

Collaborative Proposal Cover Page

Institutions: UC Santa Cruz, W. M. Keck Observatory, and Caltech
Theme: 2, AO for Extremely Large Telescopes
Principal Investigator: Don Gavel

Proposal Title: System Level Modeling and Optimization of the Polar Coordinate Detector Combined with Modeling and Simulation of Algorithms for Wavefront Sensing with Elongated Sodium Laser Guide Stars

This is a collaborative, single year project.

Phone: 831-549-5464
Email: gavel@ucolick.org

BUDGET, Total Funds Requested from CfAO: \$40,700

Funds are requested to partially support a new postdoc at Caltech, cost-shared 50/50 with TMT. The Laboratory for Adaptive Optics will also provide in-kind support by assigning a postdoc (Sandrine Thomas) at roughly half time to this project.

Proposal Participants

Don Gavel, UC Santa Cruz
Sean Adkins, W. M. Keck Observatory
Luc Gilles, Thirty Meter Telescope (TMT) Project Office
Sandrine Thomas, UC Santa Cruz
Jerry Nelson, UC Santa Cruz
Postdoc at Caltech (to be recruited)
Brent Ellerbroek, TMT Project
Glen Herriot, HI

Time Scale: 1 year

Non-technical Abstract

This is a collaborative project designed to produce a wavefront sensor that is optimized for laser guide stars. There are two components: 1) specifying the parameters of a new wavefront sensor CCD specifically designed for extended laser guide stars, and 2) developing and analyzing optimal algorithms for laser guide wavefront sensing, with predictions anchored against experimental results at the W.M Keck Observatory and at the UCSC Laboratory for Adaptive Optics.

Technical Abstract

1. CCD Development

The current design for the Thirty Meter Telescope (TMT) AO system utilizes multiple Shack Hartmann (SH) wavefront sensors in conjunction with multiple sodium

wavelength guide star lasers. The large number of subapertures and the significant perspective elongation of the LGS image that occurs with the large telescope aperture are both challenges to SH wavefront sensor designs. We are prototyping a design for a CCD that will accommodate the needs of extremely large telescopes for LGS AO wavefront sensing and that is suitable for use with both CW and pulsed lasers in a project funded by the Adaptive Optics Development Program (AODP) and titled “Development of the Next Generation Optical Detectors for Wavefront Sensing”. For CW lasers the design offers increased sampling along the axis of elongation, and for pulsed lasers the design offers the ability to track the laser spot. In the work to be funded by this proposal we will extend our polar coordinate detector simulation to include realistic sodium layer profiles, effects of the atmosphere for both uplink and down link, and variations in seeing. We will then use the results of these simulations to drive various wavefront reconstruction algorithms, both closed and open loop in order to quantify the benefits of the polar coordinate detector in a LGS AO system.

2. Elongated Spot Centroider Development

Quasi-static wavefront sensor (WFS) non-common path aberrations (NCPA's) induced by elongated sodium laser guide stars (LGS's) have recently been observed on the low bandwidth wavefront sensor (LBWFS) of the Keck II AO system. These aberrations change with sodium layer structure, telescope elevation and pupil rotation, and are compensated for by applying subaperture centroid offsets on a subaperture per subaperture basis. Four sources of NCPA's have been quoted [1]: (i) subaperture spot elongation, (ii) quad cell undersampling of the elongated spots, (iii) limited angular subtense of the quad cell pixels and (iv) focus range mismatch between telescope (infinity) and extended range LGS. In February 2007, the W.M Keck Observatory will upgrade its LGS WFS to an 8 x 8 pixel WFS. This upgrade will provide an opportunity to learn more about the LGS aberrations by comparing how they change after the upgrade. We propose to model and perform detailed wave optics simulations of these different effects to allocate their contributions to the Keck II and Thirty Meter Telescope (TMT) LGS wavefront error budgets, anchor these predictions against experimental results at the W.M Keck Observatory and assess the potential improvements that are possible with advanced wavefront sensor (WFS) designs and processing algorithms (“polar-coordinate” CCD, weighted centroiding, matched filtering, correlation tracking etc).

Proposal Cover Page

Institution: W. M. Keck Observatory
Theme: 2, AO for Extremely Large Telescopes
Principal Investigator: Sean Adkins

Proposal Title: System Level Modeling and Optimization of the Polar Coordinate Detector for Laser Guide Star Adaptive Optics Wavefront Sensing

This is a collaborative, single year project.

Phone: 808-881-3775
Email: sadkins@keck.hawaii.edu

BUDGET, Total Funds Requested from CfAO: \$53,000

Funds are requested for salary, tuition and benefits for a graduate student research assistant and support for limited travel by the graduate student and a postdoctoral research associate at the LAO. Because of the timely need for starting the work of this proposal we are requesting funding for a July 2006 start date instead of a November 2006 start date.

Proposal Participants

Sean Adkins, W. M. Keck Observatory	Graduate Student at the CfAO, (to be recruited)
Don Gavel, LAO	Brent Ellerbroek, TMT Project
Sandrine Thomas, LAO	Glen Herriot, HIA
Jerry Nelson, CfAO	

Time Scale: 1 year

Abstract

The current design for the Thirty Meter Telescope (TMT) AO system utilizes multiple Shack Hartmann (SH) wavefront sensors in conjunction with multiple sodium wavelength guide star lasers. The large number of subapertures and the significant perspective elongation of the LGS image that occurs with the large telescope aperture are both challenges to SH wavefront sensor designs. We are prototyping a design for a CCD that will accommodate the needs of extremely large telescopes for LGS AO wavefront sensing and that is suitable for use with both CW and pulsed lasers in a project funded by the Adaptive Optics Development Program (AODP) and titled "Development of the Next Generation Optical Detectors for Wavefront Sensing". For CW lasers the design offers increased sampling along the axis of elongation, and for pulsed lasers the design offers the ability to track the laser spot. In the work to be funded by this proposal we will extend our polar coordinate detector simulation to include realistic sodium layer profiles, effects of the atmosphere for both uplink and down link, and variations in seeing. We will then use the results of these simulations to drive various wavefront reconstruction algorithms, both closed and open loop in order to quantify the benefits of the polar coordinate detector in a LGS AO system.

System Level Modeling and Optimization of the Polar Coordinate Detector for Laser Guide Star Adaptive Optics Wavefront Sensing

The current design¹ for the Thirty Meter Telescope (TMT) AO system utilizes multiple Shack Hartmann (SH) wavefront sensors in conjunction with multiple sodium wavelength guide star lasers. The large number of subapertures and the significant perspective elongation of the LGS image that occurs with the large telescope aperture are both challenges to SH wavefront sensor designs.

Each of the TMT LGS wavefront sensors will have about 3,000 subapertures in the first light 60 x 60 AO system, and about 12,000 subapertures in the second-generation 120 x 120 AO system. Frame rates of 800 Hz or higher are needed in order to meet the temporal error budget requirements. The current approach to SH wavefront sensor design is to use a CCD with a pixel array that covers the entire wavefront sensor focal plane. For the TMT this would require a CCD approaching the size of typical science detectors, and achieving the desired signal to noise ratio and read out speeds will be very difficult using this conventional approach. A conventional detector also lacks the features needed to aid in the mitigation of perspective elongation and the changing altitude of the mesospheric sodium layer.

The mesospheric sodium layer varies in thickness with time and typical values are in the range of 10 to 20 km. The guide star laser illuminates the entire sodium layer, resulting in a column of excited sodium atoms. When viewed from off the axis of laser projection the column is seen, effectively elongating the LGS image on the axis corresponding to the height of the column. This condition is commonly referred to as perspective elongation². On an extremely large telescope this elongation is quite significant. For center projection of the guide star laser and assuming a 10 km thick sodium layer with a 30 m telescope at an elevation of ~4200 m the illuminated column in the sodium layer appears to be ~3.8" in extent in the outer subapertures of a SH wavefront sensor. If the guide star laser beam is uplink corrected to compensate for the atmospheric turbulence the LGS image may be ~0.4" across (FWHM) meaning the LGS image is more than 8 times bigger in the elongation direction.

One method that has been proposed to mitigate the effect of perspective elongation is to use a pulsed laser. For properly timed pulses of sufficiently short duration only a small portion of the total sodium layer thickness will be illuminated by the laser pulse, reducing the height of the illuminated column and therefore reducing the elongation of the LGS image. Realizing that as the pulse transits the sodium layer it will appear to travel up the column seen with CW illumination, and therefore transit across the detector along the axis of elongation we can take advantage of the essentially noiseless process of CCD charge transfer and track the laser pulse as the LGS image travels across the detector, increasing the wavefront sensor integration time for each laser pulse.

This approach is illustrated in Figure 1, which shows a small CCD imager with 6 columns and 10 rows. The dashed outline shows the area illuminated by the elongated spot image of a CW laser, and the small circle corresponds to the area illuminated by the

pulsed laser spot image. The pulsed laser spot image transits across the detector as indicated by the arrow. In order for this to work we need to align the column axis of the imager pixel array with the axis of elongation for the laser spot in every subaperture of the SH wavefront sensor. This is illustrated in Figure 2, which shows an array of square subapertures over a portion of the telescope aperture with the laser projected from the center of the telescope. As indicated in the figure the axis of the elongated spot in each subaperture is aligned to a radial line connecting the center of the subaperture to the laser projection point, in this case at the center of the telescope aperture.

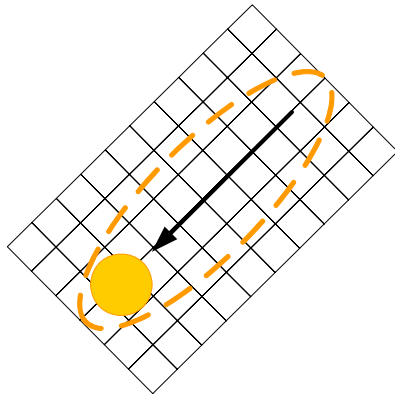


Figure 1: Rectangular CCD pixel array in a single SH wavefront sensor subaperture with an elongated LGS image

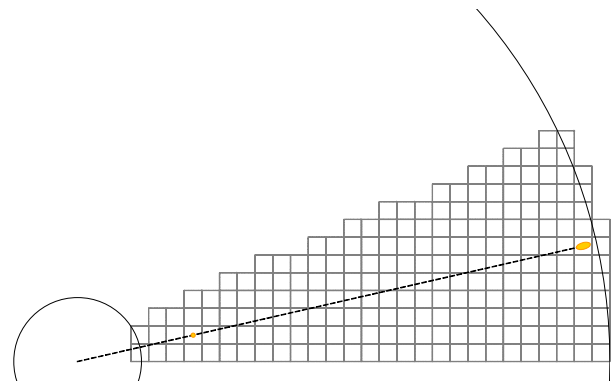


Figure 2: LGS image elongation across a portion of the telescope aperture

For pulse tracking the length of the path traveled by the spot across the imager will vary as a function of distance from the laser projection point. Since the spot transits the sodium layer in a fixed time, this means that the spot travels faster in the outer subapertures. This requires that we arrange the imager row clocks to the pixel arrays in rings of subapertures corresponding to annuli around the laser projection point.

It is also important to keep in mind that the perspective elongation, and therefore the apparent transit time will vary as a function of zenith angle, making it necessary to adjust the clock rate as the telescope elevation changes. Since the amount of elongation is directly proportional to the distance of the subaperture from the projection point, a single master clock suitably divided down will produce the different row-to-row transfer rates needed across the detector. This master clock may then be varied as a function of zenith angle according to an appropriate function that is conveniently approximated by using the cosine of the zenith angle squared.

The use of a variable clock to compensate for the change in perspective as the telescope elevation changes may also be used to compensate for altitude variations by realizing that a change in sodium layer altitude also results in a change in the perspective elongation. This is similar to the variation with zenith angle, although over a much smaller range. It may be possible to use a focus term from a focus tracking wavefront sensor to adjust the detector master clock rate and compensate the sodium range variations more quickly than will be possible with an opto-mechanical focus mechanism.

For a CW laser, by using a rectangular pixel array we can provide additional pixels to sample the LGS image in the elongation direction without adding unused pixels in the non-elongation direction, as we would have to do if we used a conventional square pixel layout.

We are prototyping a design for a CCD that will accommodate the needs of extremely large telescopes for LGS AO wavefront sensing and that is suitable for use with both CW and pulsed lasers in our project³ funded by the Adaptive Optics Development Program (AODP) and titled “Development of the Next Generation Optical Detectors for Wavefront Sensing”. For CW lasers the design offers increased sampling along the axis of elongation, and for pulsed lasers the design offers the ability to track the laser spot.

This CCD, nicknamed the “polar coordinate detector”, is based on a “novel pixel geometry” consisting of small “islands” of pixels within each subaperture. The pixel islands are rectangular in shape with the major axis of each pixel island oriented along radial lines from the center of projection for the laser (hence the name “polar coordinate detector”). This means that the elongation direction of the LGS image in each subaperture will be along the major dimension of the rectangular pixel island. The concept for the pixel islands in each subaperture of the polar coordinate detector was described in a poster presentation at the 2005 Scientific Detectors Workshop in Italy⁴.

The polar coordinate detector offers the opportunity to address a key challenge in a SH wavefront sensor with a large number of subapertures by allowing a significant reduction in the total pixel count for the detector. In order to optimize the design we want to establish the optimal number of pixels for each subaperture. This optimal number of pixels will provide adequate sampling of the LGS image in the presence of read noise by allowing us to use the fewest number of pixels possible. This will also help with overall detector design issues, particularly the trade off between read out speed and the number of read out ports. It is important to optimize the number of read out ports to balance overall layout complexity and to manage CCD controller and interconnect complexity.

To better understand the influence of sampling and signal to noise ratio on the performance of the CCD we have developed a model of one subaperture of the detector and performed a series of simulations using that model⁵.

For a CW laser our simulation and modeling efforts have allowed us to estimate the optimal sampling of the LGS spot based on signal to noise ratio. We have also estimated the number of pixels required to accommodate the effects of seeing and operation of the LGS wavefront sensor off null due to the presence of aberrations in the optical relay of the AO system and offset adjustments imposed to compensate for non-common path errors.

We are now working on the design of the subapertures for the polar coordinate detector and using this design to understand the interconnection and multiplexing design issues for a complete polar coordinate detector. Within the AODP funded project we plan to fabricate a prototype of the polar coordinate detector (referred to in our AODP proposal

as the “phase 2 device”) that will demonstrate all of the CCD design features required for the TMT LGS AO wavefront sensor, using 30 x 30 subapertures corresponding to one quadrant of a 60 x 60 subaperture device designed for center projection of the guide star laser*. We are planning to complete this prototype development early in calendar 2007. Within our AODP funded project we also have the resources to develop a test system for laboratory operation of the prototype device and a pulsed laser simulator designed to allow us to demonstrate tracking of a pulsed laser spot.

This proposal results from discussion of the polar coordinate detector at the recent CfAO Spring Retreat session on Advanced Modeling and Simulation for Extremely Large Telescopes. These discussions raised a number of system level issues for LGS AO on the TMT that require further study. We were also able to identify additional opportunities for collaboration with both the TMT project and the Laboratory for Adaptive Optics (LAO) at UCSC.

In the proposed TMT AO system designs (NFIRAOS, MOAO) the polar coordinate detector will operate with an AO relay where aberrations due to the finite altitude of the sodium layer may vary with range and focus. The effects of these aberrations on the performance of the detector need to be understood.

The impact of variability in the sodium layer due to changes in altitude and density need to be understood, particularly the impact on the dynamic range of the detector. The effects of uplink correction, particularly LGS spot profiles, uplink correction servo performance and the impact of seeing need to be simulated.

Other system level effects that need to be reviewed include the effect of windshake on the telescope structure including the laser launch telescope and the effects of “fratricide” from simultaneously projected LGS.

There are also issues related to laser performance, including power stability for both CW and pulsed lasers, duty cycle and peak power trade offs for pulsed lasers, and pulse tracking clock accuracy and matching. There are also SNR and frame rate trade offs for pulsed laser operation that need to be considered.

For open loop (MOAO) applications we need to identify and understand all of the systematic error terms associated with high dynamic range wavefront sensing. We need to understand the calibration procedure (i.e. what effects are most important to calibrate) and the resulting residual nonlinearities over the wavefront sensor dynamic range. We also need to further investigate the optimal algorithms for Shack Hartmann spot displacement measurement with the polar coordinate CCD for both CW and pulsed lasers.

In order to address these issues there is a need to develop system level simulation efforts for the polar coordinate detector as part of a LGS AO system. To do this we propose to

* Although we understand the current design of the TMT LGS AO system uses center projection, all of the concepts described here are also applicable to the design of a CCD for use with offset projection.

enhance and support collaboration between our AODP funded polar coordinate detector prototyping and test effort, the TMT project modeling efforts for LGS AO, the CfAO and the LAO at UCSC.

In this project we will extend our polar coordinate detector simulation to include realistic sodium layer profiles, the effects of atmospheric turbulence for both uplink and down link, and variations in seeing. We will then use the results of these simulations to drive various wavefront reconstruction algorithms, both closed and open loop, in order to quantify the benefits of the polar coordinate detector in a LGS AO system.

Collaboration Participants and Work Assignments

Through this proposal we will fund additional work by a graduate student research assistant, to be recruited by Don Gavel and located at the CfAO to extend the simulation and modeling of the polar coordinate detector to the system level and quantify the performance gains that may be realized from using this detector in the TMT LGS AO system. This student will be supervised by Sean Adkins and by Gavel, and will also work with postdoctoral research associate Sandrine Thomas at the LAO. We are including travel funds for the student and Thomas to work with Brent Ellerbroek and Luc Gilles at the TMT project office in Pasadena, CA.

We will also collaborate with Ellerbroek and Gilles, and with Glen Herriot of the Herzberg Institute for Astrophysics, to incorporate performance modeling of the polar coordinate detector in the TMT LGS AO design and simulation efforts. We will base our performance modeling on work by Herriot for the TMT AO relay design and collaborate with Herriot and Ellerbroek on the implementation of a polar coordinate detector WFS for the TMT first light AO system NFIRAOS. The activities of Ellerbroek and Herriot are supported by the TMT project.

As described above Adkins and Jerry Nelson are co-investigators on the AODP funded project to develop a prototype of the polar coordinate detector. In that project we will develop the detector and a test system to operate it. We will also design and build a pulsed laser simulator to allow us to demonstrate tracking of a pulsed laser spot. All of these activities are funded by the AODP and no funds from this proposal will be used to pay for these activities.

Through the support from this proposal and the LAO we will consult with Gavel and Thomas at the LAO on the design of the simulator and the test program. Through the support from this proposal and the LAO we will also collaborate with the LAO to perform the actual testing of the prototype detector at the LAO. The AODP funded project will provide support for the participation of Adkins, and the CfAO and UCO/Lick are supporting the participation of Nelson in the AODP project.

CfAO Year 8 Project Plan

The milestones, funding sources and collaborator involvement for the activities in this proposal and the related AODP funded project are summarized in Table 1. These dates are based on a July 2006 start for the project. We are requesting this early start date in order to complete the additional modeling work that we expect will influence the polar coordinate detector prototype design effort, already in progress.

Date	Milestone	Funding Source	Collaborators
October 2006	Additional modeling completed	This proposal	Graduate student, Adkins, Gavel, Thomas, Nelson
February 2007	Polar coordinate detector design completed	AODP	Adkins, Nelson
May 2007	Pulsed laser simulator completed	AODP	Adkins, Gavel, Nelson
April 2007	System level simulations of polar coordinate detector completed	This proposal	Graduate student, Adkins, Gavel, Thomas, Ellerbroek, Herriot
July 2007	Polar coordinate detector prototype completed	AODP	Adkins, Nelson
August 2007	Polar coordinate detector testing begins	This proposal	Graduate student, Adkins, Gavel, Thomas
September 2007	Polar coordinate detector testing completed	This proposal	Graduate student, Adkins, Gavel, Thomas
September 2007	Project completed		

Table 1: CfAO Year 8 Project Milestones

A project timeline is shown in Figure 3.

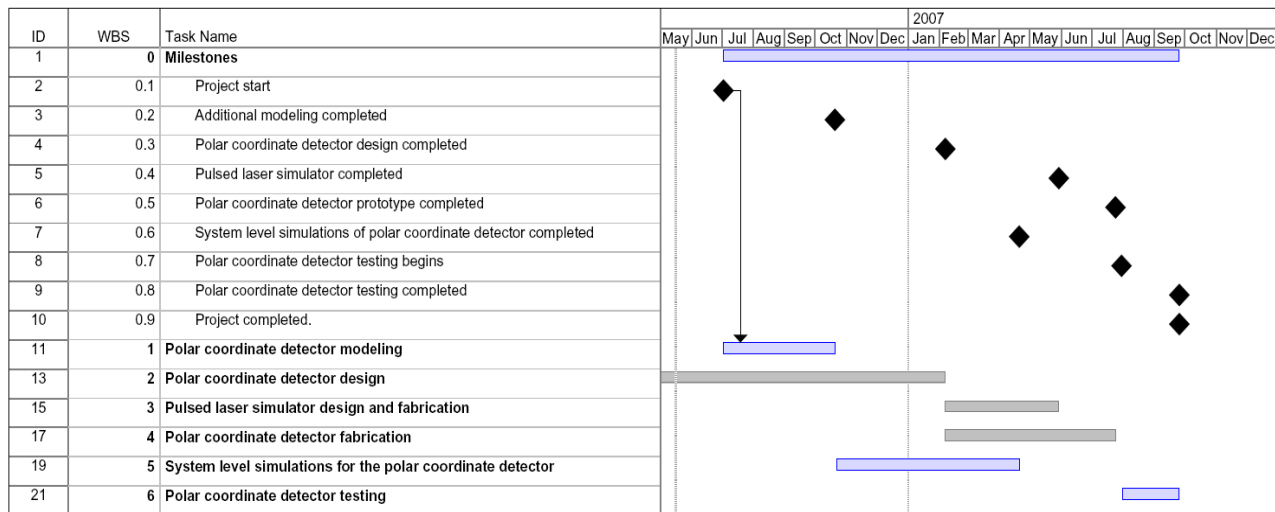


Figure 3: Project Timeline

Proposed Education & Human Resources Activities

We plan to recruit a graduate student to participate in this project who will be based at the CfAO. Through this proposal the student will have the opportunity to collaborate with Adkins and Nelson at the CfAO, Gavel and Thomas at the LAO, and with Ellerbroek and other TMT project staff members.

References

1. Ellerbroek, Brent; Britton, Matthew; Dekany, Richard; Gavel, Don; Herriot, Glen; Macintosh, Bruce; Stoesz, Jeff, "Adaptive optics for the Thirty Meter Telescope", *Astronomical Adaptive Optics Systems and Applications II*, Edited by Tyson, Robert K.; Lloyd-Hart, Michael, *Proceedings of the SPIE*, Volume 5903, pp. 20-31, 2005.
2. Beckers, Jacques M., "Overcoming perspective elongation effects in laser-guide-star-aided adaptive optics", *Applied Optics*, Vol. 31, No. 31, pp. 6592-6594, November 1992.
3. Beletic, James W., Sean Adkins, Barry Burke, Charlie Bleau, Ray DuVarney, Richard Stover, Jerry Nelson, Francois Rigaut, "Development of the Next Generation Optical Detectors for Wavefront Sensing", a proposal to the Adaptive Optics Development Program, W. M. Keck Observatory, October 2003.
4. Beletic, James W., Sean Adkins, Barry Burke, Robert Reich, Bernie Kosicki, Vyshnavi Suntharalingham, Charlie Bleau, Ray DuVarney, Richard Stover, Jerry Nelson, Francois Rigaut, "The Ultimate CCD for Laser Guide Star Wavefront Sensing on Extremely Large Telescopes", *Scientific Detectors for Astronomy 2005*, Springer Dordrecht 2006.
5. Adkins, Sean M., Oscar Azucena, Jerry E. Nelson, "The design and optimization of detectors for adaptive optics wavefront sensing". *Proceedings of the SPIE Volume 6272, Advances in Adaptive Optics II*, in press. SPIE 2006.

5.0 Proposal Cover Page

Institutions: Thirty Meter Telescope (TMT) Project Office, W.M. Keck Observatory
Theme: AO for Extremely Large Telescopes (theme 2)
Principal Investigator: Luc Gilles

Proposal Title: “Elongated Sodium Laser Guide Star Adaptive Optics: Anchoring Modeling and Simulation Results”

Proposals affiliated with a theme are strongly preferred.

- Collaborative Project Seed funding proposal (If seed funding, **only** this box and the collaborative project box should be checked)
- Single investigator project
- New multi-year project Continuing project New single year project

Check all appropriate Boxes

Phone: (626) 395-1622

Email: lgilles@caltech.edu

BUDGET: Total Funds Requested from CfAO:

Total Funds Requested from CfAO: \$40,700

6.0 PIs who lead current Year 7 projects: Additional Information Required by NSF for Inclusion in the CfAO Annual Report

6.1 List all Center publications (*those that acknowledge Center support*) in standard format, dated from May 2004 to the present. Distinguish among the following types: peer reviewed, books and book chapters, and other non-peer reviewed publications.

B.L. Ellerbroek, “Linear systems modeling of adaptive optics in the spatial-frequency domain,” J. Opt. Soc. Am. A **22**, 310-322 (2005).

R.M. Clare and B.L. Ellerbroek, “Sky coverage estimates for adaptive optics systems from computations in Zernike space,” J. Opt. Soc. Am. A **23**, 418-426 (2006).

B.L. Ellerbroek, “Adaptive optics without borders: performance evaluation in the infinite aperture limit,” in *Advancements in adaptive optics*, D.B Calia, B.L. Ellerbroek and R. Ragazzoni, eds., Proc. SPIE **5490**, 625-636 (2004).

G. Herriot, P. Hickson, B.L. Ellerbroek, D.A. Andersen, T. Davidge, D.A. Erickson, I.P. Powell, R. Clare, M. Smith, L. Saddlemyer, J.-P. Veran, “NFIRAOS: TMT facility adaptive optics with conventional DMs,” in *Astronomical Adaptive Optics Systems and Applications II*, R. K. Tyson, M. Lloyd-Hart eds, Proc. SPIE **5903**, 1-11 (2005).

N. Hubin, B.L. Ellerbroek, M. Le Louarn, J.-P. Veran, E. Marchetti, G. Herriot, C. Verinaud, R.M. Clare, M. Kasper, J. Stoesz, S. Oberti, R. Arsenault, “Adaptive Optics for Extremely Large Telescopes,” Proc. IAU, in press.

6.2 List all of your Center participants (*an individual who spends 160 or more hours on Center activities over a 12 month period*).

Brent Ellerbroek and Richard Clare.

6.3 List each CfAO graduate student or postdoctoral researcher who has left. *Designate degrees achieved and/or number of years to degree. Also designate her/his new placement.*

None, but Richard Clare leaves in June for the W.M. Keck Observatory.

6.4 List all awards and honors *with names of those honored, reason for award, award name and sponsor, and the date of the award.*

None

6.5 Provide demographic information for each NEW Center participant

- *Name:* Luc Gilles
- *Category:* TMT adaptive optics analyst
- *Gender:* male
- *Disability:* none
- *Ethnicity:* not Hispanic or Latino
- *Race:* White
- *Citizenship:* Permanent Resident

6.6 List all Patents and Licenses *with patent name, inventors/authors, patent/license number, application date, and receipt date*

None.

6.7 List names of all start-up companies *and designate their main product(s)*

None.

6.8 Describe any other outputs of knowledge transfer activities *made during the reporting period not listed above.*

Periodic updates to an AO simulation code (CIBOLA) have been uploaded to the CfAO website.

7.0 Research Proposal Format: Single PI Project or Co-PI of a Collaborative Project

7.1 Proposal Participants

- 1 postdoc to be hired, based at the TMT headquarters in Pasadena, will develop laser guide star (LGS) AO analytical models and implement them into the LAOS code.
- Dr. Luc Gilles, TMT AO analyst, lgilles@caltech.edu, will provide technical direction for the postdoc and spend a fraction of his time working on related upgrades and applications of the LAOS code.
- Dr. Brent Ellerbroek, TMT AO group lead, brente@caltech.edu, will supervise the postdoc and coordinate the project with TMT.
- Dr. Richard Clare, Keck postdoc, rclare@tmt.org, will collect telescope data on LGS AO aberrations, implement a finite element model describing LGS elongation and its effect on the WFS, and help implement realistic features of the Keck II system in the LAOS code.
- Dr. Marcos van Dam, Keck AO scientist, mvandam@keck.hawaii.edu, will help Richard Clare with all the above.

7.2 Time Scale This is a 1 year proposal

7.3 Abstract

Technical Abstract

Quasi-static wavefront sensor (WFS) non-common path aberrations (NCPA's) induced by elongated sodium laser guide stars (LGS's) have recently been observed on the low bandwidth wavefront sensor (LBWFS) of the Keck II AO system. These aberrations change with sodium layer structure, telescope elevation and pupil rotation, and are compensated for by applying subaperture centroid offsets on a subaperture per subaperture basis. Four sources of NCPA's have been quoted [1]: (i) subaperture spot elongation, (ii) quad cell undersampling of the elongated spots, (iii) limited angular subtense of the quad cell pixels and (iv) focus range mismatch between telescope (infinity) and extended range LGS. In February 2007, the W.M Keck Observatory will upgrade its LGS WFS to an 8 x 8 pixel WFS. This upgrade will provide an opportunity to learn more about the LGS aberrations by comparing how they change after the upgrade. We propose to model and perform detailed wave optics simulations of these different effects to allocate their contributions to the Keck II and Thirty Meter Telescope (TMT) LGS wavefront error budgets, anchor these predictions against experimental results at the W.M Keck Observatory and assess the potential improvements that are possible with advanced wavefront sensor (WFS) designs and processing algorithms ("polar-coordinate" CCD, weighted centroiding, matched filtering, correlation tracking etc).

Non-technical abstract

Laser guide star (LGS) adaptive optics (AO) was developed for astronomy to dramatically increase the sky coverage for high resolution imaging and spectroscopic observations. LGS AO

has been implemented successfully up to date at least on 5 telescopes: Keck II, Gemini, VLT, SOR and Lick. Several important wavefront sensor (WFS) issues arise when using an LGS system, particularly in terms of linear dynamic range and sensitivity to noise. Indeed, the LGS moves on the sky due to atmospheric turbulence and telescope vibrations, and it is important to maintain the subaperture beacon images stable on the detectors. Moreover, sodium beacons are extended in three dimensions due to the structure of the mesospheric sodium layer, degrading the sensitivity of the WFS. Wavefront aberrations induced by a combination of these effects have recently been measured at the W.M Keck Observatory. We propose to model and perform detailed wave optics simulations of wavefront sensing with elongated sodium beacons, anchor the predictions against experimental results at the W.M Keck Observatory, allocate their contributions to the Keck II and Thirty Meter Telescope (TMT) wavefront error budgets, and assess the potential improvements that are possible with advanced wavefront sensor designs and processing algorithms.

7.4 Proposal

This proposal is related to Theme 2: “AO for extremely large telescopes”.

7.4.1 Technical Description

Implementing elongated sodium LGS AO on large telescopes presents numerous challenges. Wizinowich et al. [2] share the lessons learned in this process for the Keck II system and the approaches taken to overcome the LGS specific issues. During LGS AO operation at the W.M. Keck Observatory, 5 control loops are running simultaneously, whose bandwidths must be optimized:

1. A laser pointing loop fed by the LGS WFS controls the fast steering mirror (FSM) to stabilize the laser beacon on the sodium layer to maintain reasonable dynamic range on the LGS WFS.
2. A deformable mirror (DM) loop fed by the LGS WFS provides high-order wavefront correction. Note that this loop requires computation of non-uniform subaperture centroid gains to take into account the increasing spot size with distance between the sensing subaperture and the laser launch telescope (LLT). At the W.M. Keck Observatory, the LLT is located on the side of the telescope, yielding subaperture spots as big as 3 arcsec (FWHM) at 12 m separation from the LLT.
3. A tip/tilt mirror (TTM) loop fed by a separate tip/tilt natural guide star (TT NGS) WFS (TT information cannot be obtained from LGS WFS's).
4. A focus loop fed by a tip/tilt/focus (TTF) NGS WFS to track variations of the sodium layer mean altitude with time and zenith angle. This is implemented on Keck II by a low-bandwidth WFS (LBWFS) having the same order as the LGS WFS. The LBWFS is mounted on a translation stage to maintain its registration with the DM actuators, and its integration time varies between tens of seconds to a couple of minutes depending on the TT NGS brightness. The LBWFS controls the WFS stage position while maintaining the pupil size on the lenslet array to drive the time averaged focus measurement to zero.

5. An image sharpening loop fed by the LBWFS computes non-uniform subaperture centroid offsets to correct for LGS induced WFS NCPA's.

We propose to model and perform high-fidelity wave optics simulations of each of these effects, and compare the results obtained against LGS AO field test results collected at the W. M. Keck Observatory. The simulations will be performed using LAOS, a Matlab end-to-end Linear Adaptive Optics Simulator using minimum variance wavefront reconstruction implemented efficiently using sparse matrix techniques [3]. The original features of the code are summarized in Table 1, which also outlines current capabilities and planned upgrades to support more detailed modeling of LGS AO systems for TMT and other AO projects. Anchored against analytical performance estimates for 8 to 10-m class telescopes, LAOS is able to simulate with some level of detail single conjugate AO (SCAO i.e. one LGS and one DM), multi conjugate AO (MCAO i.e. several LGS's and several DM's), laser tomography AO (LTAO i.e. several LGS's but only one DM), multi object AO (MOAO i.e. several LGS's and one DM per field point), and ground layer AO (GLAO i.e. improved seeing when turbulence is concentrated near the ground). As the name implies, the original implementation was based upon linear (i.e. first order) models of all AO components and phenomena [4]. The additional current capabilities [5] and planned upgrades described in columns 3 and 4 of Table 1 have been developed (or are under development) to assess the impact of several implementation error sources.

In order to analyze the LGS WFS NCPA's induced by elongated sodium beacons observed at the W.M Keck Observatory, we plan to develop a more refined model of the 3D laser beacon in LAOS. A simple approach is to divide the sodium profile into a few number of slabs, compute the image of each slab assuming that the laser is focused at the slab mean range, and co-add the resulting images. We also plan to provide a higher fidelity simulation of the Keck II system, in particular develop capabilities to incorporate the vector-matrix-multiply reconstructors used at the W.M. Keck Observatory, pupil misregistration and pupil amplitude modeling (non-circular pupils). The current and planned LGS capabilities of LAOS, namely advanced radial format CCD, centroiding, matched filtering and correlation tracking, will be used to estimate the potential benefits of these concepts for the Keck II LGS system and for TMT. The W.M. Keck Observatory will also be studying these effects with a separate code for cross-validation. The overall goal of our effort is (i) to improve Keck II AO performance and (ii) anchor the LAOS code used to predict LGS AO performance for TMT against experimental results collected at the W.M Keck Observatory.

In the process of performing this work we will also obtain a broader assessment of overall LGS AO performance at the W.M. Keck Observatory, and develop a high-order error budget for the effects of fitting error, WFS measurement noise, servo lag, and the cone effect (focal anisoplanatism). This error budget will be compared to the existing LGS AO error budget [6] and differences will be analyzed. The impact of primary mirror segment alignment errors on LGS WFS performance will also be studied, and the results obtained will again be compared against experimental results collected at the W.M. Keck Observatory.

Table 1. Existing and planned LAOS modeling capabilities

	Initial Implementation	Additional Current Capabilities	Planned Upgrades (Estimated Date)
AO Modes	SCAO, LTAO, MCAO	GLAO, MOAO	
Trade space limits	Order ~60x60 MCAO	Order ~120x120 MCAO and MOAO	
Wavefront disturbances	--von Karman atmospheric phase screens --Taylor frozen flow temporal dynamics	--Static telescope aberrations (continuous and segmented) --Non-common path aberrations	--Low order dynamic telescope aberrations (late 2006)
Telescope pupil	Circular with circular central obscuration		--General amplitude profile (mid-2006)
Reconstruction algorithms	--Pseudo-open loop minimum variance tomographic wavefront control (computationally efficient multigrid implementation) --RMS best fit of actuator influence functions to the estimated turbulence profile		--Fourier domain minimum variance reconstruction (mid-2006)
Control system architectures	Common temporal filter for all DM's and actuators	Woofers-tweeters tip/tilt control	Woofers-tweeters higher-order control
WFS modeling	Subaperture-averaged wavefront gradients plus additive measurement noise	--Wave optics NGS SH-WFS's --Wave optics LGS SH-WFS's with uplink propagation and beacon elongation --Photon statistics and detector read out noise --Centroiding --Matched filtering --Radial format CCD	--anisoplanatic beacon modeling --Pupil misregistration (mid-2006) --Correlation tracking (mid-2006)
DM modeling	Linear superposition of bilinear influence functions	--Hysteresis --Finite stroke	--Pupil misregistration (mid-2006) --Modal low-order influence functions for bimorph mirrors and adaptive secondary mirrors (late 2006)
Performance	RMS wavefront	Time averaged PSF's	

7.4.2 Nature of Collaborations

Richard Clare and Marcos van Dam will ensure that high fidelity simulations of the Keck II system are implemented correctly in LAOS, and will exchange ideas, data and knowledge they gain about the LGS aberrations. We will consult with Chris Neyman and Ralf Flicker on their work to develop performance estimates for the Next Generation AO (NGAO) system at the W.M. Keck Observatory. Finally, we will also collaborate with Mitchell Troy to cross check and validate our models for the effect of segmented mirror alignment and figure errors on AO system performance.

7.5 Specific Year 8 and Multi-year Schedule and Milestones

We will begin work in September 2006.

By April 1 2007, we intend to have completed the following tasks:

- Detailed 3D laser beacon modeling capability implemented in LAOS
- Pupil misregistration implemented in LAOS
- Pupil amplitude modeling implemented in LAOS
- Models for vector-matrix-multiply reconstructors, LBWFS and Keck LGS AO parameters specified in LAOS

By October 1 2007, we intend to have completed the following tasks:

- Detailed analysis and simulation of the LGS WFS NCPA's induced by elongated sodium beacons. Simulation codes anchored against Keck codes and field tests.
- Contributions allocated to the Keck II and TMT wavefront error budgets.
- Assessment of potential improvements that are possible with advanced wavefront sensor (WFS) designs and processing algorithms.

7.6 Proposed Education & Human Resources Activities

- *List and briefly describe the participation in Year 7 in CfAO sponsored EHR activities of the PI, postdocs, and grad students. Include identified milestones and their status.*
- *Describe your proposed participation for Year 8 (also see Section 7). If proposing a CfAO funded internship activity, briefly outline possible projects.*

7.7 Progress Report on Year 7 CfAO funded Research

- *Clearly identify Technical Milestones and progress relative to them.*
- *Describe current technical challenges and status.*

The milestones set out in the Year 7 proposal are listed below, and each is followed by a summary of progress and results.

- July 2005: Have a complete sky coverage model for ELT LGS AO systems that takes into account the finite bandwidth of the control system, actual wind velocity profiles at astronomical sites, wavefront sensor noise, and NGS magnitude distributions.

We have completed a Monte Carlo sky coverage simulator which calculates tip-tilt errors from NGS constellations generated from published star count models. The work is published in references [7] and [8]. The most important details are described here. The tip-tilt errors are calculated by applying minimum variance reconstructors to WFS measurements that are generated by propagating wavefronts from the natural guide star (NGS) constellation, laser guide star (LGS) asterism and science field through the turbulence profile to the aperture. The residual wavefront error calculated for the minimum variance reconstructor includes the tilt anisoplanatism, residual atmospheric tip-tilt and NGS WFS noise terms. The tip-tilt error due to wind-shake is calculated separately using the TMT wind-shake model and added to these terms. The median tip-tilt error is calculated from Monte Carlo simulations of 500 NGS constellations randomly generated using published star count models (Bahcall-Soneira model in V band, and the Spagna model in J band). The sampling rate of each NGS constellation is optimized to balance the errors due to wind-shake, NGS WFS noise and the focus error incurred from the mean height of the sodium layer changing with time.

We have used this model to generate a tip-tilt error budget for the Narrow Field Infra-Red Adaptive Optic System (NFIRAOS) for TMT and complete a number of design trade studies for this system. Firstly, three NGS WFS architectures were considered: two WFS that measure the tip-tilt modes only (i.e. a 1x1 Shack-Hartmann) and one WFS that measures the tip-tilt-focus-astigmatism modes (i.e. a 2x2 Shack-Hartmann), a single WFS that measures the tip-tilt-focus-astigmatism modes only, and a single tip-tilt WFS used in conjunction with a Rayleigh LGS. All three options employ the NFIRAOS sodium LGS asterism. Focus has to be measured from the NGS to determine changes in the altitude of the sodium layer, since the sodium LGS are not able to disentangle the atmospheric focus from these altitude variations. For each of the three cases, if there were more NGS in the field than the number of NGS WFS, then every combination of NGS and WFS was evaluated to optimize performance.

In Figure 1, the cumulative density function (CDF) of performance for the three NGS WFS architectures is shown. Each point in the graph is a different NGS constellation. The auxiliary Rayleigh LGS option always provides the lowest wavefront error, followed by the 2 tip-tilt WFS and 1 tip-tilt WFS focus option, and then the 1 tip-tilt-focus-astigmatism WFS. The WFS architecture chosen for NFIRAOS is 2 tip-tilt NGS WFS and 1 tip-tilt-focus-astigmatism NGS WFS, as a trade-off between performance and implementation complexity.

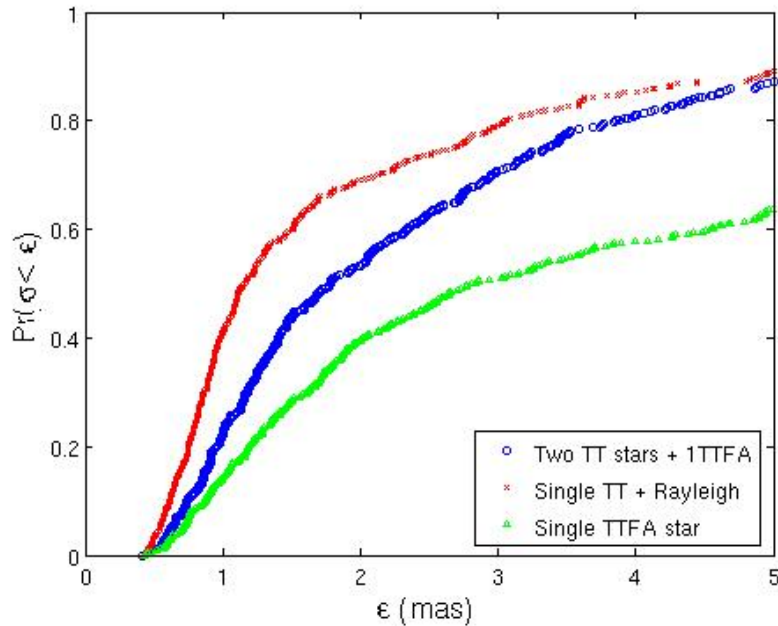


Figure 1: Cumulative Density Function of total on-axis tip-tilt error (mas) of baseline NFIRAOS for three WFS architectures: three tip-tilt stars and one tip-tilt-focus-astigmatism star(blue), a tip-tilt-focus-astigmatism star (green), and a tip-tilt star used in conjunction with a Rayleigh LGS (red).

We used the sky coverage simulator to compare using optical (V band) stars and sensors with infra-red (J band) stars and sensors. The NGS in J band are expected to be partially corrected, whereas in V band the NGS are assumed to be seeing limited. With these assumptions, the median tip-tilt error in J band is 2 mas and clearly superior to V band where the median tip-tilt error is 11 mas.

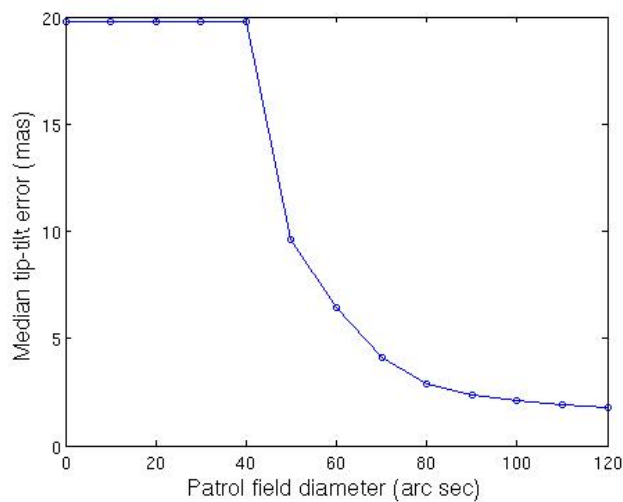


Figure 2: The median TT error (mas) over 500 NGS constellations versus the patrol field diameter for J band stars and sensors.

The sky coverage simulator was used to optimize the diameter of the patrol field for locating NGS. In Fig. 2, the median tip-tilt error over 500 NGS constellations is plotted versus the patrol field diameter. The lowest error is effectively obtained with a 2 arc min diameter field; stars further away from the science field effectively suffer too much anisoplanatism and the Strehl or partial correction of these stars is significantly reduced.

Although the sky coverage simulator is largely complete, further refinements are planned to use the code to compute tip-tilt errors on real science fields, and to estimate the improvement in performance of using J+H or J+H+K bands to perform the NGS WFSensing.

- September 2005: Complete detailed simulations of noise optimal NGS tip/tilt sensing algorithms and upgrade sky coverage estimates based upon these results.

We have evaluated two methods for estimating the tip-tilt from the NGS: the standard Shack-Hartmann quad-cell, and the matched filter (noise-weighted least squares) approach. The latter approach will require improvements in detector technology to produce infra-red detector arrays with large numbers of pixels and low read-out noise at high frame rates. The sky coverage simulator discussed previously was used to evaluate the performance of the two methods for estimating tip-tilt with 3 NGS WFS for the TMT facility AO system NFIRAOS over 500 NGS constellations at the galactic pole for J band stars generated with the Spagna model. A summary of the median total tip-tilt error with these two approaches is tabulated below for a range of detector read noise levels and a range of detector pixel sizes for the matched filter approach.

Method	Pixel Size (rads)	Median tip-tilt error (mas)			
		0 e/pixel	5 e/pixel	10 e/pixel	15 e/pixel
Quad-cell	λ/D	1.34	1.79	2.19	2.55
Matched Filter	$\lambda/2D$	0.92	1.65	2.05	2.38
	λ/D	0.98	1.39	1.72	1.98
	$3\lambda/2D$	1.00	1.41	1.76	1.99

Table 2: Median on-axis tip-tilt errors for NFIRAOS for the matched filter and quad-cell tilt estimation algorithms for a range of detector pixel sizes and read noise levels.

The matched filter algorithm produces lower TT errors than the quad-cell Shack-Hartmann for all pixel sizes and read noise levels investigated. With current technology, using a quad-cell detector with 10 electrons of read noise per pixel, the median total tip-tilt error is 2.19 mas. However, with improvements in detector array technology allowing larger arrays and 5 electrons of read noise per pixel, we estimate the median tip-tilt error can be reduced to 1.39mas.

- November 2005: complete a study of subaperture tip/tilt measurement via matched filtering for elongated Shack-Hartmann images of laser guide stars.

We have completed an analytical study on the degradation of sodium laser guide star Shack-Hartmann wavefront sensor measurement accuracy that will occur due to the spatial structure and temporal variations of the mesospheric sodium layer. The study has been accepted for

publication [9]. Using a contiguous set of LIDAR measurements of the sodium profile, we have analyzed and compared the performance of a standard centroid and of a more refined noise-optimal matched filter spot position estimation algorithm as a function of subaperture to laser launch telescope distance and CCD pixel read out noise. Fig.3 displays a 1 hour average and a sample frame of sodium profile from LIDAR measurements. We have compared both algorithms in terms of their rms spot position estimation error due to photon and read noise, their associated wavefront error when implemented on NFIRAOS, their linear dynamic range and their bias when detuned from the current sodium profile. Fig.4 illustrates sample subaperture spot cross-sections along the elongation direction and its orthogonal direction for a central and an edge subaperture of the TMT.

We found that the rms spot position estimation error due to photon and read noise is significantly increased at the edge of the TMT aperture due to the impact of laser guidestar elongation, but the effect can be reduced with noise optimal matched filter processing. This is particularly true when CCD read out noise is non-zero. For a mean photon return yielding 1,000 photo-detected electrons per subaperture per integration time, the wavefront error budget for NFIRAOS employing a radial format CCD with 16x4 pixels per subaperture is on the order of 32nm in absence of read noise and 45nm with 5 electrons rms read noise per pixel per read for the matched filter algorithm. The additional RSS wavefront error for a centroid algorithm is on the order of 14nm and 55nm respectively.

In terms of linear dynamic range, we found that the matched filter has a linear response for input tilts from approximately -100mas to +100mas, whereas the centroid algorithm provides 2-3 times more dynamic range, but the effect is expected to be small since (i) the null point for each LGS WFS subaperture may be calibrated to account for non-common path wavefront aberrations without dynamic range degradation, and (ii) the time varying tip/tilt subaperture wavefront aberrations due to atmospheric turbulence is expected to be smaller than the dynamic ranges in question.

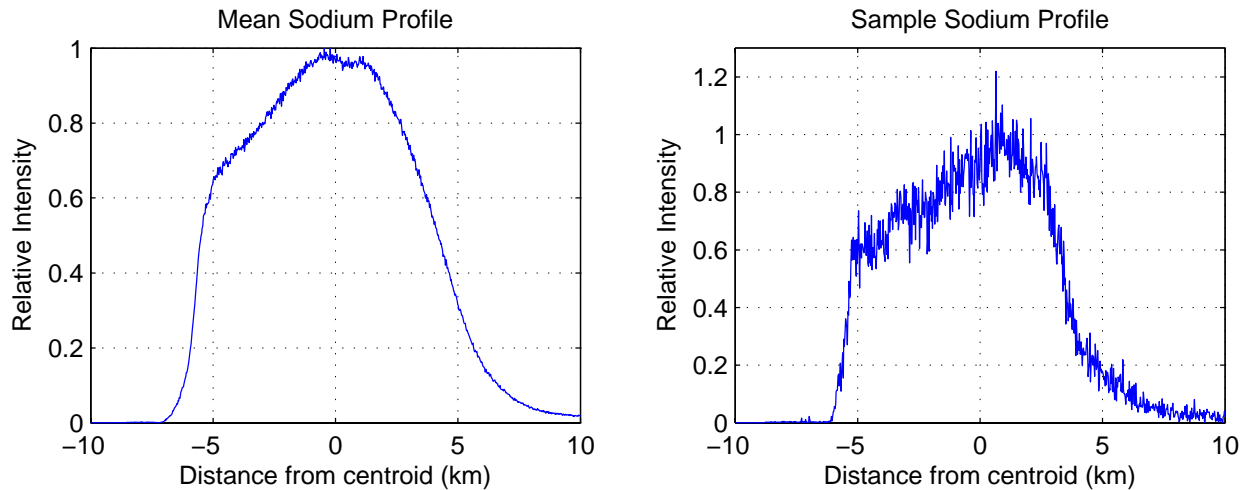


Fig.3 Left panel: mean sodium profile obtained by averaging 88 contiguous frames of centroid removed LIDAR measurements of the sodium layer with spatial and temporal resolution of 24 m and 70 sec respectively. Right panel: sample sodium profile frame.

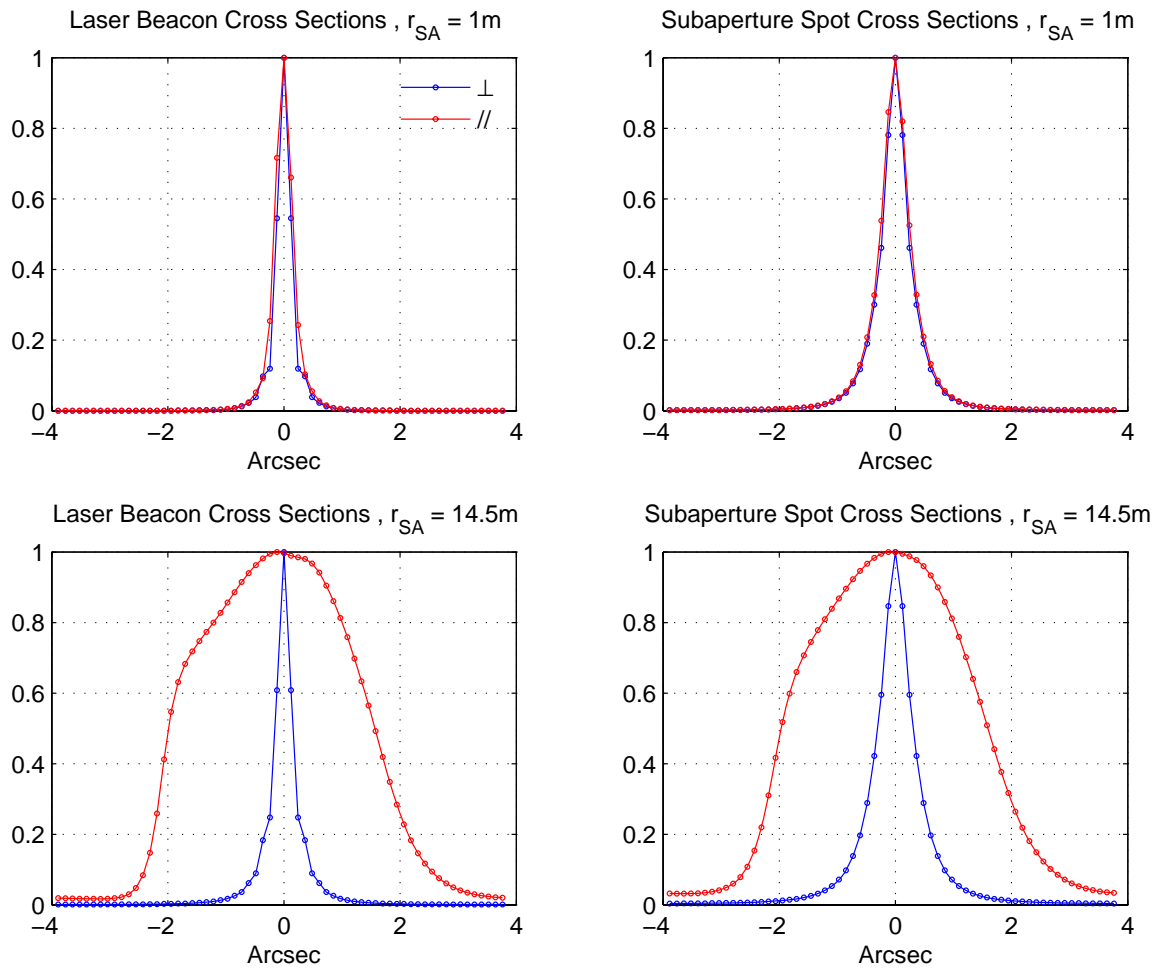


Fig.4 Left panel: Nyquist sampled normalized average beacon radial and azimuthal cross-sections as seen from a subaperture 1 m and 14.5 m away from the TMT LLT. Right panel: subaperture spot obtained by convolving the beacon with a short-exposure subaperture PSF.

- March 2006: complete an investigation of different algorithms for adaptive subaperture tip/tilt measurement to track the changes in the shape of Shack-Hartmann laser guide star images.

We have not addressed this milestone, but have identified the time scale at which the update should occur. Indeed, we found that when the centroid and matched filter algorithms are detuned from the current sodium profile by approximately 1min, a small wavefront error on the order of 12nm is introduced, assuming perfect focus correction.

7.8 Potential Partnerships with Industry that you intend to pursue

7.9 CfAO Service other than EHR

- *eg. workshop organized, committee service, website etc.*

7.10 Funding requests related to this research for Workshops, Colloquia etc

7.11 List up to three external reviewers for your proposal (optional).

Miska Le Louarn (ESO), Andrei Tokovini (CTIO), Francois Rigaut (Gemini)

11.0 Budget Template

- 50% postdoc salary at TMT (TMT will fund the other 50%)
- 50% of relocation allowance (TMT will fund the other 50%)
- Travel for two trips from TMT to Keck
- Matlab license for Richard Clare

12.0 References

- [1] M. van Dam, A.H. Bouchez, D. Le Mignant and P.L. Wizinowich, “Quasi-static aberrations induced by laser guide stars in adaptive optics,” submitted.
- [2] P.L. Wizinowich, D. Le Mignant, A.H. Bouchez, R.D. Campbell, J.C.Y. Chin, A.R. Contos, M. van Dam, S.K. Hartman, E.M. Johansson, R.E. Lafon, H. Lewis, P.J. Stomski and D.M. Summers, “The W.M. Keck observatory laser guide star adaptive optics system: overview”, *PASP* **118**, 297-309 (2006).
- [3] L. Gilles and B.L. Ellerbroek, “LAOS: Linear Adaptive Optics Simulator”, available from the authors upon request.
- [4] B.L. Ellerbroek, L. Gilles, and C.R. Vogel, “Numerical Simulations of Multiconjugate Adaptive Optics Wavefront Reconstruction on Giant Telescopes,” *Appl. Opt.* **42**, 4811-4818 (2003).
- [5] L. Gilles, B.L. Ellerbroek and J.-P. Veran, “Laser guide star multi-conjugate adaptive optics performance of the Thirty Meter Telescope with elongated sodium beacons and matched filtering”, *Proc. SPIE, Advances in Adaptive Optics II*, Orlando (2006).
- [6] M. van Dam et al., “The W.M. Keck Observatory Laser Guide Star Adaptive Optics System: Performance Characterization,” *PASP* **118**, 310-318 (2006).
- [7] R.M. Clare and B.L. Ellerbroek, “Sky coverage estimates for adaptive optics systems from computations in Zernike space,” *J. Opt. Soc. Am. A* **23**, 418-426 (2006).
- [8] R.M. Clare, B.L. Ellerbroek, J.-P. Veran, G. Herriot, and D. Anderson, “Sky coverage and tip-tilt analysis for TMT,” to appear in *Advances in Adaptive Optics II*, *Proc. SPIE* 6272 (2006).
- [9] L. Gilles and B.L. Ellerbroek, “Shack-Hartmann wavefront sensing with elongated sodium laser beacons: centroiding versus matched filtering”, *Appl. Opt.* (2006).

All PIs: For single year proposal complete 2006 column, for multi year proposal complete up to year

Note: Collaborative Research Group Leaders provide additional budget that integrates budgets of individual collaborators

Gavel, Adkins, Gilles: "Polar Coordinate Detector and Modeling and Simulation of Algorithms for Elongated LGS"	Year 8: Nov 2006 through Oct 2007	Year 9: Nov 2007 through Oct 2008	Year 10: Nov 2008 through Oct 2009
A Senior Personnel			
A1			
A2			
A3 PI + Faculty Associates			
A4 Visiting Faculty Associates			
10A Total Senior Personnel	0	0	0
B1 Post Doctoral Associates	27,500		
B2 Other Professional			
B3 Graduate Students (acad) Summer			
B4 Undergraduate Students acad summer			
B5 Secretarial-Clerical			
B6 Other (Shop Charges)			
A+B Total Wages	27,500	0	0
C Fringe Benefits	6,500		
ABC Total Sal., Wages, Fringes	34,000	0	0
D Permanent Equipment	2,000	0	0
E Travel	4,700		
F Visitor Support Costs	0	0	0
G1 Materials and Supplies			
G2 Pub. Costs/Page Charges			
G3 Consultant Services			
G4 Computer Services			
G5 Facilities Charges Shop Charges Tuition+Ins.			
G Total Other Direct Costs	0	0	0
H Total Direct Costs (A thru G)	40,700	0	0
Ia Facilities and Administrative Costs			
Any other F&A Costs			
Total F&A Costs	0	0	0
J Total	40,700	0	0