

DESIGNING AND IMPLEMENTING AN ADAPTIVE OPTICS SYSTEM FOR THE UH HOKU KE`A OBSERVATORY

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ABSTRACT

The presented project is to implement a small adaptive optics system for the University of Hawai`i (UH) Hoku Ke`a Observatory (HKO). Adaptive optics (AO) is a technique used to correct for distortions introduced by the atmosphere in order to produce clear images for precise data measurements (Wizinowich et al., 2000). HKO is planned to be fully operational by 2017. The observatory is meant to provide astronomy and physics students with hands-on experience in their field of study. Without an adaptive optics system, the 0.7-m telescope is limited by the atmospheric blurring (i.e., the “seeing”; Chromey 2010). With the introduced adaptive optics system, the telescope’s resolution will improve by a factor of 6.8,¹ reaching the diffraction limit of the telescope. The adaptive optics system will be a foundation for students to learn adaptive optics. Implementing this technique for the UH HKO will be very advantageous for UH Hilo Department of Physics and Astronomy’s goal of teaching future astrophysicists.

INTRODUCTION

The AO system for this project is a commercial “AO demonstrator” acquired from a company known as IrisAO. Initially, the AO demonstrator was bought by the Institute for Astronomy (IfA) on Maui, but in 2013 it was shipped to Dr. Mark Chun at IfA-Hilo. The goal of this project was to redesign and integrate the AO demonstrator so it could be used with the future HKO. Work thus far has consisted of testing the AO demonstrator and getting the system running in the lab. All of the basic components have been integrated on the optical bench and some characterization of the AO system’s performance was done.

THE OPTICAL LAYOUT

For an astronomical adaptive optics system, a star is the object of interest (Rousset et al. 1990). To simulate a star on the optical bench, a collimated laser was used (see Figure 2). A pinhole was positioned in front of the laser to act as a hypothetical telescope aperture and a 100mm focal length lens was positioned in front of the pinhole to focus the light. This simulates the “telescope,” since a telescope would focus the light from a star onto the telescope’s focal plane. After the light from the star passes through the telescope, the light then reaches the adaptive optics system, which images the star onto the deformable mirror (DM) and the wavefront sensor (WFS) to correct for the atmospheric distortions.

¹ Assuming a telescope limited by a seeing of 1” (arcsecond) and observing in the optical wavelength, the adaptive optics demonstrator would improve the resolution of the HKO telescope to approximately 0.147”.

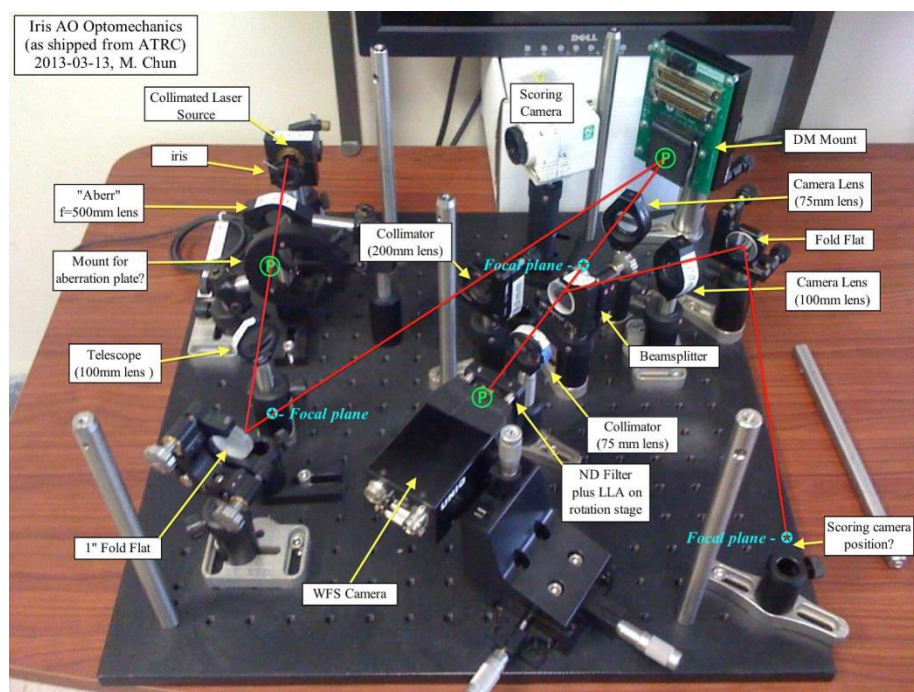


Figure 1 – The AO Demonstrator when it was first received by Dr. Mark Chun at IfA-Hilo. The components needed to be realigned by calculating where each component should be (see Figure 2).

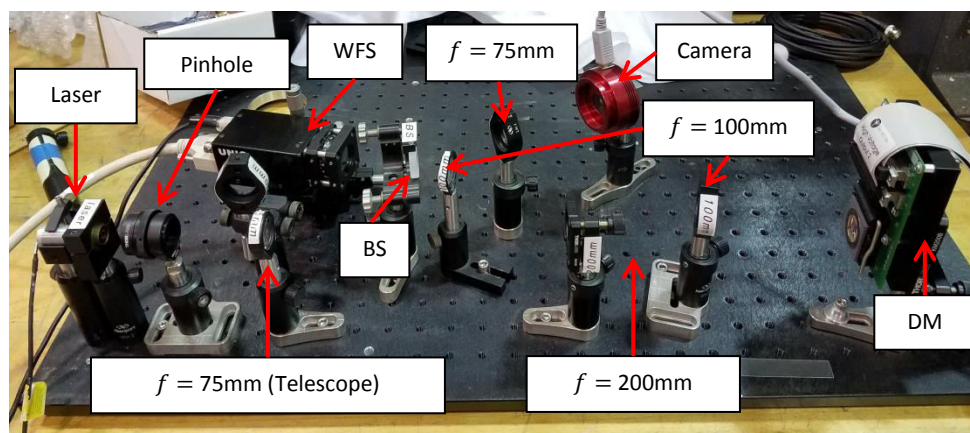


Figure 2 – The final optical layout. The system was designed so that the light from the “star” is imaged onto the DM, while the DM is imaged onto the WFS. A beam-splitter (BS) splits the light to a 75mm lens which focuses the light onto the science camera.

The WFS's purpose is to measure the shape of incoming wavefronts, where the AO system's computer interprets these measurements and sends command voltages to the DM to change its shape. The WFS has a 10mm by 8mm lenslet array in front of its detector that consists of tiny lenses that create their own images of the light source onto the detector. Additionally, a neutral density filter is placed in front of the lenslet array. This reduces the amount of light reaching the detector, since the WFS camera is very sensitive.

The DM has 37 segments (actuators) that can push, tip, and tilt to change the shape of the mirror. The mirror is 3.5 mm in diameter while each segment is about 0.5 mm in diameter (see Figure 3). The optical system was designed so that the light source illuminates all 37 segments of the DM and also illuminates 37 lenslets on the lenslet array. The DM is also *imaged* onto the lenslet array, which means an image of the DM is created at the lenslet array. That is the purpose of the two 100mm lenses (see Figure 4). When a segment on the deformable mirror moves, the WFS camera records the movement of the spot that moves due to the image created by one of the lenslet arrays (see the Software section).

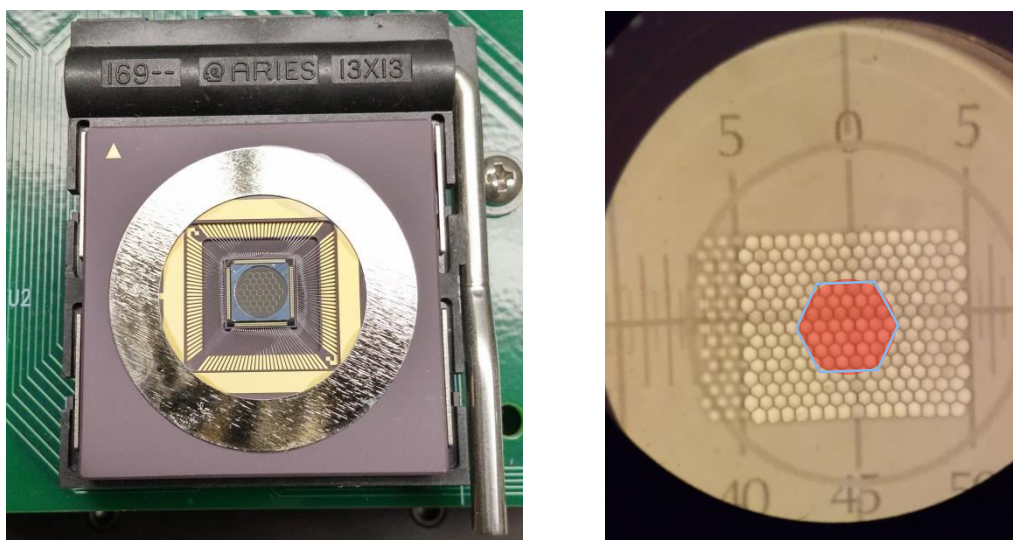


Figure 3 – The deformable mirror (left). The 37 segments are arranged in a hexagonal pattern. Each segment is about 0.5 mm in diameter while the entire mirror is 3.5 mm in diameter. The lenslet array (right). Each lenslet is a hexagonal shape to match the DM actuator pattern. The background is a measuring paper that was used to measure the lenslet array. Each lenslet is about 0.625 mm in diameter while the entire lenslet array is 10 mm x 8 mm. A hexagonal shape was edited into the image to show how the size of the light beam on the lenslet array creates an image for each actuator.

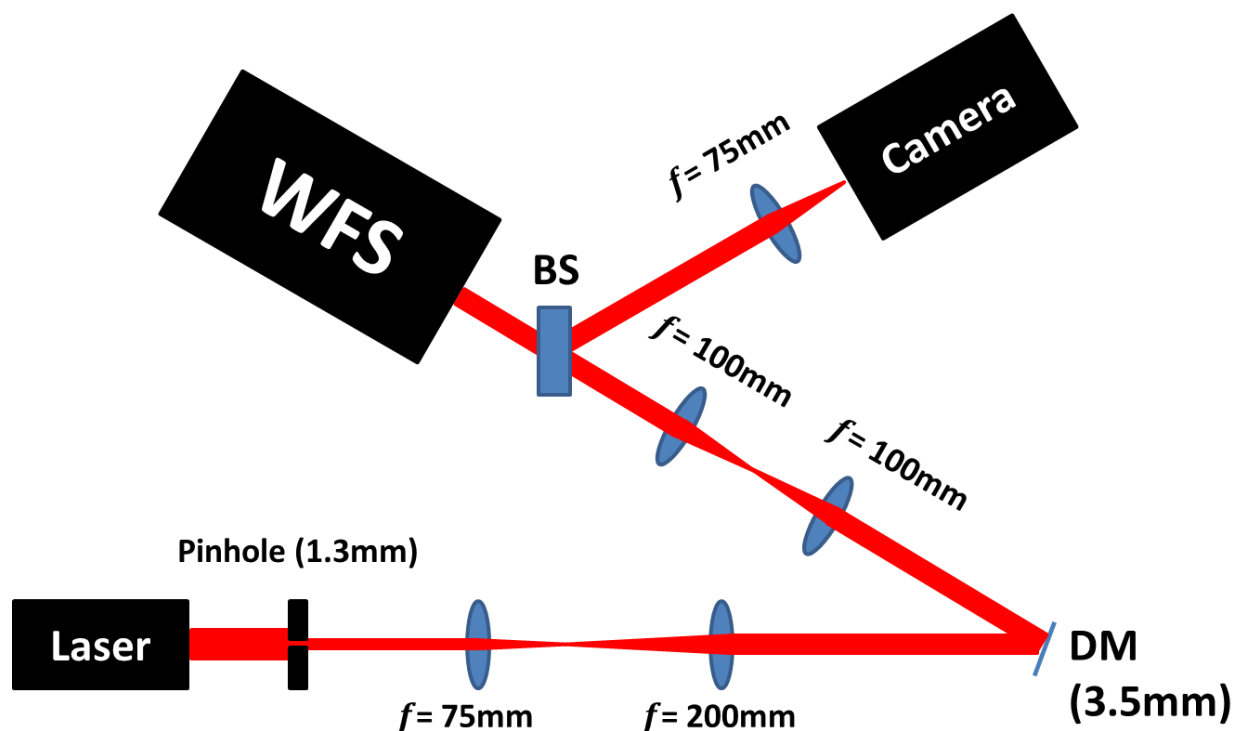
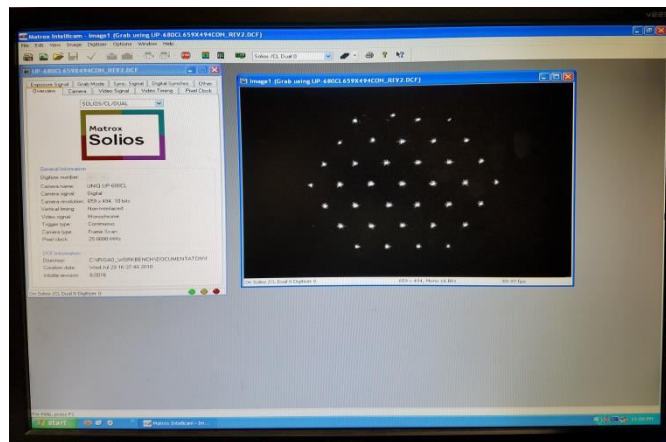


Figure 4 – A ray diagram of the optical layout. The beam must be the same size as the DM when the light reaches the mirror. The light beam should be aligned as best as possible in order to include all segments. In addition, the beam size at the WFS lenslet array must also be the same size as the DM in order to match the segments on the mirror. The beam splitter (BS) and a 75mm lens creates an image of the light source on the camera detector.

SOFTWARE

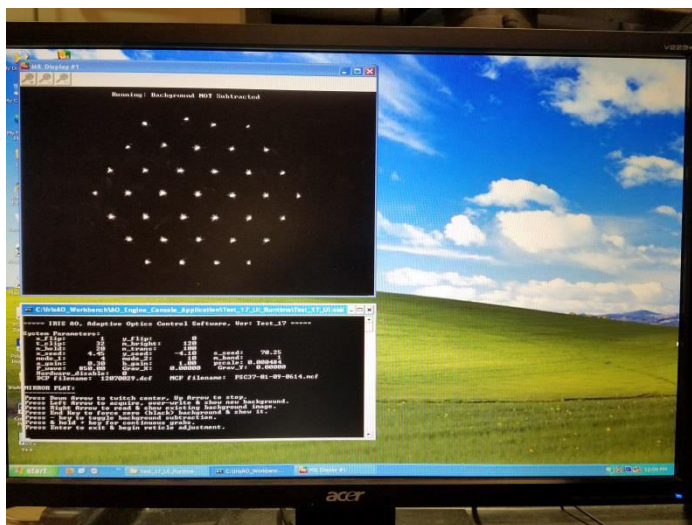
All of the AO system's documents and software can be found on its accompanying Windows XP computer. The software that runs the WFS camera is called Matrox Intellicam (below image). In continuous imaging mode, the WFS camera reads out in real time. If the



system is aligned properly and there is little to no saturation, 37 spots will be visible in the live feed, which correspond to the 37 segments of the DM. This program is used in another program called the Workbench Engine, which controls both the mirror and the WFS to correct the images. Before opening the software, connect the Camera Link cable with the WFS and "Channel 0" on the back of the computer. Plug the power cable into the WFS. Open Matrox Intellicam, and select the "New DCF" button. Browse for the 'UP-680CL 689x494CON_REV2.DCF' file which can be found in the

C:\. This is a configuration file with the WFS camera information in it. Once you have selected this configuration file, click “Continuous Grab” and a separate window will show the WFS live feed.

The software that controls both the WFS and the DM is called the IrisAO Workbench Engine. There are two versions of this software: a Graphical User Interface (GUI) version, and a console version. The GUI version is not functional and needs further investigation if the user is interested in using it, but the console version has the same capabilities and runs faster. The IrisAO Workbench console version is located in C:\AO_Workbench_Engine. To make sure the application runs properly, the mirror and driver configuration files must be placed in this folder. These are named FSC37-01-09-0614.mcf and 12070029.dcf, respectively. Also, check AO.Engine.dll.config to make sure the driver and mirror configuration files are named correctly. The application is named Test_17_UI.exe. Before running the application, connect the driver USB to the computer, plug in the power, and connect the DM cables to the DM. Output 1 should be inserted into the J1 input, while Output 2 should be inserted into the J2 input. Once this is done, the user may run the application. The console version uses Matrox Intellicam to stream a live feed of the WFS camera (see image above). The program then allows the user to “twitch” (tilt back and forth) the center segment of the DM, which causes a spot on the WFS Camera to move back and forth. This is used to test the alignment of the system. If the optics are aligned correctly, only the middle spot should move. If not, the system must be realigned until the center spot is the only one that moves when the twitch function is on. Make sure there is no saturation to ensure that the spots are seen clearly. Once the system is aligned, a reticle alignment is done to locate the 37 spots in the image. Finally, the WFS continuously measures wavefronts using the centroids of the spots, sending information to the DM to change its shape. This is then called a “closed loop” system.



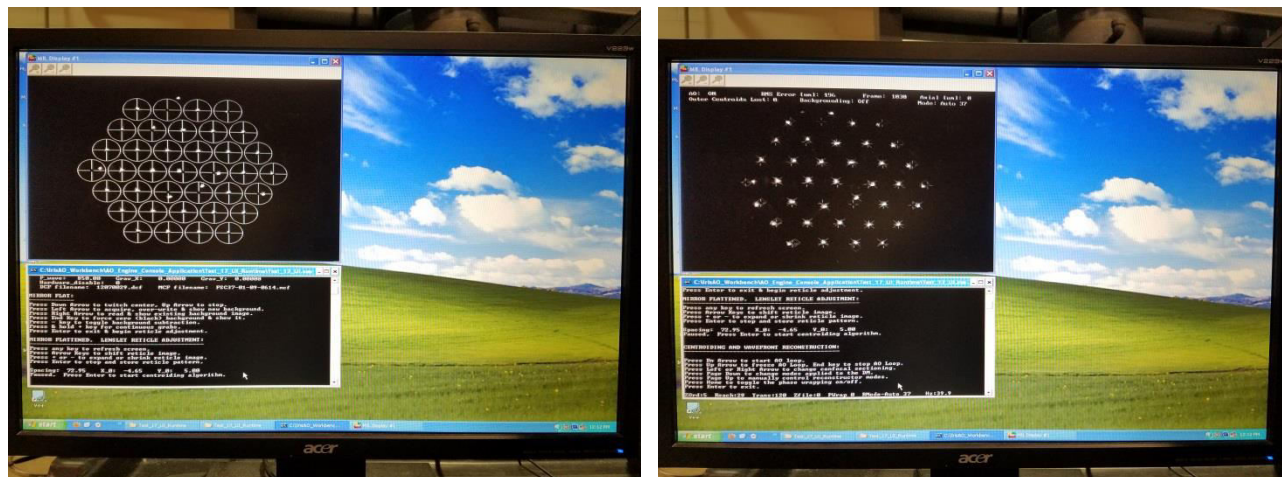
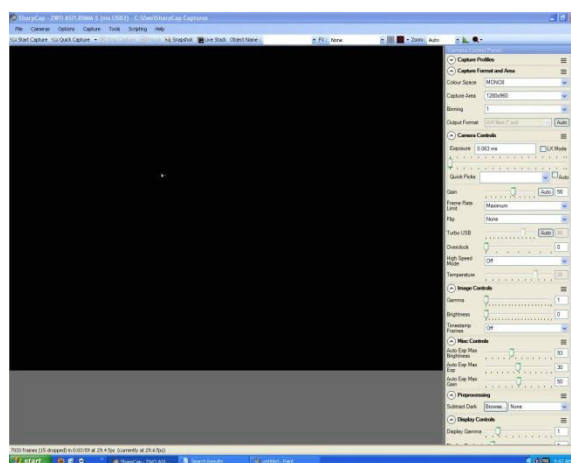


Figure 5 – Reticle alignment and AO closed loop. Align the reticles with the spots and then close the loop to continuously correct images.

The science camera is used to image the light source (i.e., the laser). By introducing distortions and measuring the full width at half maximum (FWHM) of the image on the science camera, the system's performance can be characterized. The camera, *ASI120MM-S*, is a monochromatic camera from the company known as Zwo. This camera was chosen for its low price and pixel size of $3.75\mu\text{m}$. This pixel size ensures that at least 2.5 pixels will fit within the FWHM,² which is a good sampling rate (Kester 2009), since a FWHM below 2 pixels might be difficult to resolve. A neutral density filter was placed in front of the science camera in order to reduce stray light and limit saturation. There are two programs that can read out the science camera: *SharpCap* and *FireCapture*. *SharpCap* (right image) is located on the Desktop, while *FireCapture* is located in C:\Zwo. Both programs work well, and it is arbitrary which one is used. Manuals can be found in the C:\Zwo folder in case the user would like to read about the software. To take images with the camera, make sure the USB 3.0 A-male to B-male is connected between the camera and the computer. Open *SharpCap* (for this example) and change the exposure time, gain, etc. to the user's liking. Click Capture→Start Capture→Single Frame→Start to take a single image. The image will be saved in a location on the computer determined in File→SharpCap Settings→FileNames.



² The FWHM for a given wavelength and $F_{\#}$ as a spatial dimension can be shown to be $FWHM = 1.028\lambda F_{\#}$, where the $F_{\#}$ is the ratio of the focal length of the lens in front of the science camera to the diameter of the beam size entering the lens. The laser has a wavelength of approximately 660nm, and the $F_{\#}$ is 21.4.



Figure 6 – The science camera is a 1280x960 resolution, 12bit camera. This can be used to measure FWHM values and characterize the system's performance.

CHARACTERIZATION

Official characterization of the system's performance was delayed due to an odd error with the DM. When the IrisAO Workbench console application is opened and the driver power is on, the DM's segments should move to a zero position, flattening the mirror. Instead, the segments seem to move away from zero, causing the spots on the WFS live feed to spread out. When AO is on, the image quality ends up being worse than when AO is off. The cause may be due to the fact that the DM was used in an environment with humidity usually above 50%, and ideally the mirror should be used in an environment with humidity below 40%, says IrisAO.

This problem was not always present. It only started to occur after several uses of the Workbench console. IrisAO was contacted about the situation, and they are currently examining the mirror configuration file to see if there is anything unusual. Although the DM has problems, images were taken with the science camera before and after AO was turned on and plots were made in MATLAB to measure their FWHM.

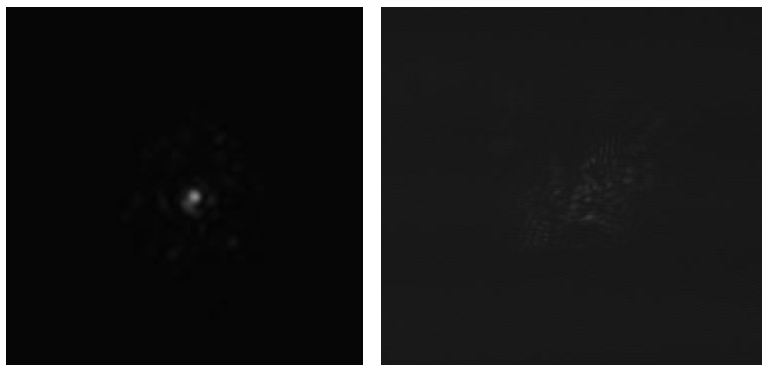


Figure 7 – Before the AO is turned on (left), an Airy disk is present. After the AO is turned on (right), the image is spread out due to the DM problem. A neutral density filter was used to limit saturation.

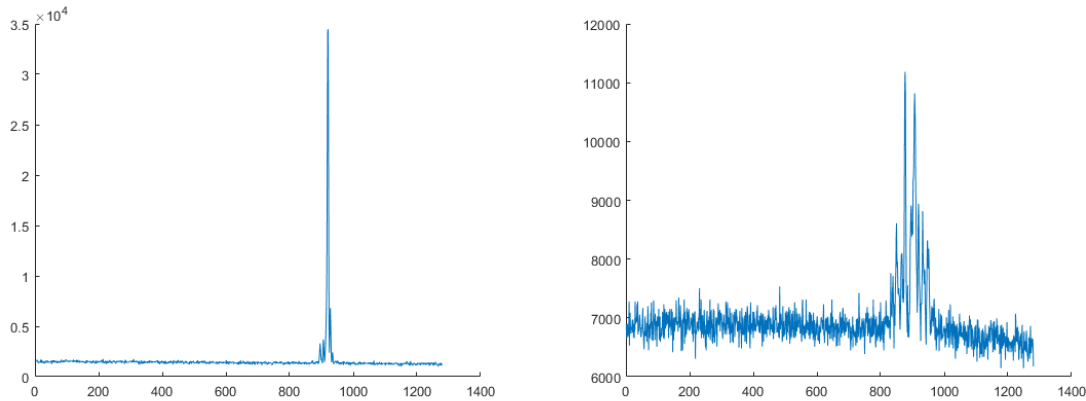


Figure 8 – A plot of the light source intensity over pixel number with AO turned off (left) and a plot of light intensity over pixel number with AO turned on (right). The FWHM was roughly measured to be 4.6 pixels in the left image and 37 pixels in the right image.

As expected, an Airy pattern is seen in the first image when AO is not turned on. This is more obvious in the left plot of Figure 8. Any optical system imaging a point-source will see an Airy pattern so long as there is no interference such as an atmosphere. When AO is turned on, the image quality decreases because the DM segments tilt to the wrong positions, increasing the FWHM. Ideally we would want the opposite transformation; low image quality to high image quality when AO is applied. Due to the DM problem, this is not the case for now, and needs more investigation to fix the problem.

CONCLUSION

The AO demonstrator is now functional, besides the fact that the DM has a problem with its segments. The first priority is to fix the DM problem in order to characterize the AO system's performance. IrisAO is a useful resource in this matter, so consulting with them is advantageous. Characterizing the system can be done by introducing distortions with items such as a hair dryer or using lenses to defocus the image. The FWHM should be measured before and after AO is turned on to see how well the image was corrected. A more robust method of measuring the FWHM should be designed through a program such as MATLAB, IDL, or Python. Once the system is characterized, the AO demonstrator can be designed and implemented for the UH Hoku Ke`a telescope. To do this, visit [the Hoku Ke`a Website](#) and consult with Dr. Rene Pierre Martin, the telescope director. The AO system's optical components will have to be redesigned in order to suit the HKO. One of the limiting factors is the maximum brightness the AO demonstrator can resolve, so this must be determined before observing an actual star.

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