The GMT Ground-Layer AO Experiment at the Magellan Telescopes

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ABSTRACT

It has recently been suggested that up to half of the wavefront variance can be removed from the total atmospheric distortion by correcting only the lowest seeing layer (Rigaut 2000, 2001). This Ground-Layer AO (GLAO) correction could provide improved image quality over a very wide field of view; however, no development work has been done on existing telescopes. The implications are profound for optical designs of future AO optimized telescopes (e.g. the ELTs) as accurately compensating for this ground-layer strongly favors an adaptive element conjugated to the median height of the ground-layer. The gains of GLAO are tantalizing but substantially unproven, and thus, the Giant Magellan Telescope (GMT) project has developed a multi-phased study with the goal of providing an on-sky demonstration of GLAO technology at the Magellan Telescopes.

The first phase of this experiment is to measure the the height and boundary of the ground-layer through multiple, fixed wavefront sensors on very bright cluster fields over the full 24 arcminute Magellan field of view. With a typical wind speed of 9 m/s and a presumed secondary ground-layer conjugation error of 100 m, the equivalent decoherence time is approximately 0.04 seconds. Therefore, we have designed and constructed high resolution Shack-Hartmann sensors running at 100 frames per second with coarse, 0.5m sub-apertures.

We present a technical description of the wavefront sensors and image analyzer, as well as current results from the first deployment of this instrument at Magellan. In addition, we discuss the implications for ground-layer modeling and describe the next phases of the GMT's GLAO experiment.

Keywords: Adaptive Optics, Ground-Layer, GLAO, Seeing

1. INTRODUCTION

Detailed studies of the atmosphere at astronomical sites have seen a recent boom with the development of advanced seeing monitors, in addition to balloon launches with micro-thermal detectors.[1–6] It is now possible to measure both the total seeing and to have a breakdown of the seeing contribution by several layers sampled in the atmosphere. One of the surprises contained in this new data suggests that frequently more than half of the turbulent power in the atmosphere is contained in a low altitude layer (< 1.0 km). This ground-layer is thought to arise when moving air interacts with the local mountain topology and will differ from site to site in characteristics, depending on wind directions and the geography upstream of the telescope.

This strong, low altitude turbulence layer provides an opportunity for improved seeing conditions with a modest adaptive optics, AO, system.[7] Additionally, since low atmospheric layers are near the telescope, the isoplanatic angle should be large. Thus, the promise of ground-layer AO, GLAO, is a low frequency (~100 Hz) AO system that will improve seeing by a factor of two and will provide this improvement over a large field (several to tens of minutes of arc). Because a GLAO system's goal is merely to improve seeing, the point-spread function (psf) of the corrected images should be well behaved and precision photometry measurements need not deal with the increased complexity of the changing ratios between the core and halo portions of PSFs generated through diffraction limited imaging. Also note that a gain of a factor of two in seeing results in gain of a factor of four in sensitivity for background limited observations, effectively doubling the collecting area of a telescope with a perfect GLAO system. The gains of a GLAO system are evident, however, most of the work to date has been modeling based on the atmospheric measurements and only limited amounts of data have been taken at the telescope.

Many of the fundamental questions concerning ground-layer turbulence are unanswered, and yet optical designs for future AO optimized telescopes, such as the extremely large telescopes, ELTs, are nearly finalized. The Giant Magellan Telescope (GMT), with which we are associated, has GLAO capabilities built into the design as a baseline operating mode. However, the ground-layer height, thickness, and variability of these two quantities is unknown, since even the most advanced new seeing monitors do not have resolution below 0.5 km, while the ground-layer is thought to occur between 50 and 250 meters. The frequency of time that the ground-layer turbulence dominates the seeing has only been measured at a limited number of sites and typically over inadequate time scales. (Typical campaigns are weeks to a two months). Because of the strong dependence on local mountain topology, each site will be unique, but few comparisons have been done with similar equipment. Finally, because of its recent discovery, existing AO and soon to be commissioned AO systems have not been able to take advantage of GLAO, and thus the technology remains unproven.

As a result of the unknowns in the ground-layer turbulence, the potential large gains in sensitivity offered by a GLAO system, and the significant impact on the ELT designs, we have begun a program to investigate the ground-layer of the atmosphere above the Las Campanas Observatory (LCO) in Chile. Our initial goal is to ascertain the expected seeing improvement at one of the Magellan 6.5m telescopes by measuring the turbulence profile through multiple Shack-Hartmann wavefront sensors deployed over the 24' field of view. By simultaneously deploying up to eight wavefront sensors with varying separations, we will be able to determine very detailed information about the turbulent structure of the lower atmosphere. If our results confirm the current theoretical predictions, then we plan to develop a GLAO guider and subsequently a scientific instrument. In this proceeding we report on our first year of work, including the development and deployment of a two wavefront sensor system and some preliminary data analysis. We conclude with a short discussion of the next phase of our investigation.

2. SYSTEM DESCRIPTION

We have developed a multiple Shack-Hartmann wavefront sensor system to investigate the ground-layer of the atmosphere as seen through one of the Magellan 6.5m Telescopes. The system records data at a frame rate of 100 Hz with overhead remaining for real-time analysis. The current system is a prototype designed for a unit component consisting of two cameras and a PC. Within the next year, we will construct four of these units to comprise a system of eight cameras. The system was designed to use off-the-shelf components to minimize cost and development time at the expense of sensitivity.

The optical designs consist of two off-the-shelf components, an achromatic field lens and a lenslet array which images directly onto the detector. The lenslet array, provided by A.O.A. Inc., has a pitch of 203μm and a focal length of 5.8mm. The optics sample the pupil in an 11x11 grid, which results in 88 usable sub-apertures when the shape of the pupil and secondary obscuration are taken into account. The sub-apertures correspond to 60 cm sub-apertures on the primary.

Key to the accurate correlation of multiple SH sensors is the alignment of the pupil on the lenslet, ensuring that sub-apertures will correspond to identical places in the sky. To first order, this requires that we mount both wavefront sensors with the same orientation relative to the sky. On a finer scale, it is necessary to adjust the pupil alignment on the lenslet. This requirement drove the optical design to a slightly non-focal position of the lenslet array relative to the field lens. With this optical configuration, we were able to make small motions on the sky of an individual wavefront sensor, which would adjust the alignment of the telescope pupil on the lenslet. The optical system was designed so that a 1' motion of the star would correspond to 75μm motion on the detector or about 1/3 of the spacing between sub-apertures. In practice the wavefront sensors were mounted to x-y-z translation stages, where the pupil alignment was controlled by adjustment screws in x and y and focus and field curvature were roughly matched using the z-axis translation.

The cameras are commercial units purchased from Basler Vision Technologies. The Basler A602f cameras use a Micron CMOS detector (MT9V403C125STM) which is quick (up to 200 frames per second with full frame readout), but relatively noisy with 80 electron read-noise. The cameras have a trigger signal used for camera synchronization and use a firewire or IEEE 1394a bus for data I/O. The data has 8 bits of dynamic range. The pixel size is 9.9 microns with a format of 656 by 491. In operation we read out a 312 by 312 section of the chip and then immediately bin 2x2. With this region of interest, the maximum frame rate is 210 Hz, but, in practice

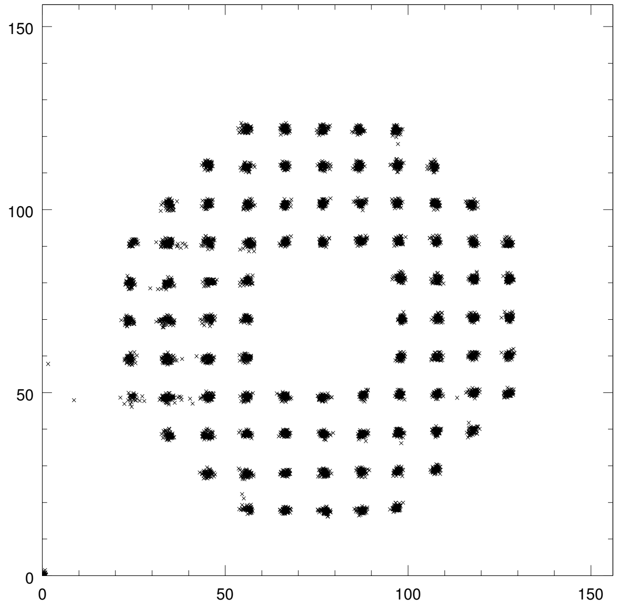

Figure 1. This plot displays the centroid positions of all sub-apertures for 100 frames in pixel coordinates. In the post-processing, we derive a long-term, high S/N, average centroid position for each sub-aperture every 5 seconds or every 500 frames. Then for each instantaneous frame, we centroid the sub-apertures and calculate the difference vector from the long-term average position. These difference vectors are then correlated between the two Shack-Hartmann sensors (corresponding to the two stars).

we operate between 100 and 128 Hz using the trigger feature, ensuring camera synchronization to less than a microsecond. With the gain set to its maximum, the bias level is significant, but subtraction of a bias frame leaves the data flat to within a few percent. The peak efficiency of the detector is 32% at 550 nm.

The Basler A602f camera follows an industry standard for firewire cameras (version 1.30 of the “1394 - based Digital Camera Specification” (DCAM) issued by the 1394 Trade Association). This allowed us to write our own control software on a linux-based PC using the open-source implementation of the DCAM specifications (libdc1394).

The modest demands of a 100 Hz AO system can be met with off-the-shelf PC components. Our system is designed to operate two cameras per PC. The raw data rate is substantial at 0.5 Gigabyte/min/camera, which puts the toughest requirement on saving the raw frames. The system is comprised of an Intel Pentium 3GHz CPU on a main board using the Intel 875P chipset. We installed serial ATA hard drives for their added bandwidth which allowed us to stream data to disk from both cameras at the rate of 1 gigabyte/min. Besides saving the raw frames, the data acquisition machine also is required to centroid ˜1 million sub-apertures a minute, which is well within the abilities of the PC, but has yet to be implemented in the data acquisition mode. These centroid positions will be forwarded to a machine which does the correlation analysis between different SH stars.

The positioning of the wavefront sensors on the sky is accomplished through specific, predetermined and fabricated field plates mounted to the Nasmyth instrument rotator. The optics are mounted in a custom machined tube, which also serves as the mounting head for the detector and electronics box. The fine-scale positioning of the wavefront sensors described above is accomplished through x-y-z translation stages purchased from OptoSigma.

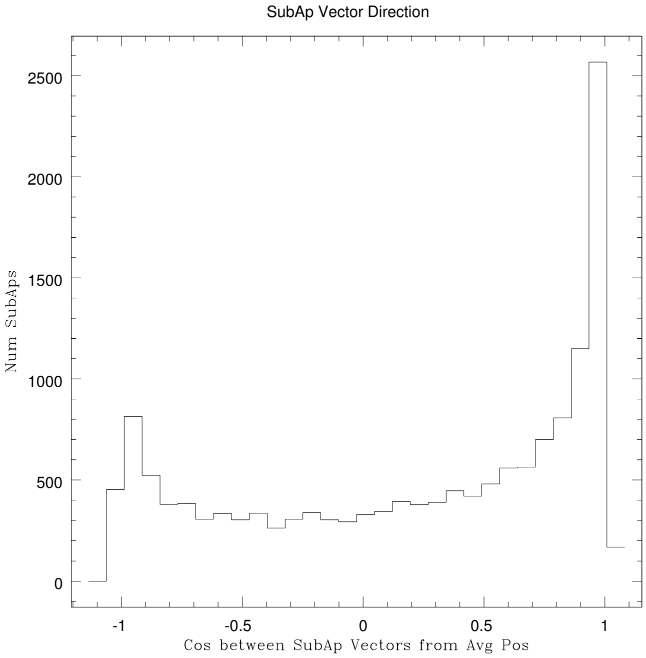

Figure 2. As described in the caption for Fig. 1, each frame and each sub-aperture has a difference vector defined. The difference vector is formed from the long-term, but moving, average centroid position and an instantaneous centroid. This is done for each of the two Shack-Hartmann stars. Correlations are examined between the different stars for equivalent sub-apertures.
This figure displays a histogram of the cosine of the angle between the difference vectors. When the cosine is 1, then the centroids of individual sub-apertures in both stars is displaced in the same direction.
The strong peak at 1 reveals that frequently, the centroids are moving in the same direction. The distribution of the magnitude of this motion is examined in Fig. 3. The peak at -1 indicates that the centroids are moving in opposite directions. We believe this peak at -1 occurs when a seeing cell enters one of the sub-aperture, but has yet to enter the other side of the telescope. Further analysis, employing Fourier time domain analysis, will be able to verify this theory.
For this particular observation the separation of the two Shack-Hartmann stars is 12 arcminutes. The seeing reported by the standard Magellan guiders was 0.62 arcseconds and the ground speed wind was 5 mph as measured by a weather station on the mountain.

3. OBSERVATIONS AND PRELIMINARY DATA ANALYSIS

We selected fields that were near zenith and had two or more bright (R¡7.5) stars with separations up to 12'. To find these fields we used the Tycho Catalog (ESA, 1997, The Hipparcos and Tycho catalogues, ESA SP-1200) and *SphereMatch* (http://spectro.princeton.edu), an IDL utility developed for analysing the Sloan Digital Sky Survey .

We had two successful engineering runs on May 5-6, 2004 and partial nights from June 3-8. During the first run one camera was operated on sky, while we finalized the mechanics of the setup. During the June engineering times, we successfully aligned both wavefront sensors and recorded the raw frames to disk. We observed 11 fields with separations ranging between 2.5' to 12'. The seeing conditions, as reported by the standard Magellan guiders,[8] varied between 0.46" to 1.3", with ground speed wind conditions between 0 - 15 mph.

We are in the process of analysing the 36 million frames (and 3 billion sub-apertures) collected in June . Before our next run in September, we plan to have the real-time analysis code ready, eliminating the need for frame saving and post processing. In Figs. 1 - Fig. 3 we present a preliminary reduction and examination of the data for a "proof-of-concept" demonstration. In the small amount of data we have examined so far, we do not

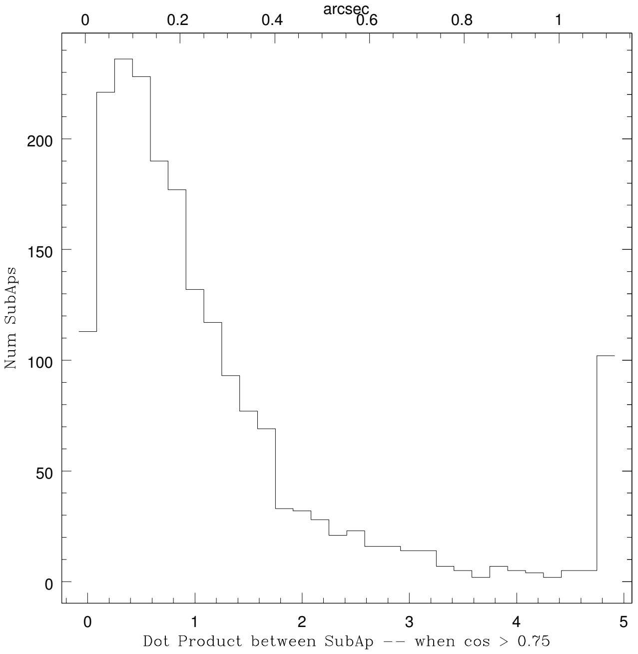

Figure 3. In this plot, the magnitude of the displacement is investigated. The average magnitude of the the difference vectors (see Fig 2 for definition) are plotted in cases were the vectors pointed in the same direction (cos $>$ 0.75). The lower x-axis is the dot product of these two difference vectors and has units of pixels ^{2}. The upper axis is the square root of the dot product, which reveals the size of the offset in arcseconds when the pixel scale is applied. The peak of this distribution is seen to occur at slightly less than 0.1 arcseconds.
The separation of these two stars is 4.7 arcminutes and the seeing at the time of the observations was 0.52 arcseconds with a wind speed of approximately 9 mph. The secondary peak in the histogram greater than 1 arcsecond is not real and is an artifact of the data processing.

see the ground-layer dominating the seeing. However, this situation is thought to arise only 45% of the time, using data taken at Paranel.[9]

4. ONGOING DEVELOPMENT

A number of upgrades are planned before the end of the year and we have at least one more opportunity for engineering time on the telescope. A MASS-DIMM site monitor is expected to be installed on the LCO site, which will help us to identify the times when the ground-layer is expected to dominate the seeing. As soon as our two wavefront sensor system is fully operational, we will clone the unit to increase the the number of simultaneous wavefront sensors to eight. This will allow us to explore a variety of baselines for triangulating the ground-layer height. Currently, we are using the existing Magellan guider, which restricts field access to the central 12'. Once, we interface our cameras to assume the guiding and active optics control for the telescope, then we will be able to remove the existing guiders and access the full 24' field.

If the data warrant further pursuit, we will construct a GLAO guider that will have 8 deployable Shack-Hartmann wavefront sensors. This guider will be placed on a Magellan focus and will collect data throughout the year, building up statistics whenever the instrument on that port is used. We would have to move to more costly and sensitive detectors to reach the desired sky coverage. This would almost certainly require using on-chip avalanche amplification CCDs such as E2V's L3 chips. After the guider construction, we would then begin to seek funding to build a wide field GLAO imager or spectrograph, depending on the status of the adaptive secondary currently being fabricated at Arizona.

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