2.3 Alignment Plan

Kelsey Miller

1 Introduction to OAPs

The optics requiring the highest level of precision alignment within the MagAO-X beam path are the off-axis parabolic mirrors (OAPs). OAPs are fundamental to the design of MagAO-X because they are capable of delivering diffraction limited imaging (used to both collimate and focus the incoming beam at different points in the system) while deviating the incoming beam off-axis at a designed reflection angle (see Figure 1).(1) This deviation provides access to the system focal point without obstruction to the beam. OAPs also have the added benefit of being non-wavelength dependent, meaning they are free of aberration across a broad wavelength range.(2) To benefit from the high quality imaging OAPs provide, they must be precisely aligned. Below we discuss plans for initial system alignment as well as a plan to maintain that alignment after moving the MagAO-X instrument.

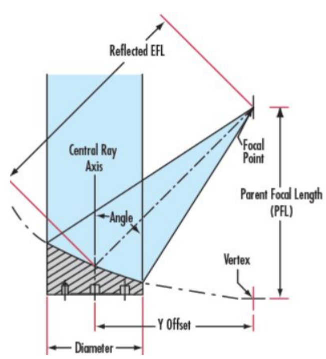

Figure 1: OAP diagram demonstrating the ability to focus an incoming collimated beam while deviating the beam off-axis at a designed reflection angle.

2 Initial Alignment

2.1 Degrees of freedom: OAPs have five degrees of freedom (DOF) accessible to the user for alignment: tip, tilt, translation in height, lateral translation, and translation along the optical path. A sixth degree of freedom key to OAP alignment is the rotation of the OAP around the optical axis; this is also referred to as clocking. This DOF however, is dealt with by having all OAPs permanently mounted by the manufacturer in the correct orientation before delivery. The remaining five degrees of freedom, however, are very sensitive and require an iterative approach to correctly adjust for ideal alignment.

2.2 Mounting: To have access to all five adjustable DOFs, the OAP will be mounted in a kinematic mount with three actuators to allow for tip and tilt. The kinematic mount is placed in an adjustable post holder to allow for height alteration. (It should be noted that OAPs are heavy optics and tend to sink into the adjustable post holders over time; it is therefore crucial that a c-clamp is added to maintain the OAP height after alignment.) For lateral translation and translation along the beam path, the mounted OAP is then placed on two translation stages: one along the beam path and one perpendicular to the beam path. This allows for precise, easy translation of the OAP; these stages will be locked into place after initial alignment. With the optic properly mounted, an iterative approach is used to align the OAP.

2.3 Iterative alignment approach: OAP alignment requires a few essential tools: an iris for height verification, as well as a narrowband* spatially-coherent light source and a shear plate interferometer to check for collimation and misalignment-induced optical aberrations. (*Note: the internal source must be narrowband to allow for the use of the shear plate interferometer which uses interference fringes created by a temporally-coherent source to diagnose optical aberrations.) In this section, we layout the steps required to align an OAP in two ways: (1) using an incoming light source that is diverging (so that the OAP collimates the light), and (2) using an incoming light source that is collimated (so that the OAP brings the light to a focus). Recalling that OAPs are used both to focus and collimate light, both alignment schemes will be used to align the MagAO-X instrument since it implements a cascading system of OAPs which will each be aligned one by one in a successive fashion.

2.3.1 Aligning to a diverging light source: The following steps describe how to align an OAP to a diverging light source: (1)

1) Verify the angle of the incoming beam

   a. Prior to the first OAP, make sure that the incoming beam is at the desired system height and is propagating parallel to the reference surface (in many cases an optical bench). This can be done by placing two irises set to the system beam height in the beam path: one close to the source and one further down the beam path. The source height and angle with respect to the table can then be adjusted until the beam passes straight through both irises without clipping.

2) Adjust the height of the OAP mount

   a. The center of the OAP in the vertical direction should match the center of the beam.

3) Position the OAP

   a. Place the horizontal center of the OAP at a distance of one OAP focal length from the light source. Be sure to use the reflected focal length of the OAP, not the parent focal length.

   b. Approximate the angle of the OAP to match the designed reflection angle. This can be approximated by eye using a mounted protractor placed in front of the OAP in the beam path such that the incoming and reflected beam pass over the protractor, thereby allowing the user to see the angle between the two beams.

4) Check collimation using a shear plate interferometer

a. Position a shear plate interferometer in the path of the reflected beam. The shear plate will produce straight fringes parallel to the reference line when the beam is perfectly collimated and without aberrations. It is therefore important to orient the reference line towards the incident beam. The angle of the fringes relative to the reference line tells the user about the state of collimation. If the lines are tilted, the beam is defocused, meaning that the OAP must be translated along the beam path. If the fringes are not straight, there is some aberration in the wavefront, which is usually caused by a tilt or de-centering of the OAP. Adjust the tip/tilt and lateral position of the OAP as necessary to achieve straight fringes parallel to the reference line.

5) Check collimation in the orthogonal direction

a. Rotate the shear plate by 90 degrees to check collimation in the tangential or sagittal plane. Make the same adjustments to achieve collimation.

Figure 2: Shear plate interferometer showing straight line fringes indicating the light reflecting off of the OAP is collimated and free of aberrations.(1)

6) Iterate steps 4 and 5

a. Adjustments of collimation in the two orthogonal planes are not entirely decoupled. When you make an adjustment in one plane, it is likely to affect collimation in the other. Alignment is therefore an iterative process of minor adjustments and checking collimation in both planes. The OAP is well-aligned when the fringes in both directions are straight and parallel to the reference line as shown in Fig 2 .

7) Check the angle of the output beam

a. The output beam should be parallel to the reference surface, just like the input beam. This can again be done using two irises set at the system beam height: one placed near the OAP and one placed further away. Tilt the OAP until the beam passes straight through both irises.

2.3.2 Aligning to a collimated light source: The following steps describe how to align an OAP to a collimated light source: (1)

1) Verify the angle of the incoming beam (same as above)

2) Adjust the height of the OAP mount (same as above)

3) Position the OAP (same as above)

4) Check the image

   a. Look at the focused spot formed by the OAP using a detector. Adjust the angle of the OAP relative to the incoming beam (tilt) to achieve good imaging quality. By adjusting the OAP angles in small increments you can minimize the aberrations observed in the focal plane.

5) Check the angle of the output beam (same as above)

2.4 High precision adjustments: Some small residual error can be expected at the end of this alignment scheme given the precision of the above methods. To deal with this residual, a Zygo Verifire interferometer will be placed at the end of the system which will allow for high-precision adjustments of each OAP to be made to fine-tune the alignment. This interferometer ensures reliable ”ripple-free” phase measurements in vibration-prone environments, and will allow for small residual errors in the alignment to be removed by small final adjustments made to the OAPs.(3)

3 Maintaining Alignment

Initial alignment of the system is crucial, and maintaining the same quality of alignment over time and after shipping the MagAO-X instrument is essential to maintain system performance. Misalignment is expected to occur in shipping, and it is important to minimize the amount of time required to realign the system before going on-sky. We have therefore developed a rough alignment strategy to quickly realign the system.

For maintaining alignment, we propose using three methods: (1) a series of irises placed along the beam path to check for tip/tilt and height variation, (2) an individual reference for each OAP to monitor any changes in the OAPs position with respect to its initial, ideal-alignment orientation, and (3) a series of flip mirrors and cameras to check PSF quality and beam location.

3.1 Method 1: Irises: A series of irises will be centered on the beam along the optical path after initial alignment of the instrument and epoxied in place to keep them from moving during shipment (see Figure 3).(**?**) The irises will be oversized and fully opened while the instrument is in operation to avoid affecting the beam. For alignment, the irises will be stopped down to check for beam misalignment that will result in clipping by the iris. These irises can be fully epoxied to remain in place, will have no moving parts, and will therefore be the least likely of the three methods to be affected by shipping.

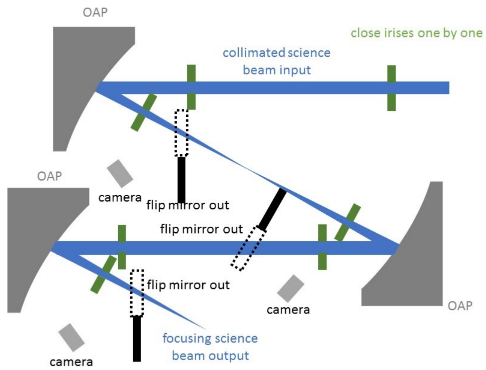

Figure 3: Iris method: close down each iris individually in succession down the beam path (with the flip mirrors out of the beam). Misalignment on the iris will give tip/tilt misalignment information for the preceding OAP.

3.2 Method 2: Laser/back reflection/camera: The back surface of each OAP will be polished to allow for a 4% reflection off the uncoated back surface. (Note: the OAP mounts are designed to be open in the back, thereby allowing access to the back surface of the optic. For specifics on these mounts, see Section 2.1: Overall Design) A small laser will then be set up and epoxied in place to reflect off the back of the OAP and onto a camera (also epoxied in place with a square post and post holder to avoid rotation in the mount during transit). (See Figure 4)

The rough alignment maintenance strategy will proceed as follows:

1) Initial alignment of the full optical system

2) Set-up a laser and camera (one of each per OAP) behind each OAP to reflect the laser off the polished back surface of the OAP and onto the camera.

3) For each OAP, take an image of the laser beam footprint with the camera and save as the ideal reference image for each OAP.

4) After shipping, or at any given time after the initial alignment, turn on the laser for each OAP and take an image of the beam footprint on the camera.

5) Measure the shift in position of the beam with respect to the reference image. (See Figure 5) This will provide information on how the OAP has tipped and tilted since the initial alignment. (Note: these are the two most sensitive DOFs and are therefore the most likely misalignments to occur during shipping. The OAPs will be locked in place in height, in position along the beam path, and laterally with respect to the beam, and will therefore be less likely to move.)

6) Use the actuators on the OAPs kinematic mount to adjust the OAPs tip and tilt to return the beam to its reference position on the camera.

7) To ensure that the OAPs, not the laser/camera system has moved in transit, this procedure will be augmented

by iterating on the initial alignment steps 3 - 5, checking the centering of the beam on each OAP, the input and output angle of the beam, and the beam height along the optical train.

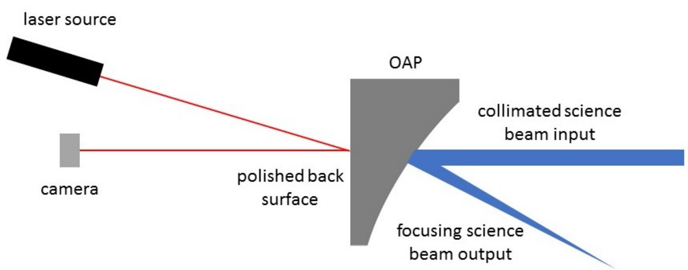

Figure 4: OAP layout for rough alignment strategy using a laser reflection of the polished back surface of each OAP reflected back to a camera

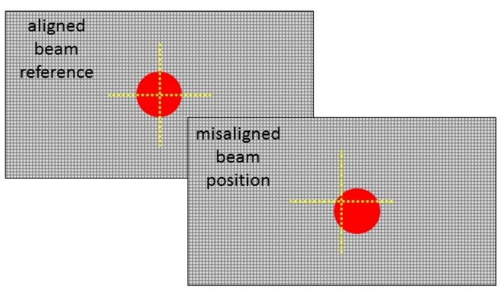

Figure 5: Beam displacement used to adjust tip/tilt OAP actuators to realign the OAP.

This strategy will bring the OAPs back into alignment. However, OAPs are sensitive optics, so it is possible some residual aberration may remain after this rough alignment. If this is the case, it will be seen in the image quality at the end of the optical system. Smaller, more precise adjustments of the OAPs will then be required to fine tune the final image quality. This can be achieved by checking the beam height throughout the optical system with an iris or target set to the beam height, checking for wavefront aberrations using a shear plate interferometer, and adjusting the OAPs accordingly (see previous section for initial alignment).

3.3 Method 3: Flip-mirrors/camera: Flip mirrors will be placed along the optical path after each OAP that will be out of the beam during operation and flipped into the beam, reflecting it back to a camera, one at a time starting at the beginning of the system. In collimated space, the beam footprint location on the camera will be used as in Method 2 to determine any tip/tilt that has been induced on the OAP before it (see Fig 5). After OAPs where the light is coming to converging, the camera will be placed at focus. The position of the beam at the camera will be again be used to identify tip/tilt, but the beam at the camera will now be a PSF, the quality of which can be used to more precisely diagnose optical aberrations induced by the preceding OAPs. This method, as well as method 1, has been demonstrated successfully at Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) by Nemanja Jovanovic, whose expertise and on-sky experience have contributed significantly to this alignment scheme.(**?**)

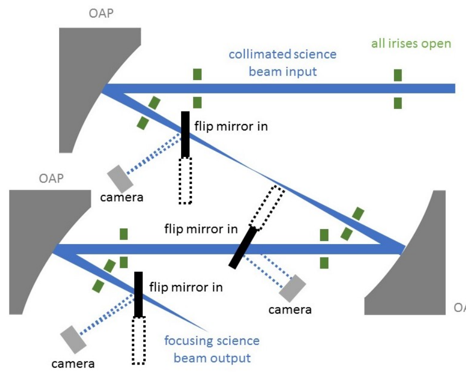

Figure 6: Flip mirror method: flip each flip mirror into the beam in succession down the beam path (with the irises fully open). The reflected beam, both collimated and the PSF, will give tip/tilt error information for the preceding OAP, and the PSF will give higher precision error information for the preceding OAP.

4 Laser Safety

The internal broadband light source for MagAO-X is a class IIIb Fianium Whitelase micro laser(**?**) with a total power output > 200mW and a bandwidth of $400 - 2200$ nm, with a significant fraction of the total power lying outside of the visible band. Specular reflections as well as direct exposure to this laser can be harmful to the eye. This makes laser safety an important topic for consideration. The upper bench of the MagAO-X instrument is designed to be 1.465 m tall, making it below the average eye level. To further mitigate safety concerns, a near-infrared (NIR) filter will be used to cut off all light past 800 nm, ensuring that all light delivered to the instrument is within the visible spectrum. This filter decreases the total output power being delivered to the instrument to less than 5mW, downgrading it to a class IIIa. This beam will therefore be eyesafe and will allow for personnel to align the instrument without the use of safety goggles. Standard procedure for operating this laser will still include avoiding direct eye exposure to the beam (straight from the source as well as any reflections) by keeping the users eyes above the level of the beam at all times. Should the NIR filter need to be removed at any time for instrument testing, personnel working on the optical bench will be required to wear laser safety goggles with high OD (optical density) in the lasers peak wavelength regimes. The same Fianium Whitelase micro source that will be used for the MagAO-X bench is currently in use at the University of Arizon's Extreme Adaptive Optics Lab, and the above safety precautions, including procedures and hardware, have been and are currently being successfully implemented.

References

[1] K. Newman, "An introduction to off-axis parabolic mirrors," tech. rep., 2013.

[2] E. Optics, "Off-axis parabolic first surface metal mirrors," tech. rep., 2017.

[3] Zygo, "Verifire," tech. rep., 2017.