Introduction

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 henceforth in this document. The implementation and performance characterization of these algorithms will be the driving force wide field Adaptive Optics (AO) and AO fed spectroscopy for other more ambitious AO systems for 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) projects. 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 á priori turbulence statistics. Slope detection and ranging (SLODAR) 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 for better estimation of our results and as a diagnostic.

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 seconds of arc, while the star selection mirrors in PALAO lets 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 with CCD39 (80x80 pixel) detector. We have characterized these cameras, to find that the read noise is 3 e’s at 500 Hz and creeps up to 7e’s 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.

Salient features of the system

1. The system can be used with the PALAO tip-tilt and high order AO loop closed or with both or either being open using low noise CCD based wavefront sensor. We can record data 50-2000 Hz.
2. 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. BoPs can acquire guide stars over a continuous 90 arc-sec. diameter field. 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. Linux based camera control interface 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 used to pick off 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 pick off arm.

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
Project Activities:

Simulations and Algorithm development

The general scope of the experiment is to use the information from three NGS to estimate the wavefront at a fourth position, where also 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 (tomography sensors) with a fourth star in the center (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 case the open loop turbulence produces too strong nonlinearities).

Given simultaneous measurements from four WFSs on a 4-star asterism as described above, one can apply a number of different analysis methods that will answer different questions about the data set and the outcome of the experiment. 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 would, in the presence of high quality data, provide the most convincing tomography validation case, 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 Kolmogorov turbulence. The fourth step is an additional simulation exercise, using MASS/DIMM data obtained concurrently with the MGSU data acquisition, that may be of interest mainly if we successfully complete the analysis in step 1, and 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).

Other than this, CalTech is collaborating with the astronomy department at UC Irvine to study the strengths and heights of turbulence layers using cross correlation analysis from synchronous wavefront sensor data obtained from this system two channels at a time.
Analysis implementation

The sequence of analysis steps, including simulation and matrix generation, will be distributed over various already existing codes plus new code written in IDL. The components include:

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

The main analysis, including crunching through the MGSU and HOWFS data frame by frame computing centroids, wavefront estimates, performance and correlation measures, 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 most obvious choices 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 in the lab and tested. 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 is presented as a presentation 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:
Chico Hartmann spots

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).
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).

**Experiments that were done**
We have performed timed wavefront sensing experiments with the instrument we have developed at Palomar during the 11th and 12th of January. The data will be used to test
(a) To verify basic tomography algorithms
(b) To find the height of strong turbulence layer using cross-corelation of Shack-Hartmann data from 2 channels at one time.

**Conclusions/ Project findings**
We have developed a high order 4 channel wavefront system system. We can pick off stars over ~90 arc-sec FoV and record data at rates up to 2000 Hz. Software has been developed to ease the process of moving the wavefront sensors and picking off stars with them and record data simultaneously from 4 WFS channels. We can time these channels
using a custom timing module so that the cameras can run at frame rates that are integral multiples of a master trigger. The system can be used to do a variety of wavefront sensing experiments. The results and publications will be made available to the astronomical community at large.

Contributions

This project is unique in trying to apply tomography algorithms to astronomical AO. For this purpose we have designed and built a system called the Multiple Guide Star Unit (MGSU). This work is the result of state-of-the-art development work in opto-mechanical engineering, algorithm development, and high speed electronics and data storage all working hand-in-hand. We have devised a scheme to align and manufacture wavefront sensing channels in a batch process using special jigs that give us an understanding of how to replicate wavefront sensors for doing wide-field AO for ELTs. With more field-testing of this system we will calibrate the system to gain knowledge on how to acquire stars faster. This will greatly improve the observing efficiencies of big observatories and is currently an issue with most single laser guide star systems. We have the niche at this point to smooth out this complex acquisition process for as many as 5 stars at a time.

Future Work

After gaining confidence in our tomography algorithm(s) and optimizing them, a Digital Signal Processor (DSP) or Field Programmable Gate Arrays (FPGA) based real time computer can be built to utilize the data from the various wavefront sensing channels to run one or two Deformable Mirrors (DMs) to correct wavefront aberrations over a larger field. The PALAO system is currently planning a major upgrade of existing Laser Guide Star (LGS) AO system along simultaneous paths. Firstly, we are signed up to upgrade our 241 active element AO system to a 3000 active element AO system that will have two DMs, the current 241 active element DM which acts as a woofer and a new 3217 active element DM will serve as the tweeter. As a second step we are upgrading our diode-pumped, mode-locked, pulsed laser with 1.0 GHz line-width centered at the sodium resonance line, from a current 8.5W to a 20W system. Lastly, an optical integral field spectrograph designed to take advantage to the nearly diffraction limited Point Spread Functions (PSFs) produced by PALAO called Oxford Short Wavelength Integral Field Spectrograph (OSWIFT) is being built by Oxford University, U.K. to go behind the PALAO. A variety of experiments and use for the MGSU can be devised, keeping in mind, the grand scheme of PALAO upgrades planned in the imminent future.

Publications

3. Ralf's paper tomography algorithms (in preparation)
4. Lianqi's paper on estimation of height of turbulent layer(s) using cross-correlation and shifting analysis of centroids from Shack-Hartmann data (in preparation)

Websites/ Documentation and version control

1. We have developed a public website that has project documentation including schedules, manuals, project status reports, presentations, sample data is hosted at http://eraserhead.caltech.edu/palomar/MGSU/MGSU.html
2. We also maintain all the control software on eraserhead control revision control using a CVS Repository.
3. A plone based website for internal project with data-mining and Wiki capabilities has been developed.
   http://www.astro.caltech.edu:8080/OIR/Palomar/PALMAO/MultipleGuideStarUnitMGSU
4. Information on algorithm development and simulations directly related to the project can be found at http://www.astro.caltech.edu/~rflicker/