ASTRONOMICAL ADAPTIVE OPTICS USING MULTIPLE LASER GUIDE STARS

by

Christoph James Baranec

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SIGNED: Christoph James Baranec
For those I love...
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ABSTRACT

Over the past several years, experiments in adaptive optics involving multiple natural and laser guide stars have been carried out at the 1.55 m Kuiper telescope and the 6.5 m MMT telescope. The astronomical imaging improvement anticipated from both ground-layer and tomographic adaptive optics has been calculated. Ground-layer adaptive optics will reduce the effects of atmospheric seeing, increasing the resolution and sensitivity of astronomical observations over wide fields. Tomographic adaptive optics will provide diffraction-limited imaging along a single line of sight, increasing the amount of sky coverage available to adaptive optics correction.

A new facility class wavefront sensor has been deployed at the MMT which will support closed-loop adaptive optics correction using a constellation of five Rayleigh laser guide stars and the deformable F/15 secondary mirror. The adaptive optics control loop was closed for the first time around the focus signal from all five laser signals in July of 2007, demonstrating that the system is working properly. It is anticipated that the full high-order ground-layer adaptive optics loop, controlled by the laser signals in conjunction with a tip/tilt natural guide star, will be closed in September 2007, with the imaging performance delivered by the system optimized and evaluated.

The work here is intended to be both its own productive scientific endeavor for the MMT, but also as a proof of concept for the advanced adaptive
optics systems designed to support observing at the Large Binocular Telescope and future extremely large telescopes such as the Giant Magellan Telescope.
INTRODUCTION

1. Explanation of the problem and its context

The future of ground-based astronomy in the coming decades lies with the next generation of extremely large telescopes (ELTs) as detailed by the decadal review in astronomy and astrophysics (2001). A top recommendation by the review committee is the development of a 30 m diameter class, segmented, filled aperture telescope. It will dramatically increase the capability of ultraviolet, optical and infrared observations over the current 8 – 10 m class telescopes and usher in a new era of ground-based astronomy. As a result of the size of such a telescope, substantial advances in telescope design and adaptive optics (AO) will be required.

Adaptive optics is a system for dynamically compensating wavefront errors that are introduced into an optical system. Without adaptive optics, the resolution of all ground-based telescopes is limited by turbulence in the atmosphere, typically to around 1 arc second in the visible. With adaptive optics, these telescopes are limited only by diffraction, set by the diameter of the aperture, and the adaptive optics system’s ability to overcome the errors introduced by the atmosphere. As such, adaptive optics will be critical to the success of future ELTs as they will enable resolution exceeding that of both the Hubble and James Webb Space Telescopes.
The requirements for adaptive optics systems on ELTs have been studied extensively and are qualitatively different than for those of current 8 -10 m telescopes (Ellerbroek et al. 2005, Ellerbroek et al. 2006; Fabricant et al. 2006; Johns 2006; Lloyd-Hart et al. 2006a; Stoesz et al. 2006). The amplitude of the Kolmogorov turbulence in the atmosphere increases as the 5/6 power of the telescope diameter while the residual wavefront error after AO correction to reach a given Strehl ratio is independent of aperture size. The AO systems for ELTs will therefore need to correct for a much higher percentage of wavefront error than is corrected for at smaller telescopes. In addition, high-resolution access to the majority of the sky will be essential for ELTs (Oschmann 2004). Since natural guide star AO systems are severely limited in sky coverage, laser guide stars will be required. Focal anisoplanitism, the incorrect sampling of the turbulence due to the finite height of the laser beacon, also increases with the 5/6 power of the telescope diameter. For current 8 – 10 m telescopes using Sodium laser guide stars, focal anisoplanitism is not great enough to prevent diffraction limited imaging, however for ELTs this becomes a dominating term. To overcome this deficiency, multiple laser beacons will be required to completely sample the volume of atmospheric turbulence.

With volumetric information of the turbulence, many flavors of adaptive optics can be implemented. Laser tomography adaptive optics (LTAO) integrates the wavefront error along a particular line of sight within the volume to a science target. This error is then explicitly corrected, giving diffraction-limited imaging
towards the science target with AO correction that drops off with the standard isoplanatic angle seen in single natural guide star adaptive optics. Multi-conjugate adaptive optics (MCAO) attempts to correct the turbulence at discrete heights in the atmosphere. This leads to diffraction-limited imaging over a much wider, up to ~1 arc minute, field of view. Another enabled AO mode, which is unconventional because it is not trying to correct to the diffraction-limit, is ground-layer adaptive optics (GLAO). Wavefront measurements from laser guide stars located far from each other (2 – 10+ arc minutes) can be averaged to estimate the turbulence close to the telescope aperture. When correction of just this low lying turbulence is applied, it will produce a partially corrected field over the large laser guide star constellation.

Before work on the adaptive optics systems of future ELTs can begin, the technologies and techniques first need to be demonstrated. One of the main goals of building a multi-laser AO system for the MMT is to demonstrate that it can indeed be done. Showing that the advanced AO techniques, like GLAO and LTAO, can be used to support science is paramount in convincing the astronomical community that many of the engineering challenges of AO systems on ELTs can be overcome. In addition, the geometry of the AO system at the MMT is a scale model of the AO system being planned for the 25 m Giant Magellan Telescope (GMT), and is therefore particularly relevant to the GMT’s AO design.
The idea of using multiple guide stars in adaptive optics is not new. Multi-conjugate AO was proposed by Beckers (1988) as a way to increase the size of the isoplanatic patch seen by traditional AO systems. Tyler (1994) outlined the use of multiple laser guides stars to overcome the focal anisoplanitism introduced by only using a single laser guide star. The first tests of tomographic wavefront reconstruction were carried out by Ragazonni et al. (2000) with four natural guide stars and Rigaut (2002) proposed the concept for ground-layer adaptive optics as a way to improve wide field imaging. Many of these advanced techniques are just now coming to fruition at many telescopes around the world.

Open-loop validation of GLAO was performed in 2003 at the 1.55 m Kuiper telescope (Baranec et al. 2007). More recently, experiments at the 6.5 m Magellan and MMT telescopes have demonstrated open-loop performance of GLAO and LTAO correction (Athey et al. 2006; Baranec et al. 2006; Lloyd-Hart et al. 2006b, 2005). Experiments at Palomar, using the multiple guide star unit (MGSU), have also demonstrated open-loop tomographic adaptive optics (Velur, 2006).

Adaptive optics systems working in closed-loop with multiple guide stars have so far only used stellar sources. MCAO has been demonstrated at the Dunn and GREGOR solar telescopes (Langlois et al. 2004; Berkefeld et al. 2004). In addition, the Multi-conjugate Adaptive Optics Demonstrator (MAD) was fielded at the VLT in early 2007. Using three bright natural guide stars on a 1.5
arc minute diameter, the MAD was able to demonstrate MCAO, LTAO and GLAO. Unfortunately, due to the limited number of suitably bright natural guide star constellations on the sky, the system will not be able to support routine science observations.

Current closed-loop laser AO systems, with the exception of the MMT, use exclusively a single laser beacon, with the majority being Sodium resonance beacons. These Sodium laser AO systems are now being used at a number of major observatories: Lick, Palomar, Keck, Gemini North, VLT and the Starfire Optical Range. As an example of the scientific impact of these systems, Keck has dedicated approximately 30% of its 2007B schedule exclusively to laser guided adaptive optics observing.

There are future plans to implement multiple laser AO systems at a number of observatories. Gemini South and Keck are jointly developing a 50 W sodium laser which will be split into multiple beacons on sky. At Keck, the laser beacons will be projected onto a 15 arc sec diameter circle to solely support LTAO and mitigate the focal anisoplanatism from their current single laser AO system. At Gemini South, the lasers will cover a much larger field and support MCAO with at least two deformable mirrors.

In addition, plans are underway to implement GLAO at several telescopes around the world with a variety of techniques. The European Southern Observatory will build an AO system with multiple sodium laser guide stars for the Very Large Telescope (VLT) that can work in GLAO mode correcting
a 7.5 arc minute field (Stuijk et al. 2006, Casali et al. 2006). The Southern Astrophysical Research telescope is planning to use a single low-altitude Rayleigh LGS to recover the effects of low-level turbulence, correcting a 3 arc minute science field (Tokovinin et al. 2004c). The Gemini North telescope is exploring the feasibility of a GLAO system using a new deformable secondary mirror and sodium LGS (Szeto et al. 2006). The Large Binocular Telescope (LBT) is including a GLAO mode as part of its NIRVANA multi-conjugate adaptive optics system, which uses adaptive secondary mirrors and up to 16 natural guide stars (Ragazzoni et al. 2003).

Recently there have been plans to add a multi-laser system to the LBT (Lloyd-Hart et al. 2007). The deformable secondary mirrors at the heart of the AO system will be delivered and integrated by the end of 2009 and there is a desire to have a laser AO system operational by then. The current plan is to install two beam projectors, one behind each of the secondary mirrors, which can be used for both Rayleigh and Sodium laser beacons. The design of the laser AO system will be very similar to that of the MMT's laser AO system, with each primary mirror having its own independent AO correction. Each aperture will project six Rayleigh LGS and will use dynamic refocus technology to increase the return from the beacons. The first goal of the AO system will be to enable GLAO mode, with a future implementation of LTAO. In the next year, experiments at the MMT should validate closed-loop LTAO with laser beacons and this will be incorporated into the LBT AO design. The ability to add a sodium laser in the
future will be incorporated into the design as a hybrid Sodium / Rayleigh laser AO system may be critical for higher Strehl on-axis diffraction-limited correction (De La Rue & Ellerbroek 2002).
2. Explanation of the Literature

The following are summaries of the published literature appended to this dissertation.


Observational tests of ground-layer wave front recovery have been made in an open loop using a constellation of four natural guide stars at the 1.55 m Kuiper telescope in Arizona. Such tests explore the effectiveness of wide-field seeing improvement by correction of low-lying atmospheric turbulence with ground-layer adaptive optics (GLAO). The wave fronts from the four stars were measured simultaneously on a Shack-Hartmann wave front sensor (WFS). The WFS placed a 5 x 5 array of square subapertures across the pupil of the telescope, allowing for wave front reconstruction up to the fifth radial Zernike order. We find that the wave front aberration in each star can be roughly halved by subtracting the average of the wave fronts from the other three stars. Wave-front correction on this basis leads to a reduction in width of the seeing-limited stellar image by up to a factor of 3, with image sharpening effective from the visible to near infrared wavelengths over a field of at least 2 arc minutes. We conclude that GLAO correction will be a valuable tool that can increase resolution.
and spectrographic throughput across a broad range of seeing-limited observations.


Adaptive optics to correct current telescopes over wide fields, or even to correct future very large telescopes over narrow fields, will require real-time wavefront measurements made with a constellation of laser beacons. Here we report the first such measurements, made at the 6.5 m MMT with five Rayleigh beacons in a 2 arc minute pentagon. Each beacon is made with a pulsed beam at 532 nm of 4 W at the exit pupil of the projector. The return is range-gated from 20 to 29 km and recorded at 53 Hz by a 36-element Shack-Hartmann sensor. Wavefronts derived from the beacons are compared with simultaneous wavefronts obtained for individual natural stars within or near the constellation. Observations were made in seeing averaging 1.0 arc seconds with two-thirds of the aberration measured to be from a ground-layer of mean height 380 m. Under these conditions, subtraction of the simple instantaneous average of the five beacon wavefronts from the stellar wavefronts yielded a 40% rms reduction in the measured modes of the distortion over a 2 arc minute field. We discuss the use of multiple Rayleigh beacons as an alternative to single sodium beacons on
8 m telescopes and the impact of the new work on the design of a multi-sodium beacon system for the 25 m Giant Magellan Telescope.


We describe results from the first multi-laser wavefront sensing system designed to support tomographic modes of adaptive optics (AO). The system, now operating at the 6.5 m MMT telescope in Arizona, creates five beacons by Rayleigh scattering of laser beams at 532 nm integrated over a range from 20 to 29 km by dynamic refocus of the telescope optics. The return light is analyzed by a Shack-Hartmann sensor that places all five beacons on a single detector, with electronic shuttering to implement the beacon range gate. A separate high-order Shack-Hartmann sensor records simultaneous measurements of wavefronts from a natural star. From open-loop measurements, we find the average beacon wavefront gives a good estimate of ground-layer aberration. We present results of full tomographic wavefront analysis, enabled by supplementing the laser data with simultaneous fast image motion measurements from three stars in the field. We describe plans for an early demonstration at the MMT of closed-loop ground-layer AO, and later tomographic AO.

We describe an innovative implementation of the Shack–Hartmann wave-front sensor that is designed to correct the perspective elongation of a laser guide beacon in adaptive optics. Subapertures are defined by the segments of a deformable mirror rather than by a conventional lenslet array. A bias tilt on each segment separates the beacon images on the sensor’s detector. One removes the perspective elongation by dynamically driving each segment with a predetermined open-loop signal that would, in the absence of atmospheric wave-front aberration, keep the corresponding beacon image centered on the subaperture’s optical axis.
3. Explanation of dissertation format

3.1 Relationship of papers to overall problem

Each of the first three appended papers demonstrates a unique contribution to the understanding of how to use multiple sources for wavefront sensing and correction in adaptive optics. In the first paper, natural guide stars are used in GLAO mode, predicting the image enhancement of such a system. The second and third papers describe the use of laser guide stars in GLAO and LTAO mode, also predicting the image enhancement of the eventual closed-loop system at the MMT.

The fourth paper represents an innovate approach to correcting the perspective elongation of laser guide stars used in wavefront sensing, an effect that arises when the length of the beacon column imaged onto the wavefront sensor is greater than the telescope’s seeing-limited depth of focus. ELTs using Sodium laser guide stars will suffer from perspective elongation in a similar way as the Keck telescope does with its side-mounted laser projector (Contos et al. 2003). Correction of perspective elongation is critical for the use of laser beacons at ELTs and while the dynamic refores system at the MMT can be used, this fourth paper presents an alternate method.

Unfortunately, at the writing of this dissertation, a fifth paper on the results of the closed-loop experiments does not yet exist. The final part of the present study section details all of the work and results from the world’s first
closed-loop multi-laser AO system. This milestone represents a significant leap forward in adaptive optics technology which will lead to the implementation of similar AO systems on current large and future extremely large telescopes.

3.2 Contributions to papers

Appendix A – This paper was a standalone project with the primary contributors being the author, Michael Lloyd-Hart, and Mark Milton.

The author designed the optics for the multi-guide star wavefront sensing camera, wrote a majority of the data analysis software, and solely reduced all of the data. The author was also responsible for the write-up and production of the paper.

Mark assisted in the acquisition of data and produced additional data analysis software. Michael acted as an advisor on the project and gave intellectual support. Matt Rademacher assisted with the mechanical design.

Appendices B and C – These two papers were the result of a large collaborative effort undertaken by the author, Michael, Mark, Miguel Snyder, Tom Stalcup, Nicole Putnam and Roger Angel.

The author was responsible for the optical design and implementation of the natural guide star wavefront sensor, the various wide-field tilt sensors, and beam-splitting optics. The author and Mark developed the data analysis tools and
were responsible for the data reduction. The author provided written contributions and figures for the two papers.

Michael was responsible for a majority of the write-up and production of both papers. The laser guide star wavefront sensor was a joint effort by Jamie Georges, Tom, Miguel, Roland Sarlot, Nicole and Roger. Tom was responsible for the laser beam projector and Matt Rademacher provided mechanical engineering support.

Appendix D – The concept for this paper was originally Michael’s, starting with an idea presented in Brian Bauman’s dissertation (2003) of dynamically tilting subapertures to correct for perspective elongation and extended to include the function of the prism array / lenslet array in a Shack-Hartmann wavefront sensor.

The author derived the equations describing the perspective elongation problem and defined the requirements of a device to correct them. The author was responsible for the write-up and production of the paper.

Michael assisted by providing additional analysis and writing the introduction. Mark conducted several lab experiments in support of the paper.
3.3 Additional contributions

In addition to the work on the papers above, a large commitment of effort went into the closed-loop experiments. The results of this section are a collaboration of the following: the author, Michael, Mark, Tom, Miguel, Matt, Vidhya Vaitheeswaran, Dan Cox, Don McCarthy, Craig Kulesa, Manny Montoya, Keith Powell, Chris Johnson, Steve Moore and Will Bronson.

The author took the role of project manager under Michael’s guidance, which included running and organizing meetings, and preparing schedules for the observing runs. He oversaw the overall layout of the optical and mechanical systems within the wavefront sensing instrument. The author was specifically responsible for the optical design, implementation and tolerance analysis of the natural guide star wavefront sensor, the tilt sensor, the wide field acquisition camera, the on-axis alignment laser and the natural guide star calibration fiber source.

As primary investigator, Michael provided leadership and vision for the project.

Mark wrote new code for the PC based reconstructor to use information from the LGS WFS to generate signals for the deformable secondary mirror. He also supported testing of the PCR with the test stand setup.

Tom was responsible for the electronics layout of the new LGS WFS instrument. He wrote the camera control and system control software. Tom also
set up the test stand environment. With assistance from Keith, Tom developed
an up-beam laser jitter control system.

Miguel transferred the laser wavefront sensor system from the
prototype to the new instrument. He made several improvements to the system,
did additional optical tolerancing, and was in charge of aligning laser wavefront
sensor.

Matt designed the mechanical structure and the custom optical mounts
within the instrument. Matt also provided guidance for Steve and Will, who both
provided manual labor.

Vidhya was responsible for ensuring the new PC based reconstructor
could support the LGS experiments.

Dan and Chris were responsible for supporting the Microgate
reconstructor, and each attended one of the observing runs at the MMT.

Don supplied the experiment with the science instrument PISCES and
both he and Craig supported the instrument during the three runs it was used.

Manny was responsible for wiring up many of the electronics in the
instrument under Tom’s guidance.

Data collection for the experiments was carried out by the author,
Michael, Mark, Tom, Vidhya, Don and Craig. Subsequent analysis was done by
the author, Mark and Michael.
PRESENT STUDY

1. Overview of work

The University of Arizona’s Center for Astronomical Adaptive Optics has a rich history of pioneering adaptive optics. A major milestone was achieved with the natural guide star adaptive optics system for the MMT telescope (Wildi et al. 2003; Brusa et al. 2003). The system includes the world’s first deformable secondary mirror with 336 voice coil actuators, and a 108 subaperture Shack-Hartmann wavefront sensor. It routinely supports observing every trimester and can host a suite of science instruments sensitive from 1.1 to 25 μm.

More recent work has focused on the development of technologies to enable the research presented here. Dynamic refocus was the topic of Georges’ dissertation (2003). By correcting the focus term of a returning laser pulse, it enables the use of Rayleigh laser beacons for wavefront sensing at much greater heights and speeds than previously possible with simple range gating techniques. In addition, the multi-laser projection system at the MMT was the topic of Stalcup’s dissertation (2006). With these technologies demonstrated and operational, the next step was to combine this with the adaptive secondary and create a closed-loop laser guide star adaptive optics system capable of supporting science, which is the topic of this dissertation.
The current research effort is focused on both predicting the closed-loop performance of the laser adaptive optics system at the MMT and building and testing such a closed-loop system. The first experiments of closed-loop performance estimates were done at the 1.55 m Kuiper telescope. There, an asterism of four natural guide stars was used to validate and estimate the correction achievable with a ground-layer adaptive optics system. Following from this, a prototype wavefront sensor instrument was developed for the MMT to use the return from the laser beacons. Open-loop measurements were performed to estimate both ground-layer and tomographic correction of the later closed-loop system. With these estimates in hand, a facility wavefront sensor was designed and built which could be used in closed-loop operation and would be able to support observing with the current suite of F/15 AO science instruments. The next step was then to integrate the wavefront sensor with the adaptive secondary mirror and close the AO loop initially in ground-layer mode.

In the immediate future, ground-layer AO will be used to support science on PISCES (McCarthy et al. 2001), a near infrared imager with 0.11 arc second pixels and a 110 arc second field of view. There are plans for a future science instrument with a similar plate scale and a 4 – 5 arc minute field of view which is described in Appendix E. In addition, ground-layer AO can be used for partial correction of narrow field thermal infrared instruments such as Clio (Freed et al. 2004) in cases where science targets are not close to a sufficiently bright natural guide star to use the NGS AO system.
In the more distant future, the system will be used to enable tomographic adaptive optics correction. This diffraction limited line-of-sight correction mode will be particularly powerful when combined with the spectroscopic arm of ARIES now coming online (McCarthy et al. 1998), and will be of benefit to all current instruments in increasing the sky coverage of adaptive optics correction. Research is also currently ongoing in optimizing the tomographic reconstructor through both measuring the $C_n^2$ profile with covariance calculations of the wavefronts of the laser beacons (Milton et al. 2007) and better understanding the alignment and pupil mapping of the laser wavefront sensor.

The laser AO system at the MMT also has a number of upgrades that are available. The number of laser heads being used can be increased from two to five, eliminating the need for a hologram, increasing the effective laser output on the sky by over a factor of 3, enabling the system to be run at faster update rates and/or with higher spatial sampling. The addition of separate camera heads, one for each laser beacon, will be necessary to increase the spatial sampling of the wavefront sensors, but will increase the flexibility of CCDs used in the camera. Lower read noise detectors will be used, further decreasing the error terms in the system. A new dynamic refocus optical system can be used which has been designed to relay a flat pupil to the wavefront sensor, which may increase the performance of the tomographic AO mode. A variable radius laser constellation would be another upgrade path that would enable the optimization of the correction type to the particular science objective; swing the lasers out wider than
the current 2 arc minute diameter to enclose a ground-layer corrected field, or bring them in tighter when doing tomographic correction.

The current work at the MMT is also laying the groundwork for future multi-laser guide star AO systems at the Large Binocular Telescope (LBT) and the Giant Magellan Telescope (GMT), which both include deformable secondaries. Convinced by the productive results at the MMT, the LBT is now in the design stage of a multi-Rayleigh laser system to initially support ground-layer adaptive optics, which will hopefully be used eventually in a tomographic and multi-conjugate mode of operation. Many of the lessons learned from the MMT system will be transferred over into the design of the LBT system.

The GMT is also planning to use multiple lasers, but because of the sheer size of the aperture, sodium lasers will be required. Many of the same designs in laser projectors and techniques in wavefront sensing can be transferred. Geometrically, the height of the Rayleigh lasers at the MMT is in similar proportion to the telescope diameter as the Sodium lasers proposed for the GMT, making the problem scalable to the larger aperture. The multiple Sodium lasers will make ground-layer and tomographic correction immediately available with expansion to extreme, multi-object and multi-conjugate correction in the second generation of the GMT AO system.

The methods, results and conclusions of the current study are presented in the papers appended to this dissertation. The following is a summary of supplemental material and the most important findings in these documents.
2. Initial experiments at the Kuiper Telescope

2.1. Motivation

The motivation behind this experiment was to explore multi-beacon wavefront sensing and predict the on-sky performance of a closed-loop AO system. Many simulation studies of multi-beacon AO systems have concluded that multi-beacon wavefront sensing could enable various types of AO correction including, GLAO, LTAO, MCAO and MOAO. Prior to the AO system installed at the MMT, there were few experimental studies of multi-beacon wavefront sensing; only Ragazzoni (2000) had published a paper on tomographic wavefront reconstruction using the defocused images of four stars within a small field. To gain insight into multi-beacon wavefront sensing before building the multi-LGS AO system at the MMT, a simpler experiment would be performed at the 1.55 m Kuiper telescope using natural guide stars. It would be quick to implement and would predict the on-sky performance of ground-layer and tomographic AO modes.

2.2. Method

To explore the feasibility of ground-layer and tomographic AO correction, an experiment was designed to record wavefront information from multiple guide stars simultaneously. The performance of a closed-loop system using ground-
layer and tomographic algorithms could then be predicted from the recorded wavefront information.

The natural choice was to do this experiment at the 1.55 m Kuiper telescope which provides an easily accessible and available on-sky test bed environment with little overhead. To further ease requirements on the experiment, only natural guide stars were used.

The next step was to design a camera that could capture wavefront information from multiple sources in a selected field by simultaneously imaging multiple Shack-Hartmann patterns onto a single CCD. To minimize cost, only off-the-shelf optics were utilized. Using the equatorial Kuiper telescope’s F/13.5 configuration, the camera had a 2.5 arc minute square field of view with the constraint that stars be separated by a minimum of 30 arc seconds so that their patterns did not overlap. The pupil was divided by a standard lenslet array into a 5 × 5 grid of square subapertures, 31 cm on a side when projected back to the primary mirror, of which 20 were illuminated. The final plate scale on the camera is 0.57 arc seconds per pixel. A Zemax layout of the camera is presented in figure 2-1.
Figure 2-1. Zemax layout of WFS design showing simulated fields of target stars. From left to right, the optical components: Focal plane of telescope (1), where images of stars are formed, collimating lens (2) which images the pupil onto the lenslet array (3). Next is a field lens (4) that corrects aberrations and following is a relay system (5,6) which images the Shack-Hartmann spot patterns onto a CCD chip (7).

The detector was a 512 × 512 pixel Kodak KAF-0261E CCD with 20 µm pixels, which were binned 2 × 2 on-chip. Since the shortest exposure afforded by the camera’s internal shutter was 100 ms, an external manually operated photographic shutter was used to shorten exposures down to 33 ms on the sky, which still gave high enough signal-to-noise ratio on the camera for the chosen asterism. Figure 2-2 shows the camera attached to the Cassegrain focus of the Kuiper telescope.
Figure 2-2. The assembled wavefront sensor camera attached to the Cassegrain focus of the 1.55 m Kuiper Telescope.

The time between exposures was approximately 2 s, much larger than the exposure time, so that successive frames are temporally uncorrelated. Data were
taken in sequences of 25 frames with 20 dark frames recorded in between each data set for later background subtraction.

The stars used for the experiment form a close asterism in the constellation Serpens Cauda. The four brightest stars range in V magnitude from 9.4 to 10.6, with separations from the central star between 57 and 75 arc seconds.

The useful data obtained from this experiment was taken on the night of 2003 June 17. Figure 2-3 shows an example of the 512 frames of data recorded at 33 ms exposure time over a 67 minute period. The images show four different Shack-Hartmann spot patterns corresponding to the four brightest stars of the asterism with the same geometry as seen on the sky.
The spot positions in the Shack-Hartmann patterns were calculated by the same convolution and parabolic fit method as described in the later analysis of the open-loop data from the MMT, section 3.3.1. The effects of the spot distortion as seen in figure 2-3 are explicitly corrected. For each subaperture, the calibrated mean spot position over all 512 frames was subtracted from its instantaneous position in order to remove the effects of static aberrations. The subaperture slopes were then calculated by multiplying the corrected differential spot positions in each axis by the measured plate scale on the optical axis.

Wavefronts from each of the four stars were reconstructed from the 40 subaperture slope measurements by using a synthetic reconstructor matrix.
derived from a model of the pupil on the Shack-Hartmann lenslet array. The reconstructor matrix creates a vector of coefficients for the first 20 Zernike modes (orders 1-5) from the input slope measurements.

2.3. Results

The main focus of this experiment was to predict and quantify image improvement by using ground-layer and tomographic AO correction. In this experiment, an estimate of the ground-layer turbulence is calculated as the average of three of the stellar wavefronts. The coefficients for each of the 20 Zernike modes are averaged to give the ground-layer estimate, which is then subtracted from the fourth star’s measured Zernike coefficients to calculate the residual error after ground-layer correction. After reconstructing wavefronts from each of the four stars, estimates of GLAO correction were made by averaging the coefficients from three of the stars and using that to predict a fourth star’s wavefront aberration. Table 2-1 shows the RMS wavefront error for each star by Zernike order, along with the residual error after ground-layer correction from the other three stars. The angular separation $\alpha$ between the star and the geometric center of the three other stars used for ground-layer AO correction is also given. It was found that the wavefront error over the modes sensed could be reduced by almost a factor of two-thirds and ground-layer AO correction was found to extend well beyond the diameter of the beacons being used for the correction.
Table 2-1. Wavefront aberration before and after ground-layer AO correction

<table>
<thead>
<tr>
<th>Zernike Order</th>
<th>1 (nm)</th>
<th>2 (nm)</th>
<th>3 (nm)</th>
<th>4 (nm)</th>
<th>5 (nm)</th>
<th>α (arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3468</td>
<td>215</td>
<td>144</td>
<td>93</td>
<td>92</td>
<td></td>
</tr>
<tr>
<td></td>
<td>382*</td>
<td>146*</td>
<td>109*</td>
<td>75*</td>
<td>78*</td>
<td>113</td>
</tr>
<tr>
<td>2</td>
<td>3459</td>
<td>226</td>
<td>144</td>
<td>92</td>
<td>91</td>
<td></td>
</tr>
<tr>
<td></td>
<td>206*</td>
<td>117*</td>
<td>82*</td>
<td>56*</td>
<td>57*</td>
<td>17</td>
</tr>
<tr>
<td>3</td>
<td>3467</td>
<td>232</td>
<td>146</td>
<td>92</td>
<td>91</td>
<td></td>
</tr>
<tr>
<td></td>
<td>276*</td>
<td>122*</td>
<td>85*</td>
<td>60*</td>
<td>60*</td>
<td>65</td>
</tr>
<tr>
<td>4</td>
<td>3461</td>
<td>241</td>
<td>157</td>
<td>98</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300*</td>
<td>142*</td>
<td>102*</td>
<td>72*</td>
<td>72*</td>
<td>85</td>
</tr>
</tbody>
</table>

The RMS stellar wavefront error, summed in quadrature over all the modes in each Zernike order. The numbers marked by asterisks (*) denote residual wavefront error after ground-layer AO correction by the three other stars. The last column reports the angular separation α between the star and the geometric center of the three other stars used for ground-layer AO correction.

A tomographic estimate of star 2 was made from a self referenced least-squares reconstructor, described in more detail in section 3.3.2. The calculated residual error after tomographic reconstruction leads to only a 17% decrease in wavefront error compared to the ground-layer estimation. This is due to the correcting beacons decorrelating quickly as a function of height and therefore not
able to estimate high-altitude seeing which would be necessary for a full tomographic estimate. Unfortunately this means that the geometry of this particular experiment was inadequate for properly testing tomographic correction.

Stellar PSFs were simulated over a range of wavelengths from the visible (500 nm) to the near infrared (2.2 µm) from the residual wavefront errors after GLAO correction. From these PSFs, different metrics of image quality such as spot full-width half maximum and encircled energy were measured and compared to simulated seeing limited PSFs. With the use of natural guide stars, there was noticeable ellipticity with the ratio of major to minor axes of 1.25. However, it is shown in the J band that the radial-averaged stellar FWHM can be reduced by a factor of 3, with FWHM reduction by 42% even at visible wavelengths. EE%(0.5") and EE%(1.0") was also calculated for corrected and seeing limited images. It was determined that in the near-infrared wavelengths (J, H and K) that GLAO correction can give either a resolution improvement of factor of two or with same resolution, increased throughput of a factor of 3.

2.4. Conclusions

The experiment and subsequent analysis suggest that ground-layer AO correction will be a powerful tool for reducing the effects of atmospheric seeing over wide fields and it is clear that there are gains to be made using multiple beacon wavefront sensing. The next logical step would be to attempt this method
of correction in a closed loop AO system. This would need to build on the existing AO hardware available at the MMT, in particular the deformable secondary mirror. In addition, with the scarcity of suitable asterisms of natural guide stars, laser guide stars would be required. With the successful demonstration of dynamic refocus of Rayleigh guide stars and the work on the multi-beacon laser projector for the MMT, the focus shifted to the laser guide star AO experiments at the MMT.
3. Open-loop experiments at the MMT Telescope

3.1. Motivation

The addition of a multi-laser guide star AO system at the MMT is a continual engineering challenge. It was built in multiple stages in order to progressively identify design issues as it was constructed into its final form. To this end, the first step was to build an open-loop prototype wavefront sensor to be used with the MMT’s F/9 secondary. It would be a much simpler instrument than a closed loop system, making it cheaper and faster to fabricate with its primary function to confirm that signals from the laser wavefront sensor could be used to correct for stellar wavefront distortions. This had been shown to work in theory (Lloyd-Hart & Milton 2003a) but had never been previously demonstrated on-sky. The lessons learned from building a prototype wavefront sensor would be invaluable in the design for the later closed-loop system which would be inevitably more complicated and able to accommodate science instruments.

With an open-loop wavefront sensing system, ground-layer AO and tomographic AO with multiple lasers could be tested for the first time. The results of the ground-layer experiment with natural guide stars at the Kuiper telescope could now be compared with experiments at the MMT. In addition, the prototype MMT wavefront sensor could now explore parameters of GLAO in much more detail, such as correction as a function of field and as seeing conditions change. With the much more favorable geometry at the MMT, due to its much larger 6.5
m primary mirror, tests of tomographic wavefront reconstruction would be much more likely to give positive results than seen at the Kuiper telescope.

3.2. Method

3.2.1. Description of hardware

The open-loop experiments at the MMT were supported by two main parts, the lasers and beam projector to generate the five laser-guide stars and the wavefront sensor detectors and associated optics located at the telescope’s Cassegrain focus.

3.2.1.1. Laser guide stars

The laser guide star system at the MMT is the topic of Stalcup’s dissertation (2006) and will be briefly described here. The laser projection system was designed to project 5 Rayleigh laser beacons from behind the secondary of the MMT. The source consists of two commercially available diode pumped Nd:YAG lasers doubled to $\lambda = 532$ nm, each with a rated power of 15 W at 5 kHz repetition rate. The two lasers are combined with a polarizing beam combiner to increase the effective power and have a measured output of 27 W after the output window of their enclosure. The lasers are attached to the side of the telescope in a thermally controlled environment, whence the beam is relayed to a
folding mirror at the top of the telescope tube, and then on to projection optics located behind the secondary of the telescope. A computer generated hologram located near a pupil, with an efficiency ~ 80%, splits the laser beam into a regular pentagon of spots on the sky with a radius of 60 arc seconds. Although this diameter is not ideal for either GLAO, where simulations have shown that fields of up to 10 arc minutes may be desired, or LTAO, where a 40 arc second field may give better on-axis correction, this was a compromise between the two. The 60 arc second radius allowed tests of both AO modes without additional components in the laser projector and return wavefront sensor.

The beam quality from the projector has been tested on numerous occasions (Stalcup et al. 2007b). Laser spot widths are routinely measured at a factor of $\sqrt{2}$ times the measured stellar seeing width, due to the double pass through the atmosphere; meaning the laser projection optics are not limiting performance. The measured widths are seen through both the laser guide star WFS and the entire aperture of the MMT. The smallest spot width measured was 0.73 arc seconds, using only a single laser head, in October 2006 when the seeing was measured at 0.59 arc seconds.

The return from the lasers was last measured in April 2006 at $1.4 \times 10^5$ photoelectrons/m$^2$/J over a range gate of 20 – 29 km above the telescope. This is roughly equivalent to an $m_V = 9.6$ guide star, and the returns from typical Sodium laser guide stars (Ge et al. 1998). With more recent upgrades to some of our optical coatings this return may have increased.
3.2.1.2. Wavefront sensing instrument

The aim of the design for the wavefront sensing instrument was the simultaneous detection of high order wavefronts from the five Rayleigh laser guide stars, a single natural guide star and tilt information from a natural guide star, each using a specialized wavefront sensor (WFS) camera. Using the information from the laser WFS and the tilt sensor, the wavefront as measured on the NGS WFS could be fully predicted. The instrument, seen in figure 3-1, was built as a steel cage, mounting to the Cassegrain focus of the MMT, which allowed modular pieces of the instrument to be placed together in a tight space.

Figure 3-1. Layout of the wavefront sensing instrument: (1) Wide field imaging optics and tilt camera, (2) NGS beamsplitter, (3) natural guide star wavefront sensor optics, (4) closeup of NGS WFS camera, (5) dynamic refocus ‘resonator’ and optics, (6) laser guide star wavefront sensor arm, (7) closeup of LGS WFS Camera.
3.2.1.2.1 Wide-field imaging camera

There are three main platforms of optics on the instrument cage and the first sensor, located closest to the secondary, is the wide-field imaging camera. It serves multiple purposes, as a wide field acquisition camera for alignment and as a separate camera to measure tilt of a natural star. Since it is not feasible to disentangle the atmospheric tilt and beam projection jitter from the laser wavefront sensor, a separate camera trained on a natural guide star is needed to measure atmospheric tilt.

Over several observing runs at the MMT, the wide field camera evolved in its design and functionality. The first incarnation used a video rate Hitachi CCD which was of poor quality. It was used for crude alignment, but because of its interlaced video output, was inadequate for use as a tilt sensor. Later on, the detector was replaced with an E2V CCD67. It was designed to have a 2.5 arc minute field and was able to capture tilt information from multiple stars within the field at a time, which helped improve tomographic reconstruction.

The pickoff mirror for the camera also changed. Originally it was a solid mirror that slid in and out of the telescope axis on an optical rail, but this limited the simultaneous operation of all of the cameras. The first scientific results neglected tilt estimation as this had been exhaustively tested in many other closed-loop AO systems. The solid mirror was then replaced with a stock Edmund Optics hot mirror that reflected light of $\lambda > 700$ nm to the wide field.
camera and transmitted light of shorter wavelengths to the wavefront sensing cameras.

3.2.1.2.2. Beam splitters

Directly underneath the wide field imager is a beam splitting mirror that separates light between the laser and natural guide star wavefront sensors. It was first designed as a custom Omega Optical short-pass dichroic mirror with a cutoff wavelength of $\lambda = 750$ nm and a broadband anti-reflective coating on the back side. The shorter wavelength $\lambda = 532$ nm laser light is transmitted and the longer wavelength visible light was reflected.

With the addition of the hot mirror to the wide field camera, an alternative to the short-pass mirror for the wavefront sensors was needed. At the place of the beam splitter, the laser beams’ footprint did not cover the entire field, so a partially silvered mirror was used to reflect part of the field towards the natural guide star WFS while allowing the constellation of laser beacons to pass through. Each of the beacon footprints can be seen in figure 3-2 with a natural guide star footprint varying from 0 to 1 arc minute in the direction between two beacons. A closeup picture of the partially silvered mirror used is shown in figure 3-3. The mirror is a 3 mm thick piece of BK-7 with a broadband anti-reflective coating on both sides. The optic was masked off with Kapton tape before being spray
silvered. Because the silver tarnished within a few months, the coating needed to be reapplied before each telescope run.

Figure 3-2. Footprint diagram showing the laser beacons and NGS at the beamsplitter.
3.2.1.2.3. Natural guide star wavefront sensor

The natural guide star wavefront sensor is on the second platform along with the beam-splitting mirror. The camera used for this sensor is the spare camera head that is normally used for closed-loop natural guide star adaptive optics at the MMT. An optical relay that converted the incoming light to an F/23
beam was used, replicating the MMT AO optical configuration. It has an adjustable field stop to prevent subaperture misregistration.

The design of the MMT AO camera head (Rhoadarmer 1999) has the lenslet array mounted directly in front of the CCD chip, simplifying its design. The lenslet array is designed to break the telescope pupil into $12 \times 12$ subapertures of which 108 are illuminated and used for reconstruction. Each subaperture covers $6 \times 6$ pixels on the CCD. In normal closed-loop natural guide star AO operation, the camera is binned to act like an array of $2 \times 2$ quad-cells, giving a fast frame rate of up to 1 kHz.

The camera and relay optics were mounted on a set of translation rails, so the whole assembly could be slid perpendicular to the optical axis. This allowed the wavefront sensor to be moved to pickup a natural guide star that was located off-axis along a single direction. This allowed exploration of open-loop AO correction as a function of field. With the original dichroic beam splitter, a full axis of natural guide star correction could be explored, while the silvered beam-splitting mirror only allowed for the positive direction of one axis.

3.2.1.2.4. Dynamic refocus system

The third platform includes both the dynamic refocus system and the laser guide star wavefront sensor. For a more thorough account of these systems, please see Georges’ (2003) and Stalcup’s (2006) dissertations. Directly beneath
the natural guide star beam splitter is a pierced mirror that passes light from the Rayleigh laser guide stars to the dynamic refocus optics and resonator. The dynamic refocus system follows the laser pulse from 20 to 30 km as it passes up through the atmosphere and removes the focus term from the light that is sent to the laser guide star WFS. Because of the parity flip introduced by the mirror in the dynamic refocus optics, the field going back through the mirror is rotated 180 degrees. The pierced mirror has through holes drilled in it to allow the reflected beams to pass. The refocused laser light then enters the laser guide star WFS.

3.2.1.2.5. Laser guide star wavefront sensor

The laser guide star wavefront sensor used in this experiment is of a novel design. Images of each of the five Rayleigh laser guide stars first pass through a periscope structure to demagnify the field, and their common pupil is imaged onto a prism array (Putnam et al. 2004). With interchangeable prism arrays, the pupil can be broken into 36 or 60 equally sized subapertures in a hexapolar geometry, which are then reimaged onto a single detector. The detector is a Lincoln Labs CCID18 chip with a built in electronic shutter, with a resolution of 100 ns, that allows range gating the returning laser light from each pulse from 20 to 30 km. The detector can be run at a rate of up to 915 frames per second.
3.2.1.2.6. Wavefront camera synchronization

The two WFS cameras were run asynchronously. Data capture was externally registered by the use of a flashing LED in front and to the side of each camera. The LEDs illuminated the detectors simultaneously at the start of data capture and would flash the chips again for a single frame at regular intervals to make sure that the data streams were synchronized. The LED trigger was integrated into the camera control software developed for this project.

3.2.1.2.7 F/converter

One last optical system that was introduced in later experiments was the F/9 to F/15 converter. More details can be found in Stalcup (2006). As preparations were made to utilize the wavefront sensing instrument with the F/15 secondary, it was decided to redesign the optics to accept F/15 light while still using the F/9 secondary. The F/converter simulated the F/15 light when the instrument was paired with the F/9 secondary. When the prototype instrument was first to be used with the F/15 secondary, September 2005, it was simply removed from the system.
3.2.2. Experimental design

The open-loop experiments at the MMT were designed to test ground-layer and tomographic adaptive optics using a constellation of laser beacons. To accomplish these tests, simultaneous wavefront information from the lasers, and a natural guide star were needed. The reconstructed laser wavefronts, with optional tilt information from a natural star, were used to make an estimate of the reconstructed natural guide star’s wavefront. The residual difference between the estimate and the measurement of the natural star’s wavefront represents the limit in performance that could be expected in a closed-loop adaptive optics system.

The experiments spanned a period of time from June of 2004 to April of 2006, including four telescope runs. During the first run, simultaneous data from both sets of wavefront sensors was not collected, but much was learned about the system and how to make improvements for subsequent runs.

The second run, in September 2004, marked the first time simultaneous data was captured from both the laser and natural guide star wavefront sensors. The two cameras were running at 50 frames per second with data taken in sets of 9 second intervals. A bright, $m_V \sim 5$, natural star was placed at five different locations from the center of the laser constellation, enabling exploration of adaptive optics correction as a function of field. The laser wavefront sensor was fitted with the 36 subaperture prism array, so correction was estimated from Zernike radial orders 2 through 6. Simultaneous tilt measurements were not
taken as this was a hardware limitation which would be overcome for the following run.

For the telescope run in June of 2005, there was a major upgrade to the system. A new tilt camera allowed the imaging of multiple tilt stars within a 2.5 arc minute field simultaneous with the wavefront sensor cameras. Data sets were taken as a series of simultaneous frames recorded at 100 frames per second for 60 seconds. Ground-layer AO performance, including tilt, was estimated using a bright star located from 0 to 85 arc seconds from the center of the laser constellation. Tomographic performance was also estimated at this frame rate with a bright star using the higher spatial resolution laser wavefront information collected with the use of the 60 subaperture prism array allowing reconstruction up to Zernike radial order 8. Additional tomographic estimation was done while observing an asterism of 4 stars, $m_V = 10.7$ to 12.6, in NGC 6811, at 50 frames per second. With this data, prediction of the wavefront for the central natural star was made only from the lasers and tilt information from the surrounding three stars.

In April of 2006, the closed-loop version of the top-box was fielded for the first time. With the exception of the wide field of the tilt camera, all of the functionality of the previous instrument was preserved and this is discussed in more detail in the closed-loop experiments section. The instrument was only operated in open-loop mode and some improvements were made. Data collection could now be made at 200 frames per second from all three cameras,
with data sets lasting typically 60 seconds. Ground-layer and tomographic correction were predicted using the lasers and a single bright star which could be steered anywhere in the laser constellation field.

3.3. Data reduction
3.3.1. Wavefront sensor data processing

The results of the open-loop experiments have all been based on the successful reconstruction of wavefront information from Shack-Hartmann camera data. Shack-Hartmann cameras are derivative, or slope, wavefront sensors. The pupil of an incoming wavefront is broken up into smaller subapertures, as with a lenslet array or a prism array, and the local slope over that subaperture is measured by the relative position of the image compared to a flat wavefront’s image position. Once the image motion in each subaperture is measured, and therefore the local slope of the wavefront, the overall phase of the wavefront over the entire pupil can be reconstructed. For a more detailed description of a Shack-Hartmann wavefront sensor, please see Hardy (1998). Since the wavefront slope is directly related to image position, a very accurate method is required to determine image position. As the aberrations introduced by the atmosphere change with time, the individual images, also known as ‘spots’, appear to dance around a mean position in an approximately random Gaussian way. In these experiments, the objects to be imaged through the Shack-Hartmann cameras are
either natural guide stars, effectively point sources at infinity, or dynamically refocused laser guide stars, which have a Gaussian width in intensity. Both are imaged through the atmosphere and are thus subject to the blurring effects of the atmosphere. Typically, the images of the natural guide star is seeing limited, $\lambda/r_0$, and the laser guide star images are of $\sqrt{2}$ times the seeing limit, due to the double pass through the atmosphere. Example frames of the laser and natural guide star WFS cameras can be seen in figure 3-4. Note the same data reduction pipeline was used to analyze data from the Kuiper experiment (section 2).

Figure 3-4. Example WFS data: natural guide star WFS (left) and laser guide star WFS (right), running at 460 frames per second, from April 2007.
3.3.1.1. Centroiding algorithms

The first step in the data reduction process is to identify the position of each of the spots, known as centroiding. Although this may seem like a trivial task, most of the data reduction research time was spent finding the best algorithms which could both accurately calculate the spot position and do it in a reasonable amount of time. There are many different algorithms that were tested, and as better algorithms were developed, they were integrated into our data processing pipeline.

3.3.1.1.1. Iterative PSF deconvolution

The first set of reducible data from our laser WFS, from September 2004, was of very poor quality and a very robust method of finding the image motion from each of the subapertures was needed. Figure 3-5 shows an example frame from the laser WFS. The images suffer from a low signal-to-noise ratio, the majority of which was caused by an inferior detector which had a poor modulation transfer function, causing a >2 pixel full-width at half maximum response to a less than half-pixel illuminating spot.
An iterative deconvolution method was used to calculate the spot positions from this data. For each given spot in the image that covers a set of \( i \) pixels, there are associated intensities for each pixel, \( d_i \). Since the images should be roughly Gaussian in shape, an estimate of the image is constructed over the same set of pixels with values \( g_i \), assuming a Gaussian function centered at some nominal best initial guess of the spot location, \( x, y \). An error function is
created to measure the norm of the difference between the image and its estimate averaged over all of the pixels,

\[ R^2 = \langle |d_i - g_i|^2 \rangle. \]  

(3.1)

One then wants to minimize \( R^2 \) by adjusting the parameters \( x \) and \( y \) in the Gaussian function. To do this, the partial derivatives of \( R^2 \) with respect to \( x \) and \( y \) are expressed analytically. A gradient descent algorithm is then used to iterate on changing \( x \) and \( y \) until the decrease in \( R^2 \) becomes small compared to a predetermined threshold value.

Although this algorithm ended up giving useful information from very poor data, allowing publication of the first paper on wavefront sensing with multiple laser guide stars (Lloyd-Hart et al. 2005), it was extremely slow, taking several days to process a few hundred frames, and was not suited to the amount of data which would be acquired in future runs.

3.3.1.1.2. Center of mass

Another useful algorithm for centroiding is the center of mass (COM). The image position is calculated separately for each axis by first summing along the rows or columns of a subregion of an image. For each element in this summed
vector, there is an associated pixel position, \( p_i \), and summed mass, \( m_i \). The center of mass coordinate, \( c^{\text{COM}} \), is then given by,

\[
c^{\text{COM}} = \sum_i p_i m_i / \sum_i m_i.
\]  

This algorithm is used in many closed loop AO systems because of its low computational overhead; however it does have some drawbacks. It is sensitive to any DC signal in the data, either due to a bad background subtraction or a bias drift in the CCD. It can also be non-linear in its response if the image is not fully contained within the sub-image used for the calculation. In this case, a look up table (LUT) needs to be precalculated. LUTs can be made by first realizing a finely sampled image, centered at regular small steps, of the spot and binning down to the required resolution. The center of mass position is then calculated and compared to the position of the spot where it was created. In this way, the non-linearity can be calibrated out. LUTs tend to be linear around the center of their sub-image, when a majority of the intensity from the spot is contained, and roll off near the edges. If the LUT does not perfectly model the system to be calibrated, errors can occur in the slope measurements. However, because of the near-linear behavior near the center, a simple gain factor can be used to compensate for modeling errors. For this reason, most closed-loop AO systems...
that try to drive spots to the center, or ‘null’, of a 2 × 2 or 4 × 4 detector use this center of mass centroiding algorithm.

It has been found that using the center of mass centroiding for offline data analysis is good for giving fast results, but since the spots in the laser WFS data do not necessarily lie near the center of a 2 × 2 or 4 × 4 cell, and background subtraction is not always perfect, the results are not always very accurate. If aligned properly, the spots in the natural guide star WFS should be positioned on pixel boundaries and the center of mass algorithm is used during closed-loop operation with the natural guide star AO system. For some of the open-loop experiments using the natural guide star WFS, there were large static aberrations that reduced the fidelity of wavefront reconstruction when using the center of mass algorithm.

3.3.1.1.3. Peak tracking via Gaussian cross-correlation

A much slower, but more robust method of centroiding was developed in order to overcome the drawbacks of using the center of mass inaccuracies. This involves finding the correlation peak of the spot image with an idealized image. For an idealized image, a Gaussian with a similar FWHM to that of the image is used. Because the Gaussian is both real and even, the cross-correlation is exactly the same as a convolution, and as such, any DC signal in the data does
not affect the measurement. This method is also more immune to non-linearities since the cross-correlation is less dependent on the tails of the image PSF.

If a cross-correlation using the same pixel scale as the original image is attempted, an estimate of the image position is limited in its precision to a single pixel. In order to achieve sub-pixel resolution, the image must be resampled by an integral factor several times finer than the CCD pixels using the block replication method. A Gaussian of matching FWHM on a grid with the same number of resampled pixels is then realized. After computing the cross-correlation, the pixel with the maximum amplitude is identified, and its coordinates are the estimate of the spot position.

For the natural star WFS data, two resampling factors were originally used, 10× and 100×. When using 10× sampling, and a 5 × 5 sub-image, ~12000 frames of data could be processed in 1 hour. This gave good results, but was further improved by using 100× sampling, which could process only ~150 frames per hour. To answer the question of whether taking the extra time to run the 100× was actually worth it, Monte Carlo simulations were run. In the simulations, a higher resolution (typically 400×) idealized Gaussian spot was created in a random position on a sub-image. It would then be binned down to the resolution of typical data. The fake spot was then rescaled to match the total energy from a typical data image, with photon and read noise then added. The cross-correlation algorithm was then run on the simulated spot and the error in the centroid measurement was then recorded. For simulations matching typical data, the 10×
sampling was only good to about a tenth of a pixel, meaning the centroid estimate was limited by the algorithm. However, when using 100× sampling, the best precision achievable was \( \sim 1/30 \) of a pixel. This meant a limitation set by the noise in the system. This precision varied from data set to data set as a function of both image signal, photon noise and read noise, so it was decided to use the 100× sampling since it would most likely get all of the information possible using this method, even if it took slightly more time.

3.3.1.1.4. Parabolic fitting refinement to Gaussian cross-correlation

As the amount of open-loop data recorded on successive runs increased, it became increasingly important to find a centroiding algorithm that was much faster than the 100× Gaussian cross-correlation, yet just as accurate. A solution was found in a paper by Poyneer (2003), which described a method of centroiding by fitting a parabaloid around the peak of a function. The peak of a parabolic function is given by

\[
c_{\text{Parabolic}} = x + \frac{f(x + \Delta x) - f(x - \Delta x)}{f(x + \Delta x) + f(x - \Delta x) - 2f(x)} \times \frac{\Delta x}{2},
\]

(3.3)

where \( x \) is the location of the peak pixel, \( \Delta x \) is the pixel spacing, typically 1, and \( f(x) \) is the value of the pixel at \( x \). Essentially this formula takes the peak pixel and
the two pixels on either side to calculate the location of the peak of the fit paraboloid. Attempts to try this method on the raw data gave erroneous results, as the data were not very smooth. However, this method does work well after refining the result given by the 10× resampled Gaussian cross-correlation as the convolved image has been effectively blurred. Instead of just picking the peak pixel in the cross-correlation, if a parabolic fit is applied, one can get below the tenth of a pixel precision. In the Monte Carlo simulation of the 10× Gaussian cross-correlation with parabolic refinement, there was no noticeable additional error over the 100× Gaussian cross-correlation. Once this had been discovered, all of the newer data is now processed with this algorithm, being as fast as the 10× and as accurate as the 100× Gaussian cross-correlation.

3.3.1.1.5. Sub-image selection

All of the above algorithms for calculating the centroid of an image require a sub-image of the total image to be effective. For example, in figure 3-4, of the natural star WFS data, there are 108 spots whose locations need to be calculated. Each frame of data needs to be broken up into small boxes that each contain a single spot upon which the algorithms can run. There are many ways in which boxes for each spot can be defined and they are described below.

The simplest approach is the ‘fixed box’ method. Given a set of data, a mean frame can be computed. The coordinates of a box around a mean spot
image can then be defined in terms of pixel coordinates. For each frame of data, the spot position is calculated within those pixel coordinates. This works well for data where the spots do not move very close to the edges of the box. However if they move close to the edge, or even outside, the centroiding algorithms are not smart enough to realize this and still return a calculated position based on the available pixel data which is not reflective of the actual spot position.

A more dynamic method is the ‘floating box’ method. With this method, a box is constructed around a spot in the first frame of temporally correlated data set. Once the centroiding algorithm has calculated the spot position, the position is then used for the center of the box in the subsequent frame. This method works under the assumption that the frame to frame motion of the spot is small compared to the box size and that the box is free to float around and track the spot with time. One of the downsides to this method may occur if two adjoining spots get too close to one another. In this case, the box may have two spots within its boundaries, confusing the centroiding algorithm. The floating box may lock onto the wrong spot and be confused during the rest of the data analysis.

A further refinement is the ‘rubber-banded box’ method. This is basically a mixture of both the fixed and floating box methods. Similar to the fixed method, a mean centroid position is computed, as well as the previous frame’s centroid position. (For the first frame the mean position is used as the previous frame’s centroid position.) The search box is then centered on the average of those two positions. This gives the search box the flexibility to follow a spot if it is near the
edge but does not let it go too far from the mean position, keeping it from tracking neighboring spots except during large sigma events. In practice, this method has worked best on the natural star WFS data.

Another method developed specifically for the laser WFS is the global center of mass offset. The boxes for each spot are defined on the mean/first frame of the data set and the center of mass of the entire frame is calculated. In subsequent frames, the center of mass of the entire frame is calculated again and the initial boxes are shifted by the difference in the global center of mass. This has proven to work well as the spots in the laser patterns don’t move much relative to each other but the overall patterns move by, at times, several pixels. This gross movement is due largely to the jitter caused by the vibrations in the laser beam projector, and is largely in a single direction.

3.3.1.2. Wavefront reconstruction

For each subaperture, the calibrated mean spot position over all frames in a given dataset is subtracted from its instantaneous position in order to remove the effects of static aberrations. The subaperture slopes are then calculated by multiplying the corrected differential spot positions by the measured plate scale. To recover the wavefront over the entire pupil, the calculated slopes need to be multiplied by a reconstructor matrix which is a linear operation converting them into Zernike amplitude coefficients.
A reconstructor matrix is calculated by first making a model of the pupil geometry on the lenslet or prism array that will subdivide the pupil. An example of this model can be seen in figure 3-6. Each color represents a different subaperture corresponding to a different spot in the natural star WFS data in figure 3-4. Within each subaperture there should be enough points to adequately describe its geometry. As a general rule, subapertures that are less than 50% illuminated are not included in the reconstructor calculation. In addition, if there are any subapertures that are not used, due to defects in optics, these can be accounted for by specifically excluding them in the model.

Figure 3-6. Pupil model of the F/15 MMT natural star WFS camera. Each color corresponds to a different subaperture of the Shack-Hartmann lenslet array.
For the model in figure 3-6, individual unit amplitude Zernike, or any other suitable basis set such as disk harmonics (Milton & Lloyd-Hart 2005) or Karhunen-Loève, mode phase maps are realized over the entire pupil. The phase maps are then divided according to the subaperture model. For each subaperture, a 2-D least-squares solution to the best fit plane is calculated. From the fit parameters, the corresponding slope is calculated. An influence matrix is thus derived that links each unit amplitude Zernike mode with the slope offset for every subaperture. In order to then create a reconstructor matrix, the influence matrix must be inverted. This can be done using a number of methods for inverting non-square matrices; however for all of the MMT reconstructors Singular Value Decomposition (SVD) has been used. With SVD, there is an option of conditioning the inverted matrix to eliminate singular or near singular eigenvalues of the matrix to be inverted. In practice, it has been found that there is no need to truncate the singular values so long as the order of Zernike modes to be reconstructed is less than the number of subapertures spanning the pupil on the WFS. Once the reconstructor matrix is created, Zernike amplitude coefficients are generated from the WFS data by multiplying the slope vector by the reconstructor matrix.
3.3.2. Estimation of adaptive optics correction

One of the main goals of the open-loop experiments was to prove that the wavefront information recovered from the laser wavefront sensor could be used to predict the wavefront from a natural star. In a closed-loop system, this prediction would be used to command a deformable mirror to correct the natural star’s wavefront. In the open-loop tests, the residual error is calculated as the difference between the prediction and measurement of the natural star’s wavefront. Based on the amount of residual error, it is possible to calculate how well an adaptive optics system will perform using image quality metrics such as image full-width at half-maximum (FWHM), encircled energy (EE) and Strehl ratio.

3.3.2.1. Ground-layer adaptive optics correction

In these experiments, an estimate of the ground-layer turbulence is calculated as the average of the five reconstructed laser wavefronts. The Zernike amplitude coefficients are averaged and compared to the coefficients of the stellar wavefront and the residual is used to predict ground-layer AO correction. Atmospheric turbulence close to the ground is common to the star and each laser beacon, while higher altitude aberration, different for each beacon, will be mitigated in the average. Since all field points share this common ground-layer
turbulence, the use of GLAO promises a reduction of stellar wavefront aberration over a wide field.

3.3.2.2. Tomographic adaptive optics correction

Tomographic estimation is the 3-dimensional reconstruction of turbulence in the atmosphere. In the simplest application, the instantaneous wavefront from an astronomical object is estimated by integration through the volume along the line of sight to the object, and the compensating phase is applied to a single deformable mirror. The technique, often called laser tomography AO, will deliver a diffraction-limited field of view limited by the normal isoplanatic angle.

3.3.2.2.1. Geometric tomographic reconstructors

One approach to building a tomographic reconstructor is to model the geometry of the laser beacons and the science target to be corrected on the sky and through a model atmosphere. More detail on this type of approach can be found in Hardy (1998), Roggemann & Welsh (1996) and Rodier (1999). Typically a model of the atmosphere includes a layer of turbulence at the ground with one or more layers of turbulence located at higher altitudes. The model atmosphere can be improved with any measured $C_n^2$ data available, as described in Milton et al. (2007), but it has been found that there is a shallow minimum in
reconstruction performance regarding the quantity and heights of higher altitude layers that are modeled (Lloyd-Hart & Milton 2003b).

Once a vertical profile of the atmosphere has been modeled, a meta-pupil at each height is constructed. The meta-pupil is the largest circle of each layer which contains the footprints of the laser beacons and natural stars. For each layer, each element of the reconstruction basis set (such as Zernike polynomials) is realized as a phase map over the meta-pupil. Next, the sub-pupil corresponding to the beacon or stellar footprint on the meta-pupil is masked off. The resultant phase map on the sub-pupil is then projected onto the entire basis set. In this way, an influence matrix is calculated relating the basis set of modes at each meta-pupil to a set of measured modes for each beacon.

Two matrices need to be calculated to determine the tomographic reconstructor. The first matrix is a reconstructor that determines the modes on each meta-pupil from the wavefront information from the laser beacons. This is done by inverting the influence function of meta-pupil modes on the laser wavefront information. This is typically done using SVD and in practice requires careful conditioning as noise can be easily amplified with this inversion technique. The second matrix is the influence matrix relating the modes of the meta-pupil to the stellar wavefront modes. The product of these two matrices gives the tomographic reconstructor which maps the measured modes from the laser beacons to the modes seen in the stellar wavefront.
An improvement to this method is the use of a different type of pseudo-inverse for the matrix inversion. Any additional information about the statistics of turbulence or noise can be used to give a better inverse when using a maximum a posteriori (MAP) inverse (Flicker et al. 2000; Rodier 1999). This technique has not yet been used, but may improve future results of generating geometric tomographic reconstructors.

3.3.2.2.2. Least-squares tomographic reconstructor

Another approach to building a tomographic reconstructor is the least-squares approach. In this case, a best-fit reconstructor is computed from both the reconstructed laser and tilt wavefront information and the reference natural star wavefront. From a full set of this wavefront information, a reconstructor can be calculated, and applied to either the same set of data to estimate the information content and noise floor from tomographic reconstruction, giving a limit on how well it can perform, or used on future data as would be the case if implemented while observing on sky in a closed-loop system. The least-squares reconstructor inherently models all geometry, turbulence profiles and noise, although projecting this information out from the reconstructor has yet to be calculated.
The tomographic reconstruction assumes a linear relation between the wavefront of the natural star and those of the lasers and tilt stars, represented by the equation

\[ \hat{a}_i = T b_i, \]  

(3.4)

where, for the \( i \)th frame in a data sequence, \( \hat{a}_i \) is the vector of Zernike polynomial coefficients characterizing the estimate of the natural star’s wavefront, \( b_i \) is the vector containing the Zernike coefficients of the lasers’ and any tilt stars’ reconstructed wavefronts, and \( T \) is the optimal linear reconstructor matrix relating the two. The reconstructor \( T \) needs to be found such that it minimizes \( \langle |a_i - \hat{a}_i|^2 \rangle \), the squared norm of the difference between the natural star’s measured wavefront coefficients \( a_i \) and their estimates, averaged over all the frames.

To investigate the limit of performance permitted by the data in this least-squares sense, \( T \) is derived by a direct inversion of the data, using singular-value decomposition (SVD). This approach does not rely on any a priori model of the atmospheric \( C_n^2 \) profile or knowledge of the noise characteristics. A matrix \( B \) is constructed from the data vectors \( b_i \). \( B \) is typically well conditioned and so may be inverted with singular value decomposition to give \( B^+ \) with no truncation of the singular values. A similar matrix \( A \) is constructed from the corresponding \( a_i \) vectors. The optimal linear reconstructor is then given by

\[ T = AB^+. \]  

(3.5)
Applying $T$ to vectors $b_i$ drawn from the same data set used to compute it yields the best-fit solution $\hat{a}_i$ and characterizes the noise floor in the data. It gives an estimate of the best the system could perform on-sky. The reconstructor $T$ can also be applied to another measurement of vectors $b_i$ taken at another time. In practice it would be possible to calculate $T$ on-sky with a bright star, then go to a dim science target and use the reconstructor for correction.

3.3.2.3. Temporal filtering

In every case of comparison between the laser and natural star modes, for ground-layer, tomography or single beacon correction, it was found that temporally filtering the laser modes increased the performance of correction. Figure 3-7 shows an example power spectrum of a single mode from one of the laser beacons. There is a slope in the power spectrum, decreasing in power at higher frequencies, until a noise floor is reached at about 10 Hz. Beyond this point, the signal is dominated by noise. Temporally filtering the data by using a low pass filter greatly improves the fidelity of all modes of correction with the beacon. It was also found that this cutoff frequency decreases with increasing spatial frequency of the mode, or radial Zernike order. In practice, the cutoff frequencies would be determined manually for each order and a low pass-filter would be implemented on the laser wavefront information. Some of the earliest
data needed to be filtered to 3 Hz, while improvements to the CCD and increased signal-to-noise ratio have led to filtering only at the 30 Hz level.

Figure 3-7. Power spectrum of an astigmatism mode from a single laser beacon. Data were taken in open-loop in April 2007 with a ~400 Hz frame rate. The knee in the spectrum occurs around 10 Hz.

3.3.2.4. Point-spread function (PSF) simulations

3.3.2.4.1. Generation of PSFs

Simulated point-spread functions (PSFs) of both the natural seeing and post adaptive optics correction can be created based on the recorded Zernike
amplitudes and measured coherence length. For each frame of data, a random pupil phase map obeying the measured Kolmogorov statistics is created with inner and outer scales of 2 mm and 100 km, respectively. In this way, the effects of uncorrected high order aberration and measurement uncertainty are included in the PSF estimates. Each frame’s PSF is generated by calculating the power spectrum of the complex amplitude pupil map with the final long-exposure PSF image being the sum of all the individual frame PSFs. If desired, servo lag can be introduced by delaying correction by an integral number of frames.

For the seeing limited cases, Zernike modes are fit and subtracted up to the radial order of reconstruction and replaced with the modes as measured off of the natural star wavefront sensor. For the ground-layer and tomographically corrected images, the same Zernike modes are fit and subtracted and replaced with the Zernike modes measured from the residual of the AO corrections. The simulated PSFs are therefore based on the measured modes themselves, not their statistics.

3.3.2.4.2. Calculation of image metrics

From the simulated PSFs, many image metrics can be computed. Image FWHM can be useful in determining achievable resolution and rough energy concentration which can affect exposure times. The FWHM from each of the generated PSFs was measured by using the rimexam tool in IRAF. A Moffat fit to
the resultant PSF with manual adjustment to the beta parameter was used to
determine the FWHM.

Another useful metric is encircled energy. This is of more importance in
spectroscopy where light from a target needs to be fed down a fiber or slit of a
certain size when projected on the sky. PSFs used for encircled energy
calculations typically need pixel scales of at most $\lambda/4$, with finer sampling
required in high Strehl regimes, with fields large enough to enclose >99% of the
total energy. The first step to calculating the metrics is using a simple script that
finds the cumulative amount of energy as a function of radius from the center of
the PSF. From these curves, metrics such as EE%(0.5''), the amount of encircled
energy within a 0.5 arc sec diameter, or $\theta_{50}$, the diameter within which 50% of the
energy is contained, can be calculated.

In regimes where the AO correction brings the total residual error below
$\sim 1/4$ of a wave at the science wavelength, Strehl ratio is a useful metric. This is
calculated as the ratio of peak intensity between the aberrated PSF and a
diffraction limited PSF with no aberration.

3.3.3. Atmospheric parameter estimation

The aberrations produced by turbulence in the atmosphere can be thought
of as random variables that obey certain statistics. In the data reduction, the
integrated effects of the turbulence, seen on the Shack-Hartmann wavefront
sensor cameras, are projected into a set of Zernike amplitude coefficients. In subsequent analysis, it has been assumed that the atmosphere obeys either Kolmogorov (Noll 1976) or von Karman statistics (Ishimaru 1978). Although neither fully characterizes the atmosphere, useful information about the turbulence such as its overall strength, the Fried parameter, $r_0$, and, in the case of von Karman, the outer scale can be recovered.

Characterization of the ground-layer of turbulence can also be made from the data. The percentage of total power in the ground-layer can be calculated from ground-layer AO residuals. The turbulence-weighted mean height of the ground-layer can also be estimated based on the anisoplanatic nature of correction of a single star with a single laser beacon.

3.3.3.1. Kolmogorov power spectrum

Kolmogorov statistics are defined by having a spatial power spectral density given by

$$\Phi_n(\kappa) = 0.033 C_n^2 \kappa^{-11/3},$$

(3.6)

where $C_n^2$ is the structure constant, and $\kappa$ is the spatial wavenumber vector. For a given strength of turbulence, $r_0$, there exists an amplitude of the variance of
each individual Zernike mode. The variances of modes within the same radial order are all the same. All of the variances are of the form,

$$\sigma_i^2 = k_i (D/r_0)^{5/3},$$

(3.7)

where $k_i$ is a coefficient based on the particular Zernike mode and $D$ is the telescope diameter. The values of $k_i$ have been calculated by Noll (1976).

For the data reduction, the amplitudes of the Zernike coefficients are calculated on a frame by frame basis. Over a whole data set, the variances for each of these modes are calculated and with equation 3.7, $r_0$ can be estimated for each mode, or more practically, $r_0$ for a given radial order of Zernike modes. A script has been written which uses these equations and calculates $r_0$ given a set of Zernike coefficients. An example output bar chart is presented in figure 3-8. If the data perfectly obeyed Kolmogorov statistics, the $r_0$ calculated for each order would be the same. Smaller values of $r_0$ indicate more power in that order. Note that there is excessive power in the first order modes, tip and tilt, with the majority of this power due to telescope shake and pointing error. This error adds in quadrature with atmospheric tilt and it is impossible to disentangle the two with just the camera measurements. There is also excessive power in the higher orders, such as in order 9 in figure 3-8, caused by noise in the camera. Since the higher orders are at higher spatial frequencies, they are much more sensitive to random noise in the CCD camera.
Since the estimates of $r_0$ vary by order, it is hard to get an accurate assessment of the overall strength of the atmospheric turbulence with just a single parameter. In the presence of the outer scale, which reduces power at lower spatial frequencies, the asymptotic $r_0$ value was estimated by using modes that were negligibly affected by both outer scale and noise. In earlier work, $r_0$ was estimated by averaging the calculated values for $r_0$ from orders 3 through 7. For the data in figure 3-8, this gives an estimate of $r_0 = 17.0$ cm at $\lambda = 500$ nm.
3.3.3.2. Von Karman power spectrum

Von Karman statistics are defined by having a spatial power spectral density given by

$$
\phi_n(\kappa) = -\frac{0.033}{\sigma_n^2} \frac{C_n^2}{(\kappa^2 - \kappa_0^2)^{11/6}} \exp\left(\frac{-\kappa^2}{\kappa_m^2}\right),
$$

(3.8)

where the exponential is approximated by 1 when the inner scale is small, typically millimeters, compared with the size of the Shack-Hartmann subaperture size. \(\kappa_0\) is the wavenumber representation of the outer scale, \(L_0\), and is related in the following way: \(\kappa_0 = \frac{2\pi}{L_0}\). In the case of an infinite outer scale, the von Karman and Kolmogorov PSDs are equivalent. When the outer scale is finite, it has the effect of reducing the power of the turbulence in the lowest Zernike order modes. At the MMT, it has been found that \(L_0\) varies from about 8 to 45 meters or more.

A method to jointly estimate the values of \(r_0\) and \(L_0\) from the measured variances of the Zernike coefficients from the data has been devised. Similar to the equations found in Noll (1976), Chassat (1992, eq. 2.43) describes the variances of Zernike modes given both \(r_0\) and \(L_0\). This is reproduced below in a slightly modified format.
\[ \sigma_n^2 = 1.168(n + 1) \times \left( \frac{D}{r_0} \right)^{5/3} \times \]

\[
\sum_{p=0}^{\infty} \frac{(-1)^p}{p!} \left( \frac{2\pi D}{L_0} \right)^{2p+2n-\frac{5}{2}} \frac{\Gamma[p + n + \frac{3}{2}] \Gamma[-p - n + \frac{5}{6}] \Gamma[p + n + 1]}{\Gamma[p + 2n + 3] \Gamma[p + n + 2]} + \\
\sum_{p=0}^{\infty} \frac{(-1)^p}{p!} \left( \frac{2\pi D}{L_0} \right)^{2p} \frac{\Gamma[-p + n - \frac{5}{6}] \Gamma[p + \frac{7}{3}] \Gamma[p + \frac{11}{6}]}{\Gamma[p + n + \frac{23}{6}] \Gamma[p + \frac{17}{6}]} \right)
\]

(3.9)

where \( n \) is the radial order of the Zernike mode. The terms in the infinite sums quickly converge to zero, so in practice, a calculation of how many terms are necessary given a particular \( D \) to \( L_0 \) ratio, will significantly speed up subsequent calculations. For the case of the MMT with an effective \( D = 6.3 \) m (the F/15 secondary mirror is undersized to reduce thermal background) and \( L_0 \) being as small as 8 m, it is only necessary to calculate the first eight terms in the series.

To make a joint estimation of \( r_0 \) and \( L_0 \), the following error function is calculated

\[
\epsilon^2 = \max_{n=2} (n + 1) (\sigma_n^2 - \sigma_n^2)^2,
\]

(3.10)

where the tilde represents the measured average variance of modes within a radial order and max is the maximum radial order of modes used in the calculation. The \((n+1)\) term accounts for the number of modes in a given order. The first order modes are excluded from this calculation since they are never
purely atmospheric and always have some extra power due to tracking error or telescope shake. The values of $r_0$ and $L_0$ are found which minimize $\varepsilon^2$ by using a minimization algorithm such as the FindMinimum function in Mathematica. When using FindMinimum, an initial guess and starting range of acceptable values for each of the variables is required, otherwise the function may not converge. Starting values that have worked well for reducing data both at the MMT and Kuiper telescopes are $r_0 = 10$ cm and $L_0 = 30$ m, with ranges of $10$ cm $< r_0 < 35$ cm and $0$ m $< L_0 < 40$ m. The ranges given are not absolute limits and searches outside of these values can occur.

As an example of how this procedure works, this method will be used on the same data presented in figure 3-8. The measured values for the total standard deviation by order of the Zernike polynomials are presented in table 3-1. Running the minimization problem we find that $r_0 = 15.8$ cm and $L_0 = 13.2$ m. If we then run the forward problem, we find the predicted standard deviation from these $r_0$ and $L_0$ values.
Table 3-1. Measured vs. fit values of RMS power by Zernike order for the data found in figure 3-8.

<table>
<thead>
<tr>
<th>Zernike Order</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured Standard Deviation (nm)</td>
<td>1711</td>
<td>327</td>
<td>236</td>
<td>174</td>
<td>142</td>
<td>116</td>
<td>101</td>
</tr>
<tr>
<td>Fit Standard Deviation (nm)</td>
<td>470</td>
<td>327</td>
<td>237</td>
<td>172</td>
<td>138</td>
<td>112</td>
<td>94</td>
</tr>
<tr>
<td>RMS Delta (nm)</td>
<td>1645</td>
<td>0</td>
<td>22</td>
<td>26</td>
<td>33</td>
<td>30</td>
<td>37</td>
</tr>
</tbody>
</table>

The fit does a reasonably good job at predicting the lower order modes; however it suffers from some error with the noisier higher order modes. The predicted amount of atmospheric tilt is much different than measured; again showing that tilt measured includes additional non-atmospheric power. Notice that this von Karman estimate of $r_0 = 15.8$ cm is only slightly less than the previous Kolmogorov estimate of $r_0 = 17.0$ cm, and is a refinement on what was attempted with Kolmogorov statistics by not using modes that looked like they were affected by outer scale effects.

3.3.3.3. Estimation of ground-layer parameters

The amount of power in the ground-layer turbulence compared to the total integrated atmospheric power can be calculated. Once the integrated $r_0^{\text{total}}$ is calculated, the contribution of this from the free atmosphere, $r_0^{\text{FA}}$, is calculated
from the residuals after ground-layer AO correction. The residual variances of each mode are put through the above algorithm to determine $r_0^{FA}$. Since ground-layer AO does not correct for the free atmosphere, anything that is not part of the ground-layer, the residuals must be due to the higher altitude turbulence. Since the Fried parameter adds to the power of $-5/3$,

$$r_0^{total -5/3} = r_0^{GL -5/3} + r_0^{FA -5/3},$$

(3.11)

the strength of the ground-layer, $r_0^{GL}$, can be calculated. The percentage of total power in the ground-layer is then just $r_0^{GL -5/3} / r_0^{total -5/3}$.

Another key parameter for ground-layer AO is the thickness of the ground-layer, since it determines the corrected field of view. Very little is known about the ground-layer from current site surveys because the ground-layer AO concept is quite recent, and the ground-layer thickness has almost no impact on any other observing mode of a telescope. The thickness during observations has been estimated by a method which examines the anisoplanatic behavior of the stellar wavefront with respect to the individual LGS wavefronts. The RMS difference between the two with angular separation $\theta$ is expected to grow as $(\theta/\theta_0)^{5/3}$. The isoplanatic angle $\theta_0$ for the ground-layer is related to the turbulence-weighted mean height $h$ of the layer through $\theta_0 = 0.314 \cos \zeta \left( r_0 / h \right)$ (Hardy 1998).
3.4. Data analysis

The results presented in this section are summaries of the most important results found in the papers in appendices B and C and in Baranec et al. (2006). Full results can be found appended or in the appropriate references.

3.4.1. Results of open-loop ground-layer adaptive optics correction

Open-loop ground-layer AO correction has been demonstrated during three of the observing runs at the MMT, in September 2004, June 2005 and April 2006. During these runs, a natural star was placed at varying radii from the center of the laser constellation; however only a few data sets from April 2006 were analyzed. Tilt data was not generally presented in the results since the lasers are insensitive to tilt.

Data recorded in September 2004 was taken under seeing conditions of ~1.1 arc seconds, the 75th percentile of the MMT’s seeing conditions over the past two years. Ground-layer wavefront reconstruction estimated the 25 modes of Zernike orders 2 through 6 from the laser guide stars. Ground-layer correction of this data yielded an average 38% improvement in RMS wavefront aberration over the full field enclosed by the beacons, and extended well outside the constellation. This can be seen in figure 3-9 which shows the residual stellar wavefront error after ground-layer AO correction as a function of angle from the
center of the laser constellation. Calculations of the mean height of the ground-layer turbulence put $h_{GL} = 380$ m.

![Figure 3-9](image)

**Figure 3-9.** Wavefront correction of starlight on the basis of the average laser guide star signals for Zernike orders 2 through 6. The dashed lines show the uncorrected error while the solid lines show the RMS residual wavefront phase after ground-layer correction as a function of angular distance between the star and the geometric center of the laser guide star constellation.

In June of 2005, data exploring ground-layer correction as function of field was obtained in seeing of ~0.5 arc seconds, the 15th percentile of seeing at the MMT. This is also plotted in Figure 3-9 for comparison. For this data, when the
seeing was already excellent, ground-layer correction was consistently beneficial across the field, although the fractional improvement within the constellation was actually less at 25%, with correction not extending as far beyond the beacon radius. This may be explained by the fact that the mean height of the ground-layer was calculated at $h_{GL} = 530$ m. As this height increases, the isoplanatic patch outside the laser constellation will naturally decrease.

Additional data in June was collected for the tomography experiments with the higher order reconstruction up to Zernike order 8. This was also reduced in ground-layer correction for comparison. These data were in median, 0.7 arc seconds, seeing and displayed a higher percentage of RMS correction.

Only a few data sets have been analyzed from April of 2006, but they are consistent with results from the previous runs. Table 3-2 presents summary ground-layer corrected results of example data sets from each of the three runs.
Table 3-2. Example RMS wavefront error before and after ground-layer AO correction.

<table>
<thead>
<tr>
<th></th>
<th>Sept. ’04</th>
<th>June ’05 (1)</th>
<th>June ’05 (2)</th>
<th>April ’06</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncorrected RMS</td>
<td>645 nm</td>
<td>374 nm</td>
<td>511 nm</td>
<td>448 nm</td>
</tr>
<tr>
<td>GLAO corrected</td>
<td>397 nm</td>
<td>290 nm</td>
<td>360 nm</td>
<td>249 nm</td>
</tr>
<tr>
<td>% RMS correction</td>
<td>38 %</td>
<td>23 %</td>
<td>30 %</td>
<td>44 %</td>
</tr>
<tr>
<td>Zernike orders used</td>
<td>2-6</td>
<td>2-6</td>
<td>2-8</td>
<td>2-8</td>
</tr>
<tr>
<td>$r_0$ (at $\lambda = 500\text{nm}$)</td>
<td>12.6 cm</td>
<td>22.6 cm</td>
<td>14.8 cm</td>
<td>18.0 cm</td>
</tr>
<tr>
<td>$L_0$</td>
<td>19.6 m</td>
<td>14.4 m</td>
<td>12.0 m</td>
<td>12.5 m</td>
</tr>
<tr>
<td>Frame rate (fps)</td>
<td>50</td>
<td>100</td>
<td>100</td>
<td>200</td>
</tr>
</tbody>
</table>

PSF simulations were done for the data exploring the ground-layer AO field from June 2005 from the measured and residual stellar wavefront information. These simulations included a temporal lag of 0.02 seconds (2 frames). Synthetic residual tilt errors were also added assuming that global image motion was measured from a natural star at the center of the field, with noise and anisoplanatic errors determined empirically from separate observations of a five star asterism on the tilt camera. Table 3-3 summarizes a number of measures of image quality calculated from the resulting PSFs. Encircled energy plots for the same PSFs are shown in figure 3-10.
Table 3-3. Radially averaged quality metrics computed for synthetic GLAO PSFs from open-loop wavefront data. FWHM, \( \theta_{50} \), and \( \theta_{80} \) are in arc seconds. Results are shown for field angles of 5, 25, and 50 arc sec in both H (\( \lambda = 1.6 \, \mu m \)) and K (\( \lambda = 2.2 \, \mu m \)) bands.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Field angle (arc seconds)</th>
<th>Diffraction limit</th>
<th>Seeing limit ((r_0 = 22.5cm))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>FWHM</td>
<td>0.10</td>
<td>0.10</td>
<td>0.13</td>
</tr>
<tr>
<td>( \theta_{50} )</td>
<td>0.21</td>
<td>0.13</td>
<td>0.21</td>
</tr>
<tr>
<td>( \theta_{80} )</td>
<td>0.51</td>
<td>0.46</td>
<td>0.51</td>
</tr>
<tr>
<td>Peak intensity</td>
<td>0.082</td>
<td>0.21</td>
<td>0.056</td>
</tr>
</tbody>
</table>
Figure 3-10. Encircled energy graphs for synthetic GLAO PSFs in the H (top) and K (bottom) bands. Plots are shown for three different radii within the LGS constellation, though the results for 25 and 50 arcsec radii are almost indistinguishable. All assume that a single tip-tilt star is used at the center of the LGS constellation. Also shown for comparison are curves for PSFs at the diffraction limit and the seeing limit. The latter assumes the mean value of $r_0$ (22.5 cm at 500 nm) at the time of the observations, and no additional contribution from telescope vibrations or tracking errors.
Even though the seeing was already excellent, ground-layer AO further improved the resolution, to within about a factor 2 of the diffraction limit. $\theta_{50}$ also saw substantial improvement, particularly in the K band. Furthermore, the variability of the PSF over the explored field, with a radius of 50 arc seconds, is remarkably small. While these results by themselves are encouraging, the value of ground-layer AO is not restricted to periods when the seeing is already good. Unlike conventional AO where the diffraction limit is the goal, the more modest reach of ground-layer AO is also more robust to adverse atmospheric conditions. Data from September 2004 when the value of $r_0$ was 10.1 cm, approximately half the value for the results in June 2005, show that improvement of the K-band PSF to FWHM of 0.2 arc seconds will still be possible under such conditions.

This experiment and subsequent results suggest that ground-layer AO correction will be a powerful tool for reducing the effects of atmospheric seeing over wide fields, with correction extending beyond the beacon radius. It is robust against seeing conditions as even in poor seeing, such as seen in September 2004, ground-layer correction accounted for considerable improvement in the residual wavefront error.
3.4.2. Results of open-loop tomographic adaptive optics correction

3.4.2.1. Least-squares tomography

Open-loop tomographic AO correction has been demonstrated during two observing runs at the MMT, in June 2005 and April 2006. The tomographic reconstructor used for these results is the least-squares reconstructor built from simultaneous measurements of the laser and stellar wavefronts as described in section 3.3.2.2.2. It has been found that the tomographic approach yields a substantially better estimate of a star’s wavefront than the corresponding ground-layer recovery. To illustrate, figure 3-11 shows the evolution of the focus term in a star’s wavefront over a 10 s period and its ground-layer AO and tomographic AO estimates.

![Figure 3-11. Evolution of focus in a star’s wavefront, shown in solid blue on the two plots, with the ground-layer estimate (left) and tomographic estimate (right) plotted in dashed black.](image)
The RMS residual wavefront aberration after correction with both the ground-layer and tomographic AO techniques over Zernike orders 2 through 8 were calculated. Figure 3-12 shows two examples of the RMS residual wavefront error as a function of time over four seconds. The data represent sets taken in June 2005 and April 2006 corresponding to the last two columns in table 3-2. The RMS residual errors for each set are presented in table 3-4. Notice that there is improvement in the floor of the tomographic residual in the most recent data. This is a measure of the information content in the recovered wavefront estimates, and the improvement is due in part to improved alignment of optics, increased throughput and faster frame rate. The residual is now dominated by the fitting error of our chosen laser and natural guide star Shack-Hartmann WFSs which has been calculated at ~ 130 nm from Hardy (1998).

Figure 3-12. An example of the RMS residual error over Zernike orders 2 through 8 for an uncorrected stellar wavefront (thick solid blue), after GLAO correction (dashed red) and after LTAO correction (thin solid green). Data from June 2005 is presented left and data from April 2006 is presented right.
Table 3-4. Residual RMS wavefront errors for the data sets presented in figure 3-6.

<table>
<thead>
<tr>
<th>Correction type</th>
<th>June 2005</th>
<th>April 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncorrected</td>
<td>511 nm</td>
<td>448 nm</td>
</tr>
<tr>
<td>GLAO Corrected</td>
<td>360 nm</td>
<td>249 nm</td>
</tr>
<tr>
<td>LTAO Corrected (with a single tip/tilt star)</td>
<td>259 nm</td>
<td>172 nm</td>
</tr>
<tr>
<td>LTAO Corrected (with 3 tip/tilt field stars)</td>
<td>243 nm</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Synthetic corrected PSFs were calculated for a source on axis in J (1.25 μm), H and K band from a 60 s continuous data sequence from June 2005 recorded in seeing conditions of $r_0 = 14.7$ cm. The reconstruction estimated the first 44 modes of the star’s wavefront, now including tip-tilt. Table 3-5 below shows the corresponding widths and relative peak intensities for the time averaged ground-layer and tomographically corrected PSFs.
Table 3-5. Image quality metrics of ground-layer and tomographic AO in the near-infrared.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Waveband</th>
<th>Uncorrected</th>
<th>GLAO</th>
<th>LTAO</th>
<th>Diff. Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWHM (arcsec)</td>
<td>J</td>
<td>0.774</td>
<td>0.378</td>
<td>0.113</td>
<td>0.040</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>0.683</td>
<td>0.171</td>
<td>0.086</td>
<td>0.052</td>
</tr>
<tr>
<td></td>
<td>K</td>
<td>0.553</td>
<td>0.125</td>
<td>0.089</td>
<td>0.070</td>
</tr>
<tr>
<td>Rel. Peak Intensity</td>
<td>J</td>
<td>1.0</td>
<td>2.0</td>
<td>3.9</td>
<td>498</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>1.0</td>
<td>3.7</td>
<td>9.4</td>
<td>239</td>
</tr>
<tr>
<td></td>
<td>K</td>
<td>1.0</td>
<td>7.0</td>
<td>15.0</td>
<td>92</td>
</tr>
</tbody>
</table>

With tomographic correction, the K band is corrected almost to the diffraction limit, with a 15-fold increase in peak intensity to a Strehl ratio of 16%. This relatively low order reconstruction is insufficient to achieve the diffraction limit at the shorter wavelengths, but the improvement in resolution and peak brightness are both substantial.

From the results here, it can be seen that the open-loop tomographic correction is pushing towards the desired diffraction limited imaging. Results from June 2005 suggest a Strehl ratio of 16% in K band; however the lower residual error seen in the April 2006 data means a much higher Strehl ratio should be possible. At this time, simulated PSFs from April 2006 have not been evaluated as focus shifted towards building the facility closed-loop WFS instrument. The residual tomographic errors approaching the fitting error suggest that the system is performing close to its current limit set by the spatial sampling of the LGS.
WFS. The successful least-squares reconstruction of the atmosphere shows that three dimensional information of the turbulent atmosphere is being measured by the five laser beacons.

3.4.2.2. Additional least-squares and geometric tomography

In addition to the self-referenced least-squares tomographic reconstructor results presented above, a number of other least-squares techniques have been applied. One which had the promise of some improvement is the use of a least-squares reconstructor that had been computed on the first 90% of the data, and applied it to the last 10% of data. This has the advantage of being a possible observing mode at the telescope, where a reconstructor is computed based on laser measurements and measurements from a bright star. The telescope could be then slewed to a dim science target and corrected with the just computed tomographic reconstructor. Using minute long data sets from June 2005, running at 50 fps trained on the four star asterism, it was found that technique does not have any traction. When the tomographic reconstructor computed from the first 90% of the data is used to correct the data it was built from, the correction is similar to the results seen in the previous section. When applied to the last 10% of data, the correction level is comparable to ground-layer correction. There is no gradual degradation in performance with time as might be expected, but it is
more like a step function, suggesting that the tomographic reconstructors computed are over-fitting noise.

There is some usefulness to this technique when used on a larger baseline of data. There were 17 of the minute long data sets taken over a period of 50 minutes. It was found that if a reconstructor was calculated from a total of 60 seconds of data from equally spaced frames from multiple data sets, for example every fifth frame from five data sets, that considerable improvement over the simple ground-layer correction would be shown. Typically, the residual RMS wavefront error would be halfway between the self-referenced least-squares tomographic reconstructor and the ground-layer reconstructor and not be dependent on dynamics. It was not obvious why this would have worked as over the 50 minute time period the structure of the $C_n^2$ profile was most likely changing. The least-squares inversion must not have been fitting the vertical turbulence profile characteristics, and the fitting of noise seen in the shorter data sets must have gone down. Unfortunately, due to the long temporal baseline needed to compute such a reconstructor, this technique would be very costly to implement for real on-sky AO correction.

The geometric reconstructor approach has many problems of its own, typically performing worse than the estimated ground-layer correction. For this reconstruction method to work, the location of the beacons with respect to the science target and the fidelity of beacon wavefront reconstruction must be very accurate. The best measurements of the beacon and science target on-sky
geometry are done with the wide field camera. Because of the aberrations present in the current wide field camera lens (figure 4-13), it is difficult to identify the locations to better than 10 arc seconds. An additional reason for the poor performance is the difficulty measuring the pupil geometry for each laser beacon. The current dynamic refocus lens cell reimages the pupil from the secondary to the prism array in front of the laser wavefront sensor camera. Once reimaged, the pupil is curved such that its sagittal depth is roughly equal to its diameter of approximately 40 mm (Snyder 2007). In addition, the light from each laser beacon is coming in at an approximate 1.4 degree angle from the optical axis and the centration and size of the pupil as placed on the prism array is not well known due to difficulties in alignment feedback. In the current model, the pupil has been assumed to be flat and perfectly scaled and centered for every beacon while the actual mapping between the subapertures and the pupil is unknown. It has been found in simulation that even a 1% shift in the diameter of the mapping can cause the tomographic results to be seriously affected, and the current alignment of the laser wavefront sensor easily exceeds this error.

There are multiple solutions to overcome the deficiency in measuring the optical system and improving the geometric tomographic reconstructors. Each of the following will benefit from an improved wide field imaging camera to determine the geometry of the beacons and science target on-sky. The first solution, which will be attempted during the September 2007 observing run, involves placing a few low order static shapes, such as Zernike modes, on the
deformable secondary mirror. By taking a long integration of images on the wavefront sensor, \( \geq 10 \) minutes, and measuring how the Shack-Hartmann spots for each beacon move in response to each applied mode, parameters of the pupil shape may be estimated in a least squares sense. Simple parameters such as pupil decenter and size will be estimated. A custom wavefront reconstructor using these values will be realized for each beacon. The geometric tomographic reconstructor can then be used with the more accurate reconstructed wavefronts from each beacon. If the major source of reconstruction error is due to pupil size and decenter mismatch, then this approach has potential to increase the performance of the geometric tomographic reconstructor.

A more thorough, but more time consuming, approach is to place every shape that will be controlled by AO system onto the deformable mirror. Again, by taking a long integration of images on the wavefront sensor, and measuring how the Shack-Hartmann spots for each beacon move in response to each applied shape, an influence matrix for each beacon can be calculated. The matrices then just need to be inverted by SVD in order to create reconstructor matrices for each beacon. This approach is limited by the time it takes to fully average over atmospheric statistics, making sure that the mean spot positions are estimated with little error.

Another more long term solution is an upgrade to the laser wavefront sensor optics. This is described in more detail in Stalcup (2006). In the design, the mirror on the dynamic refocus resonator is flat instead of steeply curved.
This, in conjunction with a new lens cell, creates a flat, non-distorted pupil to be imaged at the prism array. In practice, the new optical design more closely matches the idealized model currently used for the laser guide star wavefront sensor, and while the calibrations described above will still need to be performed, their impact on tomography will be lessened. The main drawback to this solution is the replacement of a large portion of the optical system, which is both costly and time consuming.

Unfortunately, flexure will still be an issue with any of these solutions. Although the mechanical structure of the wavefront sensing instrument has been designed to be stiff (section 4.2.1.1.6.), any flexure within the instrument can cause the pupil to move or change shape. This will in turn affect the fidelity of wavefront reconstruction and will adversely affect any tomographic wavefront reconstruction.
4. Closed-loop experiments at the MMT Telescope

4.1. Motivation

Upon successful completion of tests of open-loop wavefront sensing it was decided that the system should be integrated with the closed-loop NGS AO system at the MMT. A major goal for the project is to support science observations with the laser AO system, providing diffraction-limited images in the thermal infrared bands and substantial image improvement in K and shorter bands over all the sky accessible above 45° elevation. This can only be achieved by first closing the control loop between the laser wavefront measurements and the deformable F/15 secondary mirror. The first attempt at closed-loop operation was scheduled to occur in September 2005 with minor modifications to the prototype wavefront sensing instrument so it could accommodate the science instrument Clio. Due to the Florida fire of 2005 and the delay in aluminizing the primary mirror, the time allotted for this first test was lost. The next chance at observing was in April 2006, so it was decided to focus on building a facility wavefront sensing instrument which would be a drop in replacement for the current NGS wavefront sensing instrument. As a facility instrument, the ability to accommodate all of the science instruments that work with the NGS AO system would be built into the design.

In addition to supporting science, actual on-sky AO correction performance could be evaluated. In previous experiments, all performance
estimates were based on wavefront measurements from the different WFS cameras. With a closed-loop system sending AO corrected light to science cameras, the imaging improvement can be directly measured and the parameters which affect correction can be explored. This would lead to a greater understanding of the important factors in upgrading the MMT’s laser AO system and building new systems for the LBT and the GMT.

Secondary goals for this experiment include providing a test environment for the exploration of other AO ideas. The current NGS AO wavefront sensor is used routinely for science and is not the ideal place to modify hardware. The new laser wavefront sensor is more easily modified to accommodate any new prototype hardware such as infrared pyramid wavefront sensors or interferometric focal plane sensors, and can be used to test new centroiding and control loop techniques.

4.2. Method

4.2.1. Description of hardware

The closed-loop experiments at the MMT are supported by four main parts: the lasers and beam projector, the new facility wavefront sensor, a real-time reconstructor computer and the deformable secondary mirror (Wildi et al. 2003; Brusa et al. 2003). A picture of the F/15 secondary during the July 2007 run appears in figure 4-1. The laser system is identical to that used in the open-
loop tests. The new wavefront sensor uses many of the same optics from the prototype design and the details are described below.

Figure 4-1. F/15 secondary at the MMT in July 2007.

4.2.1.1. Facility wavefront sensing instrument

The design of the new facility wavefront sensing instrument was driven by the desire to support the current and future suite of AO science cameras at the MMT. The instrument was designed as a modular drop in replacement for the NGS AO wavefront sensing instrument and preserves many of the same features. It is comprised of similar components to that of the open-loop prototype wavefront sensor: the laser wavefront sensor, the natural guide star wavefront
and tilt sensors, a wide field acquisition camera and several optical alignment aids. Figure 4-2 shows an initial mechanical model of the top box with embedded optical design before it was fabricated with major components of the system indicated. Figure 4-3 shows a picture of the final completed instrument in April 2006 with the light path for the different optical systems overlaid for clarity. Figures 4-4, 4-5 and 4-6 show the instrument from three different views from July 2007.

Figure 4-2. Initial mechanical/optical design of facility wavefront sensor showing many of the components of the system.
Figure 4-3. Photograph of the wavefront sensing instrument as built in April 2006. Arrow in white shows the light coming off of the F/15 adaptive secondary. The yellow arrow shows the visible light reflected off of the tilted dichroic / science entrance window. The green arrow shows the path of the $\lambda = 532$ nm reflected off of the rugate filter into the laser wavefront sensor. The red arrow shows the remaining visible light as it passes to the tilt and wavefront sensor cameras.
Figure 4-4. Southeast view of wavefront sensing instrument in July 2007.

Figure 4-5. Northwest view of wavefront sensing instrument in July 2007.
4.2.1.1.1. Laser guide star wavefront sensor

The laser guide star wavefront sensor has essentially the same optical design as the open-loop laser wavefront sensor, with the majority of the changes in repackaging the system and improving the alignment adjustments. More details on the current laser wavefront sensor design and alignment can be found in Snyder's thesis (2007). Figure 4-7 shows the layout of the LGS WFS on the optical breadboard. $\lambda = 532$ nm light from the F/15 secondary is reflected off of the science dichroic and then off of the rugate filter to the field lens. The rugate
mount, like the majority of the mounts, is attached to the breadboard by a number of clamps which bolt directly to the breadboard. Next is a single assembly that holds the field lens, pierced mirror and periscope. The whole assembly can move via three actuators. In addition, the field lens has its own tip actuators and x/y translation stages so it can move independently. The field lens creates an image of the secondary at the front of the lens cell. The lens cell reimages the pupil onto the resonator mirror and reflects the light back out. The resonator now has two flexure actuators located at the node of the resonator. This allows for small adjustment of the resonator mirror in x and y. The light passes back through the lens cell after being reflected off of the resonator mirror then hits the pierced mirror which has been remanufactured as a core drilled CVI laser line mirror. The light then goes through the periscope assembly. For each of the five periscope sub-assemblies, one of the two mirrors has a full range of translation and tilt adjustment. The pupil is then imaged onto the front of the prism array with a lens pair mounted on z-translation stages and finally imaged onto the CCID18 camera with a custom camera lens. The camera, with lens and prism array rigidly attached, also has a full range of tip/tilt and translation adjustment.
Figure 4-7. Zemax layout of the LGS WFS in the new instrument.
4.2.1.1.2. Natural guide star optics

The design of the natural guide star optics arm was much different from the prototype design. In many respects it was an attempt to replicate the existing design from the NGS AO instrument; however, the goal was to increase the field of view from a 1 to a 2 arc minute diameter. The design of the NGS AO system (Rhoadarmer 1999) used a pair of off-axis parabolas (OAPs) to change the F/ratio of the light from 15 to 23 before entering the WFS head. Replicating the existing optical design was impractical due to the cost and lead time of the custom OAPs, so an off-the-shelf solution with a lens and parabolic mirror was found.

Figure 4-8 shows an optical layout of the natural guide star arm of the wavefront sensing instrument. Light from the F/15 secondary is reflected off of the science dichroic towards the 4” diameter fold mirror, passing through the rugate filter. The size of all of the optics before the field steering mirror is dictated by passing a 2 arc minute diameter unvignetted field. The 4” fold mirror is the tallest optic of the entire bench, and reflects light down to the 6” diameter achromatic lens. This lens is a Melles Griot LAO 367 lens with a 1 m focal length. After reflecting off of a 6” fold mirror, a pupil is formed by the 6” lens at the field steering mirror (FSM). The field steering mirror is remotely actuated in tip and tilt with a pair of PI actuators which allow for the selection of field to be sent downstream to the following optics which have a narrower, < 10 arc second, field
of view. After reflection off of the field steering mirror, the light is reflected by a
semi-custom OAP with a focal length of 1.524 m. The OAP is a core-drilled 4.25"
diameter subsection of an Edmund Optics 32-274-533 10" diameter master
parabola. The light is then focused down and is reflected by the tilt beam-splitting
mirror and/or the 1" fold mirror for the wavefront sensing camera, depending on
the optical configuration. The 1" fold mirror has the same actuators as the field
steering mirror and they are used to center the pupil on the wavefront sensor if
necessary. The mounts for all of the optics that are not motorized in this arm are
fitted with tip/tilt actuators. The full alignment procedure for these optics can be
found in Appendix F.

The alignment tolerances on the natural guide star arm are relatively loose
and additionally many of the misalignments can be compensated by the tip/tilt
adjustments on all of the optical mounts. Translating any of the optical
components by 100 µm, or tilting any of the lenses by up to 2° has a negligible
effect on image quality. The only element that has tighter tolerances is the off-
axis parabola which can handle 3 arc minutes of tilt with negligible image quality
loss. It was also found in the finite element analysis of the breadboard and frame
that the largest tilt angle caused by deflection of the breadboard with ARIES
attached, and pointed from Zenith to horizon, was 10 arc seconds. Therefore the
natural guide star arm should be robust against flexure of the breadboard due to
gravity.
Figure 4-8. Layout of the natural guide star optics. Light going to the wide field camera is in red, to the tilt camera in green and to the wavefront sensor in blue.
4.2.1.1.2.1. Wavefront Sensor

The wavefront sensor camera is the same as used in the NGS AO system and as in the prototype instrument. The combination of the lens and OAP give a focal ratio of 1.524 which is slightly smaller than the desired focal ratio of 1.53 as given by the NGS AO prescription. This difference causes the pupil to be undersized on the lenslet array by an acceptable 0.4%. The achromatic effect of the lens in the optical relay has negligible effect. Figure 4-9 shows the spot diagram on the Shack-Hartmann sensor. The wavelength weighted diffraction spot size is 0.29 arc seconds and the maximum geometric spot size is 0.31 arc seconds at the edge of the pupil. Essentially this means the sensor is close to diffraction limited, and in practice will be seeing limited. Distortion is also small with the outer edge spots only 0.02 arc seconds from their nominal positions.
The dominant aberration going through the natural guide star arm is astigmatism produced by the rugate dichroic since it is an 8 mm thick plane parallel plate at 45 degrees. It produces approximately 205 nm of Zernike astigmatism. In the lab, approximately 290 nm of astigmatism was measured using the fiber source in October 2006 as can be seen in figure 4-10; the difference likely due to misalignment of the off axis parabola. The alignment has been improved since with lower measured astigmatism, but unfortunately none of these measurements have been recorded.

Figure 4-9. Shack-Hartmann pattern as seen through the wavefront sensor.
Figure 4-10. Screen capture of the NGS viewer program. The upper right shows the spot pattern on the wavefront sensor of the fiber source. In the lower left are the reconstructed Zernike amplitude coefficients in waves at 632 nm. The first two modes are tip and tilt, then 45 degree astigmatism, defocus, 90 degree astigmatism and higher order modes.

The camera is equipped with an adjustable iris at the focal plane to reduce cross-talk between subapertures and suppress sky-background. The camera head is also electrically isolated from its mount to reduce noise. There is a manually adjustable neutral density filter wheel located just before the fold mirror which can be used to attenuate the light going to the camera. The optical density
can be adjusted from 0 to 4.5 in steps of 0.5. The camera mount is manually adjustable in tip/tilt and is mounted on a remote controlled translation stage to adjust focus.

4.2.1.1.2.2. Tilt Sensor

The current tilt sensor uses an L3 electron multiplying CCD from E2V. A Melles Griot LAL 007 lens is placed in an adjustable sliding tube in front of the CCD to establish a plate scale from roughly 0.25 to 0.33 arc seconds per pixel with a limited field of view of ~ 5 arc seconds. The camera is also mounted on a motorized translation stage to adjust for focus.

The chromatic effects of using the 6” achromatic lens are most apparent in the image quality delivered to the tilt sensor. Figure 4-11 shows the spot size and optical path difference for on-axis and the worst off-axis field points. The wavelengths used, from 500 to 900 nm, are weighted by typical Silicon CCD response curves. The RMS and geometrical spot diameters on-axis are 0.31 and 0.68 arc seconds respectively. For the worst off-axis case, the RMS and geometrical spot diameters are 0.41 and 1.24 arc seconds respectively. For the time being, this amount of aberration is tolerable as the image spot covers ~ 2 – 3 pixels on the detector. In order to push the limits of sensitivity on the tilt sensor, a fully reflective design for the optical relay should be implemented.
4.2.1.1.2.3. Wide field Camera

A wide field camera is installed in the natural guide star optics arm and can been seen in figure 4-12. It is fed by a 4 inch diameter lightweight mirror on a remote controlled flip motor. The mirror reflects the entire 2 arc minute field towards a first 4 inch diameter achromatic lens. The lens makes an image of the pupil which is 44 mm in diameter. A 2 inch diameter, F/0.95 camera lens is
mounted at approximately this pupil location. This images the entire field onto an Astrovid camera. The camera output is in video mode and can be seen in real time in the MMT control room. Single images can also be captured. Unfortunately the camera lens has seen significant abuse and has rather poor image quality, but is useful as an acquisition camera. An example frame from the wide field camera can be seen in figure 4-13. The bright spot in the middle is an $m_v \sim 5$ star. The five dark spots in a pentagram around the star are the out of focus shadows of the secondary mirror and spiders as cast by each of the five laser beacons.
Figure 4-12. Wide field camera in the laser wavefront sensing instrument. The red line indicates the path of an on-axis light beam. The lightweight flip mirror, pictured in the down position, interrupts the light going to the tilt and WFS cameras (dashed arrow) and redirects it to the wide field camera (solid arrow).
4.2.1.1.3. Beam splitters

There are three beam splitting elements that exist in the wavefront sensing instrument to distribute light to the different cameras. The first is a dichroic entrance window for each of the science instruments. The windows are provided by Spectral Systems Inc. and have a CaF$_2$ substrate that is 120.24 mm
in diameter and 8 mm thick. The windows are coated on the outside to have high reflectance from 350 to 950 nm and high transmission from 1.1 to 25 μm. In reality, the reflectance at 632 and 532 nm is 90.3% and 80.6% respectively. The window is tilted at 15° to send the visible light into the wavefront sensing instrument.

The second beam splitter is a rugate filter located right after the instrument dichroic in the optical path and is tilted at 45°. It has an 8 mm thick fused silica substrate and is large enough to pass a 5 arc minute diameter field to the natural guide star sensors. The substrate was provided by Tucson Optical Research Corp. and the coating was done at Barr Associates, Inc. It is attached to a large mount with three pads of silicone and is actuated to give tip, tilt and piston adjustment. Figure 4-14 shows the filter in the wavefront sensing instrument and figure 4-15 shows a transmission trace of the filter using a Perkin-Elmer spectrophotometer. The transmission at 532 nm is 0.25% with a FWHM of the reflectance notch of 30 nm.
Figure 4-14. Laser rugate filter mounted in the wavefront sensing instrument.

Figure 4-15. Transmission through the rugate filter.
The third beam splitter is located after the off-axis parabolic mirror in the natural guide star optics arm. It is a 1” diameter visible beam splitter from Edmund optics which reflects ~ 30% of the light to the tilt sensor and transmits ~ 70% of the light to the wavefront sensor camera. It is mounted on a kinematic mount, so it can be either removed entirely, sending all of the light to the wavefront sensor, or replaced with a protected silver mirror when maximum intensity is needed on the tilt camera.

4.2.1.1.4. Science dichroic mount

The wavefront sensing instrument is intended to be used with science cameras that have an entrance window which reflects visible light. Since only Clio has been fitted with one of the larger dichroics needed to reflect the full laser guide star field, a solution was needed to hold the science dichroic independently when using other instruments like PISCES. The first telescope run with the new wavefront sensing instrument occurred in April 2006 and there was no intention of closing the AO loop so a science instrument was not needed. In that case, a 6” flat mirror with tip, tilt and piston adjustment was located where the science dichroic should be and was attached to the science interface plate with a piece of 8” wide aluminum channel. This mirror was also left in place whenever the on-axis alignment laser was needed to align downstream optics.
In preparation for the first closed-loop run, PISCES was to be mounted to the science interface plate and therefore an alternative method of holding the science dichroic was needed. The designed mount attaches to the inside edge of the opening in the middle of the breadboard and does not interfere with PISCES or its mount. A dummy mirror was used during alignment since there is concern that the coating on the dichroic mirrors is damaged by humidity; they are only brought out during observing on the sky at the MMT and kept in air tight containers with desiccant for storage. The science dichroic mount, as seen from the top and bottom of the wavefront sensing instrument, is presented in figures 4-16 and 4-17. The science dichroic is held on an aluminum bed with three pads of PTFE tape to prevent scratching. A plastic retainer ring is placed on top and bolted gently to the aluminum bed. The mount for the science dichroic is held in place by 3 threaded actuators and springs and can be removed easily and reinstalled semi-kinematically.
Figure 4-16. Science dichroic mount pictured from the top. The PTFE tape prevents the dichroic from being scratched while the plastic retaining ring keeps the dichroic in place.

Figure 4-17. Science dichroic mount pictured from the bottom of the instrument. The mount is held in place by three actuators which can be used to tip, tilt and piston the dichroic.
4.2.1.1.5. Calibration Optics

4.2.1.1.5.1. On-axis laser

As an alignment aid, an on-axis laser has been built into the design of the wavefront sensing instrument. This can be seen in figure 4-18. The laser is mounted on a motorized translation stage that can be moved over the science dichroic and points downward. The on-axis laser is a combination of a $\lambda = 532$ nm Nd:YAG and a $\lambda = 632$ nm HeNe laser using a dichroic beam combiner so that the laser and natural guide star optics arms are aligned to the same axis; the rugate filter splits off the $\lambda = 532$ nm light so two wavelengths are necessary. The two lasers are coaligned by a combination of tip/tilting one of the lasers and tip/tilting the dichroic.
The lasers are meant to replicate the axis of the telescope when not mounted to the MMT. The position and angle of the laser is controlled by a pair of tip/tilt actuated mirrors. The initial calibration of the laser had to be done while on the telescope, and was done coincidentally with the epoxy shims. The laser was
first roughly centered on the telescope axis with the telescope pointed at zenith. A cup of coffee was placed where the laser hit the ground and the beam was reflected. The downward angle on the laser was adjusted until it was retro reflected back on itself. At this point, the coffee cup was removed and replaced with a piece of paper on the floor. The rotator bearing was rotated to 0, ± 90 and 180 degrees and the laser position marked on the paper. The laser assembly was then translated to move the laser spot to the center of those four positions and locked down. This process was repeated until both the laser was pointed straight down and upon rotation, the laser didn’t translate. It was estimated that the pointing error for the laser was approximately 1 arc minute as the best one could tell by eye that the laser was truly retro reflecting.

Once the system had been calibrated, an additional piece of hardware was used to check for any future misalignment of the system. A plate with two kinematic locators was bolted to the science interface plate. It has a thin sheet of copper with a 1 mm hole over a much larger hole near the middle of the plate. The copper plate is translated so that the laser beam is centered on the 1 mm hole and locked down. In the future, if the on-axis laser is moved into position and it does not go down this hole then it can be assumed that the alignment has been lost and needs to be recalibrated.

Being a new instrument, there are many times when access to the inside is necessary to adjust the hardware. As such there is concern that critical optics like the on-axis laser might be accidentally bumped. While the calibration plate is
useful in telling if a misalignment occurred, preventing an accident would be preferred. Protection for the on-axis laser is provided by the on-axis laser garage. This garage is a three sided structure within the instrument which the on-axis laser can translate out of for alignment, and back into for protection.

4.2.1.1.5.2. Natural guide star fiber source

Another calibration tool located on the on-axis laser translation stage is the natural guide star fiber source. This source mimics a natural star by being placed on the optical axis at the infinity focus of the telescope. The fiber source is created by using a small diode laser optically coupled to one end of a fiber. The other end is placed in a holder tube on the on-axis translation stage. Since the fiber source is located on-axis, it is offset from the alignment laser and only one of the two can be used at a time. The translation stage has a position for each to be on-axis. The fiber source can be used to evaluate the quality of the natural guide star alignment when viewed through the wavefront sensor and tilt cameras.

4.2.1.1.5.3. Laser guide star simulator

The laser guide star wavefront sensor also required a simulated source for evaluating alignment in the lab. Initially it was thought that the simulator could be used to define the non-aberrated Shack-Hartmann pattern on the laser wavefront
sensor camera. In reality, if perfectly aligned, there would be about 250 nm of coma for each beacon. Since there is currently no procedure to tell if the simulator is aligned properly, it is not used as an absolute reference, but as a rough alignment tool. More details on the laser simulator can be found in Snyder (2007). The simulator consists of five laser sources, a pupil and a lens system as seen in figure 4-19. The lasers are conjugated to a height of 25 km on a 2 arc minute diameter and the pupil / stop is projected to match the size and location of the F/15 secondary mirror. The simulated focal plane matches the location of the field lens in the laser guide star wavefront sensor. The last fold mirror in the simulator is on a motorized translation stage and is rolled in when needed. When not used, it translates back towards the lens pair and out of the beam from the rugate filter.
4.2.1.1.6. Mechanical structure

The structural design of the instrument was driven by three main considerations, the first being the minimization of changes needed to accommodate the current suite of AO instruments, Clio (Freed et al. 2004), ARIES (McCarthy et al. 1998), BLINC-MIRAC (Hinz et al. 2000) and PISCES (McCarthy et al. 2001). This meant preserving the idea of the dichroic entrance
window to the science instruments, reflecting visible light to the wavefront sensing instrument. In addition, the science instruments would mount to the wavefront sensor in a similar way as they do with the NGS AO system. The second was driven by the needs of the ARIES spectrograph. As the largest and heaviest science instrument, with the tightest tolerances, ARIES would need to be held very rigidly by the AO instrument. The last consideration was to make the instrument easy to modify and react to design changes as necessary.

To accommodate all of the science instruments, it was decided to copy many of the dimensions of the existing NGS AO system. All of the instruments would bolt to a ½ inch thick steel interface plate machined to a flatness of < 0.25 mm after welding and stress relief. This plate is located such that it allows the science instruments to be mounted in the same physical coordinates regardless of whether the NGS or LGS wavefront sensing instrument is used. The wavefront sensor and each of the four cameras were interfaced together in AutoCAD to check for any interference or clearance issues.

To support the spectroscopic capabilities of ARIES, tight tolerances between the science and wavefront sensing instrument needed to be considered. Over an elevation change of 15 degrees, i.e. an hour or longer of integration time, the x / y translation difference could be at most ± 10 µm to keep an object on the spectroscopic slit, and an x / y rotation limit of ± 75 arc seconds would keep the pupil to within a 1% shift. This required the interface between ARIES and the wavefront sensing instrument to be rather stiff. In addition there was an
approximate 2000 lbs. weight limit to be respected as ARIES already weighs ~ 1200 lbs. with cryogens. The structure for the instrument was primarily made from 6" × 4" steel frame tubing along the bottom, and 4" × 4" steel tubing for the uprights. Additional cross bracing was provided to the uprights. Parts of the frame can be seen in figure 4-20. In addition, a 5' × 5' × 4" breadboard was mounted inside of the steel frame. A breadboard was chosen for several reasons. It could be manufactured quickly as opposed to the cast aluminum bed that the NGS AO system uses. It also addresses the ability to make changes to the optical design within the instrument easily, since the entire surface is covered with ¼ - 20 tapped holes at 1" spacing. The steel frame and breadboard were attached together by steel L-brackets anchored with 64 × ¼-20 bolts. In addition, three female threaded tubes, 1.25" in diameter, are welded to top skin of the breadboard and epoxied to bottom. These are connected to the steel frame by three ¾ -10 screws. Since the breadboard is held together by epoxy, in the event of a delamination failure, these three tubes and bolts would keep the structure from falling apart.
Light baffling was added to the instrument because the open nature of the steel frame let in stray light from the telescope chamber. The light baffling consists of four corner panels and four panels that attach behind the electronics boxes. They attach to the steel frame with thumb screws for easy removal. Each panel also has rubber tubing at the top to seal off the interface to the rotator bearing. In the future, panels will also be made to block stray light coming in through the bottom opening where the science instruments attach.

Sound baffling has been added around the dynamic refocus ringer in order to reduce the sound produced. A sound pressure level meter was used to
measure > 118 dBm coming from the system in normal operation. This is well beyond a safe limit for hearing damage without protection. The baffling was installed by creating a frame which enclosed the ringer and by attaching removable panels to that frame which had 2 inch thick melamine sound damping material epoxied to the inside. A hole was left in the baffling for the light to enter and exit from one end, but it made a dramatic difference. Hearing protection is no longer required while in the telescope chamber for short periods of time, but is still advisable when working within the instrument.

In preparation of the first attempt at closed loop operation, all of the internal surfaces were anodized or blackened. The entire breadboard was stripped of all optical and mechanical components and was left bare. Each assembly was disassembled and labeled using an engraving tool. The aluminum parts were all sandblasted before being anodized. The steel parts were to be oxidized, but no suitable agent was found. Eventually these were inked black with permanent marker, along with top surface of the breadboard and any other exposed surfaces. Reassembly and alignment of the optics once the parts had returned from being anodized took about a week. There are a few parts, most notably the light baffles around the outside of the frame and the sound baffle enclosure, that still need to be anodized since they were not ready for the initial anodization run.

A new procedure was developed to match the interface between the instrument and the derotator bearing of the telescope. Welding the steel frame
together and keeping the flatness specification of the top of the 8 upright beams was not easily achievable, nor cost effective. Instead, at the top of each upright was a 4'' × 4'' spring loaded mild-steel pad with a small cavity underneath, pictured in figure 4-21. Once the steel frame was completed, it was taken up to the MMT during the summer shutdown in August 2006. It was then bolted up to the rotator bearing with three bolts, which were positioned closest to the support from wheels on the bottom; this maintained the alignment of the optics and reduced differential flexure. The bolts were tightened, making sure that all of the pads were fully contacting the rotator, but not bottoming out on their springs. Epoxy was then injected underneath of the pads and allowed to harden for 24 hours. The instrument was removed and sealant applied to any exposed parts of the epoxy. This procedure allowed the instrument to exactly match the surface of the rotator bearing without incurring the time or cost associated with maintaining a flatness specification over a large area.
Figure 4-21. Epoxy shim on the wavefront sensing instrument. The steel pad is mounted on three springs on top of each of the eight upright beams. Three flathead screws act as retainers for the pad. When mounted to the telescope, epoxy was injected through a hole on the side and allowed to harden for 24 hours. Excess overflow epoxy was trimmed off the edges and coated with a sealant.

To ease movement of the instrument around and for installation to the MMT, wheels were added to the bottom of the instrument instead of having a separate cart. Initially, these were tubeless pneumatic wheels that would offer an amount of cushioning as the instrument would be pushed around or picked up with a crane. It was found that the wheels were somewhat hard to turn and one wheel came off the rim during turning on the chamber floor carpet. The wheels
were then replaced with balloon wheels which still had cushioning but with a much smaller footprint. These were much sturdier and made the instrument easy enough for a single person to move around.

4.2.1.1.7. Electronics

All of the electronics for the instrument were to be held in four boxes around the outside of the steel frame. Each box is attached to the frame with hinges on one side and latches on the other. This makes for easy access into the instrument if necessary. One of the boxes was built by Microgate s.r.l. to house the slope computer and LGS WFS controller electronics (figure 4-22).
Figure 4-22. Microgate electronics box housing the LGS WFS controller and SSC slope computer.

Of the other three, one houses all of the motion controllers, temperature sensors, Ethernet and BNC communications (figure 4-23). The other two contain the NGS WFS camera controller and a standard PC for running the tilt camera (figures 4-24, 4-25). Each box is sealed and contains a heat exchanger that is linked into the MMT’s liquid cooling supply. This removes any excess heat produced from the telescope chamber.
Figure 4-23. South electronics box holding the motion controllers, temperature sensors, Ethernet and BNC communications.
Figure 4-24. East electronics box with the NGS WFS controller.
4.2.1.2. Real-time reconstructor computer

One of the main components of the closed-loop system, not used in the open-loop experiments, is the real-time reconstructor computer. The computer takes images from the wavefront sensor and tilt cameras and computes slope measurements. It then reconstructs each beacon’s wavefront and calculates the signals to be sent to the deformable secondary mirror. There are two different reconstructor computers used for this task, one provided by Microgate s.r.l. and another based on the PC architecture.

The Microgate reconstructor is comprised of a separate slope computer (SSC) and reconstructor computer (RTR). The SSC is a custom computer using
floating point units (FPU) and digital signal processors (DSP) with Ethernet and RS-485 communications. Parameters in the SSC memory are first initialized by a separate control computer. Frames from the LGS WFS are read in by the SSC and a gain and offset, in the form of background subtraction, are applied. A lookup table (LUT) is used to map frame pixels to 4x4 subapertures and slopes are calculated using a center of mass algorithm and another LUT which linearizes the algorithm's response. The slope measurements from each subaperture are then combined with the tilt signal from the tilt computer and forwarded to the RTR.

The RTR is also a custom computer built of DSPs with Ethernet communications and an interface to talk to the deformable secondary mirror. It is also initialized by the same separate control computer which initializes the SSC. The RTR multiplies the slope vector received from the SSC by a reconstructor matrix to obtain deformable mirror (DM) delta commands. When in closed-loop, the RTR first reads the initial DM position. It then applies a gain and modal filtering matrix to the computed delta commands. The delta commands are then truncated, with bounds checking applied to the commands, feed-forward forces and position of the mirror. The delta commands, with any offsets, are then sent to the DM. The loop automatically opens if any error condition is detected during the bounds checks.

The PC reconstructor is an alternative to the Microgate reconstructor that was built in-house. It uses dual quad core Xeon X5355 CPUs running at 2.66
GHz, with a 1333 Mhz front side bus, 1 MB L2 cache per core and 2GB of DDR2-667 ECC memory. It runs the CentOS operating system with RTAI real-time extensions, and uses an EDT PCI-DV framer grabber card for communication with the wavefront sensor controller. The NGS AO system had been relying on a VME based reconstructor during the past several years and it was very difficult modifying any of its internal software. With the current increase in performance of PCs, it was thought that the VME could be replaced with a computer of higher speed, using C code that would be easy to modify. Indeed the PC reconstructor was used successfully in 2006, and has now fully replaced the VME reconstructor for the NGS AO system. In addition, it has now been modified to accommodate the LGS WFS in ground-layer AO mode, where the slopes from corresponding subapertures are averaged before being multiplied by the reconstructor matrix. The PC reconstructor essentially follows the same steps as the Microgate reconstructor, when controlling the DM, but the internal software is much easier to modify. The PC reconstructor is currently being used as the baseline reconstructor, although its future use for LTAO, where a much larger reconstruction matrix multiply needs to be performed, is uncertain.
4.2.2. Closed-loop lab tests

To test the laser AO system while not on the sky, the test stand was used to hold the deformable secondary mirror (Stalcup et al. 2007a). The test stand environment, seen in figure 4-26, was originally built to update the calibrations of the secondary mirror using an interferometer and a Hindle test setup. For testing of the closed-loop laser system, modifications were made to integrate the laser wavefront sensor. The interferometer was still sending light to the secondary, but upon its return, a portion of the light was picked off by a pellicle beam splitting mirror. This light was then relayed to the laser wavefront sensor. The PC reconstructor was set to receive signals from the wavefront sensor, calculate mirror commands and send them to the secondary mirror. In this way, there was an optical feedback loop between the mirror and the wavefront sensor.
Figure 4-26. Test stand environment with the F/15 deformable secondary mirror (left) integrated with the laser guide star wavefront sensor (right).

In this setup, since there was only a single source, the reconstructor was modified to use only information from the one illuminated beacon. The extension to multiple beacons is in principle trivial. Initially, the focus only loop was closed at 30 Hz and it was found that the sign of the correction was wrong. Once set properly, the focus loop remained stable. Next, additional modes like astigmatism and trefoil were added to the control space until the rotation of the reconstructor matrix was determined properly. Once this had been determined, the full Zernike order 1 through 8 reconstructor was used and the loop remained closed for over 10 minutes. The disk harmonic basis set was tried as an alternative to the
Zernike set and it worked just as well. Switching back to the Zernike basis set, the loop was closed for five minutes at 200 Hz before the tests were determined to be a complete success.

The test stand work had demonstrated that issues with the software had been resolved and any remaining obstacles to closing the loop on sky would have to be discovered during observations.

4.2.3. Description of experiment

The closed-loop experiments at the MMT were to demonstrate closed-loop adaptive optics correction for the first time using multiple laser guide stars. The facility wavefront sensing instrument had been successfully tested for the first time in April 2006, producing more open-loop wavefront data, and was ready for closed-loop testing.

The first attempt at closed-loop operation occurred over 6 nights starting in December 2006. The first four nights were lost due to snowfall and ice on the telescope dome. The days were productive, allowing extra time to spend on hardware improvements and alignment of the wavefront sensing cameras to the F/15 deformable secondary mirror. The second half of the last two nights were lost due to secondary contamination and 3+ arc second seeing as the wind was coming from over Mt. Wrightson to the East. With the short amount of sky time available, it was found that there were serious errors in the software of the
Microgate reconstructor computer. Illegal commands were being sent to the secondary mirror which were not caught by its internal safety software, or 'back-end edits'. Fortunately the mirror has redundant safety software and no damage was caused. Once this had been diagnosed, it was decided to switch to development of the PC reconstructor.

The second closed-loop run started in March 2007 with five nights of clear weather. The tip/tilt loop was closed for the first time using the new PC reconstructor and a natural guide star. The high order adaptive optics loop was closed around the laser signals, but proved to be unstable due to a number of issues. There was excessive beam jitter caused by secondary hub vibrations causing the laser Shack-Hartmann spots to fall outside of their determined subaperture locations. This in turn led to incorrect slope measurements and an inaccurate reconstruction of the laser wavefronts. In addition, the calibration of the zero centroid offset positions was done with only two seconds of data; not enough time to average over the statistics of the atmosphere. A minute, or more, would have been more appropriate as has been seen in the open-loop data. This led to encoding non-real static errors into the closed-loop system. There was also an attempt to put static shapes on the secondary mirror by applying offsets to the slope calculations in order to test the system. It was later determined that the offsets were handled incorrectly and modes other than the ones desired were being put on the mirror. This caused our initial diagnosis of problems to be faulty.
In response to the success of closing the control loop around the tilt star, but not achieving success with the laser system, it was decided to work the bugs out of the system by using the test stand environment. Several software issues were resolved and the adaptive optics control loop was closed between the deformable secondary mirror and the laser wavefront sensor during the middle of June 2007. The loop was closed for over five minutes at 30 and 200 Hz using both the Zernike and disk harmonic basis sets. With the system now proven to work in the lab, the next step was bringing it back to the sky.

The latest attempt at closing the adaptive optics loop occurred in July of 2007 for 4 nights. The run was almost entirely lost due to weather, but about four hours were usable. During that time, the tip/tilt loop using a natural guide star was again closed to confirm the system was still working. Subsequently, the laser loop was closed around a focus only reconstructor for the first time. Shortly after this success, the clouds rolled in and there were no more clear skies for the rest of the run.

4.3. Operation of the closed-loop system

As a new system at the MMT, the operation and implementation of the closed-loop laser AO system is a continually evolving process. Closing of the AO loop and obtaining corrected images on a science camera will be detailed as it is currently best understood.
The first step is the alignment of the telescope and science camera. The deformable secondary mirror is set to the ‘flat’ position. This position most closely resembles a non-aberrated aspheric shape. Next, a star is imaged on the science camera and the telescope is purposely defocused to obtain an image of the pupil. The telescope is then adjusted to achieve collimation. The focus is then reset and corrected such that the image of the star on the science camera is at best focus.

The next step is to calibrate the laser wavefront sensor camera. First, a bright star is placed on the natural guide star wavefront sensor and the loop is closed with this system. This reduces most of the effect of the atmosphere and provides a less aberrated path between the laser beacons and the laser wavefront sensor. While the NGS loop is closed, images of the laser beacons are recorded on the laser wavefront sensor over a period of a minute or more. The images are averaged and the centroid position of each Shack-Hartmann spot is calculated. These will be used as the zero mean position of the spots. This can be done without the natural guide star sensor, using just the flat position of the mirror, but more of the non-common path errors will be taken out if the closed-loop NGS system is used in the calibration.

With the mean spot positions calculated on the laser wavefront sensor, a 4 × 4 pixel sub-image for each spot is identified. This will be the region over which the center of mass algorithm will be used to determine slopes for each spot. The slopes are then calculated from the averaged laser wavefront sensor
frame and are saved as slope offsets and sent to the PC reconstructor along with the subaperture locations. A background frame is also taken with the laser beacons turned off and sent to the PC reconstructor.

The PC reconstructor is then ready for closed-loop operation. Frames from the laser wavefront sensor are sent directly to the reconstructor. Each frame is processed by first applying a background subtraction. Slopes are then calculated for each subaperture and the offset is removed. The vector of slopes is then pre-multiplied by a reconstructor matrix and commands to the deformable secondary mirror are produced. A multiplicative factor, called the system gain, is applied to the commands sent to the deformable mirror. When the loop is first closed, this is set to zero. It is slowly increased until the loop appears stable. Typically, gains of 0.5 are used, but this is the focus of ongoing research.

The full procedure detailed has yet to be implemented. In July 2007 the laser AO loop was closed; however, with very limited sky time, the calibration of the laser wavefront sensor with the closed-loop natural guide star system was skipped. This will be required in future observing runs when the system performance will be analyzed in more detail.
4.4. Data analysis

On July 8th 2007, the adaptive optics control loop was closed around the ground-layer focus signal from the laser guide stars. Telemetry data was recorded on the PC reconstructor; although it appears that large portions of the data and every other data frame from the laser guide star wavefront sensor were not recorded. The seeing conditions at the time of observations, calculated from the uncorrected laser modes and independent PISCES images, were: $r_0 = 8.1$ cm, the 88th percentile of seeing, and $L_0 = 19$ m.

After calibration of the laser wavefront sensor camera using only the flat position of the mirror, the hexapod holding the secondary mirror was moved 20 µm towards the primary mirror. This added a static offset of -426 nm of Zernike focus for the AO system to correct in addition to atmosphere. Figures 4-27 and 4-28 show the measured ground-layer focus and 45° astigmatism modes as recovered from the recorded slope information from a single data set. The data show every other frame while the system was running at ~ 208 Hz. The control loop gain, a user defined multiplicative factor applied to the deformable mirror commands, was initially set to zero, set to 0.2 at frame 1300 and incrementally increased to 0.9. As can be seen in figure 4-27, the measured focus mode moves towards a mean value of 0 nm when the loop gain is increased from zero, correcting the static offset added with the movement of the hexapod.
Figure 4-27. Measured ground-layer focus mode during closed-loop correction of focus. The tick marks show when the gain factor, which starts at zero during frame 1, increases to a new value.
The RMS wavefront error in astigmatism during the closed loop correction of focus was 341 nm. Since both astigmatism and focus modes are from the same Zernike radial order, they should have the same statistics. Over the first 1300 frames, when the gain was still set to zero, and assuming a mean value set by the offset of -426 nm, the RMS focus error is 265 nm; the difference due likely to small number statistics of temporally correlated data. Table 4-1 lists the RMS wavefront error measured as a function of gain value. After the control loop was closed and the gain set to 0.9, the wavefront error in focus drops to 130 nm.
RMS, approximately a 60% reduction compared to the uncompensated astigmatism mode. This is comparable to the estimated wavefront improvement of ground-layer AO correction of a natural star (Baranec 2007; Lloyd-Hart et al. 2005, 2006b).

Table 4-1. RMS wavefront error during closed-loop correction of focus as a function of gain factor. *Focus of zero gain assumed a mean value of -426 nm.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Gain</th>
<th>RMS (nm)</th>
<th>Number of frames</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astigmatism</td>
<td>0</td>
<td>341</td>
<td>12965</td>
</tr>
<tr>
<td>Focus</td>
<td>0</td>
<td>265*</td>
<td>1301</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>190</td>
<td>1352</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>127</td>
<td>520</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>142</td>
<td>936</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>144</td>
<td>2600</td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>130</td>
<td>6256</td>
</tr>
</tbody>
</table>

Figure 4-29 shows the power spectra of the modes shown in figures 4-27 and 4-28 during closed-loop operation. The focus power spectrum is split into times of low gain (0.2, 0.4 and 0.6) and high gain (0.8 and 0.9). The ground-layer AO loop is correcting for power in focus below ~ 2 Hz, with greater correction occurring with a higher gain factor. There is a spike in the spectra at 13.7 Hz due to vibrations in the secondary hub.
Figure 4-29. Power spectrum of astigmatism (green), focus at low gain (0.2, 0.4 and 0.6; blue) and focus at high gain (0.8 and 0.9; red) during closed-loop correction of focus.

The commanded focus position of the deformable secondary mirror has also been recorded. This appears in figure 4-30 along with the times the gain factor was changed. The mean position of the mirror during non-zero gain is -202 nm. Because of the factor of two between the mirror shape and the optical path difference added by the mirror, it is compensating for -404 nm of static defocus; agreeing to within 5% of the -426 nm added by moving the hexapod 20 µm prior to increasing the loop gain from zero.
Figure 4-30. Deformable mirror command of focus mode during closed-loop correction of focus.

The power spectrum of the commanded focus position of the deformable secondary mirror has also been calculated and appears in figure 4-31. The spectrum has been calculated during times of low and high gain. With a higher gain factor, the deformable mirror is putting more power into higher frequencies, above ~ 1 Hz, with no noticeable noise floor. It is currently unclear why this increased amount of correction in the higher frequencies does not show up in the power spectrum of the corrected focus mode (figure 4-29); however it may be
addressed in the future with a more intelligent controller than is currently implemented at the MMT (Biasi et al. 1998; Brusa et al. 1998).

![Power spectra of the deformable mirror command of focus mode with low gain (blue) and high gain (green) during closed-loop correction of focus.](image)

**Figure 4-31.** Power spectra of the deformable mirror command of focus mode with low gain (blue) and high gain (green) during closed-loop correction of focus.

With the limited time available, ground-layer adaptive optics with laser guide stars has been demonstrated for the first time. With the poor seeing and the control of a single mode, it is impossible to see any imaging improvement on the PISCES science camera. However, the reduction in power of the focus mode during closed-loop operation clearly show that the system and technique have
been successfully implemented and full high order correction is only a few steps away.

4.5. Future work

The next step is to go back to the MMT and test the closed-loop system again. Five nights have been allotted for the system in September 2007. During this observation run, it is intended to close the full high order laser ground-layer AO loop simultaneously with the tip/tilt loop on a natural guide star. The imaging stability, sensitivity and improvement over a 110 arc second field will be explored with PISCES as its plate scale is well matched to the expected ground-layer performance. Narrow field PSF characterization will be done using Clio, in the thermal infrared of $\lambda = 3.5$ and $4.8 \, \mu m$, with Nyquist sampling of 0.048 arc seconds per pixel. Strehl ratios of 30 to 40% are expected at $4.8 \, \mu m$ in median seeing conditions.

Imaging with both cameras will allow for the exploration of parameters which affect the ground-layer AO correction. In particular, variables such as control gain, reconstruction basis set and the number of controlled modes need to be optimized. The effect of observing conditions, such as the brightness and field location of the tilt star, also need to be explored so future science programs can anticipate the imaging performance of the ground-layer AO correction.
Looking forward to future tomographic AO correction at the MMT, calibrations will be made for the optical system. The current reconstruction errors, as explained in section 3.4.2.2., need to be addressed. The deformable secondary mirror will be commanded to static shapes and their influence on the measured wavefront of each laser beacon will be recorded. This will map out the pupil from each beacon as it is seen through the Shack-Hartmann lenslet array and will allow for increased reconstruction fidelity.
CONCLUSIONS

The experiments carried out at the Kuiper and MMT telescopes have demonstrated that adaptive optics using multiple beacons will be a powerful tool for reducing the effects of atmospheric seeing. Open-loop measurements predict that ground-layer adaptive optics can be expected to reduce the stellar wavefront error by 23 to 44% over the control space for wide fields of view. It has been shown that tomographic adaptive optics, which holds the promise of providing diffraction-limited imaging, is possible with multiple laser guide stars and should be an area of ongoing research.

Work at the MMT has produced all of the tools necessary for the closed-loop operation of a multiple laser guide star adaptive optics system: the lasers and beam projector, the new facility wavefront sensor, the real-time reconstructor computer and the deformable secondary mirror. These are now all being used together for the first time, with the first results coming from the last observing run in July 2007 where a single mode was controlled by the five laser beacons. In September of 2007, the full high-order ground-layer adaptive optics loop will be controlled by the laser signals in conjunction with a tip/tilt natural guide star. The imaging performance delivered by the system will be optimized and evaluated.

The advancements made at the MMT will increase the capability of current telescopes and will lay the groundwork for the adaptive optics systems of the future extremely large telescopes. At the MMT, a new parameter space of
science will be enabled, increasing sky coverage and the resolution and
sensitivity of astronomical observations. Statistical studies of high redshift
galaxies and sub-stellar objects in star forming regions will be supported by
ground-layer adaptive optics. Tomographic adaptive optics will allow for
diffraction-limited imaging over a much larger portion of the sky than currently
supported by the natural guide star adaptive optics system. The Large Binocular
Telescope is now planning to implement a very similar multi-laser guide star
adaptive optics system which will augment its larger entrance pupil size (Lloyd-
Hart et al. 2007). The design of the adaptive optics system for the future 25 m
Giant Magellan Telescope (Lloyd-Hart et al. 2006a) relies heavily on the lessons
learned in constructing the MMT system. Ground-layer and tomographic adaptive
optics will be enabled at the GMT by multiple Sodium laser guide stars, with
multi-conjugate and multi-object adaptive optics enabled in a second generation.
REFERENCES


Lloyd-Hart, M., et al., 2006b, “Experimental results of ground-layer and tomographic wavefront reconstruction from multiple laser guide stars,” Optics Express 14, 7541-7551


Rhoadarmer, T., 1999, “Construction and testing of components for the 6.5 m MMT adaptive optics system,” Ph. D. dissertation, University of Arizona


Stalcup, T., et al., 2007a, “Test stand for the adaptive secondary at the MMT Observatory,” in preparation


APPENDIX A: GROUND-LAYER WAVE FRONT RECONSTRUCTION FROM MULTIPLE NATURAL GUIDE STARS

11 June 2007

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Ground-layer wave front reconstruction from multiple natural guide stars

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Abstract

Observational tests of open-loop ground-layer wave front recovery have been made using a constellation of four natural guide stars at the 1.55 m Kuiper telescope in Arizona. Such tests explore the effectiveness of wide-field seeing improvement by correction of low-lying atmospheric turbulence with ground-layer adaptive optics (GLAO). The wave fronts from the four stars were measured simultaneously on a Shack-Hartmann wave front sensor (WFS). The WFS placed a 5 × 5 array of square subapertures across the pupil of the telescope, allowing for wave front reconstruction up to the fifth radial Zernike order. We find that the wave front aberration in each star can be roughly halved by subtracting the average of the wave fronts from the other three stars. Wave front correction on this basis leads to a reduction in width of the seeing-limited stellar image by up to a factor of 3, with image sharpening effective from the visible to near-infrared wavelengths over a field of at least 20. We conclude that GLAO correction will be a valuable tool that can increase resolution and spectrographic throughput across a broad range of seeing-limited observations.
1. Introduction

Ground-layer adaptive optics (GLAO) is a potentially powerful, but as yet unproven, adaptive optics (AO) technique which promises modest wave front correction over wide fields of view. By measuring and averaging the incoming wave fronts to a telescope at several different field points, an estimate of the common turbulence located near the entrance pupil of the telescope can be made, with the uncorrelated higher altitude contributions averaged away. This estimate, when applied to a deformable mirror conjugated near the telescope’s pupil, can correct the atmospheric aberration close to the telescope which is common to all field points. It has been found empirically at various sites that typically one-half to two-thirds of the atmospheric turbulence lies in this ground layer (Andersen et al. 2006; Avila et al. 2004; Egner et al. 2006; Lloyd-Hart et al. 2006b, 2005; Tokovinin & Travouillon 2006; Tokovinin et al. 2005; Velur et al. 2006; Verin et al. 2000), so when the technique is applied, the natural seeing will improve substantially over a large field. This will be of particular value to science programs that until now have not found any advantage in AO. Many observations that are normally carried out in the seeing limit will benefit from improved resolution and signal-to-noise ratio (S/N), ultimately increasing scientific throughput.

Ground-layer correction was first suggested by Rigaut (2002) as away to improve wide-field imaging for large telescopes. Since then, numerous
simulations have shown that GLAO can effectively and consistently improve the atmospheric seeing (Andersen, et al. 2006; Le Louarn & Hubin 2005; Rigaut 2002; Tokovinin 2004a, 2004b). Plans are underway to implement GLAO at several telescopes around the world with a variety of techniques. The European Southern Observatory will build an AO system with multiple sodium laser guide stars (LGSs) for the Very Large Telescope (VLT) that can work in GLAO mode (Stuik et al. 2006). A 1 arcmin square corrected field will be imaged with the instrument MUSE with future plans to correct a 7.5 arcmin square field for the High Acuity Wide Field K-Band Imager (HAWK-I; Casali et al. 2006). The Southern Astrophysical Research telescope is planning to use a single low-altitude Rayleigh LGS to recover the effects of low-level turbulence, with a 30 corrected field fed to downstream science instruments (Tokovinin et al. 2004c). The Gemini North telescope is currently exploring the feasibility of a GLAO system, with a new deformable secondary mirror (DSM), that will also use sodium LGS (Szeto et al. 2006). The Large Binocular Telescope (LBT) is including a GLAO mode as part of its NIRVANA multiconjugate adaptive optics system, which uses DSMs and up to 16 natural guide stars (NGS; Ragazzoni et al. 2003). Recently, experiments at the 6.5 m Magellan and MMT telescopes have demonstrated open-loop performance of GLAO correction (Athey et al. 2006; Baranec et al. 2006; Lloyd-Hart et al. 2006b, 2005), and it is currently being implemented at the MMT using a constellation of five Rayleigh LGSs. Commissioning runs at the MMT, beginning in late 2006, are expected to
demonstrate for the first time the real-world closed-loop performance of this new AO technique (Lloyd-Hart et al. 2006c).

Driven by considerations of aperture size and sky coverage for AO, future extremely large telescopes (ELT) such as the Giant Magellan Telescope (GMT; Fabricant et al. 2006; Johns 2006; Lloyd-Hart et al. 2006a) and the Thirty Meter Telescope (TMT; Ellerbroek et al. 2005, Ellerbroek et al. 2006; Stoesz et al. 2006) already include multi-LGS wave front sensing in their baseline designs. GLAO, as a natural capability of such systems, is expected to give useful image improvement in the near-infrared bands over fields of several arcminutes. Because the performance of GLAO is essentially independent of the size of the aperture, there is no qualitative gain for an ELT over an 8 – 10 m telescope in resolution. GLAO is nevertheless needed to preserve its quantitative advantage of higher resolution compared to the seeing limit.

Despite the plans described above, closed-loop GLAO has yet to be tested at any telescope. In order to explore its quantitative value, we have carried out open-loop wave front measurements of a close asterism at the 1.55 m Kuiper telescope on Mt. Bigelow in Arizona. The goal of this experiment was to predict on-sky performance in a closed-loop system and to explore the behavior of the correction with wavelength and other system parameters.
2. Experimental design

To explore the feasibility of GLAO correction, we designed and built a novel optical system to capture wave front information from multiple sources in the selected field simultaneously by imaging multiple Shack-Hartmann patterns onto a single CCD. To minimize cost, we used off-the-shelf optics. Using the equatorial 1.55 m Kuiper telescope’s f/13.5 configuration, the camera had a 2.5 arcmin square field of view with the constraint that stars be separated by a minimum of 30″ so that their patterns do not overlap. While this is smaller than the field that simulations suggest may benefit from GLAO (Andersen et al. 2006), it greatly eases constraints on the optical design of the wave front sensor (WFS). The pupil was divided by a standard lenslet array into a 5 × 5 grid of square subapertures, 31 cm on a side when projected back to the primary mirror, of which 20 were illuminated. The final plate scale on the camera is 0.57″ pixel$^{-1}$. The detector was a 512 × 512 pixel Kodak KAF-0261E CCD with 20 µm pixels, which were binned 2 × 2 on-chip. Since the shortest exposure afforded by the camera’s internal shutter was 100 ms, we used an external, manually operated photographic shutter to shorten exposures down to 33 ms on the sky, which still gave high enough S/N on the camera for our chosen asterism. The time between exposures was approximately 2 s, much larger than the exposure time, so that successive frames are temporally uncorrelated. Data were taken in sequences of
25 frames with 20 dark frames recorded in between each data set for later background subtraction.

The stars used for the experiment form a close asterism in the constellation Serpens Cauda; a Digitized Sky Survey (DSS) image is shown in Figure 1. The four brightest stars range in $V$ magnitude from 9.4 to 10.6, with separations from the central star between 57" and 75".

Fig. 1.—DSS2.J.POSSII image of the target asterism.
3. Data analysis

3.1. Wave front reconstruction

Data were taken on the night of 2003 June 17. Figure 2 shows an example of the 512 frames of data recorded at 33 ms exposure time over a 67 minute period. The images show four different Shack-Hartmann spot patterns corresponding to the four brightest stars of the asterism with the same geometry as seen on the sky.

The spot positions in the Shack-Hartmann patterns were calculated by first resampling the image by block replication onto a grid 10 times finer than the CCD pixels and then finding the local peaks in the convolution of the data with a Gaussian of width 1.3\"; a parabolic fit to each peak determined the centroid position of the corresponding spot (Poyneer 2003). The effect of distortion on the peripheral Shack-Hartmann spot patterns, which can be seen as the nonregular spacing of spots in each pattern in Figure 2, was corrected explicitly. The variances in tilt of each row and column of subapertures within each pattern, taken across the full ensemble of data, were measured and fit to linear functions; the fitted variance for each row and column was then scaled to the variance in tilt of subapertures in the central pattern. This correction was necessary to account for misalignment seen in the optical setup. If this systematic error is left uncalibrated, we find that GLAO correction of the measured Zernike modes leaves a residual wave front error for the most distorted star, number 1, of 515
nm rms. By applying the distortion correction, the GLAO residual is reduced to 437 nm. The uncertainty in the calibration is small compared to the difference between these results and, therefore, also small compared to the residual atmospheric wave front error.

Fig. 2.—Example frame from the Shack-Hartmann wave front sensor. Each of the four patterns corresponds to one of the stars seen in Fig. 1.
For each subaperture, the calibrated mean spot position over all 512 frames was subtracted from its instantaneous position in order to remove the effects of static aberrations. The subaperture slopes were then calculated by multiplying the corrected differential spot positions in each axis by the measured plate scale on the optical axis.

Wave fronts from each of the four stars were reconstructed from the 40 subaperture slope measurements by using a synthetic reconstructor matrix derived from a model of the pupil on the Shack-Hartmann lenslet array. The reconstructor matrix creates a vector of coefficients for the first 20 Zernike modes (orders 1 - 5) from the input slope measurements.

3.2. GLAO performance

In this experiment, an estimate of the ground-layer turbulence is calculated as the average of three of the stellar wave fronts. The coefficients for each of the 20 Zernike modes are averaged to give the ground-layer estimate, which is then subtracted from the fourth star’s measured Zernike coefficients to calculate the residual error after ground-layer correction. Because of the temporally uncorrelated nature of the data, this correction is done for each individual frame and the effects of servo lag are absent from the GLAO corrections. Figure 3 shows an example of the reconstructed phases for each star from a single frame of data, the ground-layer estimate computed from the
average of stars 1, 3, and 4, and the residual wave front of star 2 after ground-layer correction.

Fig. 3.—Reconstructed phase maps for a single frame for each star, the ground-layer estimate based on the average of wave fronts from stars 1, 3, and 4, and the residual of the phase of star 2 after GLAO correction. The scale is ±1.9 µm.

The same analysis can be applied to each of the four stars. Table 1 shows the rms wave front error for each star by Zernike order, along with the residual error after ground-layer correction from the other three stars. The angular separation $\alpha$ between the star and the geometric center of the three other stars used for GLAO correction is also given. Table 1 indicates that up to 45% of the
wave front error from orders 2 - 5 can be corrected by GLAO for the central star, 2, enclosed by the three outer stars. In the three other cases, in which $\alpha$ is large and the star to be corrected is outside of the three beacons used in the GLAO average, GLAO still has traction in correcting the aberrated stellar wave front, indicating that GLAO correction rolls off smoothly outside of the measurement constellation.

The excessive amount of power seen in the uncorrected tilt modes is due to telescope tracking error and is not indicative of the actual atmospheric tilt. The majority of the tilt power comes from jitter in the east - west direction, while there is a constant drift in tilt in the north - south direction. By applying a linear correction to the drift in the north - south direction over the 67 minutes during which data were collected, we can estimate the actual single axis atmospheric tilt to be 471 nm. This gives us a conservative lower estimate of 666 nm in both uncorrected first order modes. This also suggests that approximately 69% of the atmospheric tilt is corrected for star 2.
<table>
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<th>3 (nm)</th>
<th>4 (nm)</th>
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<th>α (arcsec)</th>
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<td>85</td>
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</table>

Notes.—The rms stellar wave front error, summed in quadrature over all the modes in each Zernike order. The numbers marked by asterisks (*) denote residual wave front error after GLAO correction by the three other stars. The last column reports the angular separation $\alpha$ between the star and the geometric center of the three other stars used for GLAO correction.

The predicted fitting error for our particular geometry of reconstruction is approximately 100 nm rms. Summing the second through fifth-order measured, uncorrected wave front errors with the estimated atmospheric tilt gives 700 nm rms of total atmospheric wave front error for each beacon, meaning the fitting error accounts for only ~1% of the total measured power. We have also modeled
the effects of shot and background noise on our slope measurements.

Propagating the error in slopes through our synthetic reconstructor leads to an additional ≤1% of total rms error in each of the stars, depending on their brightness. Because of the poor seeing during the time of observations, the measured wave front signals were considerably higher in power than our noise sources.

The total strength of the atmospheric turbulence can be calculated based on the rms values of each of the uncorrected modes (with the exception of tilt) in each of the stars. Using the method developed by Chassat (1992), we calculate a mean Fried length for these observations of $r_0 = 8.0 \text{ cm at } \lambda = 500 \text{ nm}$. We can also estimate the amount of power in the ground-layer turbulence by assuming that the residual power in the GLAO-corrected modes is attributable to the uncorrected free atmosphere. In this case we calculate $r_0^{FA} = 14.5 \text{ cm}$ from the GLAO residuals from star 2. This leads to a Fried length of $r_0^{GL} = 10.6 \text{ cm}$ in the ground layer, or 63% of the total atmospheric turbulence, in line with ground-layer estimates at other sites.

As a measure of how well the ground-layer estimate of the central star is performing, we can compare this to the optimal linear estimate of star 2’s wave front from the other three stars (Lloyd-Hart et al. 2006b). We assume a linear relation between the wave front of the star to be corrected, and the wave fronts from the other three guide stars are represented by the equation

$$\hat{a}_i = T b_i,$$  

(1)
where, for the \( i \)th frame in a data sequence, \( \hat{a}_i \) is the vector of Zernike polynomial coefficients characterizing the estimate of star 2’s wave front, \( b_i \) is the vector containing the Zernike coefficients of all the other three stars’ reconstructed wave fronts, and \( T \) is the optimal linear reconstructor matrix relating the two. We wish to find a reconstructor \( T \) that minimizes \( \langle |a_i - \hat{a}_i|^2 \rangle \), the squared norm of the difference between star 2’s measured wave front coefficients \( a_i \) and their estimates, averaged over all the frames.

To investigate the limit of performance permitted by the data in this least-squares sense, we have derived \( T \) by a direct inversion of the data, using singular-value decomposition (SVD). This approach does not rely on any a priori model of the atmospheric \( C_n^2 \) profile or knowledge of the noise characteristics. A matrix \( B \) is constructed from 512 data vectors \( b_i \). \( B \) is well conditioned and so may be inverted with SVD to give \( B^+ \) with no truncation of the singular values. A similar matrix \( A \) is constructed from the corresponding \( a_i \) vectors. The optimal linear reconstructor is then given by

\[
T = AB^+. 
\] (2)

Applying \( T \) to vectors \( b_i \) drawn from the same data set used to compute it yields the best-fit solution \( \hat{a}_i \) and characterizes the noise floor in the data. A comparison can thus be made between the correction from the simple GLAO average of measured Zernike coefficients from the three field stars and the optimal linear estimate. Table 2 shows the residual errors by Zernike radial order after both types of correction.
Table 2. Comparison of AO-Correction Methods

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<td></td>
</tr>
<tr>
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<td>57</td>
<td>263</td>
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<tr>
<td>Optimal linear reconstructor</td>
<td>173</td>
<td>102</td>
<td>70</td>
<td>50</td>
<td>52</td>
<td>224</td>
</tr>
</tbody>
</table>

Note.—The rms stellar wave front error by Zernike order for the uncorrected, GLAO corrected, and optimally corrected wave front of star 2.

The least-squares estimator implicitly accounts for correlations in the stellar wave fronts that arise from turbulence at all altitudes, not just close to the ground. The improvement in performance over the simple average, which when taken in quadrature amounts to 138 nm, is likely largely attributable to high-altitude seeing. However, the linear performance penalty of simple GLAO correction is only 17% for the particular line of sight to star 2. This result is not as dramatic as the results using this same method and open-loop data with LGS at the MMT, where the improvement over GLAO with the least-squares estimator correction ranges from 39% to 48% (Baranec et al. 2006). This difference in improvement is due to the difference in telescope diameters; the correcting beacons decorrelate much more quickly as a function of height at the Kuiper telescope and are therefore less able to estimate high-altitude seeing. As we
describe below, this modest price paid in axial performance buys a substantially wider corrected field of view than the limit, set by the isoplanatic angle, for full on-axis correction.

3.3 Predicted image quality
3.3.1. PSF simulations

Simulated point-spread functions (PSFs) of both the natural seeing and post-GLAO correction can be created based on the recorded Zernike amplitudes and measured coherence length. For each frame of data, we create a random pupil phase map obeying Kolmogorov statistics with inner and outer scales of 2 mm and 100 km, respectively. In this way, the effects of uncorrected high order aberration and measurement uncertainty are included in the PSF estimates. Each frame’s PSF is generated by calculating the power spectrum of the complex amplitude pupil map with the final long-exposure PSF image being the sum of all the individual frame PSFs. Since subsequent frames are temporally uncorrelated, servo lag was absent in these PSF simulations.

For the seeing-limited case, we fit and subtract the Zernike modes up to radial order 5 from the random pupil phase map. Because of the excessive tilt caused by telescope tracking error, random tilts drawn from a normal distribution with variance matching our estimate of the actual atmospheric tilt are added back to this phase map; in addition, the second- through fifth-order modes are
replaced with the measured modes from the four stars. For the GLAO-corrected images, we replace the lowest five orders of Zernike modes from our original random phase map with the Zernike modes measured from the residual of our GLAO corrections. Our simulated GLAO PSFs are therefore based on the measured modes themselves, not their statistics, and include the results of correcting the large telescope tracking error on-sky.

3.3.2. Calculated FWHM

Two simulated 17 s J-band exposures of star 2 are shown in Figure 4, a seeing-limited image and an expected GLAO corrected image. In J-band, the estimated seeing full width at half maximum (FWHM) under our seeing conditions is 0.91", and with GLAO this reduces the FWHM by roughly a factor of 3 to 0.27". In J-band there are approximately 1.3 \( r_0 \) lengths across a WFS subaperture diameter; explaining why we are adequately sampling the wave front with our WFS for good GLAO correction.
Fig. 4.—Simulated J-band PSF of star 2 with (right) and without (left) GLAO correction. Both PSFs have been scaled by their respective peak intensities; the peak intensity of the GLAO-corrected PSF is 6.0 times greater than the peak intensity of the seeing-limited PSF. Scaling is linear.

The elongation of the corrected PSF in Figure 4 is in the long direction of the three other stars with a calculated ratio of the major and minor axes of 1.25. The ratio of the variances in tilt of the two axes is 1.9 and is not a statistical anomaly but an actual effect of the GLAO correction. In simulation, Andersen et al. (2006) see the same effect of PSF elongation with a ~8′ diameter constellation of 3 NGS at the 8 m Gemini telescope, with a mean and maximum PSF axis ratio of 1.10 and 1.14, respectively, over the GLAO-corrected field. Interestingly, they also found that when using a constellation of five equally spaced LGSs, the PSF morphology was much more consistent over the GLAO field with a mean PSF axis ratio of only 1.02. This is due to both the symmetry of the correcting LGS
constellation of beacons and the cone effect decreasing the correlation of high altitude turbulence sensed.

Figure 5 presents the radially averaged profiles of the simulated PSF exposures seen in Figure 4 with the addition of the profiles from the other three GLAO-corrected stars. Table 3 and Figure 6 present the FWHM values for these exposures, including exposures spanning the visible to the near-infrared wavelengths.

Table 3. Stellar FWHM for Simulated PSFs

<table>
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<tr>
<th>λ</th>
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<th>Diffraction Limit (&quot;)</th>
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<td></td>
<td></td>
<td>Star 1</td>
</tr>
<tr>
<td></td>
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<td>H (1.6 µm)</td>
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<td>K (2.2 µm)</td>
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Fig. 5.—Radially averaged J-band PSF profiles. The seeing-limited PSF is the thick solid line; the GLAO-corrected PSFs are the thin lines showing star 1 (solid line), star 2 (dot-dashed line), star 3 (dotted line), and star 4 (dashed line).
GLAO performance is much improved over the native seeing at all wavelengths, with most of the performance gains being made at the near-infrared wavelengths as the corrected images are approaching the diffraction limit. Figure 7 shows this same data now by spectral wavelength as a function of $\alpha$. Star 2, only 17" from the geometric center of the other three stars, shows the best GLAO correction. Performance then degrades monotonically by distance to the corrected star from the center of its GLAO correcting constellation. Star 1, even
at 113" away, still shows a significant amount of image improvement after GLAO correction. As the GLAO correction is pushed into the longer wave bands, the performance as a function of field position starts to flatten out, as can be seen with the H- and K-band results.

![Plot of FWHM by wavelength as a function of distance to the center of the GLAO constellation of stars.](Image)

**Fig. 7.**—Plot of FWHM by wavelength as a function of distance to the center of the GLAO constellation of stars: 500 nm (thick solid line), 750 nm (thick dashed line), 1 µm (thin dotted line), J (thin solid line), H (thin dashed line), and K (thin dot-dashed line).

These simulated PSF results are comparable to the estimated performance of the MMT LGS GLAO system. In seeing of $r_0 = 14.7$ cm, the
uncorrected PSF FWHMs in the center of the GLAO field in H-, J-, and K-bands of 0.77", 0.65", and 0.54", respectively, dropped to 0.38", 0.16", and 0.12" (Lloyd-Hart et al. 2006b). The experiments at the Kuiper telescope and the MMT have two differences that affect the comparison of the results. First, the Kuiper experiment had fewer \( r_0 \) lengths across a subaperture diameter, 3.9 at 500 nm, than the MMT with 4.9, so the expectation is that GLAO correction at the Kuiper telescope would be able to extend into the shorter wavelengths. Second, the MMT GLAO results, with a much larger diameter of 6.5 m, as opposed to Kuiper’s 1.55 m, did not suffer from diffraction effects at longer wavelengths; with the Kuiper PSF FWHMs approaching the diffraction limit.

3.3.3. Calculated Encircled Energy

From these same simulated PSF images, we have calculated two figures of merit describing encircled energy; \( \theta_{50} \), the radius within which half of the PSF energy is enclosed, and \( \text{EE}\% (0.5") \), the percentage of total energy within a canonical 0.5" diameter. These are of particular interest for maximizing the resolution and throughput of spectroscopic science data. Encircled energy as a function of radius is plotted in Figure 8 for the J-band exposures presented in Figures 4 and 5.
In J-band, the seeing-limited $\theta_{50} = 0.57''$, with 14.4% of the total PSF energy within 0.5", and with GLAO, $\theta_{50}$ reduces down to 0.34" and EE%(0.5") increases by over a factor of 2 to 39.2% for star 2. These figures of merit, for the seeing limit and each GLAO-corrected star, are presented in Table 4 for wavelengths from the visible to the near-infrared.
Table 4. Stellar Encircled Energy Metrics for Simulated PSFs

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<th>GLAO-Corrected Images</th>
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<tr>
<td>500 nm</td>
<td>0.69/ 9.7</td>
<td>0.59/14.4</td>
</tr>
<tr>
<td>750 nm</td>
<td>0.64/11.6</td>
<td>0.51/19.5</td>
</tr>
<tr>
<td>1 µm</td>
<td>0.60/13.1</td>
<td>0.46/24.0</td>
</tr>
<tr>
<td>J (1.25 µm)</td>
<td>0.57/14.4</td>
<td>0.42/27.8</td>
</tr>
<tr>
<td>H (1.6 µm)</td>
<td>0.54/15.7</td>
<td>0.38/31.7</td>
</tr>
<tr>
<td>K (2.2 µm)</td>
<td>0.52/17.3</td>
<td>0.35/34.9</td>
</tr>
</tbody>
</table>

Note.—For each entry, the first number is $\theta_{50}$ in arcseconds and second is encircled energy percentage within a 0.5” diameter.

For every GLAO-corrected star, $\theta_{50}$ decreases and EE%(0.5") increases relative to the seeing limit with the largest improvements in image quality for stars closer to the center of the GLAO correcting field and at the longer wavelengths.

We have also computed the metrics, EE%(1.0") for the seeing limited J-, H-, and K-band exposures as 42.7%, 45.5%, and 48.3%. This is interesting to note as these are similar to the EE%(0.5") values for the GLAO-corrected J, H, and K values of star 2 being 39.2%, 45.1%, and 49.2%. The improvement in encircled energy afforded by GLAO correction can therefore be thought of as either increasing the resolution of observations by a factor of 2 and keeping the same throughput or increasing the throughput by a factor of 3 with a constant
resolution. The optimization of resolution and throughput will be an important consideration in the design of scientific instruments and observational programs.

4. Conclusions

Our experiment and subsequent analysis suggest that ground-layer AO correction will be a powerful tool for reducing the effects of atmospheric seeing over wide fields. We have shown here that even with only three beacons, there is enough averaging of the modes and decorrelation of the upper altitude signal to lead to a good estimate of the ground-layer turbulence. GLAO correction can potentially reduce the stellar PSF FWHM at all visible and near-infrared wavelengths; decreasing it by a factor of 3 in J-band. However, the use of NGS causes some elongation of the predicted corrected PSFs. The anticipated image improvement will also benefit spectroscopy, where in the near-infrared the increase in encircled energy afforded by GLAO correction can either increase the resolution of observations by a factor of 2 with the same throughput or increase the throughput by a factor of 3 with a constant resolution. The field over which this image improvement is expected is quite large, with the simulated GLAO correction of star 1, 73″ away from the nearest correcting beacon, showing a reduction in the PSF FWHM by almost a factor of 2 in J-band. It has been seen here and in other experiments that GLAO correction can always be expected to
improve seeing (Lloyd-Hart et al. 2006b) but will be particularly powerful when the seeing is moderate to poor, $r_0 < 15$ cm at $\lambda = 500$ nm.

In comparison, open-loop GLAO experiments with LGS at the MMT show slightly different performance estimates (Baranec et al. 2006). In moderate seeing, GLAO correction is expected to decrease the PSF FWHM by a factor of 4 in H- and K-bands. However, with a larger subaperture diameter to $r_0$ ratio, GLAO correction at the MMT will not perform as well into the shorter visible wavelengths. We would also expect the PSF morphology to be much more consistent across the GLAO field with the use of LGS.

The first attempt at closing an AO loop around a ground-layer estimate will be performed with the MMT LGS AO system in early 2007. There, a constellation of five dynamically refocused Rayleigh lasers are projected onto the sky in a pentagon of 20 diameter. The beacon signals will be averaged to get an estimate of Zernike orders 2 - 8, and when combined with the signal from a tilt camera using an electron-multiplying CCD, will be used to drive the MMT’s DSM. A near-infrared imager PISCES, with 0.11" pixels and a field of view of 110", will be used to measure the performance over the field of the laser constellation. Early science programs will focus on deep wide-field imaging that will benefit from GLAO and are slated to begin with establishing realistic performance and sensitivity limits on targets of scientific interest in mid-2007 (Lloyd-Hart et al. 2006c).
With the demonstrated work here and at the MMT, it is clear that GLAO should be of great interest to current large and future ELTs. As seen in GLAO-modeling studies for Gemini (Andersen et al. 2006) GLAO has the promise to improve the observed seeing over the raw natural seeing. This can be done either with multiple NGS or LGS beacons or other novel implementations (Morris & Myers 2006) with advantages to each method. Already the GMT and TMT projects are planning to use multiple LGSs in their designs which can be used to support GLAO observations. All current telescopes with plans to install DSMs, the VLT, Magellan, and the LBT, can also follow the lead of the MMT system by installing multiple sodium or Raleigh systems to improve the seeing of their telescopes.

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References


Lloyd-Hart, M., Baranec, C., Milton, N. M., Snyder, M., Stalcup, T., & Angel, J. R. P. 2006b, Optics Express, 14, 7541


Rigaut, F. 2002, in Beyond Conventional Adaptive Optics, ed. E. Vernet et al. (Garching: ESO), 11


Tokovinin, A. 2004a, Proc. SPIE, 5382, 490


Verin, J., et al. 2000, Gemini RPT-AO-G0094 (Hilo: Gemini Obs.),
http://www.gemini.edu/documentation/webdocs/rpt/rpt-ao-g0094-1.ps
APPENDIX B: FIRST TESTS OF WAVEFRONT SENSING WITH A CONSTELLATION OF LASER GUIDE BEACONS

11 June 2007

Christoph Baranec
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Crystal Tinch
Publications Specialist
First Tests of Wavefront Sensing With a Constellation of Laser Guide Beacons

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Abstract

Adaptive optics to correct current telescopes over wide fields, or even to correct future very large telescopes over narrow fields, will require real-time wavefront measurements made with a constellation of laser beacons. Here we report the first such measurements, made at the 6.5m MMT with five Rayleigh beacons in a 20 pentagon. Each beacon is made with a pulsed beam at 532 nm of 4 W at the exit pupil of the projector. The return is range-gated from 20 to 29 km and recorded at 53 Hz by a 36-element Shack-Hartmann sensor. Wavefronts derived from the beacons are compared with simultaneous wavefronts obtained for individual natural stars within or near the constellation. Observations were made in seeing averaging 1.0″ with two-thirds of the aberration measured to be from a ground layer of mean height 380 m. Under these conditions, subtraction of the simple instantaneous average of the five beacon wavefronts from the stellar wavefronts yielded a 40% rms reduction in the measured modes of the distortion over a 20 field. We discuss the use of multiple Rayleigh beacons as an
alternative to single sodium beacons on 8 m telescopes and the impact of the new work on the design of a multi–sodium beacon system for the 25 m Giant Magellan Telescope.

1. Introduction

Ground-based astronomical telescopes with adaptive correction are able to exceed the resolution of the Hubble Space Telescope. However, their use is currently limited almost exclusively to a small fraction of the sky, in small fields of view around the stars required to measure the wavefront error. These stars must be relatively bright because removal of atmospheric blurring requires rapidly updated command signals to the wavefront corrector. The radius of the compensated field around the star, the isoplanatic angle, is limited because atmospheric turbulence extends many kilometers above the ground, so the integrated wavefront distortion depends sensitively on the direction of view.

For telescopes in the current 8–10 m class, the limitation on brightness, although not on corrected field of view, can be largely removed by use of a laser beam projected toward a faint astronomical target to create an artificial beacon. Light from a sodium resonance beacon generated at ~90 km altitude follows the path taken by light from the target closely enough that a good estimate of the aberrations in the latter can be derived. The laser light, however, does not come from infinity, and as the telescope diameter is increased, the mismatch in optical
paths (the cone effect) eventually becomes so severe that no useful recovery of stellar wavefronts can be made.

Extremely large telescopes (ELTs) with diameters greater than 25 m will therefore require a further advance to recover diffraction-limited imaging with adaptive optics (AO). Multiple beacons placed so that their light collectively samples the full volume of atmosphere traversed by light from a target could in principle provide the solution. The instantaneous stellar wavefront would be computed by a tomographic algorithm applied to the wavefronts measured from all the beacons (Ragazzoni et al. 1999; Tokovinin et al. 2001; Lloyd-Hart & Milton 2003b). This method, implemented with sodium beacon lasers, is planned for the Giant Magellan Telescope (GMT; Milton et al. 2003) and for the Thirty Meter Telescope (Dekany et al. 2004) to recover the full resolution of their apertures.

In the simplest application of tomography, the stellar wavefront along a single line of sight is estimated from all the measured beacon wavefronts, and the compensating phase is applied to a single deformable mirror (DM). The technique, called laser tomography AO (LTAO), delivers a diffraction-limited field of view limited by the normal isoplanatic angle.

Once a telescope is equipped with multiple laser beacons and tomographic analysis, a variety of altitude-conjugated AO techniques are enabled: diffraction-limited resolution over a field many times the isoplanatic angle with multiconjugate and multiobject AO (MCAO and MOAO; Beckers 1988;
Tokovinin et al. 2000; Hammer et al. 2002; Dekany et al. 2004) and partially
improved seeing over a yet larger field with ground-layer AO (GLAO).

Of these advanced techniques, only MCAO has yet been attempted, in
experiments at two solar telescopes (Langlois et al. 2004; Berkefeld et al. 2004).
Numerical models of GLAO based on measurements of the vertical distribution of
turbulence at a number of sites (Rigaut 2002; Tokovinin 2004a, 2004b) suggest
the potential for dramatic image improvement in the near-infrared. D. R.
Anderson et al. (2005, in preparation) have modeled GLAO performance in
detail, using vertical distributions of turbulence seen at Cerro Pachòn that put
roughly two-thirds of the power in the ground layer. With a pentagonal
arrangement of laser guide stars (LGSs) and an adaptive secondary mirror, the
study concluded that the median image width in the K band would improve from
0.42″ to 0.18″ for a 5′ field and to 0.25″ for a field of 10′.

Ground-breaking work by Ragazzoni et al. (2000) has hinted at the power
of tomographic wavefront sensing. That paper describes the first experiments in
tomography, at the Telescopio Nazionale Galileo, in which wavefront estimates
were obtained simultaneously from a close asterism of four natural stars through
the simple expedient of defocusing the telescope. The instantaneous Zernike
modal amplitudes measured from one star were compared to estimates derived
from the modal amplitudes of the other three. Tomographic estimation from the
three beacon stars was shown to be substantially superior to a simple average or
the use of any one of the three individually.
We report in this paper results from the first implementation of a wavefront sensing system based on a constellation of multiple laser beacons. Previous work on laser-guided AO has been confined to a single beacon, usually created by resonance scattering in the sodium layer at 90 km altitude (Gavel et al. 2000; Fugate 2003; Wizinowich et al. 2004). For our work at the 6.5 m MMT (Multiple Mirror Telescope) we have created five beacons generated by Rayleigh scattering. Commercial, pulsed doubled-YAG (yttrium aluminum garnet) lasers at 532 nm are used, readily available at moderate cost. Single Rayleigh beacons gated to an altitude of ~12 km have previously been used for AO with small telescopes (Fugate et al. 1991), but the strong focus anisoplanatism and incomplete sampling of higher turbulence make a single such beacon of little value for an 8 m class telescope.

For our experiments, however, Rayleigh beacons are ideal. In our system the range gate is centered at 24 km altitude, high enough to collectively sample most of the turbulence. To increase signal strength, the sensor system includes optics to focus the telescope dynamically, to maintain sharp images of each laser pulse at it rises from 20 to 29 km (Georges et al. 2003; Stalcup et al. 2004). In this way, the range gate is extended to ~20 times longer than the telescope’s normal depth of field. Even at this high altitude, focus anisoplanatism would remain a difficulty with a single beacon, but with five it is not an issue, precisely because our goal is the development of tomographic techniques. The practical
advantage is that the current high capital and operating costs of tuned sodium lasers for resonance scattering are avoided, allowing us to make an early start.

2. Instrument description

The multibeacon experiment at the MMT has been designed to investigate both full tomographic wavefront sensing needed for diffraction-limited imaging and ground-layer sensing to improve the seeing. With these goals in mind and guided by previous modeling of tomography (Lloyd-Hart & Milton 2003a), we have built a pentagonal constellation of Rayleigh laser guide stars (RLGSs) with a diameter of 2′. This field is not as large as one would choose for ground-layer sensing alone, given theoretical predictions of the size of the field that could be corrected by a GLAO system; nevertheless, it is capable of taking the first steps to quantifying the degree of correction to be expected of a closed-loop system.

The experimental setup divides into two parts: the lasers and beam projector optics to generate the five RLGSs and the wavefront sensor (WFS) detectors and associated optics mounted at the telescope’s Cassegrain focus.

2.1. Generating the laser guide stars

The mean range chosen for the Rayleigh return is 24 km, where the beacons form a pentagon 14 m in diameter. The collective volume filling of this
arrangement allows for three dimensional sensing of the turbulence by
tomography for ranges up to 10 km and thus avoids the focal anisoplanatism that
would arise from a single RLGS.

The projection system employs two frequency-doubled YAG lasers from
Lightwave Electronics, rated at a nominal 15 W output each, operating at 532 nm
and 5 kHz pulse repetition rate (Stalcup et al. 2004). The two linearly polarized
beams are combined with a polarizing beam splitter to produce a single,
diffraction-limited beam measured at ~27 W. In operation, synchronized pulses of
light from the lasers are split by a computer generated hologram in the projection
optics to create the five beacons on a 2’ diameter ring on the sky. The lasers and
combining optics are attached directly to the 6.5 m telescope tube, with the
power supplies and chiller in an adjacent room in the corotating MMT building.
The laser heads are in a thermally controlled enclosure. At the top of the
telescope tube on one side is a steering mirror close to an image of the exit pupil,
used to compensate for slow misalignments in the projected beam direction
caused by flexure and temperature changes. The hologram is also at this pupil.
The beams are launched together through a single 50 cm diameter telephoto
objective lens mounted centrally on the 6.5 m telescope axis, directly above the
secondary mirror.
2.2. Cassegrain instrument for wavefront sensing

The WFS package mounts at the MMT’s Cassegrain focus and includes distinct optical arms for the RLGSs and a natural star. The first comprises a novel sensor, which includes the dynamic focus optics, described in detail in Georges et al. (2003), and a single electronically shuttered CCD, which images all five beacons.

We aim to measure laser returns from ~24 km altitude, twice the height of earlier Rayleigh beacons (Fugate et al. 1991), to allow better sampling of high turbulent layers. Because the air at that altitude is only 10% of the sea-level density, we have developed a new technology to focus the telescope continuously to follow the rising pulse from a Q-switched laser (Angel & Lloyd-Hart 2000; Lloyd-Hart et al. 2002). The sensitivity is thereby increased by an order of magnitude compared to conventional range-gating methods. The dynamic focus of all five beacons is achieved by sinusoidal motion of a single 25 mm mirror placed at an image of the telescope pupil, with approximately one-third of each cycle matched to the motion of the returning laser pulse.

The dynamic focus optics and mechanical resonator that moves the mirror are included in the fore optics of the RLGS sensor. The resonator also serves as the system’s master clock, triggering the laser pulses and the RLGS WFS detector shutter at prescribed phase delays. In this way, each laser pulse is tracked in focus over a range gate from 20 to 29 km.
The refocused laser light is imaged onto a common 35 mm pupil, where a prism array (Putnam et al. 2004) divides the light into 36 subapertures of equal size in a hexapolar geometry. A compound lens following the prism array images the beacons into five separate 36-spot Shack-Hartmann patterns on the detector, a CCID18 from Lincoln Laboratory. This is a 128 × 128 pixel frame transfer device with 16 output amplifiers and an electronic shutter. The controller, supplied by SciMeasure, reads the detector at frame rates up to 915 Hz. Operation of the electronic shutter during transitions of the CCD clock signals introduces additional noise into the image, so a carefully interleaved sequence is required of the clocks, for the frame transfer and read operations, and of the shutter, which is triggered by the dynamic focus oscillator.

In order to explore the effectiveness of the RLGS WFS as a function of position within the field, a second optical arm of the Cassegrain instrument was built with a standard Shack-Hartmann sensor to measure wavefronts from natural stars. A dichroic splitter covering a 3′ field separates the beams to the two WFSs, transmitting the laser light to the LGS arm and reflecting starlight at wavelengths longward of 650 nm to the star sensor.

The star WFS is a copy of the one normally used for adaptive optics with the MMT adaptive secondary mirror (Brusa et al. 2004). The pupil is divided into a 12 × 12 array of square subapertures of which 108 are illuminated. The camera uses an E2V CCD39 frame transfer detector with 80 × 80 pixels. The whole WFS and associated optics were placed on a mechanical slide, allowing translation in
one axis across the 20 field covered by the beacons. In practice, the telescope is offset a prescribed angle from the nominal stellar coordinates, and the WFS is moved by a corresponding angle in order to reacquire the star.

In operation, both sensors are run simultaneously but asynchronously, with the latter sensor providing measurements of the true stellar wavefront aberration to which reconstructions derived from the recorded RLGS signals can be compared. The star WFS was typically run at its maximum unbinned frame rate of 108 frames s\(^{-1}\), with the RLGS sensor running at approximately half that frame rate. Data capture was externally registered in time by the use of synchronized flashing LEDs placed in front and to the side of each camera running at approximately 1 Hz.

3. Observations and analysis
3.1. Photometric and imaging performance of the RLGS wavefront sensor

We have quantified the return flux from the RLGSs using observations of the spectrophotometric standard star HD 192281 made through a filter of 3 nm equivalent width centered on 532 nm. To do so, the prism array defining the subapertures in the RLGS WFS was replaced with a flat optic of the same construction, and the telescope was refocused to account for the substantial difference in stellar and beacon conjugates. The detected quantum efficiency of the WFS, including the telescope, optics and detector, was found to be 15%.
Throughput of the beam projector optics was estimated at 73% from measurements of each element individually.

During observations of the RLGSs, the detected return flux at zenith was $1.1 \times 10^5$ photoelectrons m$^{-2}$ J$^{-1}$ over a range gate of 20–29 km. Accounting for our estimated efficiencies in both the outgoing and incoming beams, this amounts to $1.0 \times 10^6$ photons m$^{-2}$ at the telescope aperture per joule at the output of the beam projector. The expected flux has been calculated from the lidar equation (Hardy 1998, p. 222) and the atmospheric transmission (Allen 2000), taking into account the atmospheric temperature and pressure profile measured by a routine meteorological balloon flight from nearby Tucson International Airport at approximately the same time as the observations. The agreement, within 2%, is good—fortuitously so, since the uncertainty in our estimate of the projected power is 10%–20%, dominated by uncertainty in the calibration of the lasers’ built-in power meters. The return flux is as bright as a star of $m_v = 9.9$ seen through a $V$ filter and is similar to the range of returns from sodium beacons: Ge et al. (1998), for instance, measured $1.2 \times 10^6$ photons m$^{-2}$ J$^{-1}$.

An unusual problem with the CCD in the RLGS WFS prevented the formation of sharp images. The typical FWHM of the Shack-Hartmann spots was found to be 4.4 pixels (equivalent to 3.7") when images of the beacons recorded independently on a separate acquisition camera were measured to have a FWHM of $\sim 1.5"$. A replacement chip has since been installed that shows no sign
of this blurring. The spot separation, set by the WFS optics, was just 4″, so that there was substantial overlap of neighboring spot images. An iterative deconvolution algorithm was required to recover usable spot positions. Furthermore, the increase in width reduced the signal-to-noise ratio (S/N) of the determination of each spot’s position by a factor of ~2.5. An examination of the power spectral densities of the reconstructed modal amplitudes from the RLGSs showed that frequencies above 15 Hz were dominated by noise rather than by atmospheric signal. In the following analysis, therefore, a low-pass filter with a sharp cut at 15 Hz was applied to the data.

3.2. Comparison of laser and natural star wavefronts

Wavefront data were recorded during a 2 hr period on 2004 September 30, during which the seeing, 1.0″ in the V band, was worse than the median for the telescope. The recorded data are frames from the RLGS and star WFS cameras in near-continuous sequences of 9 s. Figure 1 shows sample frames taken simultaneously from the two cameras and the corresponding reconstructed wavefronts, which in the case of the RLGSs is the average of the five individual reconstructions. Both reconstructions are complete for the 25 modes in Zernike radial orders 2–6, although the resolution of the star WFS would allow more modal amplitudes to be calculated. Overall tip and tilt are, of course, not
recovered from the lasers because of unknown beam motion in the upward paths.

Fig. 1.—Examples of the WFS data. The top panels show the WFS outputs, with the RLGS sensor on the left and the star WFS on the right. The bottom panels show the corresponding wavefronts reconstructed to the sixth Zernike order. The RLGS reconstruction is the average of the five individual wavefronts. [This figure is available as an mpeg file in the electronic edition of the Journal.]
Reconstructions of three individual modes as they evolve in time over a period of 3 s are shown, by way of example, in Figure 2. Values for the modal amplitudes for the average of the five beacons and the simultaneous values from a star near the center of the RLGS field are plotted. The generally good agreement indicates the presence of a strong ground layer. Aberration very close to the telescope’s aperture would be common to all five RLGSs and the star and so would contribute in the same way to the variation of the modes. On the other hand, high-altitude turbulence would be sampled differently by the six light beams and would lead to the differences in the recovered amplitudes.
Fig. 2.—Examples of the reconstruction of three Zernike modal amplitudes from the natural star (dashed line) and the average RLGS signal (solid line).
By subtracting the average RLGS wavefront from the stellar wavefront, one can obtain a quantitative estimate of the degree of correction possible with a simple ground-layer correcting scheme in which a DM conjugate to the telescope pupil is driven in response to the averaged beacon signals. Figure 3 shows the result for a 3 s sample of data. In general, we find that both the mean and the variance of the aberration are substantially reduced. We have investigated the potential for such correction for stars at several locations across the RLGS field. The geometry of the beacons and the positions of the stars in the field used for this study are laid out in Figure 4.
Fig. 3.—Wavefront aberration averaged over the 6.5 m pupil for a representative sample of data. The dashed line shows the total for the reconstructed modes in Zernike orders 2–6 in the stellar wavefront. The solid line shows the residual after subtraction of the average RLGS wavefront.
Fig. 4.—Geometry on the sky of the RLGSs used to measure the effect of boundary-layer wavefront sensing. The labeled positions of the natural star for which data were recorded are separated from the geometric center of the RLGS constellation by 17.2", 39.8", 48.5", 64.5", and 77.5", respectively.

For the five positions of the star, Table 1 shows the measured stellar wavefront aberration averaged over all the Zernike modes in each order, both
before and after subtraction of the average RLGS wavefront. The value of \( r_0 \), deduced from the image motion of the Shack-Hartmann spots in the stellar WFS and scaled to 500 nm wavelength, is also shown. The overall degree of correction varies from 40% near the center to 33% just outside the field covered by the RLGSs. Because the seeing varied significantly over the 2 hr period spanned by these observations, a direct comparison of wavefront correlation versus field angle is possible only by scaling the results to a common value. Figure 5 shows the results graphically, where the rms wavefront values in Table 1 have been scaled by a factor \( (r_0/10.1 \text{ cm})^{5/6} \), to the average value of \( r_0 \) of 10.1 cm seen during the observations. The greatest improvement is seen in the lowest orders, which is to be expected both because the amplitudes of the lower order modes have larger variance and are therefore sensed with greater S/N and because their angular correlation scale is larger, and therefore correction extends to a higher altitude than for modes with high spatial frequency. We also note that random noise in the reconstructions would preferentially appear as differences among the five RLGS signals, and so our estimate of the correlation between the natural star and mean LGS wavefronts is conservative.
Table 1. Wavefront Aberration Before and After Correction

<table>
<thead>
<tr>
<th>Zernike Order</th>
<th>Set 1 (nm)</th>
<th>Set 2 (nm)</th>
<th>Set 3 (nm)</th>
<th>Set 4 (nm)</th>
<th>Set 5 (nm)</th>
</tr>
</thead>
<tbody>
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<td>572</td>
<td>513</td>
<td>571</td>
<td>559</td>
</tr>
<tr>
<td></td>
<td>255*</td>
<td>316*</td>
<td>308*</td>
<td>349*</td>
<td>343*</td>
</tr>
<tr>
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<td>404</td>
<td>365</td>
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<td></td>
<td>198*</td>
<td>238*</td>
<td>226*</td>
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</tr>
<tr>
<td>4</td>
<td>223</td>
<td>285</td>
<td>261</td>
<td>276</td>
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</tr>
<tr>
<td></td>
<td>142*</td>
<td>181*</td>
<td>168*</td>
<td>184*</td>
<td>190*</td>
</tr>
<tr>
<td>5</td>
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<td>220</td>
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<td>175</td>
<td>194</td>
<td>170</td>
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<td>116*</td>
<td>143*</td>
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<td>154*</td>
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<tr>
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<td>809</td>
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<td>797</td>
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<td>397*</td>
<td>487*</td>
<td>463*</td>
<td>518*</td>
<td>518*</td>
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<tr>
<td>( r_0 ) (cm)</td>
<td>12.1</td>
<td>9.0</td>
<td>10.3</td>
<td>9.2</td>
<td>9.8</td>
</tr>
</tbody>
</table>

Notes.—The rms stellar wavefront aberration averaged over the modes of each Zernike order; asterisks denote values after correction by the average RLGS signal. The sum over all measured orders is shown near the bottom, and the last row reports the observed value of \( r_0 \) at 500 nm wavelength.
Fig. 5.—Graph of the rms residual error in the stellar wavefront after subtraction of the average beacon wavefront measurement. The plotted lines show the residual in all the modes of Zernike radial orders 2–6, averaged over time, and the contributions of each order separately. The short lines on the right represent the uncorrected rms wavefront aberrations. The points at each field angle represent averages of 9 s of data, and in each case the data have been scaled to the mean $r_0$ seen during the observations of 10.1 cm at 500 nm wavelength.

3.3. Vertical distribution of turbulence

In a simplified model in which the vertical distribution of turbulence is characterized by just two regimes, one near the ground that is well corrected and
the other at high altitude that is not corrected, one can readily calculate from our
data the division of power in the aberration between the two. Under the
assumption of a Kolmogorov spectrum with an infinite outer scale, the mean
square wavefront error in orders 2–6 is $0.118(D/ r_0)^{5/3} \text{ rad}^2$ (Hardy 1998, p. 96). A
deficit of power is observed in the two tilt modes seen by the natural guide star
(NGS) WFS, which we attribute to a finite outer scale, but in second and higher
orders, the effect is small. In these orders, the overall average ground-layer
corrected residual error inside 70" radius is 464 nm, after the scaling to the mean
seeing condition, yielding a value of $r_0^{FA}$ for the uncorrected free atmosphere of
21.7 cm. The ground layer, then, is characterized by $r_0^{GL} = 12.3$ cm. This division
of power of approximately two-thirds in the boundary layer and one-third in the
free atmosphere is consistent with typical conditions at other sites (Verin et al.
2000).

The thickness of the boundary layer is an important parameter that sets
the corrected angular field of GLAO and about which very little is known from
current site surveys. Only recently have techniques been developed, such as
SODAR (sound detection and range; Skidmore et al. 2004) and SLODAR (slope
detection and range; Wilson 2002), that address the detailed structure of the
lowest levels of turbulence.

The turbulence-weighted mean height of the ground layer, $h^{GL}$, on the
night of the observations can be estimated from the anisoplanatic behavior of the
star and RLGS wavefronts. Figure 6 shows the mean square difference, as a
function of angular separation, between the stellar wavefront and the simultaneous wavefront seen by four of the RLGSs separately. One beacon, which gave wavefronts noticeably noisier than the other four, has been omitted. All 20 pairings of the five star positions and RLGSs are plotted, after the same scaling to uniform \( r_0 \) as above. Also shown is a fitted curve of the form 
\[
y = a + b \theta^{5/3},
\]
the expected behavior of the anisoplanatic error. The fitted value of \( b \) is \( 42.5 \pm 3.4 \text{ nm}^2 \text{ arcsec}^{-5/3} \), where the uncertainty bounds an increase of 1 \( \sigma \) in the \( \chi^2 \) fit metric. This corresponds to an isoplanatic angle for the sensed boundary layer only of \( \theta_{0, GL} = 20 \pm 1'' \) at 500 nm wavelength. The isoplanatic angle is related to \( h_{GL} \) through the standard formula \( \theta_0 = 0.314 \cos \zeta r_0/h \) (Hardy 1998, p. 103), where \( \zeta \) is the zenith angle. Taking the mean value for these observations of \( \cos \zeta = 0.95 \), we find \( h_{GL} = 380 \pm 15 \text{ m} \) for the boundary-layer turbulence.
Fig. 6.—Mean square residual wavefront aberration (plus signs) after correction of the stellar wavefronts by simultaneous wavefronts from each of the RLGSs, taken singly, as a function of the angular separation of the star and beacon. A fit to a 5/3 power law is shown as the solid curve. The asterisks reproduce the top line of Fig. 5, showing the correction obtained from the average of the beacon wavefronts from the same data. The dashed line shows the mean square aberration in the uncorrected stellar wavefronts.

3.4. Projected GLAO gain with single and multiple RLGSs

Under conditions of turbulence dominated by the ground layer, represented by our data, useful correction of seeing over a field of several
arcminutes would be obtained with a simple correction system using just one Rayleigh beacon. By extrapolation of the curve of Figure 6, we find that the rms aberration would be improved out to an angle, set by $\theta_0^{\text{GL}}$, of $\approx 2.5'$ where the mean square residual caused by angular decorrelation of the ground layer equaled the contribution from the uncorrected free atmosphere. For such a simple correction system, the Rayleigh laser would be preferred over a sodium laser, because it weights the ground layer more strongly than it does the decorrelated higher layers. This is the approach adopted by the Southern Astrophysical Research (SOAR) Telescope (Tokovinin et al. 2003).

Wavefront correction with multiple beacons would perform better over wide fields. Averaging the beacon signals leads to a higher rejection of free atmosphere aberration. Correction of stellar wavefronts in the direction of any given beacon would therefore be worse than if the signal from the beacon were used on its own. Over the field enclosed by the beacons, however, the wavefront compensation is expected to be more uniform. This effect, small but appreciable for the narrow constellation diameter we used, can be seen in the bottom trace in Figure 6, where we superpose the residual error after correction with orders 2–6 from the multibeacon average from Figure 5. The improvement at 1’ radius is 13%.
4. Multibeacon systems for current and future large telescopes

4.1. Practicality of multibeacon systems

Implementation of practical AO systems with even one laser beacon has proven difficult. Sodium resonance systems were first proposed by Happer & MacDonald (1983) yet are only now starting to be scientifically productive. As a result, the concepts required for ELTs, which must rely on still more complex systems with multiple beacons to realize their unique high-resolution potential, have been even slower to develop.

Our first steps with a multibeacon system give encouragement that the engineering difficulties can be overcome. The laser WFS system was designed to be as simple as possible, yet in its early stages it has already proven capable of tracking the evolution of turbulence through sixth-order Zernike modes over a 6.5 m aperture. After the development of full tomographic reconstruction, correction to this degree in a closed-loop implementation of LTAO would yield the diffraction limit at the L band and longward, where the MMT is particularly powerful because of the low thermal background afforded by its adaptive secondary mirror.

A closed-loop system with broad scientific application would require response faster than the 15 Hz limit of the present data and smaller subapertures to provide correction at shorter wavelengths. We plan to increase the resolution of our RLGS WFS to 60 subapertures, for correction reaching down to the H
band. Replacement of the CCD in that sensor to overcome the electronic blurring is expected to allow a substantial, although as yet unquantified, improvement. Photon noise does not set a practical limit; our measured flux at the WFS of $1.1 \times 10^5$ photoelectrons m$^{-2}$ J$^{-1}$ scales to 470 photons per subaperture per frame at the higher resolution and a rate of 500 frames s$^{-1}$, adequate for full correction in the K band. We also envision a further factor of 2.5 increase in photon flux by use of one 15 W laser for each beacon, which would allow operation through the H band. We note that the required beacon fluxes do not scale with aperture. Since the sodium beacons needed for ELTs yield about the same photon flux per watt, they need be no more powerful.

4.2. Multiple beacon concept for the Giant Magellan Telescope

The primary motivation for our work has been to understand the implementation of multibeacon AO for the 25 m GMT (Johns et al. 2004). Like the MMT, the GMT will be equipped with an adaptive secondary mirror for large-field GLAO correction and optimum performance in the thermal infrared. Of particular value has been the realization that LTAO and GLAO can be considered as the extremes of a continuum provided by beacon constellations of variable diameter. The minimum diameter is that necessary for the beams to probe the cylindrical volume traversed by light from a star on-axis, 1.5’ for both the MMT with Rayleigh beacons and the GMT with sodium beacons. The maximum is ~10’ for widefield
GLAO. In the multibeacon implementation at the GMT, a single set of six beacons and six WFSs will be configured to cover this range of angles in both the projection and sensing systems.

The GMT’s AO system will incorporate features proven valuable in the MMT prototype. For example, the constellation of beacons will rotate about the telescope axis in order to counter field rotation. This is done at the MMT by turning the hologram that splits the single laser beam into five. At the GMT, where we anticipate a separate laser for each sodium LGS, the same task will instead be done with a K mirror. The sensing system will be fed by reflection from an 8’ diameter dichroic mirror located above the direct Gregorian focus and will incorporate a set of six articulated periscopes to feed light from the variable-diameter constellation to fixed sensors. Such periscope optics are used now in the MMT, with a fixed reduction from 2’ to 1’.

Perspective elongation of the WFS spots will be significant, ~4.5” in the outer subapertures of the GMT. Among several solutions proposed (Beckers 1992; Beckers et al. 2003; Ribak & Ragazzoni 2004; Baranec et al. 2005), our same dynamic refocus method at 5 kHz proven at the MMT could also be used with pulsed sodium lasers. The mechanical requirements for dynamic refocus on the larger telescope are not substantially more challenging than those already met at the MMT (Milton et al. 2003).
4.3. RLGS constellations for 8 m class telescopes

The question arises whether a Rayleigh beacon constellation could be used as an alternative to a single or multiple sodium beacon for all AO operations at an 8 m telescope. While a single sodium beacon yields a good solution for the wavefront in the direction of the beam, the corrected field is small, limited by the usual angular anisoplanatism, and neither GLAO nor MCAO is possible. Multiple sodium beacons, the route being taken by the Gemini Observatory (Ellerbroek et al. 2003), would add these capabilities, but at a high cost: the lasers are at present more than an order of magnitude more expensive than YAG lasers of the same power.

Implementations of tomography with RLGSs have been studied in simulation. Lloyd-Hart et al. (2002) modeled LTAO on an 8.4 m telescope with beacons range-gated from 16 to 30 km. The corrected field of view remains small, but the axial K-band Strehl ratio was 0.55, comparable to performance predictions for 8 m telescopes with a single sodium beacon (Viard et al. 2000) and the values now achieved in practice with a sodium beacon on the 3 m Shane telescope (Gavel et al. 2003). Although we have yet to simulate the comparison directly, we believe that it could be possible for LTAO with Rayleigh beacons to improve on the performance of a single sodium beacon. This is because the beacons could be arranged to provide 100% sampling of the atmosphere up to a height above almost all of the turbulence. This contrasts with
the single sodium beacon case, in which pupil coverage begins to drop immediately above the telescope and falls off with height. A fraction of the turbulence is therefore unsensed, and more importantly, an unknown radial shear is introduced into the measured wavefront.

Figure 7 illustrates the fractional coverage of the area filled by on-axis starlight as a function of height by a single sodium beacon at 95 km range and a regular pentagon of Rayleigh beacons in two cases. For the present constellation diameter of 20 and mean height of 24 km above a 6.5 m aperture, complete coverage is available to 8 km. SCIDAR (scintillation detection and range) measurements above nearby Mt. Graham at the site of the Large Binocular Telescope (McKenna et al. 2003) indicate that this is typically above 75% of the integrated $C_n^2$. Also shown is the case of a telescope of 8.0 m diameter, where the beacon diameter has been set to 86", which gives the greatest height for full coverage, and the beacons projected to a mean range of 30 km. There full coverage extends to 12 km. Even above that height, the Rayleigh beacons continue to provide better atmospheric sampling than a single sodium beacon up to 16.3 km, high enough to capture essentially 100% of the integrated $C_n^2$. Furthermore, tomographic reconstruction from the multiple Rayleigh beacons could in principle remove much of the focal anisoplanatism error inherent in the single sodium beacon measurement.
Fig. 7.—Fractional intersection vs. height of the area covered by light from an axial star and three LGS beacon arrangements: a single axial sodium laser guide star (SLGS) at 95 km range and pentagonal constellations of Rayleigh laser guide stars (RLGSs). We show the cases of a 6.5 m aperture with the RLGSs on a 60" radius at 24 km range (dotted line) and an 8.0 m aperture with RLGSs on a 43" radius at 30 km range (dashed line).

Lloyd-Hart & Milton (2003a) have simulated the performance of MCAO on the MMT using two DMs and five Rayleigh beacons. They find that correction to the diffraction limit in the near infrared is achieved over a 1′ field, if the RLGSs are each sampled at two distinct heights. Modeling by De la Rue & Ellerbroek (2002), comparing MCAO systems on an 8 m telescope relying on Rayleigh beacons, sodium beacons, and a combination of the two, came to the same
conclusion. That study further shows that the performance of the doubly sampled Rayleigh system approaches that of sodium beacons in the same geometry. In practice, such a system of Rayleigh beacons could be built with polarized lasers and a Pockels cell to switch each returning beam from one WFS to another as each laser pulse rose through the atmosphere. The lasers, optics, and detectors to implement the scheme would be still much cheaper than the lasers needed to construct an equivalent with sodium lasers.

Rayleigh beacons at 30 km of similar brightness to those at 24 km at the MMT could be made with individual lasers of 15 W. The results of the models described above suggest that a system on an 8 m telescope that deployed five 15 W lasers, each dedicated to a single beacon, would allow the full range of LTAO, MCAO, and GLAO techniques to be implemented.

5. Conclusions

Our results show that a constellation of RLGSs would be a powerful tool for ground-layer adaptive correction when used to drive the MMT’s adaptive secondary mirror. Other large telescopes equipped with adaptive secondary mirrors and with similar boundary layers of ~500 m mean thickness could also benefit with much improved K-band images expected from GLAO over a field as large as 10’ diameter.
The main consideration that remains unexplored so far by our experiments is the power of tomographic methods applied to multiple Rayleigh beacons to recover higher layer aberrations as well as the ground layer. Open-loop field tests to show the practicality of tomography are planned with the MMT system. Wavefronts will be reconstructed as Zernike modes on two metapupils at the ground and at high altitude. The choice of the upper altitude is not critical (Lloyd-Hart & Milton 2003b). The performance of LTAO will be evaluated by comparing direct measurements of natural star wavefronts in the center of the RLGS constellation with the integral of the tomographic solution along the same line of sight. In addition, the two-layer reconstructions will allow an early investigation of the performance of MCAO by exploring the agreement of the stellar and the integrated reconstructed wavefronts over the field enclosed by the RLGSs.

Our plans also call for closed-loop demonstrations of both GLAO and LTAO with the MMT's adaptive secondary mirror and the addition of a new real-time reconstructor computer recently received from Microgate S.r.l. Later, the addition of a second DM conjugated to high altitude will allow us to explore MCAO.

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References


Beckers, J. M. 1988, in Very Large Telescopes and Their Instrumentation, ed. M.-H. Ulrich (Garching: ESO), 693


De la Rue, I. A., & Ellerbroek, B. L. 2002, Proc. SPIE, 4494, 290


Happer, W., & MacDonald, G. J. 1983, JASON Report JSR-82-106 (MacLean: MITRE Corp.)


Ragazzoni, R., Marchetti, E., & Valente, G. 2000, Nature, 403, 54


Tokovinin, A. 2004a, Proc. SPIE, 5382, 490


APPENDIX C: EXPERIMENTAL RESULTS OF GROUND-LAYER AND TOMOGRAPHIC WAVEFRONT RECONSTRUCTION FROM MULTIPLE LASER GUIDE STARS

April 27, 2007

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Experimental results of ground-layer and tomographic wavefront reconstruction from multiple laser guide stars

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Abstract

We describe results from the first multi-laser wavefront sensing system designed to support tomographic modes of adaptive optics (AO). The system, now operating at the 6.5 m MMT telescope in Arizona, creates five beacons by Rayleigh scattering of laser beams at 532 nm integrated over a range from 20 to 29 km by dynamic refocus of the telescope optics. The return light is analyzed by a Shack-Hartmann sensor that places all five beacons on a single detector, with electronic shuttering to implement the beacon range gate. A separate high-order Shack-Hartmann sensor records simultaneous measurements of wavefronts from a natural star. From open-loop measurements, we find the average beacon wavefront gives a good estimate of ground layer aberration. We present results of full tomographic wavefront analysis, enabled by supplementing the laser data with simultaneous fast image motion measurements from three stars in the field. We describe plans for an early demonstration at the MMT of closed-loop ground layer AO, and later tomographic AO.

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OCIS codes: (010.1080) Adaptive optics; (010.7350) Wavefront sensing; (110.6960) Tomography.
1. Introduction

Key advances in adaptive optics (AO) will be enabled through the deployment of multiple laser guide stars (LGS) [1]. Constellations of beacons may be analyzed to yield a three-dimensional solution to the atmospherically induced wavefront aberration through tomography. Wider compensated fields of view than are now seen with conventional AO systems, even those equipped with single laser beacons, will be achieved with less field dependence of the delivered pointspread function. On telescopes of the current 8–10 m class, multi-conjugate AO (MCAO) using tomographic wavefront sensing is expected to yield correction to the diffraction limit in the near infrared over fields of 1–2 arcmin diameter. Compensation of turbulence close to the ground is anticipated to give substantial improvement over natural seeing for even larger fields up to 10 arcmin.

The promise of these new techniques, which remain almost entirely unexplored at the telescope, is even greater for the next generation of extremely large telescopes (ELTs)[2, 3]. Indeed, the primary motivation for our work at the MMT telescope described here is to understand how to design, build, and operate an AO system for the 25 m Giant Magellan Telescope, where multi-LGS tomographic wavefront sensing will be essential. Because laser beacons are at finite height in the atmosphere, rays of light from LGS sample the atmosphere differently from rays of starlight. The resulting difference between wavefronts
measured from a natural star and those from an LGS pointed in the same direction is called focal anisoplanatism. For 8 m telescopes, the error is not so large as to prevent high Strehl imaging in the near infrared with a single LGS, but the error grows with aperture, and for ELTs the error would be prohibitive. It can be overcome however by combining signals from multiple LGS which collectively fill the volume of atmosphere perturbing the starlight.

Current AO systems that rely entirely on natural stars (NGS) for wavefront information are severely restricted to regions of sky with suitably bright guide stars. In contrast, the gains from multi-LGS systems will be realizable over most of the sky, enormously expanding the scientific return from our present and future large telescopes. Indeed, the power of laser systems for science programs is now being demonstrated by the single LGS system on the Keck II telescope [4], with others shortly to come on line [5, 6, 7].

Pioneering work by Ragazzoni et al. [8] has hinted at the power of tomographic wavefront sensing. That paper describes experiments at the Telescopio Nazionale Galileo, in which wavefront estimates were obtained simultaneously from a close asterism of four natural stars through the simple expedient of defocusing the telescope. The instantaneous Zernike modal amplitudes measured from one star were compared to estimates derived from the modal amplitudes of the other three. Tomographic estimation from the three beacon stars was shown to be substantially superior to a simple average, or the use of any one of the three individually.
Of the advanced techniques enabled by tomographic wavefront sensing, only MCAO has yet been attempted, in experiments at two solar telescopes [9, 10]. Numerical models of ground-layer AO (GLAO) based on measurements of the vertical distribution of turbulence at a number of sites [11, 12, 13], suggest the potential for dramatic image improvement in the near infrared. Anderson et al. [14] have modeled GLAO performance in detail, using vertical distributions of turbulence seen at Cerro Pachòn that put roughly 2/3 of the power in the ground layer. With a pentagonal arrangement of LGS and an adaptive secondary mirror, the study concluded that the median image width in K band would improve from 0.42 to 0.18 arcsec for a 5 arcmin field and to 0.25 arcsec over 10 arcmin.

In an earlier paper [15], we reported results of open-loop tests of ground-layer wavefront reconstruction using a constellation of five Rayleigh laser guide stars (RLGS) at the MMT. Here, we briefly review the multi-beacon sensing system and the ground-layer results from that paper, and describe further analysis of the data in which the wavefront of a probe star is estimated from a tomographic reconstruction of the RLGS signals and the real-time image motion of other nearby stars. In this case, none of the RLGS nor the tip-tilt stars were coincident with the probe star whose wavefront was to be recovered.
2. Brief description of the beacons and wavefront sensor

For a full description of the laser beacon and tomographic wavefront sensing systems, we refer the reader to previously published accounts [15, 16]. Earlier work on laser-guided AO has been confined to a single beacon, usually created by resonance scattering in the sodium layer at 90 km altitude [4, 17, 18]. For our work at the 6.5 m MMT, we have created five beacons, generated by Rayleigh scattering, with two commercial, pulsed doubled-YAG lasers at 532 nm. Single Rayleigh beacons gated to an altitude of ~ 12 km have previously been used for AO at small telescopes [19] but the strong focus anisoplanatism and incomplete sampling of higher turbulence make a single such beacon of little value for an 8 m class telescope.

For our experiments, though, Rayleigh beacons are ideal. In our system the range gate is centered at 24 km altitude, high enough to sample collectively most of the turbulence. To increase signal strength, the sensor system includes optics to focus the telescope dynamically, to maintain sharp images of each laser pulse at it rises from 20 to 29 km [16, 20]. In this way, the range gate is extended to be ~ 20 × longer than the telescope’s normal depth of field. Even at this high altitude, focus anisoplanatism would remain a difficulty with a single beacon, but with five, it is not an issue, precisely because our goal is the development of tomographic techniques.
The five beacons, each with a projected power of 4 W, are arranged in a regular pentagon of 2 arcmin diameter. The return flux at zenith has been measured at $\text{1.1} \times 10^6$ photoelectrons m$^{-2}$ J$^{-1}$ over the full range gate. The images from all five beacons are recorded on a novel implementation of the Shack-Hartmann wavefront sensor (WFS), which includes the dynamic focus optics and a single electronically shuttered CCD. A prism array at the exit pupil divides it into 60 subapertures of equal area arranged in a hexapolar geometry.

A separate conventional Shack-Hartmann sensor looking at a natural star provides simultaneous ground-truth wavefront information for comparison with reconstructions from the LGS. The NGS sensor can be moved in order to probe different regions within the LGS constellation. In addition, a fast-framing camera with 2.5 arcmin field of view images the field in and around the LGS constellation. By tracking a suitable asterism, rapid tip-tilt signals from natural stars in this field are recorded as an aid to the tomographic reconstruction.

3. Data analysis

For the open-loop results described here, the three wavefront sensing cameras were run at typical rates of 50 and 100 fps. A typical data set comprises continuous 60-s sequences of frames from all three cameras simultaneously. Wavefronts are reconstructed on the Zernike basis set from the NGS and each of the five LGS separately, and the image motions from stars in the wide-field
camera are estimated by a correlation tracking algorithm with a Gaussian template. Figure 1 illustrates the output from the three cameras and the reconstructed wavefronts derived from them.

**Fig. 1.** Sample data from the three real-time cameras and the corresponding reconstructed wavefronts. The movie (1.8 MB) shows on the top row, from left to right, continuous and simultaneous sequences of frames from the NGS Shack-Hartmann sensor, the wide field asterism camera, and the LGS Shack-Hartmann sensor. (The star images in the asterism have been magnified ×4 compared to their spacing.) The boxed star in the asterism is the same as used on the NGS sensor; the light is split between the two. The lower panels show the reconstructed NGS wavefront (left), the individual LGS wavefronts (right) and the NGS wavefront as estimated by tomography (center).
3.1. Summary of GLAO results

The ground layer contribution to stellar wavefront aberration is computed as the average of the wavefronts reconstructed from the individual LGS beacons. Atmospheric turbulence close to the ground is common to the star and each LGS beacon, while higher altitude aberration, different for each beacon, will be mitigated in the average. Since all field points share this common ground layer turbulence, the use of GLAO promises a reduction of stellar wavefront aberration over a wide field. The technique is likely to be valuable because it is found empirically that up to two thirds of atmospheric turbulence is typically located near the ground [21].

Wavefront recoveries using this approach, under seeing conditions of ~1.1 arcsec, are described in detail in our earlier paper [15]. Since then, we obtained additional data in seeing of ~ 0.5 arcsec ($r_0 = 22$ cm at 500 nm wavelength), at the 15th percentile for the site measured over the past two years. In both cases, the fidelity of the estimation across the field encompassed by the LGS was investigated by offsetting the telescope and the beacons with respect to the NGS. The ground layer wavefront reconstruction estimated the 25 modes of Zernike orders 2 through 6 from the LGS. Figure 2 shows the residual stellar wavefront error after GLAO correction as a function of angle from the center of the LGS constellation. Ground layer correction of the data taken in poorer seeing yielded an average 38% improvement in RMS wavefront aberration over the full
field enclosed by the beacons, and extended well outside the constellation. For the new data, when the seeing was already excellent, ground layer correction was consistently beneficial across the field, although the fractional improvement within the constellation was actually less at 25%, with correction not extending as far beyond the beacon radius. Across this broad range of conditions, spanning roughly the middle half of the probability density function of seeing at the MMT, the point-spread function (PSF) delivered by a closed-loop system would show morphological variation much less than one would expect from the raw seeing. Furthermore, this result suggests that ground-layer correction with LGS will be a powerful tool for recovering good image quality especially when the native seeing is worse than median.
Fig. 2. Wavefront correction of starlight on the basis of the average LGS signals. The dashed lines show the uncorrected error while the solid lines show the RMS residual wavefront phase after ground layer correction as a function of angular distance between the star and the geometric center of the LGS constellation. Tilt (global image motion) is excluded since it is not sensed by the lasers.

A key parameter for GLAO is the thickness of the boundary layer, since it determines the corrected field of view. Very little is known about the boundary layer from current site surveys because the GLAO concept is quite recent, and the ground layer thickness has almost no impact on any other observing mode of a telescope. We have estimated the thickness during our observations by a method described in [15] which examines the anisoplanatic behavior of the stellar
wavefront with respect to the individual LGS wavefronts. The RMS difference between the two with angular separation \( \theta \) is expected to grow as \((\theta/\theta_0)^{5/3}\). The isoplanatic angle \( \theta_0 \) for the ground layer is related to the turbulence-weighted mean height \( h \) of the layer through \( \theta_0 = 0.314 \cos \zeta r_0/h \) [22]. For the observations of September 2004, we find \( h = 380 \) m. For the June 2005 data, despite the lower absolute strength of the ground layer, its mean height was greater, with \( h = 530 \) m.

3.2. Tomographic reconstruction along a single line of sight

The tomographic solution of the beacon wavefronts in principle yields a three-dimensional view of the aberration. In the simplest application, the instantaneous wavefront from an astronomical object is estimated by integration through the volume along the line of sight to the object, and the compensating phase is applied to a single deformable mirror (DM). The technique, called laser tomography AO (LTAO), delivers a diffraction-limited field of view limited by the normal isoplanatic angle. Each of the steps of this process, illustrated in Fig. 3, is linear. In practice therefore, all the steps may be multiplied to give a single linear function. In this way, LTAO can be implemented in a conventional way through a matrix multiplication of the combined vector of slopes from all the beacons to yield a command update to the DM. For clarity in our analysis, we have chosen first to reconstruct separately the wavefronts from each of the LGS and then to
apply a tomographic reconstructor matrix to estimate the wavefront of the probe star.

![Diagram of processing sequence for laser tomography AO.](image)

**Fig. 3.** The processing sequence for laser tomography AO. Light from each beacon is recorded by a wavefront sensor (1), and the individual beacon wavefronts are reconstructed (2). The three-dimensional structure of the aberration is recovered by tomography (3). A spatial integration along the line of sight estimates the stellar aberration (4), which is mapped onto the DM actuators (5) and (in a closed-loop AO system) integrated in time to give the required actuator commands (6). In practice, steps (2) through (5) can be implemented as a single matrix-vector multiplication.

Data from the three real-time cameras have been analyzed in this way. Spot positions in the Shack-Hartmann patterns recorded on the LGS WFS were extracted frame by frame to a precision of 0.03 pixels (0.026 arcsec) by finding the local peaks in the correlation of the data with a gaussian of width 1.8 pixels. For each 60 s data set, the mean position of each spot was subtracted from its instantaneous position, thereby removing the effects of telescope aberration and
long-term collimation drift. Wavefronts from each LGS were then reconstructed from the residual spot positions by fitting the first 44 Zernike modes (orders 1 through 8) using a synthetic reconstructor matrix derived from a model of the prism array in the WFS optics.

In a closed-loop system, the reconstructed LGS tilt modes would be used to control beam jitter by driving a fast steering mirror in the laser beam projector optics, but for this open-loop analysis they are discarded. Instead, the higher order LGS measurements are supplemented by the image motion from three stars in the wide field asterism camera, shown in Fig. 4. The stars allow determination of the tilt terms in the central probe star’s wavefront, and a three-dimensional solution to the second-order terms focus and astigmatism [23]. Separately, the wavefronts from the probe star were reconstructed to the same order from the NGS sensor measurements. For comparison, a ground layer estimate of the probe star’s wavefront was also reconstructed from these data.
Fig. 4. Sample frame from the asterism camera. Light from the central star was also fed to the NGS WFS. Image motion of the three brightest stars surrounding this one were used to estimate global tilt and second order modes in the tomographic reconstruction. The positions of the beacons are illustrated by the green stars. To account for field rotation, the LGS pattern was rotated in the beam projector optics, maintaining a fixed orientation with respect to the asterism as the MMT tracked.
Our tomographic reconstruction assumes a linear relation between the wavefront of the probe star and those of the LGS, represented by the equation

\[ \hat{a}_{ps} = Tb \]  \hspace{1cm} (1)

where \( \hat{a}_{ps} \) is the vector of Zernike polynomial coefficients characterizing the estimate of the probe star wavefront, \( b \) is a vector containing the Zernike coefficients of all the reconstructed LGS wavefronts and the tilt measurements from the three field stars, and \( T \) is the tomographic reconstructor matrix relating the two. We wish to find a tomograph \( T \) that minimizes \( \langle |a_{ps} - \hat{a}_{ps}|^2 \rangle \), the squared norm of the difference between the measured probe star wavefront coefficients \( a_{ps} \) and their estimates, averaged over time. The coefficients are scaled so that this also minimizes the RMS residual phase in the reconstructed wavefront.

To investigate the limit of tomographic performance permitted by the data in this least squares sense, we have derived \( T \) by a direct inversion of the data, using singular value decomposition (SVD). This approach does not rely on any a priori model of the atmospheric \( C_n^2 \) profile or knowledge of the noise characteristics. A matrix \( B \) is constructed from 3057 data vectors \( b \), and inverted with SVD to give \( B^\dagger \). A similar matrix \( A_{ps} \) is constructed from the corresponding \( a_{ps} \) vectors. The tomograph is then given by

\[ T = A_{ps}B^\dagger. \]  \hspace{1cm} (2)

Applying \( T \) to vectors \( b \) drawn from the same data set used to compute it yields the best fit solution and characterizes the noise floor in the data.
The noise sources fall into two broad categories. The first comprises instrumental effects such as read noise and charge diffusion in the WFS, and photon noise from the lasers. These can be reduced by better (and generally more expensive) hardware. The second arises because of atmospheric effects: broadening of the LGS images by turbulence in the uplink, speckle structure in the NGS Shack-Hartmann sensor spots, and aliasing of high altitude aberrations that are not well sensed by the chosen LGS constellation. These are more difficult to overcome. A full discussion of these in the context of the MMT experiments is beyond the scope of this paper, and will be addressed in a later publication.

We find, as expected, that our tomographic approach yields a substantially better estimate of the probe star’s wavefront than the corresponding ground layer recovery. To illustrate, Fig. 5 shows the evolution of the focus term in the probe star’s wavefront over a 10 s period and its GLAO and LTAO estimates. Figure 6a shows the RMS wavefront error averaged over the full 60 s of each of 9 data sets, recorded over a period of 2 hours. The values reflect the contributions from the modes through order 8 that were reconstructed, with the exception of tip and tilt. These two modes contain the majority of the wavefront error, but are not sensed by the lasers and therefore give a somewhat misleading sense of the overall degree of correction.
Fig. 5. Evolution of focus in the probe star's wavefront, shown in blue on the two plots, with the ground layer estimate (a) and tomographic estimate (b) plotted in black.

Fig. 6. For each of 9 data sets, each 60 s long, (a) shows the RMS wavefront error summed over orders 2–8 for the probe star wavefront without correction (blue squares), and with GLAO (red circles) and LTAO (green triangles) correction. Values of $r_0$, shown in (b) for a wavelength of 500 nm at zenith, have been computed for the total seeing (blue squares) and the ground layer contribution (red circles) only. The data sets were recorded over a 2 hour period and are here numbered chronologically.

Values of $r_0$ for each data set are shown in Fig. 6b at a wavelength of 500 nm and corrected to zenith. We start by computing values for the mean square
aberration in the modes of each Zernike radial order separately. Applying the formalism developed by Chassat [24] then yields estimates of both \( r_0 \) and the outer scale of turbulence \( L_0 \). Our estimates of \( L_0 \) range from 12m to 25m over the 2 hour period during which the data were recorded, in line with other observations at good sites [25]. (We note in passing that the variable directly estimated by Chassat’s method is \( D/L_0 \), where \( D \) is the telescope diameter. The truncated forms of the infinite sums given in Refs. 24 and 25, appropriate for the small apertures used in those studies, must be extended in our case where \( D/L_0 > 0.25 \).) Also shown in Fig. 6b are values for the ground layer turbulence, computed in the same manner from the strength of the Zernike modes of the ground layer estimate from the LGS. We find the average distribution of turbulence for these data puts 70% of the power in the boundary layer with the remainder at higher altitude. This represents an upper limit, since high altitude aberration on large spatial scales will remain partially correlated in the LGS signals and be indistinguishable from true ground layer aberration.

The plots of Fig. 6 show a consistent improvement with both types of wavefront compensation. Of particular note is data set 2, which stands out from its neighbors as having distinctly worse seeing. Yet after ground layer correction, the residual aberration is reduced almost to the same level in all three cases, indicating that the momentary worsening was attributable to a low lying phenomenon.
3.3. Synthetic point-spread functions

From the residual wavefront errors after either ground layer or tomographic estimation at each time step, a synthetic corrected PSF can be calculated. Figure 7 shows examples computed for a source on axis in K band (2.2 μm) from a 60 s continuous data sequence recorded in seeing conditions of $r_0 = 14.7$ cm at 500 nm wavelength. The reconstruction estimated the first 44 modes of the probe star's wavefront, now including tip-tilt. To generate realistic instantaneous PSFs for the movie of Fig. 7, the wavefronts were augmented with temporally correlated Zernike modes from orders 9 through 30 drawn from an uncompensated Kolmogorov distribution. The integrated PSFs in Fig. 7 include uncompensated Zernike modes from orders 9 through 100.
Fig. 7. Synthetic point-spread functions computed at 2.2 μm wavelength from wavefronts before and after correction. The movie (1 MB) shows PSFs with no correction (left), with GLAO correction (center), and with LTAO correction (right) over a 10 s period. The frame rate has been slowed from the original 50 Hz to 15 Hz. The lower panels show PSFs averaged over the full 60 s sequence.

Table 1 below shows the corresponding widths and relative peak intensities for the time averaged PSFs, and for PSFs computed similarly in the J band (1.25 μm) and H band (1.65 μm). Ground layer correction is of particular value in the two longer wavebands, where the image width is reduced by a factor of ~ 4, and there is a substantial increase in peak intensity. Given that the seeing at the time the data were taken was at about the 50th percentile for the
telescope, one can expect closed-loop GLAO performance at ~ 0.2 arcsec or better in H and K bands for the majority of the time.

Table 1. Image quality metrics at 1.25 μm, 1.65 μm and 2.2 μm.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Waveband</th>
<th>Uncorrected</th>
<th>GLAO</th>
<th>LTAO</th>
<th>D. L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWHM (arcsec)</td>
<td>J</td>
<td>0.771</td>
<td>0.384</td>
<td>0.100</td>
<td>0.040</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>0.651</td>
<td>0.162</td>
<td>0.081</td>
<td>0.052</td>
</tr>
<tr>
<td></td>
<td>K</td>
<td>0.543</td>
<td>0.123</td>
<td>0.088</td>
<td>0.070</td>
</tr>
<tr>
<td>Relative peak intensity</td>
<td>J</td>
<td>1.0</td>
<td>2.0</td>
<td>4.1</td>
<td>485</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>1.0</td>
<td>3.3</td>
<td>8.3</td>
<td>212</td>
</tr>
<tr>
<td></td>
<td>K</td>
<td>1.0</td>
<td>6.0</td>
<td>13.5</td>
<td>82.5</td>
</tr>
</tbody>
</table>

With tomographic correction, the K band is corrected almost to the diffraction limit, with a 14-fold increase in peak intensity to a Strehl ratio of 16%. The relatively low order reconstruction is insufficient to achieve the diffraction limit at the shorter wavelengths, but the improvement in resolution and peak brightness are both substantial.

4. Conclusion

We have taken the first steps in exploring the practical techniques required for tomographic wavefront sensing. With 60 subapertures placed over the MMT’s 6.5 m aperture and with the WFS running at 100 Hz, both the spatial and temporal scales of the wavefront estimation were modest. Nevertheless, we
can now say with confidence that there are no fundamental obstacles to closed-loop AO systems with multiple LGS driving altitude conjugated correction.

Our own work at the MMT will see the implementation of both GLAO and LTAO with the MMT's adaptive secondary mirror. Both techniques will benefit from extensions of the reconstructors used for the open loop results to date. The former will likely be improved by a tomographic analysis to identify the ground layer contribution with greater fidelity than the simple average of the LGS wavefronts. This would render more uniform PSFs within the corrected field. Tomographic recovery in general will show improved accuracy and robustness by the incorporation of *a priori* statistical knowledge of the atmospheric aberration and the system noise and optimal linear filtering [26]. The application of these principles, well studied theoretically, to our tomographic data is a high priority for future work.

A new LGS wavefront sensor instrument package, designed as a tool for scientific production has now been completed; in April 2006 it was successfully checked out in a 5-night run at the MMT with the adaptive secondary in open loop. Early application to scientific programs will focus on seeing improvement with GLAO, taking advantage of existing near infrared instrumentation. This choice is motivated by a number of considerations. Not only is GLAO the easiest multi-beacon technique to implement, but the MMT's system is likely to remain unique for several years. The exploitation of routine near infrared seeing of 0.2 arcsec or better over a field of several arcminutes is likely to be very productive,
both for imaging and high resolution multi-object spectroscopy where the many-fold improvement in encircled energy within 0.2 arcsec will be of particular value.

Further exploration of tomography will investigate the components of the algorithm outlined in Fig. 3. We will start with the recovery of $C_n^2$ profiles from two sets of open-loop LGS data, taken close together in time, where the probe star is first on axis and then further out in the field of the LGS constellation. The technique to determine the profiles is very similar to slope detection and ranging (SLODAR) [27]. The derived profiles will be collapsed into a small number of layers. A tomographic reconstructor matrix will be computed to solve for the instantaneous shapes of DMs taken to be at each of these layers. The tomograph will be applied to the NGS data in the two cases, to explore the fidelity and field dependence of MCAO correction.

Closed-loop LTAO, relying just on the adaptive secondary, will be tested in parallel with GLAO. The hardware required is identical for each, with only the elements of the reconstructor matrix to be changed. This suggests a new avenue for research, in which the corrected field of view and the degree of wavefront compensation are traded against each other according to the demands of the immediate science program and the prevailing atmospheric conditions. The MMT system will be uniquely placed to explore this parameter space.
Acknowledgements

This work has been supported by the Air Force Office of Scientific Research under grant F49620-01-1-0383 and the National Science Foundation under grant AST-0138347. Observations reported here were made at the MMT, a joint facility of the University of Arizona and the Smithsonian Institution. We are grateful for the continued support of the MMT Observatory staff, particularly M. Alegria, A. Milone, and J. McAfee. We thank the referee who alerted us to the work of F. Chassat.

References and links


14. D. R. Anderson, NRC Herzberg Institute of Astrophysics, 5071 W. Saanich Road, Victoria, BC V9E 2E7, et al., are preparing a manuscript to be called “Modelling a ground layer adaptive optics system”.


APPENDIX D: CONCEPT FOR A LASER GUIDE BEACON SHACK-HARTMANN WAVE-FRONT SENSOR WITH DYNAMICALLY STEERED SUBAPERTURES

April 27, 2007

Christoph Baranec
Center for Astronomical Adaptive Optics
University of Arizona

Dear Mr. Baranec:

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Sincerely,

Susannah Lehman
Authorized Agent
Optical Society of America
We describe an innovative implementation of the Shack–Hartmann wave-front sensor that is designed to correct the perspective elongation of a laser guide beacon in adaptive optics. Subapertures are defined by the segments of a deformable mirror rather than by a conventional lenslet array. A bias tilt on each segment separates the beacon images on the sensor’s detector. One removes the perspective elongation by dynamically driving each segment with a predetermined open-loop signal that would, in the absence of atmospheric wave-front aberration, keep the corresponding beacon image centered on the subaperture’s optical axis.

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OCIS codes: 010.1080, 010.1330, 010.7350, 220.2740.
For the next generation of giant telescopes, adaptive optics (AO) that gives high-resolution access to the majority of the sky will be essential.\textsuperscript{1} Inasmuch as natural guide star AO systems are severely limited in sky coverage, laser guide stars (LGSs) will be required.\textsuperscript{2} Furthermore, as a single LGS, even at the high altitude of the mesospheric sodium layer, suffers unacceptably from focus anisoplanatism, multiple lasers will be needed, with stellar wave-front errors recovered by use of a tomographic reconstruction algorithm.

Early research by Fugate et al.\textsuperscript{3} demonstrated the practicality of LGSs, and, more recently, sodium resonance beacons were successfully deployed at the Shane and Keck telescopes.\textsuperscript{4,5} Already the Keck telescope at 10-m diameter, with a side-mounted laser projector, suffers from perspective elongation,\textsuperscript{6} an effect that arises when the length of the beacon column imaged onto the wave-front sensor (WFS) is greater than the telescope's seeing-limited depth of focus. Subapertures far from the laser projector see the illuminated column slightly from the side and image it as a line, compromising the sensitivity of the WFS.

A simple solution is to shutter the WFS detector such that it captures light returning only from a restricted range of height. The full seeing-limited depth of field, $f$, of a telescope of diameter $D$ focused at height $H$, calculated from geometric optics, is

$$f = 2H^2s/D,$$  \hspace{1cm} (1)

where $s$ is the seeing disk’s width in radians, which we take to be equal to the acceptable amount of blur contributed by defocus. In seeing of 0.5 arc sec, a 30-
m telescope using sodium LGSs would be restricted to a range gate on the WFS of ~1300 m. Most of the backscattered light would therefore be lost.

Several strategies for overcoming perspective elongation without making such a sacrifice have been suggested.\textsuperscript{7–9} Georges et al.\textsuperscript{10} have successfully demonstrated a technique in which a sinusoidally driven mirror in the WFS optical train dynamically compensates for the change in focus of the image of a rising laser pulse. A system using this technique to compensate for five Rayleigh LGSs has been installed at the 6.5-m MMT telescope, with the beams launched from behind the secondary mirror, where it is now being used in tests of tomographic wave-front sensing for 30-m class telescopes.\textsuperscript{11–13} A single dynamic refocus mechanism serves all five beacons and allows a range gate on the WFS of 20–30 km, more than an order of magnitude larger than the telescope’s depth of field. After dynamic refocus correction, a Shack–Hartmann WFS images the five spot patterns onto a single CCD (Fig. 1).
Bauman\textsuperscript{14} describes an alternative to dynamic refocus that uses a deformable mirror (DM) by placing a segmented microelectrical mechanical system (MEMS) mirror at an image of the telescope pupil in front of a Shack–Hartmann WFS. The lenslets of a standard Shack–Hartmann WFS divide the full aperture and form separate images of the reference beacon from each subaperture onto a detector. In Bauman’s design, the same result is achieved by dynamic tilting of the individual MEMS segments to steer the light from each subaperture according to that subaperture’s perspective elongation. We suggest here an extension of this technique in which the functions of perspective
elongation removal and the WFS lenslet array are combined in a single unit. This approach also offers the potential to correct both fixed and dynamic non-common-path wave-front errors. A single lens following the DM would then form the images from all the subapertures.

Compensation for the global focus term that causes perspective elongation by correcting the induced local tilt over each subaperture is adequate if the subaperture’s seeing-limited depth of field is greater than the beacon’s column length. We take $H$ to be the mean beacon range and $f$ to be the maximum thickness expected for the sodium layer of 15 km and substitute the dimension of a subaperture, $d$, in place of the telescope diameter in Eq. (1); then, in seeing of 0.5 arc sec, a 30-m telescope could use subapertures as large as $\sim 2.5$ m before individual Shack–Hartmann spots began to be noticeably blurred. For the MMT, with 50-cm subapertures and its lower altitude Rayleigh beacons, the same criterion permits a range gate from 20 to 27.5 km.

The requirements for the DM are a function of the telescope and subaperture dimensions and of the range and the range gate, $r$, of the LGS. Segments that define subapertures at the edge of the pupil will change in angle the most. If each segment pivots about its center, then the full mechanical stroke, $x$, of the mirror required at the edge of the segment is given, to within the small-angle approximation, by

$$x = \frac{(d(D - d) \cdot r)}{(8H^2 - 2r^2)},$$  \hspace{1cm} (2)
In Table 1 we list the stroke requirements for DMs for Rayleigh beacons on the MMT and for sodium beacons on two proposed telescopes, the Giant Magellan Telescope (GMT), and the Thirty Meter Telescope (TMT). In each case the subaperture size is taken to be 0.5 m.

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Range (km)</th>
<th>D (m)</th>
<th>x (µm)</th>
<th>A (µm)</th>
<th>a (g)</th>
<th>B (arc sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMT</td>
<td>20-27.5</td>
<td>6.5</td>
<td>5.1</td>
<td>4.9</td>
<td>176</td>
<td>0.45</td>
</tr>
<tr>
<td>GMT</td>
<td>85-100</td>
<td>25.4</td>
<td>2.7</td>
<td>1.5</td>
<td>58</td>
<td>0.06</td>
</tr>
<tr>
<td>TMT</td>
<td>85-100</td>
<td>30.0</td>
<td>3.3</td>
<td>1.9</td>
<td>69</td>
<td>0.07</td>
</tr>
</tbody>
</table>

The frequency of oscillation of the DM segments must match the pulse rate of the beacon lasers. At a minimum, this must be 1 kHz for adequate temporal sampling of the changing atmospheric aberration, although candidate technologies for sodium lasers prefer higher rates. The simplest way to move the DM segments is sinusoidally at the laser pulse rate, setting the phase and amplitude of the motion to match as closely as possible the changing tilt of the LGS wave front. Figure 2 shows an example of the tilt motion required of a DM segment defining a 0.5-m subaperture at the edge of the GMT, with a sodium laser pulsed at 3 kHz.
Fig. 2. Sinusoidal radial tilt motion of the wave front from a DM segment defining a 0.5-m subaperture at the outer edge of the GMT (dashed curves) matched to the tilt of the wave front from a sodium LGS pulsed at 3 kHz, returning from 85- to 100-km altitude (solid lines). Zenith angles of 0 and 45° with corresponding height axes at the right are shown; $B$ is 0.06 and 0.08 arc sec, respectively.

We have calculated in Table 1 the required sinusoidal motion for the three cases at 3 kHz. Results are shown for semi-amplitude $A$ and acceleration $a$ at the edges of the outermost segments. Also shown is the root-mean-square mismatch in tilt compensation, $B$, weighted by the expected photon return from each height, which constitutes a residual perspective elongation. For the sodium LGS, $B$ is negligible compared with the expected seeing-limited size of the beacon images,
although some radial streaking may remain for the MMT’s Rayleigh LGS. In that case, \( B \) can be reduced by an order of magnitude if the second harmonic at 6 kHz is included in the DM driving signal with an amplitude of 20%.

Note that, in a sodium LGS, a large focus term is introduced with zenith angle because of the changing distance to the sodium layer. This term would be removed, as in present sodium LGS systems, by explicit refocusing of the WFS. The required amplitude of the oscillation to remove perspective elongation decreases off zenith (Fig. 2). This allows a larger duty cycle to match the longer pulse return caused by the apparent increase in layer thickness without substantially increasing \( B \).

Two technologies may fulfill the requirements for the DM: MEMS and stacked-actuator mirrors that use piezoelectric (PZT) actuators. MEMS have the advantage of being compact, but the technology is too immature for the present application because of limited actuator count and stroke. A conventional PZT actuator mirror, however, could be constructed with present technology. With segments of \( \sim 5 \text{ mm} \) size, such a DM for a 30-m telescope with 0.5-m subapertures would be 30 cm in diameter, giving an angular magnification of just 1003. This would allow a single DM to compensate for all LGS in a field of at least 10 arc min, the widest field contemplated for ground-layer AO.

We have verified in the laboratory that the physical demands listed in Table 1 are well within realistic limits for small PZT-driven segments. We tested a 4 x 4 element DM made by Trex Enterprises (San Diego) with 7.5-mm square
glass segments mounted on triaxial PZT actuators. During 16 h one segment was driven in tilt at 3.2 kHz with a semiamplitude of 4.3 mm, giving a peak-to-valley wave-front tilt of 4.6 mrad. The edge acceleration in this case was 175 g. In practice, the segment motion must be well controlled to avoid introducing spurious signals into the wave-front measurements.

In Fig. 3 we sketch the conceptual layout of a practical WFS in which a single DM compensates for several LGSs arranged in a ring. To reduce the field requirement, a periscope assembly brings the light from each LGS closer to the axis. By allowing the outer mirrors of the periscope to move radially, we can switch the diameter of the LGS ring from a configuration appropriate for multi-conjugate AO, at ~2 arc min, to a configuration for ground-layer AO, at ~10 arc min, without changing the spacing of the Shack–Hartmann patterns on the detector. A field lens puts the entrance pupil at infinity, so the optical train behind the periscope can be moved axially to compensate for changes in focus caused by reconfiguring the periscope and, for sodium LGS, the distance to the sodium layer.
Fig. 3. Conceptual design of a multiple-beacon wave-front sensor for the MMT, showing just 3 DM segments. Not to scale.

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References


APPENDIX E: LOKI: A GROUND-LAYER ADAPTIVE OPTICS HIGH-RESOLUTION NEAR-INFRARED SURVEY CAMERA

1. Introduction

With the MMT laser guide star (LGS) AO system now on the verge of giving partial correction over a wide field in ground-layer adaptive optics (GLAO) mode (Baranec et al. 2007a), one of the next priorities is to use this powerful new technique to support science. From open-loop wavefront measurements with the instrument (Lloyd-Hart et al. 2006; Baranec et al. 2006), ground-layer adaptive optics correction is expected to routinely have < 0.2 arc second FWHM PSFs in K band over a 2+ arc minute field. With future improvements to software and hardware, imaging performance should further improve. Potentially, all of the current MMT AO instruments can benefit from using the laser guide star AO system, provided the installation of larger entrance window dichroics, as has been done with PISCES (McCarthy et al. 2001) and Clio (Freed et al. 2004). The laser AO system alleviates the need to have a bright, $m_V$<13, science target or nearby guide star. In these cases the laser AO system could be run in one of two modes, the proven ground-layer AO mode, giving partial correction over a wide field, or the tomographic AO (LTAO) mode, which will be demonstrated in 2008, but capable of giving diffraction limited imaging along a particular line of sight. Obviously, the narrow field MMT AO instruments, Clio, ARIES (McCarthy et al. 1998) and BLINC-MIRAC (Hinz et al. 2000), would be much better suited to
tomographic AO correction; however in the thermal bands, ground-layer AO can give significant Strehl improvement which may be useful until tomographic correction is fully realized.

Currently PISCES is the only instrument well matched to the ground-layer AO corrected field. It has a 110 square arc second field with a plate scale of 0.11 arc seconds per pixel. From previous open-loop experiments (Lloyd-Hart et al. 2006) it has been found that the GLAO corrected field can extend beyond the beacon diameter in cases where the ground-layer is low, with faster roll-off of correction as the mean height of the ground layer increases. This means that even with the current configuration of the MMT LGS constellation diameter of 2 arc minutes, there is potentially a larger GLAO corrected field that could be of use to science instruments. In addition, there are future plans to upgrade the MMT LGS AO instrument to accommodate an additional three laser heads and have a beacon diameter which can be adjusted up to 5 arc minutes, ideal for GLAO, and to a narrow field ideal for LTAO. In this future AO wavefront sensing instrument, the GLAO corrected field would be potentially 5 arc minutes in diameter, much larger than any current MMT AO instrument can explore. This leads naturally to the idea of building a camera which can take advantage of such a large AO corrected field. Having this capability would give the MMT a competitive edge over many other larger telescopes in the world.

For ground based background limited surveys in the near-infrared, the signal-to-noise ratio (SNR) for a stellar source is proportional to the diameter of
the telescope divided by the image width. The total time necessary to complete
the same size and SNR survey is inversely proportional to the SNR times the
solid angle. With the given PSF diameter of the GLAO corrected images at the
MMT, and the field of the new instrument, the GLAO camera is expected to have
a higher scientific throughput than any of the seeing limited instruments at the
largest telescopes in the world. Table E-1 shows the relative time needed for
surveys at current telescopes and what is expected with a new imaging camera
using the MMT laser AO system. However, once other telescopes start to
implement GLAO systems (Baranec et al. 2007b), the MMT GLAO system may
not have as much of a competitive advantage.

Table E-1. Comparisons of the total telescope time needed for the same surveys.
*Image widths are calculated assuming excellent seeing of \( r_0=22.5 \text{ cm at 500 nm} \), and
GLAO performance presented in the following section. In worse seeing, seeing limited
image widths will increase while GLAO images will remain similar in size, so these are
conservative estimates.

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Instrument</th>
<th>D (m)</th>
<th>K-FWHM* (arcsec)</th>
<th>Relative SNR</th>
<th>( \Omega ) (arcmin(^2))</th>
<th>Relative Exp. Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gemini</td>
<td>NIRI</td>
<td>8.01</td>
<td>0.34</td>
<td>1</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>VLT</td>
<td>ISAAC</td>
<td>8</td>
<td>0.34</td>
<td>1</td>
<td>6.4</td>
<td>5</td>
</tr>
<tr>
<td>Subaru</td>
<td>MOIRCS</td>
<td>8.2</td>
<td>0.34</td>
<td>1</td>
<td>28</td>
<td>1.14</td>
</tr>
<tr>
<td>MMT</td>
<td>Loki / GLAO</td>
<td>6.3</td>
<td>0.13</td>
<td>2</td>
<td>16</td>
<td>1</td>
</tr>
</tbody>
</table>
2. Scientific goals

There are countless numbers of science programs where the ability to do deep wide-field imaging and/or spectroscopy would be important. As an example, near infrared observations of high redshift galaxies could be particularly interesting as current ground based optical observations and thermal infrared data from Spitzer leave a gap at 1-3 µm. Adding near infrared to the spectral energy distributions is important for photometric redshifts and stellar population inferences, while near infrared imaging is important to assess the morphology of the older stars. With present technology, the optical and Spitzer data are far faster to acquire, i.e., the near infrared imaging is the bottleneck for acquiring pan-chromatic data on high redshift galaxies. The new instrument Loki paired with the MMT GLAO system offers the chance of having consistently good imaging quality, well matched to the sizes of high redshift galaxies, to integrate down to the required faint flux levels. This is particularly true in K band, where GLAO will perform well and where Hubble Space Telescope has little capability.

With the increased sensitivity and resolution afforded to this instrument with the GLAO system, large portions of the sky can be quickly imaged. In just a few nights NGC 1333 could be covered down to the required sensitivity in J, H and K of 2 $M_{Jupiter}$ at 10σ, covering the high column density cloud material as well as all stars that could have drifted off the cloud within 1-2 Myr of their formation (assuming 1 km/s peculiar motion). With the on-sky spatial resolution of ~ 0.13
arc seconds, objects can be resolved as little as 40 AU apart in NGC 1333 (300 pc), close to the peak of the binary separation distribution.

With a deep survey of NGC 1333, the stellar and sub-stellar objects within the cloud can be categorized and the spatial effects on their distribution investigated. For each object, the presence of a circumstellar dust disk can be detected, which is a precursor for associated planetary bodies. This can be done by looking in the K band where the disk causes an excess in luminosity. Because the dust is transparent for wavelengths shorter than K, a color-magnitude diagram for each source can be made using observations in J and H. On the color-magnitude diagram, an extinction limited sample can be created by overplotting the isochrone for a zero age main sequence star and using a reddening vector out to the sensitivity limit. The numbers of objects over given mass ranges can then be counted, and the ratios of stars to low-mass objects, and low-mass stars to brown dwarfs can be calculated. With the wide field of view, it can be seen if these ratios change significantly as different parts of the cluster are probed. These results will be compared to studies of other clusters.

For any given sample set of objects, the number of objects can be counted within a certain mass range and an initial mass function (IMF) calculated. The IMF for different parts of the cluster will be calculated by selecting stellar regions of different radii. Using a cumulative distribution function on the masses and number of objects, the Kolmogorov-Smirnov test can be used to see if there are characteristic anisotropies in the IMF.
From these populations of different objects, it can be seen if there is any mass segregation between high and low mass objects. Mass segregation in older clusters is expected to be seen, either through collisions (Bonnell & Bate 2002) or high mass objects collecting in the center and ejecting lower mass objects. However, as in some young clusters like the Trapezium, there are strong signs of mass segregation. Observations with Loki will be able to determine if there is mass segregation also occurring within the young cluster NGC 1333, and possibly what may be the cause.

In a long term observing plan, the survey should be repeated approximately 5 years after the initial survey. Proper motions of objects in excess of 50 km/s would then be detected. In conjunction with follow-up spectroscopy measurements, a velocity distribution map of fast moving members of the cluster could be made. With N-body simulations, the evolution of the distribution of objects could be then tracked.

It is expected that there will be regions of excess of low-mass objects based on the results by Greissl et al. (2007). This will confirm the previous observations, and possibly change the understanding of how low-mass objects form in clusters. Any IMF anisotropies will be detected across the cluster which may be affecting the mass ratios observed.
3. Camera design

There are a number of requirements for the optical design of Loki, the camera that will work behind the MMT’s ground-layer AO system. The main advantage of GLAO is the consistent AO correction over a wide field, and the camera should image a large portion of that field. The expected FWHM of the corrected images will be around 0.1 – 0.2 arc seconds in diameter, and the plate scale of the camera should be smaller than this, optimally nyquist sampled at 0.05 arc seconds per pixel. There should be a location in the camera to place filters; ideally this spot should be as small as possible since larger filters are more expensive. This location would also be an ideal place to put a cold stop if observations at wavelengths greater than K short (~2.1 µm) are desired. The optical design should also be achromatic over the range of wavelengths in the near infrared (1 – 2.5 µm)

The design of Loki was first constrained by the available detectors. Steward Observatory has access to a number of the detectors used in the JWST NIRCam instrument project (Young et al. 2006), which are based on Rockwell Scientific’s HgCdTe HAWAII-2RG detector technology, and are 2048 × 2048 arrays sensitive from 0.6 – 2.5 µm. By using a 2 by 2 mosaic of these devices there will be a total of 4096 × 4096 pixels. Taking a 4 arc minute square field imaged onto the detector gives a plate scale of approximately 0.06 arc seconds
per pixel, critically sampling the GLAO PSF. This gives both a large field and high resolution plate scale.

The rest of the optical design was based on converting the incoming F/15 light to an F/ratio of 9.8 and accommodating the other design requirements. The initial design was based on a modified offner relay that had a non 1:1 magnification ratio. Using an offner design allows for the use of mirrors, immediately solving the achromatic requirement. The design was modeled in Zemax and optimum design found. A conceptual optical design of Loki appears in figure E-1.

Figure E-1. Non-folded optical layout of Loki. The F/15 secondary would be to the left on this figure.
The first element is the entrance window made of CaF₂. This also doubles as a dichroic, much like the ones on the current MMT AO science instruments, to split off the visible light to the wavefront sensors in the laser AO system.

Internally there is an image plane 250 mm behind the entrance window where a calibration source can be located. The first mirror, M₁, is located 1 m behind the focus. In actual operation, the optical design will be folded up to reduce the amount of volume occupied, as opposed to what is seen in figure E-1. M₁ and M₂ together form a pupil where filters can be placed. Figure E-2 shows the footprint of the pupil as seen from the full field points at this location. The pupil is contained within a 50 mm diameter extent, so standard 50 mm filters can be used.

**Figure E-2.** Footprint diagram showing the pupil from the central and edge field points. Each colored ring represents the extent of light from each field point.
M3 reimages the light from the pupil to the detector plane which is tilted. A corrector lens, also made of CaF$_2$, is placed in front of the detector to minimize field curvature. The image quality at J band is seen in figure E-3 for the center, edge and corners of the 4 arc minute field. The image is essentially diffraction limited except at the very corners of the field. With ~20 $\mu$m pixels, this imaging quality is more than sufficient.

Figure E-3. J-Band (1.25 $\mu$m) spot diagrams for on-axis, edge (2 arc minutes) and corner (2.8 arc minutes) field points. The black circle represents the FWHM of the airy disk core. For the longer wavelengths, the spot diagrams remain the same while the airy disk increases in size.
There is still some residual distortion that can be seen in the optical design. This can be seen in figure E-4. The maximum amount of distortion is 4.4% at two corners of the field.

The prescription for the system is seen in table E-2.

![Grid distortion diagram of the 4 arc minute square field on the detector.](image)

<table>
<thead>
<tr>
<th>GRID DISTORTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMT 5/15 GLAO IMAGER</td>
</tr>
<tr>
<td>TUE JUN 19 2007</td>
</tr>
<tr>
<td>FIELD: 0.0667 W 0.0667 H DEGREES</td>
</tr>
<tr>
<td>IMAGE: 70.56 W 74.40 H MILLIMETERS</td>
</tr>
<tr>
<td>MAXIMUM DISTORTION: 4.4193%</td>
</tr>
<tr>
<td>SCALE: 1.000X, WAVELENGTH: 1.2500 μM</td>
</tr>
</tbody>
</table>

Figure E-4. Grid distortion diagram of the 4 arc minute square field on the detector.
Table E-2. Optical prescription for the GLAO instrument Loki.

<table>
<thead>
<tr>
<th>#</th>
<th>Surface type</th>
<th>Comment</th>
<th>R.O.C. (mm)</th>
<th>Thickness (mm)</th>
<th>Glass</th>
<th>Aperture radius (mm)</th>
<th>Conic</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>Std.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Infinity</td>
</tr>
<tr>
<td>1</td>
<td>Std.</td>
<td>Secondary shadow</td>
<td>-16256</td>
<td>7200.00</td>
<td></td>
<td>3217.3</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Std.</td>
<td>Primary mirror</td>
<td>-1794.5486</td>
<td>7307.47</td>
<td>Mirror</td>
<td>3251.0</td>
<td>-1.409</td>
</tr>
<tr>
<td>3</td>
<td>Std.</td>
<td>Secondary mirror</td>
<td></td>
<td>7307.47</td>
<td>Mirror</td>
<td>321.0</td>
<td>-1.000</td>
</tr>
<tr>
<td>4</td>
<td>Std.</td>
<td>Primary vertex</td>
<td></td>
<td>1467.07</td>
<td></td>
<td>118.4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Std.</td>
<td>Derotator</td>
<td></td>
<td>381.00</td>
<td></td>
<td>850.0</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Std.</td>
<td>WFS inst. floor</td>
<td></td>
<td>180.09</td>
<td></td>
<td>67.4</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Std.</td>
<td>Instrument dichroic</td>
<td></td>
<td>8.00</td>
<td>CaF\textsubscript{2}</td>
<td>65.1</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Std.</td>
<td>F/15 focus</td>
<td></td>
<td>1250.76</td>
<td></td>
<td>65.6</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Coordbrk.</td>
<td>(Tilt 13°)</td>
<td></td>
<td>-779.1753</td>
<td>Mirror</td>
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<tr>
<td>10</td>
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<td>M1</td>
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<tr>
<td>11</td>
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<tr>
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<td>577.29</td>
<td></td>
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<tr>
<td>13</td>
<td>Std.</td>
<td>M2</td>
<td></td>
<td>577.29</td>
<td></td>
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</tr>
<tr>
<td>14</td>
<td>Coordbrk.</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Std.</td>
<td>Pupil filters</td>
<td></td>
<td>3.50</td>
<td>CaF\textsubscript{2}</td>
<td>20.1</td>
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<tr>
<td>16</td>
<td>Std.</td>
<td></td>
<td></td>
<td>577.29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Coordbrk.</td>
<td>(Tilt 6.61°)</td>
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<tr>
<td>18</td>
<td>Std.</td>
<td>M3</td>
<td></td>
<td>767.0732</td>
<td>Mirror</td>
<td>89.3</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Coordbrk.</td>
<td>(Tilt 6.61°)</td>
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<td></td>
</tr>
<tr>
<td>20</td>
<td>Coordbrk.</td>
<td>(Tilt 2.17°)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Std.</td>
<td>Corrector lens</td>
<td>-137.0158</td>
<td></td>
<td>CaF\textsubscript{2}</td>
<td>40.8</td>
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</tr>
<tr>
<td>22</td>
<td>Std.</td>
<td></td>
<td>-230.5528</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>23</td>
<td>Coordbrk.</td>
<td>(Tilt -2.17°)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Coordbrk.</td>
<td>(Tilt -4.60°)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Std.</td>
<td>Detector array</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>38.1</td>
</tr>
</tbody>
</table>
Since the instrument will be working in the near infrared, it will need to be housed in an evacuated and cooled dewar. As mentioned, the dichroic will also act as the entrance window to a dual-vessel system where the external chamber is a simple liquid nitrogen vessel that cools a cold plate upon which all of the optics are mounted. The interior vessel will be isolated from the rest of the instrument and control only the detector’s temperature. The option will be available to pump on the nitrogen to achieve temperatures below 77K which may be used to help reduce the dark current of the detectors. A vapor cooled shield will be located around both vessels to increase the hold times.

4. Conclusions and future work

With an initial working design finished and a near operational ground-layer AO system at the MMT, there should be nothing stopping the on-going development of Loki. The MMT, with a new wide field camera that exploits this technology, is poised to become the first telescope to take full advantage of ground-layer AO correction and enable a new round of deep wide-field science that will not be available at other telescopes for numerous years.

There are still refinements that need to be addressed in the system. Although the imaging characteristics of the optical design perform to specifications, flattening of the pupil is necessary if imaging is desired into the thermal K band (2.2 µm) and beyond; however the selected detectors are only
sensitive out to 2.5 μm. Once flat, a cold stop can be located at the pupil along with the filters. The optical design has yet to be folded to decrease its volume and will then need to be appropriately baffled. Another feature that would be advantageous to the instrument would be the ability to change the plate scale, if there was any desire to take higher resolution images of specific targets on the fly.

5. References


APPENDIX F: ALIGNMENT PROCEDURES

1. Note on alignment guides

   Following are the guides used to align the natural guide star optics and science dichroic within the facility laser wavefront sensing instrument at the MMT. Alignment procedures are continually improving and being updated; therefore what is described below is a snapshot of the procedures current as of the July 2007 observing run. Updated guides can be found at the laser guide star AO documents wiki at:

   https://bach.as.arizona.edu/bachwiki/index.php/LGS_AO_documents

2. Natural guide star optics and wavefront sensor alignment

   Always put polytetrafluoroethylene tape on the ends of the inside micrometers!

   Paper is ~0.004” thick, Card Stock ~0.011”

   1. Confirm laser alignment with alignment jig. Make sure N is North on instrument.
   2. Move alignment laser into position (+40.65mm).
   3. Install dummy dichroic.
   4. Set dummy dichroic to proper height below breadboard (7.0900”).
a. Align a flat across the breadboard hole with a laser target on the
topside and a corresponding target on bottom side.
b. Hold a calibrated length down from the flat to the mirror.
c. Adjust thumbscrews to adjust height of mirror.

5. Install Fold #1.
   a. Roughly adjust height of mirror to (16") above the breadboard.
   b. Adjust height of mirror to get dummy dichroic to Fold #1 distance
      (26.6019").
   c. Install alignment cover.
   d. Locate center of Fold #1 using tip/tilt on dummy dichroic.

6. Install cover over dummy dichroic which passes only the incident and
   reflected beams and leaves a viewing area for retro-reflections.

7. Install LGS dichroic.
   a. Position the dichroic so the green laser is roughly level and at
      (~8.25") above breadboard. A steel ruler and magnet work well
      here.
   b. Confirm the mirror will not interfere with the 4" roll in mirror.

8. Repeat step 5d. This leaves a small error in the alignment of the LGS
   dichroic, but this can be fixed when aligning the LGS arm with little effect.

9. Setup fold #2 with mask and/or center hole dummy fold.
10. Set fold #1 to fold #2 distance (38.6945”). *Note this distance is not critical compared to distance in 11.e. as it can be taken out with a refocus of the WFS/Tilt cameras.

11. Install 6” lens
   
   a. Set lens mount on table.
   
   b. View retro-reflections from front and rear surface of lens on the dummy dichroic screen.
   
   c. Translate mount until reflections overlap.
   
   d. Use tip/tilt adjustments to put reflections onto outgoing beam.
   
   e. Insert (15.6351”) distance between 6” lens and Fold #2. This distance is critical.
   
   f. If the distance is too short, add shims to the underside of the mount and start over at step 10.a.
   
   g. Typically, shims of (0.025-0.052”) need to be used.
   
   h. Once finished, add all of the clamps to the mount and double check the alignment and distance between 6” lens and Fold #2.

12. Setup mask/dummy mirror on field steering mirror (FSM).

13. Point the Fold #2 and FSM towards each other and adjust the distance between the two (27.7227”).

14. Remove mask on Fold #2.

15. Tip/tilt Fold #2 to center the laser on the FSM.
   
   a. Use rough adjustment to get close.
b. Use fine adjustment for final tweaks and lock actuators. (2mm hex)

16. Adjust center to center distance from FSM to OAP. (59.9663")

[Alternatively, leaving the alignment cover on the OAP make this distance. (59.7995") Use fixed posts of height 4 5/8” to hold the inside mikes.]

17. Put alignment cover on the OAP and tip/tilt the FSM until the beam is centered on the OAP. (Additionally you can hook up to the power meter and look at the reflected beam.) Remove cover.

18. Set the angle of the parabola.

   a. Mark out a transparency mask 36.000” away from OAP with a separation of 1.7061”. [Or 35.8332” away with OAP cover on]

   b. Make sure OAP is horizontal with breadboard and the ‘To Center’ is pointed towards the right (when looking from the back of the OAP)

   c. Use a metal ruler with a magnet to make sure the height of the ingoing and outgoing beams on the transparency mask are the same.

   d. Tip/tilt the mirror until the beams are the same height and proper separation at the mask. (2mm hex)

19. Install pupil steering mirror – on a 4” fixed post

   a. Set OAP to pupil steering mirror (PSM) distance. (53.3”) Distance not critical.

   b. Center the mirror on the beam, and tilt the beam toward the NGS WFS with an angle of ~43 degrees.
20. Set OAP to beam splitter distance. (50.3")

21. Install the NGS WFS
   a. Install the NGS WFS in the mount.
      i. Note the orientation of the head with the ‘LGS’ engraving.
      ii. Use the plastic collars around the bolts and washers
          between the NGS WFS and the mount to electrically isolate
          the WFS.
      iii. Previous to July 2007, the red/green and black/blue amplifier
           cables are switched.
   b. Set the PSM to WFS distance at ~9.3”.
   c. Roughly align the WFS such that the on-axis laser is going down
      the center of the lens on the WFS and the back reflections off the
      CCD/lenslet array are close to centered.
   d. Lock down the NGS WFS stage.
   e. Tape an OD 6 or 7 ND to the front of the WFS head.
   f. Align the PSM and WFS head with images off of the camera.
      i. Tip/tilt the WFS head until the laser spot is on the center of
         the CCD. (2.5mm hex)
      ii. Tip/tilt the PSM until the beam is centered on the entrance
          lens to the camera.
      iii. Repeat previous two steps until the laser is hitting the center
           of the entrance lens and is centered on the CCD.
g. Install the iris (1.555") in front of the NGS WFS head, centered on the laser.

22. Install fiber source.
   
a. Loosen collar around fiber and slip assembly down. Remove the cover on the instrument dichroic.

b. Place a dial indicator on a magnetic arm approximately where the fiber source should be in the on axis beam, (≤10.0614") away from the instrument dichroic.

c. Hold a calibrated inside micrometer (10.0614") from the center of the instrument dichroic to the dial indicator.

d. Record the reading on the dial indicator, move the indicator down to get a positive reading if necessary.

e. Reinstall the cover on the instrument dichroic

f. Set the on axis alignment stage to (+1.30mm).

g. Slip the fiber assembly up towards the dial indicator until the recorded measurement is reached. Tighten the collar around the fiber assembly.

h. Remove the magnetic arm and dial indicator.

23. Check alignment of system on CCD.
   
a. Use ND 3/4 in front of camera head and misalign laser feed to fiber.

   Get spot counts near 10,000 DN.
b. Open up iris on if necessary to get the fiber on the camera. The spot is nominally offset by a small amount.

c. Home the FSM actuators and adjust them to minimize tip/tilt.

d. Adjust the NGS focus stage to zero out focus error.

e. Read out the residual Zernike errors. Nominally these should be $+0.1 \lambda$ of 45° astigmatism and $-0.5 \lambda$ of 90° astigmatism. All other coefficients should be zero.

Dec28th: With the on-axis laser centered on WFS, roll in the fiber source and adjust the field steering mirror to center the fiber. Set the actuators to:

PI Actuator 2: -7500 counts

PI Actuator 3: -2900 counts

3. Natural guide star tilt camera alignment

1. Run the tilt camera stage to the center of its travel.

2. Attach the camera to the mount with the four metric bolts (M4?) with the cooling lines pointed towards the nearest electronics box.

3. Set the beam splitter to relay lens (lens in tube right in front of camera) distance to 48.5 mm.

   a. The angle of the beams should be ~25 degrees, being roughly parallel to the bench holes.
4. Using the on-axis laser, (make sure it is hitting the center of the NGS WFS, if not adjust the FSM) adjust the beam-splitter and camera head so they are centered and pointed at each other. Bolt down the camera head.

5. Roll in the fiber source and center the image on the NGS WFS with the FSM. Image the source on the tilt camera.

6. Adjust the Z-motion of the relay lens to get the image in focus. Note the focus location.

7. Replace the beam-splitter with the mirror. Tip-tilt the mirror until the image on the tilt camera hits the same location.

4. Wide field acquisition camera alignment

1. Roll in on-axis laser.

2. Place the flip mirror ~406.4 mm away from the 6” fold mirror.
   a. Adjust the angle of reflection so it is ~45 degrees.
   b. Make sure the beam is centered on the mirror. (There is only ~1-2 mm of tolerance to avoid vignetting over the full field)

3. Place the 3” Edmunds 45419 lens ~150 mm away from the flip mirror.
   a. Keep the beam parallel with the surface of the breadboard.
   b. Adjust the tip/tilt of the flip mirror to center the beam on the lens and adjust the height, tip/tilt of the lens to retroreflect the laser.

4. Place the camera lens ~200 mm behind the 3” lens.
a. Make adjustments to the camera lens location to get the beam going down the center of the lens. Closing down the iris and looking at the retroreflections helps.

5. Put the modified astrovid camera a few mm behind the camera lens. Get the laser beam approximately in the center of the chip.

6. Roll in the on axis fiber. (Attach the 2 arc minute field target if desired.)

7. Adjust the location of the camera to bring the image in focus and center it on the CCD. If the target is used, the 1 and 2 arcminute diameter fields should be fully visible.

5. Science dichroic alignment

1. Install dichroic assembly

2. Installation of Science Dichroic

   a. Remove aluminum plate which holds the dichroic. There are four bolts to remove this plate.

   b. Remove the plastic retaining ring.

   c. Lay down three pieces of Teflon tape near the bolt holes for the retaining ring.

   d. Lay the dichroic down on the aluminum plate. **Use latex gloves when handling the dichroic.**
e. Install the plastic retaining ring. Only tighten the bolts enough so they keep the dichroic from sliding around.

f. Install the semi-transparent dichroic cover with the hole in the mirror for the on-axis laser.

g. Re-install the plate holding the dichroic back into the rest of the assembly.

3. Roll in the on-axis laser (+40.65mm). Turn on the red laser, let

4. Install the 4" fold cover on the topmost 4" mirror. Hold it in place with electrical tape. Make sure the central hole is held against the mirror surface.

5. Install the dummy 4" mirror in the FSM.
   a. Remove the top actuator on the FSM.
   b. Loosen the two axes.
   c. Remove the 4" mirror. Be sure to wear latex gloves.
   d. Install the black plastic 4" blank.
   e. Point the blank towards the center of the 6" fold mirror.
   f. Tighten down the axes.

6. Adjust the actuators on the Science Dichroic holder
   a. Tip/tilt the actuators to get the laser centered on the 4" fold cover.
   b. View the laser spot on the black plastic blank.
c. If the laser spot is too low/high, increase/decrease the height of the dichroic. Repeat from step a. until the spot is centered on the black plastic blank.

7. The dichroic is now aligned.

8. Remove the 4" fold alignment cover.

9. Reinstall the FSM mirror.
   a. Remove the black plastic blank.
   b. Reinstall the 4" mirror.
   c. Loosen the axes.
   d. Reinstall the top actuator on the FSM.
   e. By hand, adjust the axes to get the on-axis beam to be centered on the OAP.
   f. Tighten down the axes.

10. Remove on-axis laser (+176mm).