and discuss the stability of the loop.