Building KAPAO-Alpha: A Prototype Adaptive Optics Instrument for Pomona College’s
1-meter Telescope at Table Mountain Observatory

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ABSTRACT

Building KAPAO-Alpha: A Prototype Adaptive Optics Instrument for Pomona College’s 1-meter Telescope at Table Mountain Observatory

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This thesis describes the construction, as well as in-lab and on-sky testing of KAPAO-Alpha, a prototype adaptive optics instrument for Pomona College’s 1-meter telescope at Table Mountain Observatory. KAPAO-Alpha is a natural guide star adaptive optics instrument that uses a Shack-Hartmann wavefront sensor to detect atmospheric distortion. Wavefront correction is accomplished with a 2-axis tip/tilt mirror and a 144-actuator deformable mirror.

Building the system required the development of precise techniques for optical alignment, which are described here generally, and very specifically in a step-by-step alignment guide in the appendix. In addition, to facilitate in-lab and on-sky testing, we developed a suite of simple analysis tools in Python and IDL whose purpose and functionality are described in the thesis. The control software for the hardware and wavefront correction is adopted from the similar Robo-AO project at Caltech. Because it is currently in-development, complete documentation is lacking, and this thesis also contains an in-depth discussion of the important functional understanding of the software that we have gained over the course of testing KAPAO-Alpha.

KAPAO-Alpha has been fully installed on TMO a total of four times. We have demonstrated stable closed-loop operation on a natural guide star, but correction was limited almost entirely to low-order tip/tilt aberrations due to misalignment between the telescope beam and instrument optics. In response to this, we developed a new technique for precise alignment to the telescope, and in-lab testing of this technique suggests that it should allow easy and precise alignment to the telescope. Although technical problems with the telescope itself prevented testing of this technique on-sky before submission of this thesis, at the time of this writing the telescope has been repaired and the instrument is installed and ready to demonstrate on-sky capability.

Keywords:
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Chapter 1

Introduction

1.1 Overview of the KAPAO Project

KAPAO A Pomona Adaptive Optics instrument is a four-year project to build an adaptive optics instrument for Pomona College’s 1m telescope at Table Mountain Observatory. The work presented in this thesis spans a 10-month block roughly in the middle of the KAPAO project and centers around the construction and testing of a prototype instrument that we call KAPAO-Alpha. The KAPAO project timeline, shown in Figure 1.1, has three distinct stages:

- Component acquisition and testbed construction/testing: We purchase the major components required for the project and construct a “testbed” version of the instrument in-lab to get all of the components and the software working together.

- Building a prototype instrument, KAPAO-Alpha: We use off-the-shelf optics to build a working prototype of the final instrument, intended to demonstrate the feasibility of the project and identify any problems with actual on-sky operation, allowing time to understand and compensate for these in the final instrument design.

- Building the final instrument: Once KAPAO-Alpha has demonstrated on-sky operation and
1.2 What is Adaptive Optics?

Dynamic distortions in the atmosphere limit the resolution of ground-based telescopes. Turbulent cells of air with slightly different densities than their surroundings act like very weak lenses, bending the light from stars—it is the interference of such beams taking different paths to an observer’s
1.2 What is Adaptive Optics?

eyes that causes the stars to twinkle. More importantly for astronomical observing, this causes what originally looked like a point source to be smeared out, preventing, for instance, a telescope from resolving two stars very close to one another, or a planet orbiting another star.

An adaptive optics (AO) instrument like KAPAO corrects for these atmospheric distortions.

![Figure 1.3 Schematic overview of an AO system.](image)

Conceptually, it is composed of three components:

- **Wavefront Sensor**: Detects how the incoming light is aberrated.

- **Reconstructor**: Calculates what changes would need to be made to fix the incoming light.

- **Corrector**: Applies the correction calculated by the Reconstructor.

There are several different technological solutions for both the wavefront sensor and corrector mechanisms. The reconstructor is software, and thus different implementations involve choices in programming and mathematical methodology. The KAPAO and KAPAO-Alpha instruments
use a wavefront characterization method known as Shack-Hartmann wavefront sensing, and two movable mirrors: a tip-tilt (T/T), and a deformable mirror (DM) with a flexible surface and an array of piezoelectric actuators to push and pull it, for wavefront correction.

The atmosphere is constantly changing, so it is necessary to detect and correct for distortions at very high speed–several hundred to a thousand hertz depending upon atmospheric (seeing) conditions. Obtaining a measurable light signal from a star in the night sky at this speed requires a very high quality, low-noise CCD camera, and even then, it is necessary to look at relatively bright stars. This would be a problem if we only could correct for the image of the star that our instrument is looking at; fortunately, correcting for the light from one star also corrects for the light from any objects in a small angular swath around it as well, because that light is passing through essentially the same atmospheric distortions (a more detailed discussion of this can be found in Section 2.1).

1.3 Historical Development of AO

The effect of atmospheric turbulence on astronomical observing was noted hundreds of years ago. Newton discusses the problem in his *Opticks* (1704), concluding that it is insurmountable and the only solution is to construct one’s telescope atop a high mountain. This would remain the general consensus until 1953, when Horace W. Babcock’s work on automatic guide systems led him to write a paper, “The Possibility of Astronomical Seeing” which described a theoretical system utilizing a seeing sensor and a wavefront corrector. Technology at the time–and perhaps more importantly, funding–was not sufficient to implement this idea, but interest in imaging newly launched Soviet satellites in the early 1970s led the Advanced Research Projects Agency (ARPA) to revive Babcock’s idea, and by 1973 they had built the first functional adaptive optics system. The instrument used analog electronics to convert 32 slope signals from a wavefront sensor into voltages for a 21 element deformable mirror [Hardy(1998)].
By 1982 the first full-fledged adaptive optics instrument for astronomy was in operation: The Compensated Imaging System (CIS), with a 168 actuator deformable mirror and control loop capable of running at 1000 Hz. The largest and best funded telescopes quickly followed suit, implementing AO instruments to improve the resolution of their images from 10 to 20 fold.

Today, large telescopes continue to push the boundaries of adaptive optics performance with developments like multiconjugate systems which use several laser guide stars to sample different parts of the atmosphere simultaneously.

Although the first adaptive optics instruments were designed for and tested on smaller telescopes, with 1-2 meter apertures, subsequent developments in adaptive optics have been limited to medium and large (3.5m and up) aperture telescopes due to the extremely high cost of building, operating, and maintaining these instruments.

Large telescopes have significant drawbacks for adaptive optics systems. Larger apertures mean that the wavefront must be divided into more pieces to be reproduced, and the deformable mirror must likewise have more actuators. More actuators in turn necessitate more calculations from the digital reconstructor that converts data from the wavefront sensor into actuator voltages for the deformable mirror.

Despite the advantages of designing an AO instrument for smaller telescopes, manufacturing costs of electronic components like the DM and the high-performance CCD necessary for the WFS, and especially the high cost of processing power, have prevented the development of AO instruments for small telescopes from being financially practical. Even the smallest stellar imaging telescope with an AO system to date, the 2.5m Mount Wilson, needed to use custom signal processors—essentially a miniature super-computer—to run its reconstructor loop when it was built in 1995 ([Turner et al.(2001)]). Instruments like these not only require a great deal of money to design and build, each one being a unique endeavor using custom components, but also require full-time personnel to maintain and operate them.
1.3 Historical Development of AO

Table 1.1 A list of all adaptive optics instruments in operation as of 2011 (source: [Tyson(2011)]).

<table>
<thead>
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<th>Instrument</th>
<th>Diameter</th>
<th>Description</th>
<th>Size</th>
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<td>Mt. Wilson</td>
<td>2.5m</td>
<td>Anglo-Australian Telescope</td>
<td>3.9m</td>
</tr>
<tr>
<td>Nordic Optical Telescope</td>
<td>2.56m</td>
<td>Southern Astrophysics Research Telescope</td>
<td>4.1m</td>
</tr>
<tr>
<td>Shane Telescope</td>
<td>3.0m</td>
<td>William Herschel Telescope</td>
<td>4.2m</td>
</tr>
<tr>
<td>Apache Point</td>
<td>3.5m</td>
<td>Hale Telescope, Mt. Palomar</td>
<td>5.0m</td>
</tr>
<tr>
<td>Starfire Optical Range</td>
<td>3.5m</td>
<td>Monolithic Mirror Telescope</td>
<td>6.5m</td>
</tr>
<tr>
<td>Wisconsin Indiana Yale</td>
<td>3.5m</td>
<td>Gemini North and South</td>
<td>8.0m</td>
</tr>
<tr>
<td>Astrophysical Research Consortium</td>
<td>3.5</td>
<td>Subaru</td>
<td>8.2m</td>
</tr>
<tr>
<td>Calar Alto Observatory</td>
<td>3.5m</td>
<td>Large Binocular Telescope</td>
<td>2x8.4m</td>
</tr>
<tr>
<td>Telescopio Nazionale Galileo</td>
<td>3.58m</td>
<td>Very Large Telescope</td>
<td>4x8.2m</td>
</tr>
<tr>
<td>California-France-Hawaii Telescope</td>
<td>3.6m</td>
<td>Keck Twin Telescopes</td>
<td>2x10m</td>
</tr>
<tr>
<td>New Technology Telescope</td>
<td>3.6m</td>
<td>Advanced Electro-optical System</td>
<td>3.67m</td>
</tr>
<tr>
<td>Visible and Infrared Survey Telescope</td>
<td>3.6</td>
<td>U.K. Infrared Telescope</td>
<td>3.8m</td>
</tr>
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Computer technology has finally advanced sufficiently in the past several years that high end consumer grade processors are capable of running a high-speed adaptive optics loop. High quality CCDs and deformable mirrors have also seen large decreases in cost.

1.4 Origin of KAPAO

Inspiration for the KAPAO project was provided by two similar: The Robo-AO project at Caltech, and ViLLaGES on the Lick 1-meter telescope. Both projects were conceived in the midst of this changing technological landscape; Robo-AO proposes to create a cost-efficient, modular adaptive optics system for 1-3m telescopes [Baranec et al.(2011)], while ViLLaGES is designed to advance and test new AO technologies.

The KAPAO instrument is being developed in tandem with Robo-AO, using the Robo-AO software package, as well as the same WFS and DM, it will demonstrate the viability of the Robo-AO system in being ported to other 1-3m telescopes.

KAPAO promises to increase the resolving power of our 1m telescope by as much as 10x, allowing entirely new levels of observation to be done, as well as offering a multitude of research opportunities for future students. In addition to opening new possibilities for astronomical observing, the relative simplicity (KAPAO is an NGS instrument) and small size of the instrument allows for the possibility of future research into alternative wave sensing techniques.

There are currently only 28 adaptive optics instruments in operation worldwide (see Table 1.1), all of them on large telescopes and with budgets easily in the many millions of dollars. If Robo-AO and KAPAO are successful in demonstrating the viability AO instruments for modest-aperture telescopes, resolution improvement on the order of ten times will be made available to the hundreds of telescopes in this size range worldwide for a small fraction of the cost of the original telescope and observatory.


1.5 Content and Structure of this Thesis

The work of this thesis has been focused entirely on constructing and troubleshooting the KAPAO-Alpha instrument. Design of the instrument, along with related theoretical considerations and calculations, were largely separate from this work. Consequently, the focus of this thesis is on the instrument itself, its components, construction, and demonstrated performance.

The Introduction explains the basic concept of adaptive optics, what the KAPAO project is, and how it fits into the larger field of AO. The next chapter, Theory, discusses the structure of the atmosphere as it relates to AO, and how this constrains the design of our instrument. The Hardware and Assembly chapter first gives a conceptual overview of the function of the system’s major components, then zooms in for a component-by-component ride through the instrument with pictures. The Assembly section explains general techniques that we developed to precisely align KAPAO-Alpha. Chapter 4, Installation and Alignment to Telescope, discusses our solution for mounting and aligning the instrument and its peripheries to the telescope. The next chapter is a functional overview of the software used in our system, both the C++ instrument control and wavefront reconstructor software taken from the Robo-AO project, and custom tools that we have developed in our own lab to help with troubleshooting and monitoring the instrument. The final chapter discusses our method for testing KAPAO-Alpha’s functionality in lab, and shows results of wavefront correction. Lastly, on-sky testing to date is discussed, along with the current state of KAPAO-Alpha and its future.

As part of the larger KAPAO project, much of the content is very specific, and largely intended as a reference for future work with KAPAO-Alpha and the final instrument. Readers wishing to gain a basic understanding of the instrument are advised to begin with this section, followed by the brief theory discussion in Chapter 2. A conceptual overview of KAPAO-Alpha’s components can be found in Section 3.1; Section 5.1.1 runs through what happens in one frame of wavefront detection and correction. The introduction to Section 5.2 gives an overview of the IDL analysis
1.5 Content and Structure of this Thesis

tools developed as part of this thesis to assist in analyzing and investigating the performance of KAPAO-Alpha. Finally, Chapter 6 shows the instrument at work, in lab and on-sky. Readers wishing to get a more visual introduction to the instrument might also look through Section 3.2, which follows light entering KAPAO-Alpha from the telescope all the way through the instrument, one component at a time. Much of the work in this thesis was developing optical alignment techniques for KAPAO-Alpha. These are presented in Section 3.3.

For the reader seeking more detailed reference information: The latter part of Section 5.1 provides a detailed overview of everything that we know about the control software to date. Likewise for the IDL analysis tools documented in Section 5.2; this section contains a conceptual overview of what each program does, as well as some specific equations and functions. Appendix A is a step-by-step, picture-based alignment guide for the Alpha system, showing how to construct it from the ground up. This is intended as an instruction guide whenever the system, or any of its parts, needs to be aligned or rebuilt from scratch. Appendix B is a guide to running the software written with a completely new user in mind. A step-by-step guide for aligning the instrument to the telescope can be found in Section 4.2.

A Note on Placeholder Figures

At the time of this writing, KAPAO-Alpha and its two control computers are installed at TMO awaiting testing. Several images related software and on-sky testing could not be obtained due to inability to access the Alpha computers. Specifically:

Figures:

6.7; 4.7; 4.8; 4.9; 4.10; 4.11

Pencilled place-holder images have been used for these figures in the current version of this thesis.
Chapter 2

Theory

As mentioned in the Introduction, this thesis is primarily concerned with instrument building and testing. Excellent overviews of theory related to atmospheric turbulence, wavefront sensing, and wavefront reconstruction can be found in Tyson’s *Principles of Adaptive Optics* [Tyson(2011)] and Hardy’s *Adaptive Optics for Astronomical Telescopes* [Hardy(1998)]. In addition, Alexander Rudy’s thesis on the KAPAO instrument [?] contains a boiled-down version of the content in these books. While essential for design methodology, this theory is not necessary for a functional understanding of the KAPAO-Alpha instrument, so rather than regurgitate it here, this section will introduce a subject not covered in these texts but important to understanding the design, alignment, and limitations of an AO instrument: Pupil planes and their conjugates. To understand the importance of pupil planes, we will want to first consider the structure of turbulence in the atmosphere.

2.1 Ground Layer Turbulence

Small variations in temperature in the atmosphere create pockets of slightly different density. Because the index of refraction of a medium depends on its density, light from stars is bent slightly as it passes through these pockets:
2.1 Ground Layer Turbulence

Figure 2.1 Light is refracted by differential pressure pockets in the atmosphere.

\[
\frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1} \quad (2.1)
\]

The smaller the average size of these pockets, the more “turbulent” the atmosphere. The parameter used to characterize the size of these pockets is *Fried’s Coherence Length*, often referred to as the “seeing-cell size”—the maximum allowable diameter of a collector before atmospheric distortion seriously limits performance. For plane waves it is expressible as,

\[
r_0 = 1.68 \left( C_n^2 L k^2 \right)^{-\frac{3}{5}} \quad (2.2)
\]

where \( C_n^2 \) is the *refractive-index structure constant*, a measure of the strength of the turbulence in the atmosphere at a given altitude, \( L \) is the propagation distance, and \( k \) is the wave number, both of which are independent of altitude. As can be seen in Figure 2.2, \( C_n^2 \) falls off exponentially with increasing distance from the ground.
Figure 2.2 Observed values for $C_n^2$ at different altitudes. Figure from [Hardy(1998)].

Because the Fried Parameter, $r_0$, characterizes the size of the turbulence cells in the atmosphere, Figure 2.2 shows us that the size of these “lenses” which we have to deal with increases with altitude. A larger cell size means that a wider beam of light can pass through it without being distorted, which means that two stars can be farther apart and still be refracted in essentially the same way.

2.2 Pupil Plane Conjugation

If we only had to worry about correcting for a single point source, the concept of pupil planes that we will develop here would be irrelevant to the AO instrument, and system design would be greatly simplified. Light from a star would form a single collimated beam in the instrument that we could then measure and correct. In reality, however, we are interested in correcting for multiple objects, or objects which are too dim to give sufficient signal to the instrument at the hundreds of hertz speeds at which it operates. Usually, we will want to use one relatively bright guide star to run the AO system, while we image objects of interest close by. Because of their angular separation, the
natural guide star (NGS), and the object of interest will form two separate collimated beams with slightly different angles.

Figure 2.3 Two different sources create two separate collimated beams.

Think of the green and red rays in Figure 2.3 as points on the wavefront coming from the object and NGS respectively. The points overlap at \( a' \), and the only place they overlap again after the beam has been focused and recollimated is at \( a \). This would be just as true for two other points anywhere in the incoming beam. If they overlap at \( a' \), then they will overlap again at (and only at) \( a \).

The pupil plane in Figure 2.3 is conjugate with the lens, which in this simple diagram defines the aperture. If we were to block out a spot anywhere in the two beams at the lens, those spots would overlap again at, and only at, the pupil plane \( a \). The instrument is detecting and correcting the light from the NGS, so if we want to use this to correct the light from other stars, we need to place our corrector at the pupil plane in collimated space conjugate with the place in the atmosphere that the distortion occurs.
Figure 2.4 Choosing where we put our corrector (b or c), determines which layer of distortions is corrected for. The red light is the NGS; the green light is an object that we want to use AO to correct.
In Figure 2.4, we see that the position we choose for our corrector determines what layer of distortion is corrected for the object (green beam). In either case, the corrector will be correcting the entire red beam, but because the aberration of the green beam comes from two different layers, we can only be conjugate with one of them. If the corrector is placed at \( a \), it will correct for the distortions introduced at \( a' \), but the aberrations introduced at \( b' \) to the red and green beams will not overlap at the corrector.

We saw in Section 2.1 that the characteristic size of atmospheric distortions increases exponentially with altitude. Consider Figure 2.4 again, and imagine that the distortions at \( c' \) were several times as large. In this case, by putting the corrector at \( b \), we would also be able to correct for the distortions at \( c' \), since even though the light from the green and red stars passes through different parts of the atmosphere there, the distortions are large enough that the two stars essentially are aberrated in the same way. Because Figure 2.2 tells us that the atmosphere qualitatively behaves in just this way, it makes sense to place our corrector so that the conjugate pupil plane is right at or near the aperture of the telescope, where the distortions will be smallest. For a small “isoplanatic angle”, a cone extending into the atmosphere around the star being corrected, corrections will be essentially the same, since all light coming from within the angle defined by this cone sees the same distortions. In summary:

- Atmospheric distortion is caused by turbulence cells which have a characteristic size defined by Fried’s Coherence Length.
- The characteristic size of turbulence cells grows exponentially with distance from the ground.
- We correct the wavefront of one bright natural guide star (NGS).
- In order for these corrections to apply to objects close to the NGS, it is necessary that the corrector be placed a distance from the collimating lens after the telescope primary such that its conjugate plane is at the place where the atmospheric turbulence cells are smallest.
Because the smallest turbulence cells are right near ground level, we choose to place KAPAO-Alpha’s correcting elements so that the conjugate pupil plane is at the telescope primary. Alpha has two separate correcting elements, and the need to create a conjugate pupil plane at the telescope primary lock down the distance that these must be from the two collimating lenses in the system.

Figure 2.5 The entire instrument has to be built around the distance that the two correctors (in red) must be from their respective collimating lenses in order to form conjugate pupil planes at the telescope primary.

The next chapter will examine in depth each of Alpha’s hardware components and their respective functions.
Chapter 3

Hardware and Assembly

3.1 Overview of the System

KAPAO-Alpha has two separate correcting elements, a tip-tilt (T/T) mirror, and a deformable mirror (DM). To understand the function of these two elements, it is easiest to imagine a slice of the incoming light–the wavefront–at a moment in time.

Figure 3.1 A 2-d visualization of the incoming wavefront being corrected by the DM. Note that the DM needs to be the inverse of the surface of the wavefront at any moment in time to flatten it.

A 2-d visualization of this can be seen in Figure 3.1. For the real wavefront, simply imagine
each distorted line in Figure 3.1 as a crumpled piece of paper. Before it entered the atmosphere, the paper was smooth and flat, but as it travelled through the turbulent atmosphere, pockets of differential pressure refracted the wavefront, causing some parts to travel faster or slower than the others and thus “crumpling” the paper.

The simplest aberration that the wavefront can possess is a tilt—if we took our crumpled piece of paper and tilted it relative to the DM. The DM could correct for this by simply mirroring the tilt, but it has a limited range, as represented by the blue backing in Figure 3.1. If it nears the end of its dynamic range, just correcting for the tilt in the wavefront, the edges of the DM will be unable to correct for the higher-order aberrations in the wavefront, the crinkles in the paper, because the actuators that push and pull the mirror are already at their maximum or minimum extension.

The T/T is a rigid mirror that can move in two axes around its center and is used to correct the overall tilt of the wavefront before it reaches the DM, thus preventing the problems that might arise from the DM tilting close to the edge of its range.

As discussed in Section 2.2, a correcting element needs to be placed at a pupil conjugate with the layer in the atmosphere that we want to correct. Because the T/T and DM cannot occupy the same space, it is necessary to create a separate pupil plane for each one, with both planes being mapped to each other and to the conjugate plane in the atmosphere. The goal of the optics in the instrument is to create these two pupil planes, then split the beam and focus part of it on an imaging camera (what we use to take pictures of the corrected astronomical objects) and send the other part to the wavefront sensor (WFS).
Figure 3.2 Diagramatic overview of the instrument from the telescope through the wave-front sensor.
The schematic in Figure 3.2 shows how each of these steps is accomplished in KAPAO-Alpha. The left side shows the instruments that the light from the telescope hits successively, while the right side shows the optics in between these instruments and the state of the light beam. Following it from top to bottom, we see that a converging beam enters the instrument from the telescope. Before it comes to a focus, the beam is split, and 8% of the light is sent to an imaging camera, placed at the focus of the beam. This camera sees the uncorrected image from the telescope—precisely the same as if the instrument were not there at all. The remaining 92% of the light is collimated by a lens set one focal length away from the focus of the telescope beam. Rather than an actual glass lens, we use off-axis parabolic mirrors (OAPs) in order to eliminate chromatic aberration, see Section 3.2.2. At one focal length away from the first collimating element—the pupil plane conjugate with the primary mirror of the telescope—resides the first correcting element, the T/T mirror. The collimated beam is then refocused and recollimated by two more OAPs. At the pupil plane conjugate with the T/T in this space is the DM. Light reflected from the DM is then focused by the fourth and final OAP. Before coming to a focus, the beam is again split, with 50% being sent to the science camera for imaging, and the remaining 50% being sent to the wavefront sensor optics.

After the last OAP, part of the light is sent to the wavefront sensor, where first a lens recollimates the expanding beam. This collimated beam then passes through a lenslet array—an array of tiny lenses which divide the wavefront into a grid.
Figure 3.3 Each lenslet samples a different part of the wavefront. As long as the lenslets are small enough, any part of the aberrated wavefront sampled by a lenslet looks essentially flat to the lenslet.

The lenslet array (LA) is the basic tool that KAPAO-Alpha uses to detect aberration in the wavefront. As can be seen in the 2-d diagram in Figure 3.3, it works by dividing the wavefront into a grid. So long as the grid is small enough, the wavefront seen by any one of the lenslets will appear flat, and since a flat wavefront entering a lens at an angle just casts a spot somewhere off the optical axis, the distance $\Delta x$ and an unseen $\Delta y$ can be used to calculate the slope of the wavefront incident on the corresponding lenslet.

A final lens resizes the image plane in Figure 3.3 and throws it onto the WFS—an 80x80 high-frequency, low read-noise SciMeasure CCD.

3.2 Component-by-Component Overview

The last section took a bird’s eye view of the system with an emphasis on conceptual function. This section follows a beam of light from the telescope all the way through the instrument, giving detailed information about each hardware component as it is reached.
3.2 Component-by-Component Overview

3.2.1 First Imaging Camera (SBIG)

Figure 3.4 KAPAO-Alpha top-view component overview.
3.2 Component-by-Component Overview

Figure 3.5 The SBIG imaging camera looks directly at the focus of the telescope’s secondary mirror.

The SBIG is our wide-field imaging camera. It looks at the beam directly off of the telescope, and its purpose is to aid in alignment with the telescope.

<table>
<thead>
<tr>
<th>Camera</th>
<th>Resolution</th>
<th>CCD Size</th>
<th>FOV</th>
<th>Plate Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBIG ST-8300M</td>
<td>3326x2504</td>
<td>17.96x13.52mm</td>
<td>396.63x298.58”</td>
<td>22.08”/mm (.119”/pixel)</td>
</tr>
</tbody>
</table>
3.2 Component-by-Component Overview

3.2.2 First Collimator (OAP1)

Figure 3.6 The first collimator prepares a pupil plane for the tip/tilt mirror.

<table>
<thead>
<tr>
<th>OAP #</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Angle</th>
<th>Parent Focal Length</th>
<th>Eff. Focal Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Edmunds</td>
<td>NT69-163</td>
<td>45°</td>
<td>127mm</td>
<td>148.79mm</td>
</tr>
</tbody>
</table>
### 3.2.3 Tilt Corrector (Tip/Tilt Mirror)

**Figure 3.7** The tip/tilt mirror sits at the first pupil in the system and corrects the lowest order aberration: planar tilt in the wavefront.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Dynamic Range</th>
<th>Resolution</th>
<th>Response Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>PZ 149E S-330.2L</td>
<td>2 mrad (412.5&quot;)</td>
<td>20 nrad (0.0004&quot;)</td>
<td>sub-millisecond</td>
</tr>
</tbody>
</table>
3.2.4 Creating the Second Pupil (OAP 2 and OAP 3)

![Image of OAPs with red lines indicating the second pupil]

Figure 3.8 These two OAPs create a second pupil for the DM.

<table>
<thead>
<tr>
<th>OAP #</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Angle</th>
<th>Parent Focal Length</th>
<th>Eff. Focal Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Edmunds</td>
<td>NT69-153</td>
<td>15°</td>
<td>381mm</td>
<td>387.60mm</td>
</tr>
<tr>
<td>3</td>
<td>Edmunds</td>
<td>NT47-085</td>
<td>30°</td>
<td>50.8mm</td>
<td>54.45mm</td>
</tr>
</tbody>
</table>
3.2 Component-by-Component Overview

3.2.5 Expanding the Beam (76.2mm and 150mm lenses)

![Image of beam expanders]

**Figure 3.9** These two lenses double the beam size, allowing it to cover the entire DM.

<table>
<thead>
<tr>
<th>Lens</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Type</th>
<th>Diameter</th>
<th>Focal Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Expander 1</td>
<td>Newport</td>
<td>PAC034</td>
<td>Achromatic Doublet</td>
<td>12.7mm</td>
<td>76.2mm</td>
</tr>
<tr>
<td>Beam Expander 2</td>
<td>Newport</td>
<td>PAC058</td>
<td>Achromatic Doublet</td>
<td>25.4mm</td>
<td>150mm</td>
</tr>
</tbody>
</table>
3.2.6 Correcting the Wavefront (DM)

*Figure 3.10* The DM corrects higher-order wavefront aberration. It is located at the second pupil in the system.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Type</th>
<th># Actuators</th>
<th>Size</th>
<th>Piston</th>
<th>Avg. Step Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC</td>
<td>DM35-140</td>
<td>MEMS</td>
<td>140</td>
<td>4.4mm square</td>
<td>3.5μm</td>
<td>sub-nm</td>
</tr>
</tbody>
</table>
3.2 Component-by-Component Overview

3.2.7 Creating Focus for Science Camera (OAP4)

Figure 3.11 The last OAP brings the (corrected) beam to a focus for the science camera.

<table>
<thead>
<tr>
<th>OAP #</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Angle</th>
<th>Parent Focal Length</th>
<th>Eff. Focal Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Edmunds</td>
<td>NT47-099</td>
<td>90°</td>
<td>50.8mm</td>
<td>101.60mm</td>
</tr>
</tbody>
</table>
3.2.8 Andor Imaging Camera

After being corrected by our DM, the collimated beam is focused by one last OAP and falls on the Andor camera. This is the science camera for our instrument.

![Andor Imaging Camera Image]

**Figure 3.12** The Andor camera images the corrected wavefront.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Resolution</th>
<th>CCD Size</th>
<th>FOV</th>
<th>Plate Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andor</td>
<td>iXon3 888</td>
<td>1024x1024</td>
<td>13.3x13.3mm</td>
<td>118.90x118.90&quot;</td>
<td>8.94&quot;/mm (.116&quot;/pixel)</td>
</tr>
</tbody>
</table>
3.2.9 Detecting Wavefront Aberrations (Lenslet Array and WFS)

Figure 3.13 The WFS leg measures aberration in the wavefront by breaking a pupil into a grid, with each element imaged on to the WFS CCD by a separate lenslet.

3.3 Instrument Assembly

Optical alignment is one part technique and several parts intuition and logical thinking. Unfortunately, the latter is much more difficult to convey than the former. This section presents the techniques we developed to align KAPAO Alpha, and hopefully some insight into the thinking and intuition behind them.
3.3 Instrument Assembly

3.3.1 1:1 Printout

The foundation for aligning our instrument is a 1:1 scale printout. Having designed the Alpha system in Zemax and further modelled it in Solidworks, making the printout is a straightforward process of creating a top-down view drawing in Solidworks, adding and removing lines as needed, and printing with a poster printer.

To facilitate aligning the poster to Alpha’s breadboard, we superimpose the breadboard’s bolt pattern in the Solidworks drawing.

![Figure 3.14](image.png)

**Figure 3.14** Adding the bolt pattern to the Solidworks drawing provides a great reference for poster-breadboard alignment.

The hole pattern is not only helpful for aligning the poster; it also helps when cutting holes out of the poster to bolt optics down.

Each successive optic is first aligned to the poster printout as closely as possible. Where possi-
3.3 Instrument Assembly

ble, we then use additional techniques to fine-tune the alignment, but especially near the end of the system, we have found careful alignment to the diagram to be the most effective and reproducible technique.

Modelling our mounts in Solidworks gives the additional benefit of a quick first-order placement reference for each component:

![Image of instrument assembly](image)

**Figure 3.15** It is easy to place the mounts in the right place to the 1mm level by just carefully aligning their edges to their drawings on printout.

### 3.3.2 All Beams

Careful alignment to the diagram requires a consistent way to check the beam against the line it should be parallel with, and a method for moving the optic being aligned in controllable increments along the axis of interest. We accomplish the first goal with a “target”/“reticle” combination, and the second by a combination of bar and “nudger”.
3.3 Instrument Assembly

3.3.2.1 Target/Reticule to Align Beam to Diagram

When creating the poster, we strategically add reference lines for our target and reticle.

![Figure 3.16 Our basic alignment tools: the target (back) and reticle (front).](image)

First, we use the reference lines to carefully place the target and reticle on the line we need our beam. Now when we point our beam onto the center of the target, we will be able to see how it is aligned relative to the diagram by where the shadow from the reticle falls. Let’s look at a concrete example to see this:
Figure 3.17 Using our target/reticle technique to align to the very first line in the system.

If the beam is not parallel with the line, it will cast the shadow of the reticle to one side of the target’s center:
3.3 Instrument Assembly

3.3.2.2 Bar/Nudger to Translate Mounts

The target/reticle combination is sensitive to just about the smallest nudge that one can make by hand in the optic being aligned. It is therefore necessary to have a technique that allows us to translate the optic precisely. We see from Figure 3.18 that the optic in question, once the beam is centered on it, only needs to be translated along the line of the incoming beam. We want to carefully center it on the incoming beam, then lock it down on this line with a bar. This will allow us to move up and down the beam without worrying about losing the center of our optic.

(a) Mirror needs to move to the left.

(b) Mirror needs to move to the right.

(c) Beam is aligned to the diagram.

Figure 3.18 The target and reticle tell us which way the optic needs to be shifted.
3.3 Instrument Assembly

Figure 3.19 Lock down a bar parallel to the incoming beam, eliminating the undesired dimension of motion.

Once the bar is in place, we move the optic as close as we can get it by hand, lock it down, and add a nudger:

Figure 3.20 Use a nudger to move precisely along the line defined by the bar.
3.3 Instrument Assembly

3.3.3 OAPs

Ultimately, it is only the alignment and separation of the OAPs that we care about—the mirrors in the system are just folding beams back in. The first step in OAP alignment is to treat it as a mirror that needs to be centered very carefully, and align it to the diagram with the target/reticle technique. After that, we have two tools at our disposal to fine-tune the angle that the OAP makes with the incoming beam, both relying on visible aberration that OAPs create when not aligned to their optical axes.

3.3.3.1 Collimated Beam at Distance (OAP 1 and OAP 3)

OAP 1 and OAP 3 create the two common-path collimated spaces in our system. We can throw these beams off of the table to a target several meters away and kill two birds with one stone. First, we get to check collimation of the beam by seeing if there is any expansion or contraction. With a good throw distance, this is a very precise method of checking collimation, and much more intuitive than using a shearing plate or our Thorlabs WFS. Second, small misalignment in the OAP will appear on the distant spot as a vertical, horizontal, or $45^\circ$ squishing of the image.
Figure 3.21 Throwing the beam of OAP 3 off the table to check collimation and angle.

If the OAP is misaligned horizontally, the beam will become squished horizontally or vertically. If it is misaligned vertically, the beam will be squished along a 45° plane. Since at this point we will have made a level incoming and outgoing beam, 45° squishing means that the OAP is misaligned rotationally. We devised a rubber-band technique to make fine adjustments to rotation in this case:
Figure 3.22 The “rubber-band technique” allows us to make fine adjustments to the OAP’s angle while seeing the effects on the distant beam.

It turns out that for our system, OAP 2 introduces so much aberration that this technique is only useful for checking collimation on OAP 3—the collimated beam coming off of OAP 3 looks like a triangle with sides bending in, and squishing introduced by moving the OAP off angle is not noticeable until angle changes far larger than the uncertainty of the target/reticle method.
3.3.3.2 Spot Near Focus (OAP 2 and OAP 4)

OAP 2 and 4 focus a collimated beam. Aberrations analogous to those mentioned for collimated beams can be observed with a CCD near the focus of the beam leaving the OAP.

*Figure 3.23* The effect of misalignment on our 150mm OAP (OAP4). The columns are (from left to right): direction of misalignment, spot before focus, spot at focus, spot after focus.
3.3 Instrument Assembly

3.3.3 Lenses

Aligning lenses is comparatively straightforward: All you have to do is make sure that the lens is perpendicular to the beam, and the beam is already going down the line you want it to. Mark the position of the beam, put the lens in the path, and bring the expanding or contracting beam back to the position that the beam was at—now the lens is centered. The key to using this technique is making sure that the lens remains perpendicular to the incoming beam.

3.3.4 Thorlabs WFS

The Thorlabs WFS is a standalone Shack-Hartmann style wavefront sensor camera that comes with a robust software package.

![Figure 3.24](image.png)

**Figure 3.24** The Thorlabs WFS can be used to check the quality of a collimated beam.

We utilized the Thorlabs WFS almost exclusively as our primary metric for beam alignment in the early stages of learning how to align the Alpha system. We gradually came to appreciate that it has several important limitations:

- It can only be used to examine a collimated beam, and thus is blind to alignment in half of the system.

- If the collimated beam is larger than the CCD, you will get inaccurate Zernike readings (i.e.
it will see aberration that doesn’t exist or fail to see aberration that does exist. A simple example of this is a focus term looking like a tilt in the wavefront if you are only sampling one side of it).

- The sensor needs to be moved with the optic to get a new reading. That is, as the optic being aligned is rotated to improve the wavefront coming off of it, the Thorlabs WFS must move with it to track the beam. This also means that you have to keep a very close eye on the “beam view” section of the software to make sure that you aren’t suddenly looking at only a portion of the beam while making adjustments.

- Like Alpha’s WFS, the Thorlabs WFS needs all of its subaps to function at its best, and therefore a beam much smaller than the CCD is also bound to give unhelpful readings. This excludes the beam directly after OAP 3, since it is so narrow.

Ultimately, the Thorlabs WFS has come to be used only as a tool for recording beam quality in collimated spaces.
Chapter 4

Installation and Alignment to Telescope

4.1 Mounting to Telescope

The primary concerns for mounting the instrument to the telescope were being able to mount it in precisely the same location repeatably, and having a sufficient spread on the bolt pattern to prevent sagging on any part of the breadboard.
4.1 Mounting to Telescope

4.1.1 Mounting Pins

Mounting pins installed on the base of the telescope serve the dual purpose of ensuring that the instrument can be mounted in exactly the same position every time, and making alignment of bolt holes easy.

Figure 4.1 The two mounting pins installed on the base of the telescope allow the instrument to be attached to precisely the same location every time it is bolted down.

The mounting pin holes are smaller than the 5/16” bolt holes beside them, which can be used to quickly determine which way the instrument should be facing when put on the lift to be mounted.
4.1.2 5/16” Bolt Pattern

In addition to the six-hole 5/16” bolt pattern already around the telescope base plate, we have added four bolt holes at the edges to minimize the possibility of warping in the instrument’s breadboard.

![Solidworks drawing of breadboard holes with four holes highlighted in red.]

Figure 4.2 The breadboard has a total of ten 5/16” mounting holes.

Due to the close proximity of instrumentation and optics, not all six of the central bolt holes are easily accessible.
4.2 Aligning to Telescope

4.1.3 Instrument and Computer Boxes

Our instrumentation is secured inside of a 4U Roto Rolling Rack, and the comput

![Figure 4.3](image)

**Figure 4.3** All of KAPAO-Alpha’s instrumentation and the two control computers are contained in two boxes.

Presently, the instrument boxes are left on the lift as seen in Figure 4.3. It is necessary for them to be kept close to Alpha because of several short cables. In the future, these cables will be lengthened and the boxes mounted on the telescope pillars, allowing full-range, worry-free motion of the telescope with the instrument attached.

4.2 Aligning to Telescope

We have installed and tested the instrument on-sky a total of three times. In these test runs, we have succeeded in getting starlight through the entire system, having focused spots on the SBIG
and Andor imaging cameras, as well as the WFS camera. We were successful in obtaining a stable closed loop, but only tip/tilt correction was obvious. We suspect this was due to misalignment in the non-common path optics (the WFS leg), coupled with lack of a reliable technique for checking the alignment of the telescope beam to the system.

In response to the problem of aligning the incoming beam through the instrument, we devised a new technique involving two pellicles and an “alignment camera”. Telescope malfunction has prevented us from testing this new technique on-sky before the writing of this thesis, but demonstration in-lab with a from-the-floor laser (see Section 6.2) strongly suggests that it will work excellently on the actual telescope. Because in-lab testing has made us very optimistic about this technique, we will present the entire procedure, despite lack of in-the-field vetting.

### 4.2.1 Alignment Camera and Motorized Nudgers on 45° Pickoff Mirror

Aligning the beam from a star to Alpha’s optics requires that we point the telescope so that the beam is hitting the right point on the 45° pickoff mirror, then point the pickoff mirror so that the beam is pointing down the right path. It is essentially a 2-step question of “where” and “what direction”

In order to answer the “what direction” question, we use two 8% pellicles (beam-splitters) to look at two different parts of the beam in collimated space:
Figure 4.4 Aligning a star to the instrument requires putting the beam at the right place on the pickoff (a), then pointing the pickoff so that the beam goes through the system in the right direction (b).
Figure 4.5 Two pellicles pick off the near and far end of the collimated beam between the T/T and OAP 2. An iris chokes the beam size down so that it is small enough to be seen as a spot on the Thorlabs alignment camera.
4.2 Aligning to Telescope

The two pellicles in Figure 4.5 are like transparent targets. Where the beam strikes them is recorded by the position of the two spots on the CCD. Since the beam is collimated, there is only one way that it can pass through any two points on the pellicles, and by extension only one way that it can put the spots on the camera in any given configuration.

Figure 4.6 There is only one way that the beam can pass through points A and B. The two pellicles in Figure 4.5 are functionally like these two targets.

If we were looking at the whole collimated beam, the positions of the spots on the camera would completely lock down the beam position. Unfortunately, because the beam is wide compared to the camera, we need to cut it down with an iris, obscuring all but one small portion as shown in Figure 4.5. This means that while there is only one unique angle which will allow the beam to pass through two given points on the pellicles, there are an infinite number of positions that the collimated beam could be in to create these spots—i.e., it could be shifted up or down relative to the iris in Figure 4.5 so that some part other than the center was getting through, and the pellicles and alignment camera would have no way of knowing. Thus the alignment cam answers the “what direction” question—it will guarantee that the beam is running through all the optics at the right angles, but we need an additional tool to determine the “where”.

The problem with the beam being offset is that in the next collimated space, where it is re-
4.2 Aligning to Telescope

flected off of the DM, it would not be centered, and thus the DM would be unable to use all of its actuators, since part of the beam would fall off of the mirror’s active space. Fortunately, we are already looking at the illumination of the DM with the WFS camera. The camera is already centered on the DM when the beam is . We can then adjust the position and direction of the beam in steps, rotating the 45° pickoff mirror to get the angle through the system correct, then moving the telescope to center the illumination pattern on the DM, and repeating this iteratively until the beam is both aligned and centered.

After aligning the entire system to the table laser, we insert the two pellicles and the Thor alignment camera, adjusting the pellicles so that the two spots fall on the center of the left and right side of the CCD:

![Figure 4.7](image)

Figure 4.7 After using the pellicles to align the spots on the two halves of the Thor CCD, we record their positions (the blue circles) and lock everything down. This can now be used to align any incoming beam to the system.

Now the system is ready to be aligned to the telescope.

4.2.2 Center Star on Draco

We first send the telescope to a bright (magnitude 0-1) guide star. Streaming exposures from Draco, TMO’s wide-field finder cam, we use the hand-paddle to adjust until the star is centered on
4.2 Aligning to Telescope

the position on Draco that we know to correspond to the center of the telescope’s field.

![Draco Cam](image)

**Figure 4.8** Center the telescope on a bright star with Draco cam.

4.2.3 Find and Center Star on SBIG and Andor

Next, we explore around this space until we find the star on KAPAO-Alpha’s wide-field imaging camera, the SBIG (using the same technique of streaming exposures). We then nudge the paddle until the star is centered on the Andor as well.

![SBIG and Andor](image)

**Figure 4.9** Center and focus the star on the SBIG and Andor imaging cameras.

If the star is not focused, we also adjust the focus until it is at its sharpest on both cameras.
4.2 Aligning to Telescope

4.2.4 Align Beam to Thorlabs Alignment Camera with Paddle and 45° Pick-off Mirror

We use the two directional nudgers on the 45° pickoff mirror to center the two spots on the alignment camera.

![Image](image.png)

**Figure 4.10** Align the beam directionally through the system using the 45° pickoff mirror and the Thor alignment camera.

4.2.5 Check Spots on Scimeasure

Next, we open the iris and look at the illumination pattern on the DM. If it is not centered, we point the telescope to center it, then realign the beam to the Thor alignment camera. We repeat this process until the beam is both aligned and centered.
Figure 4.11 Move the telescope to center the illumination pattern on the DM. Realign the beam with the Thor alignment camera. Rinse and repeat until both are aligned.
Chapter 5

Software

Our system uses two types of software: First, the Robo-AO code written by Reed Riddle in C++ runs the KAPAO-Alpha AO system, receiving data from the Scimeasure WFS which it uses to calculate corrections for the tip/tilt and BMM deformable mirror. Second, an assortment of tools have been developed in our lab in Python and IDL to examine the performance of the AO loop and troubleshoot problems in alignment etc.

5.1 Wavefront Sensing and Loop Control

The Robo-AO software controls all of KAPAO-alpha’s active hardware, using data from the Scimeasure WFS to calculate wavefront corrections, which it then sends to the DM and T/T mirrors. The software is currently in active development for the Robo-AO LGS AO system (see Section 1.4), and the version running KAPAO-alpha at the time of this writing, referred to as v.2 in our lab, was packaged for us by Mr. Riddle in June 2011.

With the first build of the Robo-AO software passed to our team in Spring 2010, we were also given a 17 page pdf written by Shriharsh P. Tendulkar (see Appendix D) which provides a basic overview of the software’s methodology, as well as some of its important functions and variables.
In addition, Alex Rudy’s thesis from Spring 2011 contains a summary of the Robo-AO software geared specifically toward our instrument.

Much of the work on KAPAO-Alpha between Summer 2011 and Spring 2012 has involved solving and understanding particular issues with the Robo-AO software. This section compiles knowledge that we have gained of the software during this period. The first part of the section attempts to provide an intuitive overview of the software’s functionality by following what happens through startup and one cycle of the AO loop. The second part is intended as a detailed reference to the software, examining all important components, configuration files, and data files that we have gained insight into over the past year.

Our primary goal with KAPAO-Alpha has been a demonstration of on-sky correction, rather than exhaustive analysis and optimization; thus the work during this thesis has mostly been about “getting things running”, along with understanding what particular aspects of the software do, and this chapter reflects that bias.

### 5.1.1 A Journey Through the AO Loop

**Initializing the Loop**

When the loop is started with `wfs_test`, the program first creates a `wfs_test.running` file which is stored in the Status directory of the software. This is a marker to prevent two instances of the code from running simultaneously. The program then initializes the SciMeasure WFS camera by sending it a series of serial commands to set it in the mode the software is configured for. Next, the framerate of the WFS is checked empirically and recorded, followed by initialization of the DM and the software reconstructor. Once everything has been initialized, a menu is presented. We choose to begin the AO loop, and...
Reading Telemetry

Data about the wavefront of our star is falling on the WFS camera (Figure 5.1 (a)). The software needs to record it in a meaningful way.

(a) Collimated light from a star passes through the lenslet array and is focused into points on the Scimeasure WFS CCD.

(b) Spots fall onto CCD. The WFS CCD is divided into 6x6 pixel sub-apertures, with one spot per subap.

(c) Image is binned to 3x3 pixels, making each subap 2x2.

Figure 5.1 The Scimeasure WFS sees spots from the lenslet array, bins image to 26x26. (a) and (b) are taken from the same spot pattern. The red dot in (a) corresponds with the center of the the four quadrants in (b). In (d), the software compares the four pixel values to determine how far from the center of the subap the spot is. Note that the intensities in this four pixel subap correspond to the 80x80 image in (a), where the spot in this particular subap is low and to the left of center.

Let the magnitudes of the four pixels in a subap be represented by $a_i$, where $i = 0, 1, 2, 3$
represents the individual pixels shown in Figure 5.1 (d). The position of the spot in the subaperture is then calculated by:

\[
x = \frac{a_3 + a_2 - a_1 - a_0}{a_3 + a_2 + a_1 + a_0}
\]

(5.1)

\[
y = \frac{a_3 - a_2 + a_1 - a_0}{a_3 + a_2 + a_1 + a_0}
\]

(5.2)

Before this calculation, however, the value of the slopes is checked against the low_light_limit variable. If they are lower than the limit, the low_light_flag is set to 1, and the x and y slopes are assigned values of 0 to prevent the loop from becoming unstable.

**Slope Offsets**

The WFS detects any aberration that has occurred to the wavefront it is looking at. This means that the AO system has the added benefit of being able to remove any small aberrations introduced in the instrument or telescope itself by bad optics or imperfect alignment. But the wavefront passes through several additional optics after the deformable mirror applying the wavefront correction (referred to as the non-common path), so any aberration introduced by the optics between the DM and the WFS will actually result in mis-correction, since the DM will be trying to correct for aberration that occurs in the detector itself.

Were we able to send a perfectly un-aberrated beam through the non-common path, any non-zero slopes measured would be the result of static aberration in the non-common path optics. These values could then be subtracted from the slope measurements of the actual wavefront to cancel the aberration introduced by the non-common path. This is precisely the purpose of slopeOffsets.dat, which is added to the calculated slope values.
5.1 Wavefront Sensing and Loop Control

Slope Linearization

Slopes are not related to the centroid of the spot linearly. In order to convert the relationship to a linear one, the values are compared to a precalculated table, `slope_table.dat`, and adjusted accordingly.

![Figure 5.2](image)

**Figure 5.2** The non-linear relationship between calculated slopes and centroid position: In (a) the spot is centered in the subap and the flux is balanced between A and B. In (b) the spot has moved only about 1/8 of a subap diameter to the right, but the vast majority of the flux now passes through B.

Multiplication by Reconstructor Matrix

Now the slope measurements are finally ready to be used in calculating corrections. This is done in a single matrix multiplication, the result of which is converted into individual voltages for the two T/T axes and each individual DM actuator. After the new positions are sent to the DM and T/T, a new frame is taken with the WFS camera and the process begins over again.
5.1 Wavefront Sensing and Loop Control

5.1.2 Control Programs

The control software has three separate programs: DM Control (move_dm), WFS Imaging (wfs_image), and Loop Control (wfs_test). The DM Control program opens an interface to manually control the positions of the DM and T/T actuators. WFS Imaging allows manual image capture with the WFS camera. The Loop Control program integrates both of these functions, connecting them with the Reconstructor, which uses the information from the WFS camera to calculate new position data for the DM and T/T.

Figure 5.3 The three executables in the control software. WFS Control takes images from the WFS camera, DM Control operates the DM and T/T mirrors, and Loop Control connects these two functions with the Reconstructor to create closed wavefront correction.

Figure 5.4 shows the directory structure and location of important files in the software. Besides the executables located in the bin folder, there are two important components to the software: Configuration files, marked green in the diagram, control parameters used in the software, such
as the exposure time of the WFS camera. Data files, marked pink, contain arrays of data used by the software, like the mapping between the DM control program and the USB numbering for the actuators, or the matrix that the Reconstructor uses to calculate new DM positions from slope values.
Figure 5.4 Important files and folders in the Robo-AO software.
5.1 Wavefront Sensing and Loop Control

5.1.2.1 DM Control (move_dm)

Can be used to control the DM. Call with,

```
sudo ./move_dm
```

The software then initializes the DM. This tends to crash very often—just delete the .running file in the Status directory and keep trying again until it works. It is not unusual for the program to crash 10-20 times before successfully starting up. When it does work, it provides the following menu:

a. Poke one actuator to a voltage
b. Set all actuators to the same voltage
c. Set DM actuators to the same voltage
d. Set non-DM actuators to the same voltage
e. Select an actuator pattern file
f. Move actuators in a constant way
g. Get the status of the DM

(a) Move a single actuator. Syntax is XXX XXXXX, where the first entry is the actuator number (1-140), and the second is the value to move it to (1-65535). For example, 64 20000 would move pull the actuator centered on the WFS CCD back 1/3 of its range.

(b) Move all actuators to the same position. Syntax is XXXXX, where the entry is just the value to moved to (1-65535).

(c) We have not explored this option.

(d) We have not explored this option.

(e) Move actuators to positions specified in a data file. (Blain did this; I haven’t myself; I need to check it out so that I can record how it is done here)

(f) We have not explored this option.

(g) We have not explored this option.
5.1 Wavefront Sensing and Loop Control

5.1.2.2 Image Capture (wfs_image)

Can be used to take .fits images with the WFS camera. Call with,

```
sudo ./wfs_image -p[X] -n[Y] [-options]
```

(X) Tells `wfs_image` which arcetri mode to boot the camera to. The software uses [6] to take telemetry data; use [0] for an 80x80 image. (Y) Number of frames to take (options) Use “f” to tell the program to save the image to file (necessary if you want to look at it afterward). Quite a few additional options are available–see the source code for a commented list–but they involve changing values that are otherwise set by the software’s config files, and since we usually want to see the 26x26 image that the software is seeing, we have never utilized them.

5.1.2.3 Loop Control (wfs_test)

This is the main control for the AO loop. Call it with,

```
sudo ./wfs_test
```

It will create a .running file in the Status directory and perform a few quick software initializations. When it has finished, it presents a menu:

a. Open AO system connection
b. Close AO system connection
c. Start AO loop
d. Stop AO loop
e. Get AO system status
f. Power AO system On
g. Power AO system Off
h. Power AO system Shutdown
5.1 Wavefront Sensing and Loop Control

i. Take AO system background
j. Turn Telemetry on
k. Turn Telemetry off
l. Turn calibration source on
m. Turn calibration source off
n. Check error code
o. Reload configuration files

(a) This will initialize the WFS, DM, and software reconstructor. Information about these processes will read out to the terminal. Must be done once before the loop can be activated.

(c) Sets the run_state flag in wfs_control.cpp to true, initiating loop operation.

(d) Stops the AO loop. When it closes, the total number of frames processed, and skipped (if any) will be read out to the terminal.

(j) and (k) By default, a new line of telemetry data (calculated slopes, intensities, DM positions, etc.) is only recorded every second. This is to avoid excessive data storage use when the loop is running at high speeds. Turning telemetry on makes the code save every line of telemetry data that it uses. The software will sometimes crash randomly in the first few times the loop is turned on and off if this option is not turned on.

(o) Parameters that control aspects of the software’s operation, like framerate, are loaded during initialization, and to update them it is necessary to exit wfs_test. Because restarting takes about 60 seconds even if the software does not crash, this can be very time consuming. This option should allow changing of config files on the fly; unfortunately, it currently causes the program to crash when activated.

5.1.3 WFS Control Configuration Files
5.1 Wavefront Sensing and Loop Control

5.1.3.1 scimeasure.cfg

All of the CCD options in this config file, like REPETITIONS and GAIN have the form

( $A_0 \ A_1 \ A_2 \ A_3 \ A_4 \ A_5 \ A_6 \ A_7$ )

Where the N in $A_N$ is the program number in HIGH_SPEED_PROGRAM_NUMBER (see below).

- FULL_FRAME_PROGRAM_SETTING: Tells the code which EDT camera configuration to load.
- EDT_CONFIG[X]: Points to the SciMeasure config file for program X, where X is between 0 and 7.
- FILTER: We have not explored this setting.
- CLAMP: We have not explored this setting.
- SAMPLE: We have not explored this setting.
- GAIN: We have not explored this setting.
- MAP: We have not explored this setting.

Figure 5.5 Configuration files associated with the WFS.
• **REPETITIONS**: This determines the framerate of the system. We investigated this empirically to see how it is related to the framerate:

\[
R = \left( \frac{1}{f} - 8.97 \times 10^{-4} \right) \times 10^5
\]  

(5.3)

**Figure 5.6** REPETITIONS is linearly related to the exposure time per frame.

The conversion from framerate, \( f \), to REPETITIONS, \( R \), is then

\[
R = \left( \frac{1}{f} - 8.97 \times 10^{-4} \right) \times 10^5
\]

• **BLACKLEVEL[N]** These determine the physical bias of the camera. The form is,

\[
\text{BLACKLEVEL[N]} = (A \ C \ B \ D)
\]

where A,B,C,D are the blacklevel settings for each individual quadcell of the CCD (see Figure 5.7).
5.1 Wavefront Sensing and Loop Control

Figure 5.7 How the displays of our two camera control programs relate to the physical CCD.

Figure 5.8 Empirically observed relationship between BLACKLEVEL setting and counts on covered WFS CCD.

- EDT_CONFIG[N]: Camera mode settings are stored in these. This tells the code where to
look for the settings associated with program N.

### 5.1.3.2 WFS (wfs.cfg)

This configuration file is mostly relevant to us because it points the software to the location of other config files. It is well commented, and thus included here mostly for completeness of this section as a reference.

- **NUM_WFS_BACKGROUND_FRAMES**: We have not explored this setting.

- **DM_CONFIG_FILE**: Points to the DM configuration file, usually named dm.cfg.

- **WFS_CCD_CONFIG_FILE**: Points to the SciMeasure configuration file, usually named scimeasure.cfg

- **DM_START_POSITION**: Initial position of the DM actuators, before the flat map is loaded by the software.

- **TT_START_POSITION**: Initial position of the T/T actuators, before the flat map is loaded by the software.

### 5.1.4 DM Control Configuration Files
5.1 Wavefront Sensing and Loop Control

5.1.4.1 dm.cfg

This short config file sets a few basic parameters for DM operation.

- MAX_VOLTAGE; MIN_VOLTAGE: Sets limit for values that DM actuators can be driven to—prevents damage to DM.

- MAP_FILE: The Robo-AO software stores new voltages to be sent to the DM in an array. Each element in the array is a new voltage for a single actuator. This file maps between the number for each actuator in this array, and the values assigned to the DM actuators in firmware. We call this file dm_map.dat.

5.1.4.2 dm_map.dat

This is the mapping between the numbers that the USB control of the DM uses to identify actuators, and the numbers they are identified by in the Robo-AO software. It is a 160 line file; the line number is the number for the actuator in the Robo-AO software, and the number on the line is the number that the USB connection uses to identify that same actuator.
5.1 Wavefront Sensing and Loop Control

Figure 5.10 The physical mapping of numbers in dm_map.dat. (left) The USB number corresponding to each actuator. (right) The physical DM with actuator 115 (upper left) poked.

5.1.5 Reconstructor Configuration Files
5.1 Wavefront Sensing and Loop Control

5.1.5.1 reconstructor.cfg

This config file contains a number of important variables used in the reconstructor.

- **N_SUBAPERTURES**: Tells the software how many subaps it has to utilize. This is not something we have changed in lab to date, since our hardware is fixed, but it may become relevant later if we want to mask the subaps obscured by the secondary mirror on the telescope.

- **N_ACTUATORS**: Tells the same software how many actuators it has to utilize. As with N_SUBAPS, we have not ever adjusted this.

- **MIN_LIGHT**: This sets a light count for each subap below which the software will not do a slope calculation. It is designed to avoid erroneous calculations that may destabilize the loop in very low light conditions. For the purpose of all our testing to date, it has always been set
5.1 Wavefront Sensing and Loop Control

to 0.

- **SCALAR_GAIN**: Before the reconstructor software sends new voltages to the DM, it multiplies them by this number. This is designed to prevent instability in the loop due to large overcorrections (which could occur, for instance, were the slope linearization not well-calibrated). We have run with a SCALAR_GAIN and TIP_TILT_GAIN value of 1 in lab, without any noticeable problems or deterioration in correction quality—even with an active aberration introduced by our phase screen.

- **TIP_TILT_GAIN**: Same as SCALAR_GAIN, but for the T/T mirror.

- **LEAK_CONSTANT**: The leak constant gives a small preference for the DM to return to its flat_map position, lacking other input. Every correction cycle, the actuators will move LEAK_CONSTANT value toward their flat_map position. This should be small compared to active correction calculated from the WFS image, but prevents systematic instability in which the loop would tend to slowly push the DM to one end of its range.

- **SUBAPERTURES_FILE**: Specifies the location of the subaperture configuration file.

- **ACTUATOR_MAP_FILE**: Specifies the location of the reconstructor matrix that slopes are multiplied by to be turned into DM actuator voltages.

- **FLAT_MAP_FILE**: Specifies the location of the DM flat_map file, which defines the resting position of the DM in software.

- **RECONSTRUCTOR_FILE**: Specifies the location of the reconstructor data matrix.

- **SLOPE_OFFSET_FILE**: Specifies the location of the slope offset file, which corrects for static aberration in the non-common path.
• SLOPE_LINEARIZATION_TABLE_FILE: Specifies the location of the slope linearization table, which scales slope values to reflect the nonlinear relationship of slope values to centroid position.

5.1.5.2 subapertures.cfg

This file maps between subap pixels as they are defined in the software, and the actual number assignments of the pixels as they are read off the camera. The form of each line is

SUBAPERTURE[N]=( P_0 \quad P_1 \quad P_2 \quad P_3 )

where N is the subap identifier in software, and P_i are the four real pixel numbers associated with that subap.

5.1.5.3 slope_table.dat

This file controls linearization of measured slopes. The first line has N, the total number of lines in the file. The following lines are increasing values, from 0 to 1. The line number after the first line is the value of the un-linearized slope, linenumber \times \frac{1}{N-1}, and the number on that line is the linearized value corresponding to it. When the reconstructor linearizes slopes, it looks for the line value in this file closest to the slope it is converting, and changes that value to the entry on that line. For instance, if there were 101 lines in the file, beginning with line 0, and the slope to be converted had a value of .25, the software would take that value and change it to the number on line 25 of slope_table.dat.

We have not constructed a custom slope table, and have been running the system successfully with a purely 1:1 conversion table of 100 values. While the loop is stable in lab, constructing and testing custom slope tables should be an important future project for optimization of the KAPAO-alpha instrument. This may, for instance, allow stable closing of the loop under worse seeing conditions than would be possible without linearization.
5.1.5.4  flat_map.dat

The software uses this file to define the resting position of the DM. Each line, 1-124, corresponds to the actuator assigned that number. We have always set all values to the middle of the DM’s range, 30000.

5.1.5.5  slope_offsets.dat

This file contains values to be added to each slope before they are converted into correction values for the DM and T/T. This allows the software to ignore static aberration introduced by the non-common path optics. It has 97 rows with two numbers on each row. The first is the value to be added to the x slope, the second the y slope. We have not investigated which is which.

5.1.6  Source Code (src)

A significant portion of our time troubleshooting software has involved hunting through the C++ code. It is decently commented, but lacks centralized documentation. The following section is intended as a brief structural overview and reference.

In the top of each directory is a CMakeLists.txt—these files contain instructions for the compiler about how to compile the files in that section and any below it.

All of the important files have two components: The .cpp is the meat of the code, where functions are called and various tasks performed. The .h file declares variables and functions to be used in the .cpp file.

5.1.6.1  Reconstructor and Loop Control (Control/WFS/)

This is the nexus of software operation, bringing code from the Resources and Utils folders together to perform AO correction.
5.1 Wavefront Sensing and Loop Control

reconstructor.cpp / reconstructor.h

Everything involved in wavefront reconstruction is contained here.

- Loads configuration for the reconstructor (slope linearization table, slope offset table, etc.).
- Calculates Centroids (slopes)
- Converts slopes into new DM positions to correct wavefront (matrix multiplication).

wfs_control.cpp / wfs_control.h

This is the code that controls the loop–calling on the reconstructor and hardware.

- Calculates framerate after initialization of the WFS camera. This is the most time-consuming part of software initialization, and we do not understand what its purpose is. Time lost to this process can be decreased by specifying a lower number of total frames to be taken.
- Writes telemetry files (slopes, intensities, DM positions, etc.).
- Initializes the loop, connects to the camera and DM, etc.

wfs_test.cpp

This is the top-level control software. It is essentially a menu which allows the user some flexibility in calling the lower functions.

- Starts the software, loads a menu daemon.

5.1.6.2 Hardware Control (Resources/BMM/ and Resources/SciMeasure/)

The code in these folders communicates with our two major hardware components: The WFS camera and the DM.
5.1 Wavefront Sensing and Loop Control

DM Control (Resources/BMM/dm_control.cpp)

Controls the DM.

- Get configuration information for DM.
- Initialize the DM.
- Set actuator positions.
- Remap actuators.

DM Menu (Resources/BMM/move_dm.cpp)

This is the code that creates a standalone program to control the DM.

- Bring up menu for DM control.
- Uses dm_control.cpp

SciMeasure Control (Resources/SciMeasure/SciMeasure.cpp)

The code here does everything related to controlling and communicating with the SciMeasure WFS camera.

- Get EDT config files.
- Get CCD39 (camera) config files.
- Send serial commands to camera.
- Initialize the CCD.
- Grab a frame.
- Bin images.
• Convert data to .fits format.

• Set up ring buffers (we don’t understand what these do).

**Communicate with Camera (Resources/SciMeasure/little_joe.cpp)**

This code bridges the gap between SciMeasure.cpp and the camera via EDT board.

• Talk to the EDT board

• Called on by SciMeasure.cpp

**Take Images (Resources/SciMeasure/wfs_image.cpp)**

This creates the program to allow user-controlled imaging with the SciMeasure control.

• Take images with WFS camera.

• Has many options we have not explored in lab.

• Uses SciMeasure.cpp.

### 5.1.7 Status

Whenever any of the programs in the bin directory are executed, they create a .running, or “lock” file, which is stored in the Status directory. These files prevent multiple instances of the program from running, since the first thing any of the programs does is check in the Status directory to see if there are any .running files present. If there are, it will throw up a flag and not execute. Since most of the programs crash frequently, it is necessary to always check this folder and delete any .running files before using the software.
5.2 IDL Analysis Tools

In Summer 2011 Blaine Gilbreth wrote a group of IDL procedures to leverage a 2004 reconstructor, created by Lisa Poyneer in IDL, to reconstruct our telemetry data into a wavefront. From the reconstructed wavefront we are able to easily calculate an rms and Strehl Ratio. Also, since the individual IDL functions give us an easy way of interacting with the telemetry data, we use them to create a 2-d visualization of the telemetry data.

5.2.1 Reconstructing the Wavefront

In order to utilize Lisa’s reconstructor code, we need to first take our slope data, convert it into a 3-d matrix, and scale the slope values.

5.2.1.1 Read Telemetry Files (read_telemetry)

The x slope, y slope, intensity, and position telemetry files are all in the format

\[
\begin{array}{c|c}
\text{Datestamp} & \text{Timestamp} \\
\hline
A_1 & A_2 & A_3 & A_4 & \ldots \\
\hline
B_1 & B_2 & B_3 & B_4 & \ldots \\
\end{array}
\]

where each line of the file is a single frame. This procedure takes a datestamp and telemetry type (i.e. x slopes) and opens the corresponding telemetry file. It then extracts the contents into an array, sans the datestamp and timestamp:

\[
\begin{array}{c}
A_1 & A_2 & A_3 & A_4 & \ldots \\
B_1 & B_2 & B_3 & B_4 & \ldots \\
\end{array}
\]

5.2.1.2 Convert Telemetry to 2-d (map_slopes)

In order for Lisa’s Reconstructor to process our slopes, they must be in 2-d arrays where the slope values match the physical positions of the subaps. This procedure takes each 97-element line from
the array created with read_telemetry, and turns it into an 11x11 array, making the previous $97 \times n$ array into an $11 \times 11 \times n$ data cube.

### 5.2.1.3 Convert Slopes to Distances (convert_pixels2nm)

According to the comments, Lisa’s code requires pixel distances to be converted into “nm of phase”. This doesn’t make sense to me (how can you have “nm of phase”?), but I need to understand how Lisa’s Reconstructor works in order to untangle this. The actual calculation is:

$$\frac{slope}{ratio_{over\_sampled}} \cdot \pi \cdot \frac{\lambda}{2\pi} = slope \cdot \lambda \quad (5.4)$$

where $ratio_{over\_sampled}$ is defined in set_wfs_parameters.pro as $\frac{spot\_size}{4} = \frac{1}{2}$. So we are taking slope values and multiplying them by the wavelength of the laser, which doesn’t seem to relate to phase unless there is a linear relationship between offset in subaperture and phase difference in the wavefront.

One additional note: As discussed in Section 5.1.1, slope values are not linearly related to centroid positions. Instead, it is necessary to first apply a calibrated slope table, which we have not yet created. Once we do create one, an important part of the IDL code is probably going to be applying it to the slope values before proceeding.

Ultimately, while one future task for the project is to determine exactly what kind of slope data Lisa’s reconstructor code needs, the reconstructed wavefront that we get by handing it the slope values in their current form is still qualitatively correct. This has not been an important issue for us in simply getting KAPAO-Alpha operational, since what we are interested in is the improvement in the rms and Strehl (see Figure 5.12). When we later wish to characterize closed loop performance on-sky and in lab, however, having this calculation calibrated will provide an essential measurement.
5.2.1.4 Calculate Phase Values of Wavefront (phase_from_slopes)

This procedure takes the prepared slope array and hands it off to Lisa’s Reconstructor via reconstruct_phase_from_slopes, which has its own entire set of procedures. The array returned is a $14 \times 14 \times n$ data cube with each slice being phase values of the wavefront.

5.2.1.5 Calculate RMS and Strehl Ratio

Once given a 2-d array with phase information, calculating the rms is a single function call in IDL. From there, we use a simplified approximation of the Strehl Ratio from [Hardy(1998)]:

\[
\text{Strehl Ratio} = e^{rms^2}
\]  

(5.5)

where rms is in radians ($phase$ in nm $\times \frac{2\pi}{\lambda}$).

![Figure 5.12](image)

**Figure 5.12** The rms and Strehl Ratio plotted against time as KAPAO-Alpha corrects for a static aberration.
5.2.2 Visualize Telemetry Data (show_telemetry)

It is useful to be able to see slope and intensity values as they correspond to the actual subaps. To this end, show_telemetry utilizes read_telemetry and map_slopes to put the slope and intensity data in $11 \times 11 \times n$ arrays. It then combines these into a super-array so that they can all be displayed side-by-side. We then use a versatile image viewing package for IDL, atv, which is able to display the data cubes as a scrollable series of images, making it easy to see the evolution of telemetry data over time in a run.

![Image of atv image viewing package](image)

**Figure 5.13** The atv image viewing package lets us move through the telemetry data for an entire run with a simple slider.
Chapter 6

In-Lab Characterization Results, On-Sky Demonstration, and Future Work

Work to date on the Alpha instrument has been largely focused on assembly, integration, and testing, rather than optimization or exhaustive characterization. This chapter looks at the basic tools and techniques we have developed to test functionality.

6.1 Simulating an Aberration: The “Phase-Screen”

In order to test our static and active correcting ability in the lab, we use a clear-plastic “phase-screen” attached to a motor.
6.1 Simulating an Aberration: The “Phase-Screen”

In Figure 6.2, we see KAPAO-Alpha in action, correcting a static aberration created by the phase screen. The top two images show a full 80x80 pixel image of the spots falling on the WFS CCD. As described in Section 5.1.1, the black gridlines show the individual subapertures. If there were no aberration in the beam, one spot would fall more or less dead-center in every one of the subaps, as in Figure A.47. The uneven surface of the phase screen aberrates the wavefront and decents the spots as seen in (a) of Figure 6.2. Once turned on, KAPAO-Alpha uses this decentering information to calculate positions for the DM and T/T mirrors, iteratively smoothing out the wavefront until it reaches the state shown in (b), with all of the spots recentered in their respective subaps. The improvement over time can be seen in Figure 6.3, where the horizontal axis is in frames, or single iterations of the reconstructor loop. From Figure 6.3 you can see that at present KAPAO-Alpha takes about 20 frames to correct fully for the wavefront aberration.

The corresponding images at the science camera can be seen in (c) and (d). Note that for a changing aberration, the image at the science camera, assuming it integrated for a relatively long period—say half a second or more—would be a large circular blur, rather than the single aberration
seen in (c). The corrected spot in (d), however, would remain basically the same, since it is already concentrated in a circular point.

Figure 6.2 The phase-screen in action.
6.1 Simulating an Aberration: The "Phase-Screen"

Figure 6.3 The calculated rms and Strehl ratio of the wavefront for the above aberration. Note: Loop is running at 920Hz, with each x axis unit being one frame.

In Figure 6.4, we use our IDL telemetry data viewer to look at the evolution of the x and y slopes over time. The slider can be used to move through the whole run, and as would be expected, x and y slopes move toward greater homogeneity for the first twenty frames, then stay in a relatively stable state.
6.2 Aligning to Simulated Telescope with Thorlabs Alignment Cam

In order to test the technique for aligning the incoming beam from the telescope to the instrument described in Section 4.2.1, we built a simulated telescope beam in lab to align to:
Figure 6.5 Our pseudo telescope setup. The final 250mm lens emulates the telescope secondary, creating an f/10 beam which the instrument can then be aligned to.

We support the instrument over this simulated telescope beam with four lab jacks:
6.2 Aligning to Simulated Telescope with Thorlabs Alignment Cam

Figure 6.6 The instrument is held above the simulated telescope with four lab jacks.

These lab jacks allow the instrument’s height to be adjusted so that the focus of the f/10 beam is at roughly the right location (fine adjustment can be achieved by moving the second 250mm lens).

Using the alignment technique described in Section 4.2.1, where pointing the telescope (the “where”) is replaced by translating the table above the beam, we have been able to demonstrate repeatable alignment to and closed-loop operation on the simulated telescope without any adjust-
6.3 On-Sky Demonstration

KAPAO-Alpha has been installed at TMO a total of four times between December 2011 and February 2012. The first installation was primarily a mounting test; on the second we attempted to align the telescope beam through the system with minimal success. With the third and fourth attempts we developed techniques for carefully aligning the pickoff mirror in lab before installing the instrument. On the fourth, we successfully aligned several magnitude zero stars to the instrument and demonstrated stable closed-loop operation.

![Image](image.png)

(a) Open loop (off)  
(b) Closed loop (on)

Figure 6.7 Closed-loop operation on [star]. Note that while there is no visible improvement in the psf of the star, the position on the camera has changed slightly, indicating a stable tip/tilt correction

We suspect that the lack of correction beyond low-order tip/tilt was due to a combination of three factors: (1) Misalignment in the noncommon path optics (the WFS leg). (2) Inability to
properly align the telescope beam to the instrument optics. (3) Particularly bad seeing.

The first problem was identified in lab after this run. In response to the second, we developed the new telescope-instrument alignment technique described in Section 4.2.1, which is currently awaiting on-sky testing.

6.4 Future Work

This thesis leaves KAPAO-Alpha at a very exciting point in its development. We have demonstrated successful correction on in-lab aberrations, and several installations on the telescope have allowed us to devise a new tool for alignment (the alignment camera method described in Section 4.2.1). Unrelated issues with telescope hardware malfunction have prevented another on-sky testing run since the last one in early February, but as of just a few days before this writing, the telescope issues have been resolved. The instrument currently awaits testing on a newly operational telescope, and we are optimistic that it will be able to demonstrate closed-loop correction on-par with in-lab performance.

Once proper correction has been obtained on-sky, the work on KAPAO-Alpha shifts to optimization. Aspects of wavefront reconstruction that we have heretofore left unexplored, such as slope linearization (Section 5.1.1), will be explored in order to determine how significantly they effect instrument performance. Our software tools and techniques for assessing performance will have to be refined—in particular, the IDL code used to calculate the reconstructed wavefront (Section 5.2.1) will need to be examined further in order to make the calculation of rms and Strehl Ratio quantitative rather than merely qualitative.

The results of extensive on-sky testing over Summer 2012 will inform the design of the final instrument, which we hope to fix before the end of the summer.
Appendix A

Step-by-Step Alignment Guide for KaPAO-alpha

First, we want to export our Zemax model so that we can combine it with the Solidworks model.

Once the lines of the Zemax model have been overlaid on the Solidworks model, we can then extend lines where necessary for alignment, and add 1” wide lines for easy placement of the target/reticle combination.
Figure A.1 The completed alignment diagram.

Create a custom 30x38” drawing and insert the 1:1 top view of the model. Save it as an Adobe Illustrator document. Print this to a poster, making sure to check “no scaling” in the printer options. Cut the edges down right through the middle of the outermost line of 1/4”-20 holes, then use these to align precisely to the breadboard and tape the poster down.
Bolt the laser down in the corner of the board shown in Figure A.3 and point it so that the beam passes just in front of the 5” central hole (this will determine where the pickoff mirror goes, so point it with that in mind). Add the iris and roughly center it to the beam.

Note: Make sure that the x and y translation knobs for the laser mount are in the middle of their range.
Figure A.3 Adding the alignment laser and iris.

The first step is to level the beam. Begin by setting the target to a 3” height (use a careful ruler measurement), move the target as close to the iris as possible and adjust the translation of the laser until it is centered, (b). Move the target as far away as possible and adjust the tilt of the laser until the beam is centered, (a). Repeat this process until there is no visible change across the length of the table.
The beam is now level at \( 3" \). Adjust it to the exact height of the OAP centers by using the OAPs themselves. On the back of each OAP is a hole at its center. Adjust the iris to be centered on this hole by expanding it so that the beam is slightly wider than the hole, allowing you to see a ring around the edges. Shift the iris up-down and left-right as necessary to center the ring on the hole (when you close the iris the ring should disappear from all sides at the same time). There is a video of this procedure in the folder containing the original alignment guide notes.

Now the beam is level, and the iris is centered on the exact height of the OAPs. We want to center the beam on the iris. I like to do this with the Thorlabs WFS because it has a sufficiently large CCD and the color intensity map makes the center of the laser beam particularly easy to identify. First center the WFS on the beam:
Figure A.5 Use the Thorlabs WFS to center the leveled laser launch on the iris.

Now close the iris and use the cursor to mark that position, (a). Expand the iris and move the center of the beam intensity to where the mouse is, (b). In the example the laser needs to be translated down and slightly to the right.
(a) Identify center of iris.  

(b) Translate laser to match center.

Figure A.6 Using the Thorlabs WFS to center the laser beam on the iris.

Having a well-adjusted angle on your target and reticle makes alignment much smoother. Get this right off the bat by adding spacer rings in the mounts and carefully adjusting them until the target is level and the reticle is at a 45° angle.
Figure A.7 Add spacer rings to get the angle of the target and reticle just right.

The beam is now level and aligned precisely to the height of the OAPs. Adjust the target to this height—it will be your reference from here on out.
Figure A.8 Adjust target height to aligned beam.

Now that the target is centered on the beam, center the reticle at the beam height by adjusting its height until the shadow is cast on the center of the target.
Figure A.9 Adjust reticle height to aligned beam.

We want to bring the beam into the first line of the diagram with a pickoff mirror. To align the pickoff mirror, we need to carefully place the target and reticle on the lines we printed on the diagram for them:
(a) Place target.

Figure A.10 Carefully align target/reticle on the lines printed for them. Pay special attention to rotation.

Be especially careful that they are perpendicular to the line path; a little rotation will cause them to be significantly out of line with the diagram.

(b) Place reticle.

Place the first mirror approximately, centering the beam down the target/reticle path as well as possible by hand and make sure that the beam is hitting the center of the mirror. Lock the mirror down.
Figure A.11 Place mirror roughly by hand, making sure that the beam is well centered on the mirror.

Set up a bar and nudge as explained in Section 3.3.2.2.
Figure A.12 Place a bar and nudger to fine-adjust the alignment of the first mirror.

Once you have sent the beam along the path defined by the target/reticle as well as possible by hand (don’t waste time trying to get it too perfect), lock the mirror down and use the fine tilt-adjust on the mount to center the beam precisely on the target. The shadow that the reticle casts will then tell you what direction you need to go. Loosen the OAP mount and use the nudger to adjust in the correct direction. Quickly turn the beam back on to the center of the target by hand if it moved significantly, but don’t spend time trying to get it perfect. Lock the mirror down, then use the fine-adjust on the mirror to center the beam perfectly on the target and determine how the mirror needs to be translated from there.

Note: When adjusting the translation of a mirror or OAP with the nudger, start out with bold moves (lots of turns of the nudger). It will save a lot of time if your first move or two overshoot to the other side of the alignment that you need, since this will give you a rough sense of how many
turns you need to get to center. Conversely, if you try to creep up on the correct alignment with small moves instead of overshooting it, you will waste a significant amount of time because you are making unnecessarily small movements.

The aligned beam should look like this:

![Figure A.13 Aligned beam off of the first mirror.](image)

We want to use a 100mm lens to create an f/#=10 beam that matches the one from the telescope. My approach is to use a bar to first get the lens aligned with beam, then put it in roughly the right place along the path. After placing OAP 1 according to the diagram, I will then fine-tune the distance so that the beam coming off of OAP 1 is collimated.

To determine the rough placement of the lens, just add the focal length of OAP 1 to 100mm, and use a ruler to measure that back along the beam path. Mark that place, then put the lens over it.
Figure A.14 Place the 100mm lens in the laser launch path to make the beam emulate the telescope’s f/# and focus point. Use a bar so that you will be able to fine adjust the position of the focus later on without misaligning the lens.

The beam is going straight along the path that we want to the target, which should still be where it was left for alignment (if not, put it back so that the beam is centered on it). Centering the lens is just a matter of making sure it is perpendicular to the beam and then aligning the expanding beam to be centered on the target. Do this carefully by hand, using the iris to resize the expanding beam until it is easy to check on the target. When it is perfectly centered to eye, lock down the lens. Lock down a bar against the lens base and parallel to the laser launch beam, allowing the lens to be moved back and forth without changing its side-to-side alignment relative to the beam.

Note: A short rail would also work here, and would remove the need to be careful about the rotation of the lens relative to the beam when making fine adjustments later.

Note: The position of the lens can be made much more precise by quickly placing Flat 2 and
OAP 1 on the diagram, see Figure 3.15, and finding the place that the beam is collimated coming off the OAP. This will get the lens position correct to 1mm, meaning that you will only have to adjust very slightly two steps down the road. I advise this method; it only requires an additional several minutes.

Align the second mirror with the same bar/nudger technique. Don’t forget in this case to get the first pass alignment by just placing it accurately on the diagram (see Figure 3.15).

![Second mirror aligned.](image)

**Figure A.15** Second mirror aligned.

Align the first OAP with the target/reticle and bar/nudger technique. Be especially careful to get the beam as well centered on the OAP as possible before locking it down and positioning the bar. The only reference we have here is a by-eye examination and the diagram. Because the incoming beam is aligned precisely to the diagram, that means that the most accurate method we have for centering the beam on the OAP is precisely matching the OAP mount to its Solidworks
outline on the diagram—see Figure 3.15.

Figure A.16 Align the first OAP to the diagram.
To fine-tune the collimation and angle of the first OAP, we will throw it off the table to a target several meters distant, and look at the resulting spot with a webcam. I unfortunately do not have a picture of this setup, but we use the same technique for OAP 3, which can be seen in Figure A.27. The shape of the beam may look something like this:
Figure A.18 Spot created by an imperfectly aligned OAP 1 at several meters. The larger image at the top of the screen is created with Windows Magnifier, because the Logitech video software does not support a zoom function.

Adjust the horizontal angle of the OAP to remove the vertical or horizontal squishing. For the above case:
Figure A.19 Spot after the first OAP has been horizontally aligned to the incoming beam.

There is still a 45° squishing. This is the result of the OAP being imperfectly rotated in the mount. Adjust the rotation to eliminate this 45° squishing with the rubber-band technique described in Section 3.3.3.1.
Figure A.20 Use the rubber-band technique to fine-adjust rotation of the first OAP.

The spot should now be circular:
Figure A.21 Spot from fully aligned OAP 1.

Checking collimation is easy with some properly sized graph paper. I print 1cm graph paper from http://www.printfreegraphpaper.com/, then adjust the iris so that the beam coming off of OAP 1 is 1cm (use a ruler and put it as close to the OAP as possible so that the beam doesn’t have a chance to change size). Use a nudger to adjust the position of the 100mm lens until the beam on the graph paper is also 1cm wide.
Figure A.22 Collimating the beam off of OAP 1 with 1cm graph paper.

Align the third mirror to the diagram.
Figure A.23 Aligning the third mirror to the target/reticle.
**Figure A.24** The beam off of the aligned third mirror.
The second OAP focuses a collimated beam, and thus in theory we could fine-tune its alignment by looking at the spot near focus, as explained in Section ???. Unfortunately, the aberration introduced by OAP 2’s surface is so great that it renders this technique infeasible—see Appendix C.

Align OAP 2 and the fourth mirror to the diagram using the target and reticle.

![Align OAP 2 to diagram. You can look at the spot near focus with a camera as in this picture, but the aberration from the OAP is too overwhelming to allow fine-adjustment with this method.](image-url)

**Figure A.25** Align OAP 2 to diagram. You can look at the spot near focus with a camera as in this picture, but the aberration from the OAP is too overwhelming to allow fine-adjustment with this method.

Align the third OAP to the diagram using the target and reticle.
Figure A.26 Align OAP 3 to diagram. Rather than look at the beam with a camera as shown here, throw it off the table to a distant target with the same setup as used for OAP 1 (See Figure A.27).

Throwing the beam off the table with the same setup as OAP 1 will allow you to fine tune collimation but unfortunately you will have to stick to the diagram for angle.
Figure A.27 Check collimation of OAP 3 by throwing the beam onto a distant target.
Figure A.28 Throw OAP 3 onto a distant target to check collimation. The beam is too aberrated from OAP 2 to use this technique for fine angle adjustment.
Align the fifth mirror to the diagram using the target and reticle.

Figure A.29 Align the fifth mirror.

The collimated beam is so aberrated from OAP 2 that it is difficult to align quite as precisely here; that is not a big problem, though, since being off slightly on this angle will not make any difference for the rest of the system.

Align the rail for the beam expander. Use the first lens in the beam expander for this. Leave the target with the beam centered on it at the far end of the table. First roughly place the rail and lock it down with two feet as shown in Figure A.30. Place the lens in between the feet and move it as close to OAP 3 as possible. Tighten the far foot and loosen the near foot. Now rotate the rail around the axis of the far clamped foot until the beam is centered on the target. Lock down the near foot and loosen the far foot. Move the lens to the other end of its range (far end), and pivot
the rail until the beam is once again centered on the target. Repeat this procedure until there is no visible change on the spot’s position as the lens is moved along the length of the rail. The rail is now aligned to the beam.

**Figure A.30** Align the beam expander rail using one of the lenses which will go on it. Move between lens far (diagram), and lens near, switching the loose and tight clamps each time.

Place the first lens as accurately as possible to the diagram. Do the same for the second. Fine-adjust position of the second lens to collimate the beam over a long throw.
Figure A.31 Fine-tune position of second lens in the beam expander by throwing the beam a distance off of the table. The aberration prevents precise measurement, so just adjust until the beam is not visibly expanding or contracting.

Align the DM to the diagram just like the other mirrors. Be especially careful to center the beam on the DM’s active square as closely as possible by eye.
Figure A.32 Center the beam on the active square of the DM.

Align the fourth OAP to the diagram. The angle of OAP 4 can be fine tuned with the spot-near-focus technique discussed in Section 3.3.3.2.

The primary optics of the instrument (not counting the WFS leg) are now aligned!
Before moving on to the WFS leg, we should place the Andor imaging camera as well:

Figure A.33 The system aligned through OAP 4.
A.1 Aligning the Wavefront Sensor Leg

Aligning the WFS optics is relatively straightforward—just three lenses in a straight line, and distances between lenses are measured with a ruler. It is important, however, to be as precise as possible with this alignment, as it appears that the AO loop can become unstable due to a relatively small amount of aberration in the WFS optics.

Figure A.34 Place the Andor at the focus of the beam off OAP 4.

Bring up a live feed from the camera, and center the focused spot on the Andor’s CCD, making sure that the CCD is perpendicular to the beam. Lock the camera down, then add a bar so that you can adjust the focus later while keeping the camera centered on the beam (as in Figure A.34).
A.1 Aligning the Wavefront Sensor Leg

The first step is to set up the beam-splitter:

Figure A.36 Split the light going to the camera off to be shared with the WFS.

Note that the exact angle of this beam is not important, so long as it does not cause the WFS and its optics to run into anything else on the table. Because of the large angle, the beam-splitter mount needs to be placed the direction shown in the diagram, else it will be impossible for the
A.1 Aligning the Wavefront Sensor Leg

beam to pass without being partially obstructed.

We now want to align the 6” rail to the beam. To do this, use the same process described in the beam-expander section:

(a) Place target centered on beam.

(b) Place first lens at near end of rail. Loosen near end, tighten far end. Swing rail until beam is centered on target.

(c) Slide lens to far end of rail. Loosen far end, tighten near end. Swing rail until beam is centered on target.

(d) Repeat from (b) until the beam is always centered regardless of where the lens is.

**Figure A.37** How to align the WFS rail to its beam.
The rail should now be aligned to the beam so that the spot stays centered on the target when the lens is moved up and down the length of the rail.

Don’t move the target until the final lens is set!

(a) Lens near.  (b) Lens middle.  (c) Lens far.

**Figure A.38** Rail aligned to the beam.

Adjust the first lens so that the outgoing beam is collimated. The beam will be very aberrated due to OAP 2, so rather than checking beam size at a distance, use a paper to look along the entire length of the beam and adjust until it is not visibly expanding or coming to a focus. Move the lens through collimation in both directions (seeing the expanding and contracting beam) to get a better sense of where center is.
A.1 Aligning the Wavefront Sensor Leg

Figure A.39 Use paper to check that beam is neither expanding or coming to focus.

Next, add the lenslet array (LA). The LA does not have to be aligned translationally, but make sure that it is perpendicular to the beam. Use a ruler to carefully set its distance from the first lens (see Figure A.35 for distance):
Now put the last lens on the rail. Make certain it is perpendicular to the beam, and adjust it translationally until the spot falls on the center of the target. Set the distance by carefully measuring with a ruler:

**Figure A.40** Use a ruler to set the distance of the L.A.
A.1 Aligning the Wavefront Sensor Leg

Figure A.41 Use a ruler to set the distance of the last lens.

The optics are now all aligned. The last step is to align the WFS camera to the spots coming from the LA.

First, open a live feed from the WFS in pdvshow. Now place the WFS camera roughly until you find the spot pattern coming out of the last lens. If you are not seeing anything at all, you may need to change the gain setting in pdvshow to get a lower framerate (depends on the strength of the ND on the WFS camera). Lower framerates can be obtained from settings 26, 27, and 3.
Figure A.42 Place the WFS camera and adjust until the spots are falling on the CCD.

Open move_dm and set all actuators to 30,000, then set 64 to 20,000. The result should look like this:
A.1 Aligning the Wavefront Sensor Leg

**Figure A.43** All actuators at 30,000; set 64 to 20,000.

Use the knobs to translate the LA until the distortion is centered between four spots.
A.1 Aligning the Wavefront Sensor Leg

Figure A.44 Translate LA up-down and left-right to center the distortion between four spots.

Now move the WFS camera left-right to center the distortion on the middle of the CCD (the red spot on the subap overlay). Make sure that the camera stays perpendicular to the incoming beam. Small adjustments can be made by tapping the camera with the handle of a 3/16 hex driver:
A.1 Aligning the Wavefront Sensor Leg

Figure A.45 Fine-adjust WFS camera position by tapping it with a 3/16 hex driver handle.

Figure A.46 The WFS camera centered left-right.
Once the camera has been centered left-right and locked down, you want to loosen the four bolts on its mount and adjust vertically. Use the same hex driver handle technique by pulling the camera above center and tapping it lightly from the top. Note that, as with left-right, locking the bolts down will almost inevitably change the position of the camera, making this a somewhat iterative, trial-and-error process.

Getting the right up-down placement may offset the left-right alignment. Repeat the previous step to set that again, and iterate as necessary until the camera is well-centered on the spot pattern.

Figure A.47 The WFS camera fully centered on the spot pattern.
Appendix B

Software v2 User Guide
Appendix C

Aberration Introduced by OAPs

Initial attempts to align KAPAO-Alpha consistently ran into trouble after the third OAP. For many weeks, we believed that the problem must stem from insufficiently precise angular alignment of the OAPs. It was finally by accident that we realized the degree of aberration varied significantly depending on what part of OAP 2 the beam was striking, completely independent of angle. Some research led us to the much more robust technique of looking at spots near focus (see Section 3.3.3), which in turn led us to the fact that two of our OAPs introduce significant aberration to an otherwise well-aligned beam.
Figure C.1 The OAP test setup: Prepare a collimated beam to fill the whole OAP surface. Look at spot just before focus with Pulnix CCD.

The results of the test setup shown in Figure C.1:
Figure C.2 Spot just before focus coming off of all four of KAPAO-Alpha’s OAPs.

OAP 2 clearly has a “good” half:
Figure C.3 For OAP 2, the aberration introduced by the inside half is significantly worse than that from the outside half.

Whereas all sides of OAP 3 appear to introduce significant aberration:
Figure C.4 For OAP 3, aberration appears to be introduced by every “half” that you can choose.

It turns out that the aberration on OAP 3’s surface comes from the outside edges. Doing the above test and clamping the beam down to the actual size in the system (about 2mm), there was no aberration observed in the spot near focus. Therefore in KAPAO-Alpha, all the significant aberration is being contributed by OAP 2.
Figure C.5 The beam on OAP 3 is just 2mm in diameter.
Appendix D

Shriharsh’s Robo-AO Software Manual
Bibliography

[Baranec et al.(2011)] Baranec, et al. 2011, Optical Society of America

