High contrast imaging lab

Ay122a, November 2016, D. Mawet

Introduction
This lab is an introduction to high contrast imaging, and in particular coronagraphy and its interaction with adaptive optics systems. Coronagraphy is a method to filter out on-axis starlight from the optical system and let off-axis signal from, e.g. exoplanets or circumstellar disks, go through.

The vortex coronagraph is a transparent phase-based coronagraph which imprints an $e^{i\theta}$ phase ramp (or screw dislocation) on the point spread function (PSF) of the telescope+instrument. $l$ is called the topological charge of the vortex, and quantifies the number of times the phase goes through $2\pi$ radians. For the vortex to be an efficient coronagraph, the topological charge has to be a non-zero even integer (conditions for zeroing out the Hankel transform of order $l$ of the PSF of a perfectly unobscured aperture, inside the geometric pupil area).

The layout of a classical coronagraph is shown here below, and is representative of the testbed configuration.

Figure 1: typical layout for classical coronagraphs, here the vortex coronagraph. The main ingredients are the relay optics L1, L2, L3, the focal plane mask FP1, and the Lyot stop in the pupil plane PP2.

You will get to experiment with vortex coronography hands on by performing a series of measurements described below.

Experiment 1: measure the starlight attenuation of the vortex
In this experiment you will measure the starlight attenuation of the vortex coronagraph of charge 4 currently on the bench. For that, you will measure the peak
flux of the off-axis (off coronagraph) PSF, using neutral density filters provided and you will have calibrated a priori. The use of ND filters is necessary to prevent the saturation of the camera, and allow you the full dynamic range provided by the coronagraph.

Note your observations when centering the coronagraph on the PSF, in particular the sensitivity of the starlight attenuation factor to pointing errors. Note also the influence of the size of the opening of the Lyot stop diaphragm.

**Experiment 2: measure the off-axis response and inner working angles for charge 2, 4, 8 vortices**

The inner working angle is arbitrarily defined as the 50% off-axis throughput angle, and can be easily found after tracing the peak PSF throughput as a function of separation in $\lambda/D$ units. The $\lambda/D$, or full width at half maximum (FWHM) of the PSF can be approximately measured (in pixels) by taking an image of the off-axis PSF far from the vortex center.

![Theoretical off-axis throughput curves for charge 4, 6, and 8 vortex coronagraphs.](image)

The off-axis throughput curve should be traced with sufficient sampling (e.g. 0.2 $\lambda/D$ steps). Trace the curve for all topological charges available, note the differences between them, and derive conclusions regarding potential applications of various topological charges. What is the sensitivity to pointing/centering errors of various charges?

Based on your measurements, elaborate on the fundamental trade-off of coronagraphy (IWA vs sensitivity to pointing errors).
Experiment 3: tune the adaptive optics system to maximize coronagraph performance

After calibrating the AO system using the calibration procedure described in previous classes on adaptive optics (alignment of Shack-Hartman wavefront sensor, interaction matrix, etc.) use the Thorlabs Zernike coefficient tuning tool to maximize the starlight rejection of the coronagraph. See notes below for more details about the equipment.

Explain why the tuning is necessary to reach maximum efficiency. Why does the AO system not provide the adequate correction?

Note: For each step in the measurements, describe the state of the system, your actions (hardware and software), and the result of your actions.
**Equipment**

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

**Shack-Hartman 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.

![Figure 3](image)

*Figure 3: 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.*

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 Figure 3), 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 Figure 4).
Figure 4: 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 the performance of a given Shack-Hartmann wavefront sensor are the number of lenslets (or lenslet diameter, which typically ranges from ~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 $\theta_{\text{min}}$ and dynamic range $\theta_{\text{max}}$, these are competing specifications (see Figure 5 to the right). 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.
Figure 5: Dynamic range and measurement sensitivity are competing properties of a Shack-Hartmann wavefront sensor. Here, \(f\), \(\Delta y\), and \(d\) represent the focal length of the lenslet, the spot displacement, and the lenslet diameter, respectively. The equations provided for the measurement sensitivity \(\theta_{\text{min}}\) and the dynamic range \(\theta_{\text{max}}\) are obtained using the small angle approximation. \(\theta_{\text{min}}\) is the minimum wavefront slope that can be measured by the wavefront sensor. The minimum detectable spot displacement \(\Delta y_{\text{min}}\) depends on the pixel size of the photodetector, the accuracy of the centroid algorithm, and the signal to noise ratio of the sensor. \(\theta_{\text{max}}\) is the maximum wavefront slope that can be measured by the wavefront sensor and corresponds to a spot displacement of \(\Delta y_{\text{max}}\), which is equal to half of the lenslet diameter. Therefore, increasing the sensitivity will decrease the dynamic range and vice versa.

**15 Hz CCD Sensor**

Our Thorlabs AO kit is equipped with a WFS150-5C 1.3 Megapixel wavefront sensor has a wavefront sensitivity of up to \(\lambda/50\) RMS thanks to the high 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 Adaptive Optics Kits (see Figure 6).

- CCD-Based or High-Speed CMOS-Based Wavefront Sensors Available
- 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
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 Figure 7). 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 Figure 8). 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 (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 7: The aberration compensation capabilities of a flat and MEMS deformable mirror are compared. (a) If an unaberrated wavefront is incident on a flat mirror surface, the reflected wavefront will remain unaberrated. (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.

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

Figure 9 (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 Figure 9, right frame).
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.

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-to-use packages. The mirror consists of a membrane that is deformed by 140 electrostatic actuators (i.e., a 12 x 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 (Figure 10):
- Multi-DM: 12 x 12 Actuator Array (140 Active)
- 3.5 μm Maximum Actuator Displacement
- Zero Hysteresis
- Sub-Nanometer Repeatability (Average Step Size <1 nm)
- Low Inter-Actuator Coupling of ~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: BMC MEMS Multi-DM with its drivers electronics.

The RTC & 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, coma, etcetera; 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.