Getting Started with AOS Hardware

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One of the most common set of inquiries we get is about how to setup the equipment and what tests should be done to make sure it's working. In this application note, we present some of the most basic tests that can be done to make sure the equipment is working and some of the common optical configurations that are used when setting up an optical metrology experiment, a beam shaping experiment, or an adaptive optics (AO) system. We will focus this note on a membrane deformable mirror and a Hartmann sensor, but many of the same tests can be run with a plate deformable mirror.

Verifying Functionality of a Deformable Mirror

When a customer first gets a deformable mirror (DM), they commonly want to make sure that it is working. The first step is to remove the equipment from the box and make sure that nothing was damaged during shipping. The software should be installed next. The details of how the software should be installed and when the AOS drive electronics should be connected to the computer is described in the manual.

Once the software is installed and the electronics are connected to the computer, the deformable mirror functionality can be verified. There are a variety of optical configurations that can be used for this testing, but we recommend illuminating the deformable mirror with a collimated beam no smaller than 80% of the diameter of the deformable mirror aperture. This is most commonly achieved by expanding a visible laser beam to the appropriate diameter with a pair of plano-convex lenses. The beam leaving the beam expansion telescope can be collimated using a shear plate (aka a shearing interferometer) or simply by verifying that the beam is the same size over a long propagation path. Try to use the deformable as close to normal incidence as possible to maximize the illuminated area of the deformable mirror. A circular beam used off of normal incidence becomes elliptical on the deformable mirror and can clip the beam edge and reduce the
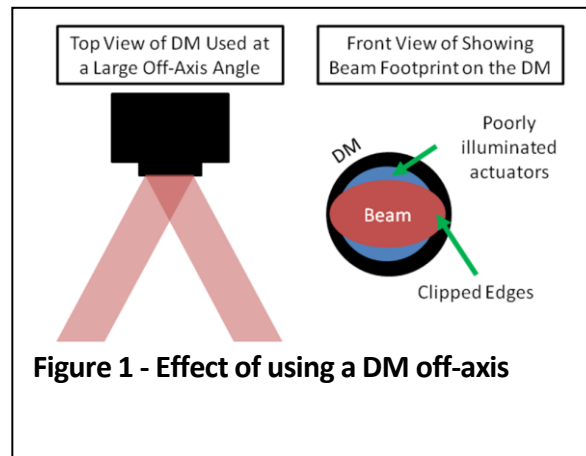
Figure 1 - Effect of using a DM off-axis

number of effectively illuminated actuators.

A quick functionality test can be easily setup by reflecting the large beam from the DM and allowing it to propagate a distance as long as possible to a wall or a small screen. If the DM is then activated, the projected intensity pattern should change. Figure 2 shows two different ways of setting up this test.
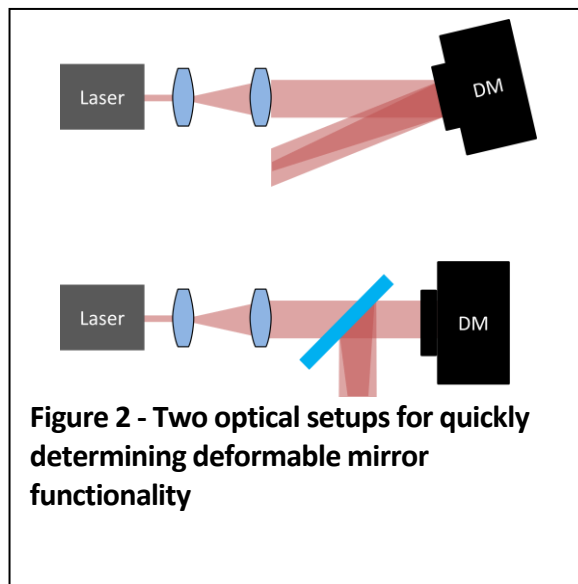
Figure 2 - Two optical setups for quickly determining deformable mirror functionality

The degree of the change will be proportional to both the amplitude of the signal applied to the DM and the distance of propagation. If all the actuators are activated and the mirror surface is not activated, the DM will be pulled into a parabolic shape over the activated area approximating a focus term. The effective focal length, f, can be calculated by

$$f = \frac{r^2}{4s}$$

where r is the radius of the mirror and s is the total peak-to-valley amplitude of the mirror displacement, which is often referred to as the sagittus. For example, a 1" diameter mirror pulled into a parabolic term with a 5 micron sagittus will focus at a distance of 7.8 meters.

To see a 10% change in the size of the beam, under this deflection, the beam needs to be propagated about 0.78 meters.

Often times it is easier to see the effect on a screen if the spot is moving. The AOS software has the ability to dynamically change the applied voltage under the "Dynamics" tab.

This test shows that the deformable mirror is functioning, but provides little insight into the magnitude of the aberration. Next we will show how to setup and test a Hartmann wavefront sensor to help with further characterization.

Hartmann Sensor Setup and Testing

Figure 3 shows two setups that are minor modifications to the setup shown in Figure 2 that enable the rapid testing of a Hartmann wavefront sensor (WFS). With this setup, we recommend starting by illuminating the WFS with a collimated beam and creating a new reference. Subsequent frames taken with the AOS wavefront sensor software will be a differential measurement relative to the
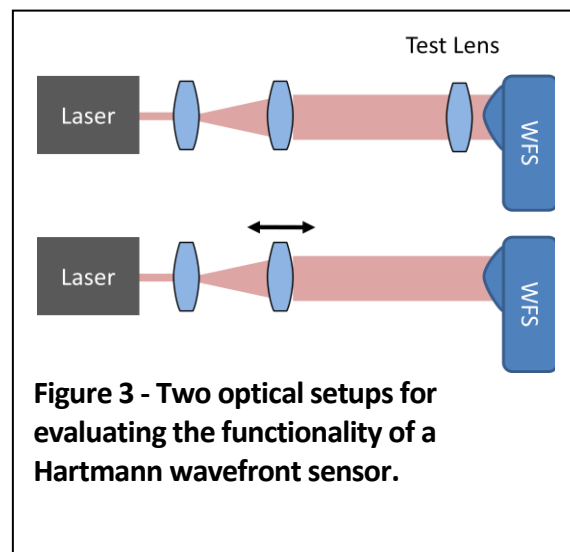

Figure 3 - Two optical setups for evaluating the functionality of a Hartmann wavefront sensor.

collimated beam. After creating the reference, the wavefront curvature can be modified by moving the second lens in the telescope, ideally on a translation stage for accuracy, or by adding a test lens into the beam. The Hartmann wavefront sensor will report the differential curvature induced by either of these changes. In either of these tests, it is important to know that the curvature induced on the beam will change with propagation. For example, if a 300-mm focal length lens is placed into a beam 50-mm before the Hartmann array, the expected wavefront curvature is 250 mm.

Beam Shaping Optical Setups

Figure 4 shows two commonly-used optical configurations derived from those shown in Figure 2 and Figure 3 that are commonly used for beam shaping applications in the laboratory. In both cases, light from the laser is expanded to better fill the deformable mirror. In one case, the beam splitter is before the telescope and in the other case it is after the beam splitter. In using either of these setups it is important that the light not be reflected back into the laser. The sampled light reflected from the mirror is then sent

Figure 4 - Two different optical configurations that are commonly used for beam shaping experiments
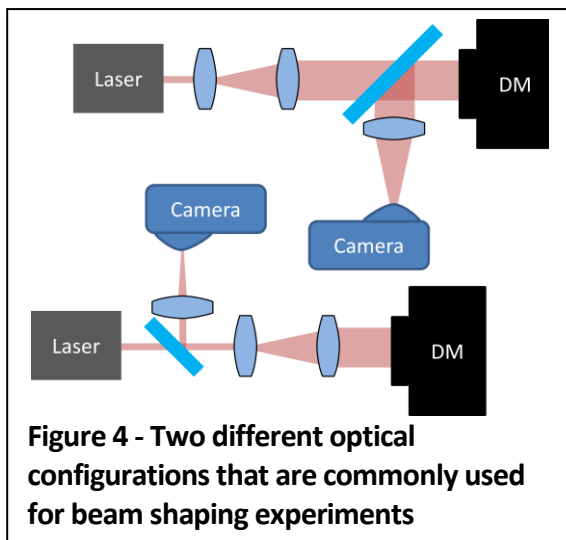
through a lens and into a camera to provide feedback on the shape of the intensity profile.

AOS has a beam shaping software module built into their Adaptive Optics software that allows a user to specify a desired beam shape and then search through actuator commands to change the shape of the beam.

The optical configurations in Figure 4 are good for laboratory demonstrations, but they send the majority of the light into the feedback camera instead of to a target. In industrial beam shaping for applications like laser machining would only take a sample of the beam for the camera and would send the majority of the light to the target, as is shown in Figure 5.

Figure 5 - Example optical setup for industrial beam shaping applications
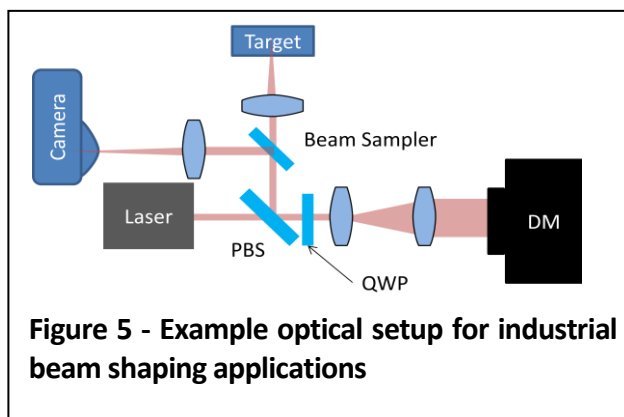
Unless the beam shaping system is responsible for compensating aberrations of the laser in addition to shaping the beam, the conjugate or image planes of the beam expansion telescope are not critical. If they are important, read the section on imaging telescope that follows.

Optical Configurations for Aberration Compensation Systems

The optical setup used for aberration compensation or adaptive optics is more difficult to setup than those we have presented earlier because it requires the user to pay more attention to the image planes of the telescopes. A section on how to design a two-lens telescope for properly imaging for adaptive optics applications is presented later in this document. Figure 7 shows two different optical configurations that are commonly used for laboratory adaptive optics. The first configuration uses polarization multiplexing by changing the laser polarization from linear to circular aft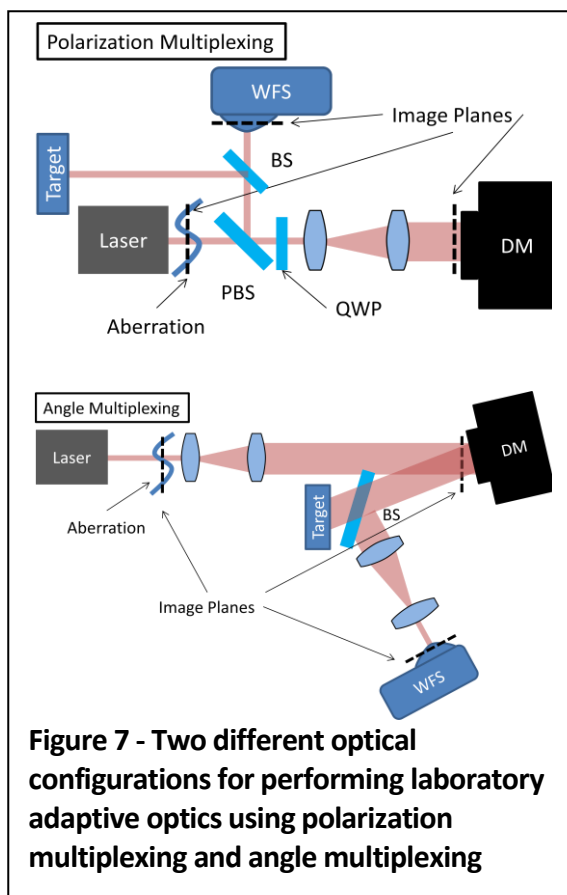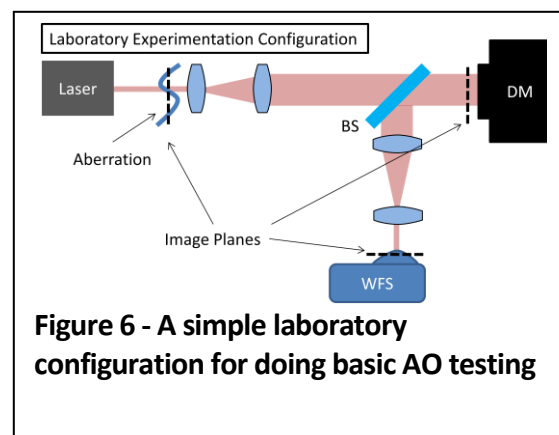er transmitting once through a quarter-wave plate (QWP) and then back to linear but at the orthogonal polarization to the input beam after a second transmission through the QWP. This configuration uses a single telescope as well to reimage the aberration to the DM and the DM plane to the wavefront sensor. In many situations, this configuration is not practical because the distance from the image plane to the first lens of the telescope is too short and the magnification needed for the two legs of the imaging is not the same.

The second configuration in Figure 7 uses angle multiplexing instead of polarization multiplexing. This setup has more optical components, but is generally easier to setup and much more flexible.

Our recommended setup for simple laboratory experiments, shown in Figure 6, is a variation on the angle multiplexing configuration that is not realistic for practical applications because it does not send the corrected light to a target, but it is often useful in laboratory testing because of its ease of setup and alignment. In this setup, the DM is used at normal incidence thereby avoiding the beam projection and field-of-view concerns presented earlier. Light reflected from the DM is sent both back toward the laser and

Figure 7 - Two different optical configurations for performing laboratory adaptive optics using polarization multiplexing and angle multiplexing

Figure 6 - A simple laboratory configuration for doing basic AO testing

reflected from a beam splitter to a WFS. With a minor tilt, the light from the DM that is heading to the laser can be easily blocked near the focal plane with an iris. This configuration can be augmented to include a metric sensor like a Strehl camera by placing a beam splitter in the feedback sensor leg of the optical train (i.e., between the existing beam splitter and the first reimaging lens).

Designing a Reimaging Telescope for Adaptive Optics Applications

In this final section, we will describe how to design a two-lens positive-focal-length telescope for adaptive optics imaging. The big difference between a telescope used for classical imaging and that required for adaptive optics is that an AO telescope needs to create an image while adding a known amount of wavefront curvature. This kind of imaging system can be solved for analytically using ray matrices. The general form of the ray matrix for propagation through a two-lens telescope is complicated, but if we assume that the separation between the two lenses is equal to the sum of the focal lengths the ray matrix simplifies to

$$\begin{bmatrix} -G/F & \dfrac{F-a}{F}G+F-\dfrac{cF}{G} \\ 0 & -F/G \end{bmatrix}$$

where the lower case letters are the distances and the upper-case letters are the focal lengths as shown in Figure 8. It is important to note that for this system, the magnification is negative. This means that imaging through the system causes the image to be inverted (or rotated by 180°). To make the telescope imaging, we need to have the B term (upper right) be zero. This creates a relationship
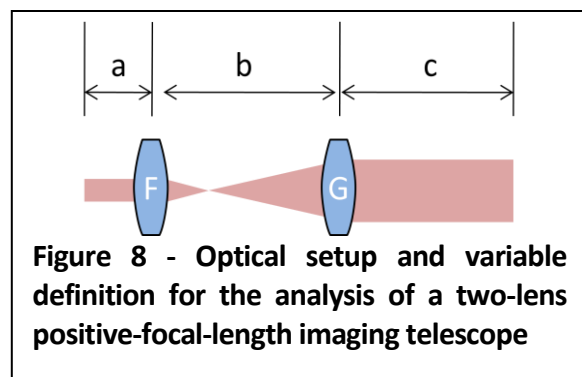
between the distances on either side of the lens pair, a and c, given by

$$a = -\left(\frac{F}{G}\right)^2 c + F\frac{(F+G)}{G}.$$

Solving the equation for c gives

$$c = -\left(\frac{G}{F}\right)^2 a + G\frac{(F+G)}{F}.$$

To design this type of telescope, we first need to choose the lenses such that their ratio is equal to the desired magnification. For example, if we want a 2.5x magnification, we could choose 100-mm and 250-mm focal

Figure 8 - Optical setup and variable definition for the analysis of a two-lens positive-focal-length imaging telescope

length lenses. Then we can set the separation to 350 mm and solve for the other two distances based on practical considerations. For example, consider a case in which we need the distance c to be 100 mm. The equation above tells us that a needs to be 250 mm.

This type of telescope configuration is useful for systems in which we want an imaging system with no added curvature. If we want to add curvature in the propagation through the imaging system, we can make a different set of assumptions. Adding curvature with the imaging telescope is often used to compensate the focal bias in a membrane or bimorph deformable mirror. The simplest form of telescope that adds curvature can be found if we set the distance from the first

plane to the first lens equal to the first lens's focal length and the distance from the second lens to the image plane equal to the second lens's focal length, or

$$a = F$$
$$c = G.$$

If we also assume that the separation is F+G+D, we find that the ray matrix transfer function is

$$\begin{bmatrix} \dfrac{-G}{F} & 0 \\ \dfrac{D}{GF} & \dfrac{-F}{G} \end{bmatrix}.$$

This solution reduces the flexibility of the system distances, but provides control over the output curvature. This system provides an effective focal length of –A/C in the ABCD ray matrix nomenclature or

$$f_{eff} = \dfrac{F^2}{D}.$$

To design a telescope for that adds a fixed curvature, begin by choosing lenses that allow their ratio to achieve the proper magnification. Then use the equation for f_{eff} above to determine the D value for D that provides the desired effective focal length.

As an example, consider a case where we want to make a 1-mm diameter beam into a 20-mm diameter beam (20x magnification). We can accomplish this by choosing a 1-m lens and a 50-mm lens. If our deformable mirror has a +10 m focal bias, we would like our imaging system to produce a beam with an effective focal length of -10 m. This means that the distance between the two lenses needs to be decreased by 1/4 mm (D = -0.25 mm).

These two different kinds of telescopes are very useful in doing imaging for adaptive optics. There are a variety of things that can be modified to improve a given system's performance. For example, the lenses can be replaced with off-axis parabolic mirrors (OAPs) in order to minimize chromatic discrepancy that can occur with simple lenses.

Adding a Field Lens
A commonly used technique that provides more flexibility in the imaging system is the addition of a field lens at the focus of the simple two-lens telescope presented above. If we add a lens with focal length E to the system, the ray matrix for propagation from the first lens to the last lens is

$$\begin{bmatrix} -M & F(1+M-FM/E) \\ 0 & -1/M \end{bmatrix}.$$

The total system with an initial propagation of a and final propagation of c is then in general form

$$\begin{bmatrix} 1 & c \\ 0 & 1 \end{bmatrix}\begin{bmatrix} A & B \\ C & D \end{bmatrix}\begin{bmatrix} 1 & a \\ 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} A+bC & Aa+B+LCa+bD \\ C & Ca+D \end{bmatrix}$$

if $C = 0$,

$$\begin{bmatrix} A & Aa+B+bD \\ 0 & D \end{bmatrix}$$

or specifically for this system where M=G/F,

$$\begin{bmatrix} -M & -Ma-c/M+F(1+M-FM/E) \\ 0 & -1/M \end{bmatrix}.$$

To achieve imaging the B matrix term (top right) needs to be zero, so the relationship between a and c is then

$$a = \dfrac{(F(1+M-FM/E))}{M} - \dfrac{c}{M^2}.$$

Using the M=G/F expression, this becomes

$$a = -\left(\dfrac{F}{G}\right)^2 c + F\dfrac{(F+G)}{G} - \dfrac{F^2}{E}.$$

When E=∞, this expression simplifies to

$$a = -\left(\frac{F}{G}\right)^2 c + F\frac{(F+G)}{G},$$

which is exactly the form presented earlier.

Reverse solving the relationship between a and c gives,

$$c = -\left(\frac{G}{F}\right)^2 a - \frac{G^2}{E} + G\frac{F+G}{F}.$$

The added $-F^2/E$ term adds flexibility to the relationship between the input and output distances. The field lens focal length is typically negative in order to push out the image distance between the object and image planes. For example, if F = 100mm and E = -25mm, F^2/E = 400 mm. This means that there is a fixed added distance between the object and image plane of 400 mm.

Positive and Negative Field Lenses

Figure 9 shows a comparison of the optical performance of a telescope with positive and negative focal length field lenses. For imaging applications, the negative focal length field lens projects the plane at the input of the first lens forward so that a real image will be placed further out from the system. The positive field lens creates a virtual image before the system. This effect of a telescope with a positive focal length field lens is to effectively propagate the beam forward. This kind of telescope is not useful for imaging a pupil, but is useful for creating a longer propagation distance between two planes than the physical space. One application for this is to propagate a beam between two phase screens in a compact space.

Conclusions

In this application note we have presented a variety of optical configurations for testing and operation of adaptive optics components and systems that will enable an AOS customer to get started with their new AOS hardware immediately.

Figure 9: Comparison of a positive and negative telescope