Introduction

The main focus of this proposal was to build a Multiple Guide Star wavefront sensing unit for use with the existing 241-actuator adaptive optics system at Palomar Observatory. This unit enables simultaneous sampling and real-time recording of wavefront slope data from four different natural guide stars by using four parallel Shack-Hartmann wavefront sensor channels.

The Palomar Tomograph (PT) is a compact multiple guide star wavefront sensor system that can be used to confirm tomographic wavefront sensing algorithms. The Palomar Tomograph (PT) is also called the Multiple Guide Star Unit (MGSU) and the terms will be used interchangeably in this document. Implementation and performance characterization of these algorithms will be the driving force in wide field Adaptive Optics (AO) and AO-fed spectroscopy for AO systems on 8-10 m class telescopes and for the planned Extremely Large Telescope (ELT) projects like the Thirty Meter Telescope (TMT) and the Giant Magellan Telescope (GMT). The results from this experiment help us learn to quantify accurately the errors and limitations of tomographic wavefront estimation for an asterism and analyze how it changes with guide star separation. We also plan to compare different algorithms and assess the importance of a priori turbulence statistics. Slope detection and ranging (SIODAR) experiments to determine the height(s) of strong turbulence layers will also be performed using cross-correlation of wavefront sensor data. Palomar has a Multi-Aperture Scintillation Sensor and a Differential Image Motion Monitor (MASS/DIMM unit) to monitor and characterize atmospheric seeing as a function of time. The MASS/DIMM data may be used with the MGSU to further characterize the quality of the tomographic reconstruction.

Figure 1a: Shows a three dimensional CAD model of the Multiple Guide Star Unit/ Palomar Tomograph

Figure 1b: Shows the MGSU assembled with all 4 Hartmann-Shack sensors in the enclosure.
System description

The system uses 5 Hartmann Shack low noise CCD based wavefront sensors. The 5 channels are composed of three 16x16 sub-aperture channels and one 3x3 sub-aperture inside the MGSU enclosure and the Palomar AO (PALAO) 16x16 Active High Order Wavefront Sensor (AHOWFS). The 4 channels inside the PT enclosure can traverse a continuous field of ~90 arcseconds, while the star selection mirrors in PALAO let the active wavefront sensor acquire guide stars. Between these two star acquisition systems, we can acquire and guide on any asterism where the maximum separation between stars is less than the above mentioned Field of View (FoV).

The PALAO system is populated with five Scimeasure cameras and controllers that can grab frames at over 2000 Hz from a CCD39 (80x80 pixel) detector. We have characterized these cameras, to find that the read noise is 3 e⁻ rms at 500 Hz and creeps up to 7e⁻ rms at 2000 Hz. For the 16x16 Hartmann-Shack wavefront sensors we use 64x64 active pixels for sensing while for the 3x3 Low Order Wavefront Sensor (LOWFS) we read out 9 sets of 3x3 pixels. The LOWFS also serves as our Laser Guide Star (LGS) tip-tilt sensor.

Features of the system

1. The system can be used with the PALAO tip-tilt and high order AO loops open or closed. We can record data on the AHOWFS 50-2000 Hz.
2. There are 3.2 Terabytes of dedicated data storage space on two striped RAID disks that can record data at 2000 Hz from 4 cameras acquiring 14 bit data from 64x64 pixels. Data is compressed using custom lossless compression format and can be extracted to fits image with time tags using a data line from each of the four computers via Ultra SCSI 160 cables.
3. Each camera acquires guide stars independently leading to a 90 arc-sec. diameter field for the instrument. The optical train is designed to be telecentric over this range so that pupil shear is ≤1.2% (2 microns) at the lenslet pupil (size=1.728 mm) over the FoV.
4. A Linux interface is used for camera control and motion control. All control schemes are written in C/C++. All control code is checked into CVS repository with version control.
5. ssh-agent, ssh-add are used to talk to all cameras from one shell.
6. A 5 ft high commercial 19” rack is populated with a KVM, a 1U rack mounted monitor, 10 Mbps network link, a network power switch etc for ease of operation. Newport’s latest LTA series high speed actuators are used to acquire guide stars with one motor controller controlling all 8 axes.
7. A custom timing module is used to trigger as many as 6 wavefront sensing channels to run at integral frame rates of a master trigger. This can be used when guide stars are of different brightness or to study variations in time of the wavefront sensed from each camera.
Figure 2a: Shows the MGSU/PT electronics rack with the 8 channel motion controller, a Windows test PC, camera controller, network power switch, 4 1U Dell PCs and 3.2TeraBytes of disk space in 2 RAID disks.

Figure 2b: Shows the MGSU assembled with all 4 Hartmann-Shack pick-off arms one behind another.

Figure 3: Schematic of the MGSU/PT showing the data, control and timing lines.

NOTES: MGSU 1 computer controls the timing module, MGSU 4 computer controls the motion control.
**Project Activities:**

**Simulations and Algorithm development**

The general scope of the experiment is to use the information from three Natural Guide Stars (NGS) to estimate the wavefront at a fourth position, where a fourth NGS is available to provide a “truth” measurement against which the 3-NGS prediction is compared and performance assessed. An ideal asterism for this type of estimation and validation would be an equilateral triangle (for the tomography sensors) with a fourth star in the center (for the truth sensor). Ideally, one would put the HOWFS (High-Order WFS) of the Palomar AO system on the central star to act as truth sensor, and train the three MGSU cameras on the encircling stars to act as the tomography system. A variation on this experiment may be carried out using only three NGS, where two are employed to make a prediction for the third, which may be located “off-axis” rather than in the central region. This experiment mimics the situation in certain MOAO (Multi-Object Adaptive Optics) designs or the off-axis sharpening of a tip-tilt NGS based on on-axis LGS tomography. The main experiment is an all-open-loop capture, which lends itself to the most general analysis approach (see next section), but captures with partial (tip+tilt) and full AO compensation in closed loop will also be done for completeness of the data set (and in the case where nonlinearities due to open loop turbulence are too strong).

Given simultaneous measurements from four WFSs on a 4-star asterism as described above, one can apply a number of different analysis methods. The analysis methods that we will be considering for the MGSU data analysis include:

- Wavefront reconstruction from centroids.
- Statistical Waller-type estimator on centroids.
- Zernike mode reconstruction and spatial correlation analysis
- Cross-validation of tomography estimation results by simulation

The first method could, with high quality data, provide the most convincing validation of the tomographic algorithms, while the second method would provide a relative performance measure as computed in centroid data domain. The third analysis is not so much a tomography validation as an additional experiment in atmospheric turbulence analysis that can be done with the data, and the results compared with analytical models for Zernike mode correlations in Komogorov turbulence. The fourth step is an additional simulation exercise, using MASS/DIMM data obtained concurrently with the MGSU data acquisition that will be of interest if we successfully complete the analysis in step 1 or to a lesser degree if only step 2 is completed.
Figure 4: Simulated MGSU detector images, with three MGSU cameras pointing to three stars located on a circle of 30 arc seconds radius (YAO simulation).

Figure 5: Simulated open loop turbulence wavefront (right) and Shack-Hartmann spots (left) on the 64x64 pixel HOWFS camera (YAO simulation).
Figure 6: Sample result screen from main IDL analysis code. Top row - wavefronts: pure open loop turbulence (left); HOWFS reconstructed wavefront (center), and MGSU reconstructed wavefront (right). Bottom row - residual wavefront errors w.r.t. the true wavefront: optimal fit of 17x17 actuator DM (left); HOWFS reconstructed wavefront error (center); MGSU reconstructed wavefront error (right).

Analysis implementation
The sequence of analysis steps, including simulation and matrix generation, will be distributed over various existing codes including:

- IDL
- YAO (http://www.maumae.net/yao/aosimul.html)
- Arroyo (http://eraserhead.caltech.edu/arroyo/arroyo.html)
- LAOS

The main analysis, including centroid computations, wavefront estimates, and performance and correlation measures, for each frame of MGSU and HOWFS data, is done in IDL, mainly by virtue of its FITS-friendly environment. For the wavefront reconstruction analysis (method 1) and simulation step, various existing AO simulation codes may be used independently of each other to generate different types of estimators. The codes used here are the YAO (Yorick Adaptive Optics), Arroyo, and LAOS (Linear Adaptive Optics Simulation) simulation packages. Below are show a few example pictures from a YAO simulation of the MGSU and HOWFS systems, together with a sample result screen from the main IDL analysis code running the wavefront re-construction analysis on simulated data.
MGSU alignment data and experimental data

- The MGSU/PT was built and tested in the lab, prior to integration into the Palomar AO system. The lab data for the system can be found at: http://eraserhead.caltech.edu/palomar/MGSU/12272005/.
- Data was also collected at Palomar Observatory after the system was installed and tested in the same configuration as it would be used on the telescope. This data can be found at: http://eraserhead.caltech.edu/palomar/MGSU/MGSU_Installation.ppt.
- The system was tested on the telescope and 80GB of data was collected that is stored in a disk at Caltech and backed up separately on tape. Some sample data is presented below:

*Figure 7:* Sample Shack-Hartmann spots from different WFSs.
Figure 8: Sample OPDs of the wavefront from above 3 images (with a focus error of 0.143 um, 0.136 um and 0.235 um respectively on the above figures).
Data at the Telescope:

*Figure 9:* Sample data taken on Palomar’s 200” Hale telescope showing open loop, tip/tilt locked and a perfect image (from a white light fiber).