W. M. KECK OBSERVATORY

Institutions: W. M. Keck Observatory, Caltech Optical Observatories, Lawrence Livermore National Lab, Leiden Observatory, Herzberg Institute of Astrophysics.

Theme: Extremely Large Telescopes

Researcher: David Le Mignant

Proposal Title: Development, implementation and validation of PSF reconstruction techniques.

Collaborative Research, Multi-Year Project

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1 Proposal Participants

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2 Time Scale

This proposal is for a two-year project, beginning in October 2007.

3 Abstract

Adaptive optics (AO) systems are producing important scientific results, and will play a crucial role for producing quantitative astronomical science with extremely large telescopes (ELTs). Astronomers are showing that the quantitative analysis (photometry, astrometry & morphology) is currently limited by spatial and time variability in the point spread function (PSF) delivered by the AO system in both natural and laser guide star modes.

We propose to implement a program for the development and implementation of AO PSF reconstruction algorithms, with the main deliverables being a working algorithm implemented for Keck NGS/LGS AO and also going a long way towards developing tomography-based algorithms for Keck's Next Generation AO (NGAO) system.

We have a strong team that includes AO experts with previous experience on PSF reconstruction, simulation of a wide variety of AO architecture, and implementation of AO systems and tools for routine science operations. This project will be primarily carried out by a CfAO-funded post doctoral AO researcher that we have already identified (R. Flicker), with technical advice and review by the experts on this proposal. The project will be coordinated and supervised by D. Le Mignant and is receiving direct support from the Observatory and its astronomy community.

We propose three large phases in this project. The first phase which will roughly cover the first 8 months of the project will include the following steps: 1.a) review and learn from the previous work on PSF reconstruction with their authors; 1.b) develop and review a subset of algorithms to simulate PSF reconstruction using simulated Keck telemetry data for both NGS and LGS.

The second phase will last about 12 months and focus on the application to real data: 2.a) select one or two algorithms for implementation with the Keck AO telemetry data; 2.b) characterize and optimize the algorithms depending on AO mode, science use cases and noise regimes; 2.c) demonstrate and validate the method by collaborating with science teams.

The third and last phase of the project (4 months) will be to 3.a) implement the PSF reconstruction tools for routine science operations; 3.b) publish the methods and results; and finally 3.c) develop a larger proposal to study and prototype PSF reconstruction and calibrations tools for multi-WFS, tomography-based AO systems on large and extremely large telescopes.

It is an important legacy for the CfAO to capitalize on previously CfAO-funded PSF reconstruction projects, and fund this PSF reconstruction project for a versatile and multi-mode instrument like Keck with the general AO users in mind. This PSF reconstruction project is also crucial to lead the way for PSF reconstruction for tomography-based, multi-WFS LGS-AO instruments.

4 PROPOSAL

4.1 Technical description

4.1.1 Introduction

Major observatories worldwide and their science community have been very successful in getting adequate funding for modeling, designing, developing and implementing AO systems. The W. M. Keck Observatory (WMKO) began offering LGS-AO-assisted instruments in November 2004 on Keck II (Wizinowich et al. 2006, van Dam et al. 2006), as did Gemini Observatory more recently with Altair on Mauna Kea (Trujillo et al.

2006). The Gemini MCAO system is expected to start science operations at Cerro Pachón in 2008, while Keck Observatory will equip Keck I with a laser guide star in 2008. The design of the next generation of AO systems for 10 to 30-m telescopes has already started (Keck NGAO, TMT NFIRAOS). The ever-increasing number of refereed papers based on NGS and LGS AO data, and the demand for LGS AO observing time (140 nights/year at Keck), is an illustration of the growing interest from the astronomy community.

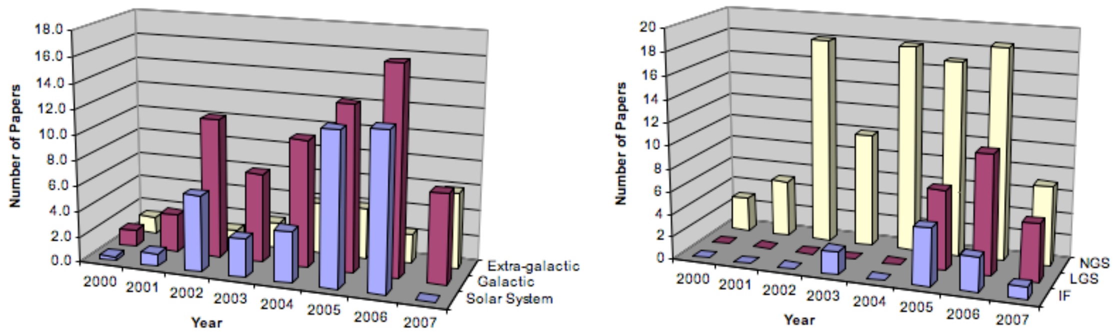

Figure 1: Refereed Keck AO science papers by astronomy domains (on the left), and by AO mode (on the right).

While the positive results from these instrument development projects are unanimously acknowledged, the Observatories and the community realized that the effort load to fully support and exploit LGS AO science is higher than expected: the maintenance and optimization require experts; the performance of the AO system is very dependant upon the observing conditions and leads to variable data quality; more observing modes are explored as more astronomers use this new technology leading to new characterization and performance requirements for the quantitative analysis of the data; *particularly, astronomers stress that full AO and instrument characterization and simultaneous PSF calibrations are critically needed for quantitative AO science (e.g., Koo et al. 2007; presentations at AO users' meeting*[1] *and NGAO science requirements meeting*[2]*)*

4.1.2 The challenge of PSF variability

The turbulence and wind profiles vary significantly on timescales of minutes to hours during the observations. The resulting AO PSF varies with time and field location as a function of observing wavelength. The main error terms can be identified as:

- The wavefront error residuals on each sensor: fitting error, servo and measurement errors for tip-tilt, low and high order wavefront sensors.
- The changing field dependent aberrations (i.e., isokinetic and isoplanatic effects, focal anisoplanatism, etc.).

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[1] http://lao.ucolick.org/twiki/bin/view/CfAO/QuantitativeAOScience
[2] http://lao.ucolick.org/twiki/bin/view/CfAO/NGAOScienceCase

- The telescope, AO and science instrument optics: dynamic wavefront errors and observational setup dependent static and semi-static errors

Figure 2 shows the measured changes in the turbulence profile and the resultant variations in key AO parameters during Keck observations of the Galactic Center (courtesy M. Britton et al. 2007). The data is recorded every minute and 20 to 100% variations are observed on scales of minutes, emphasizing the need for simultaneous monitoring of atmospheric conditions and PSF calibrations.

The temporal and field dependent PSF variability in science observations can be significantly reduced with quantitative knowledge of the PSF from telemetry-based PSF reconstruction and turbulence profiling.

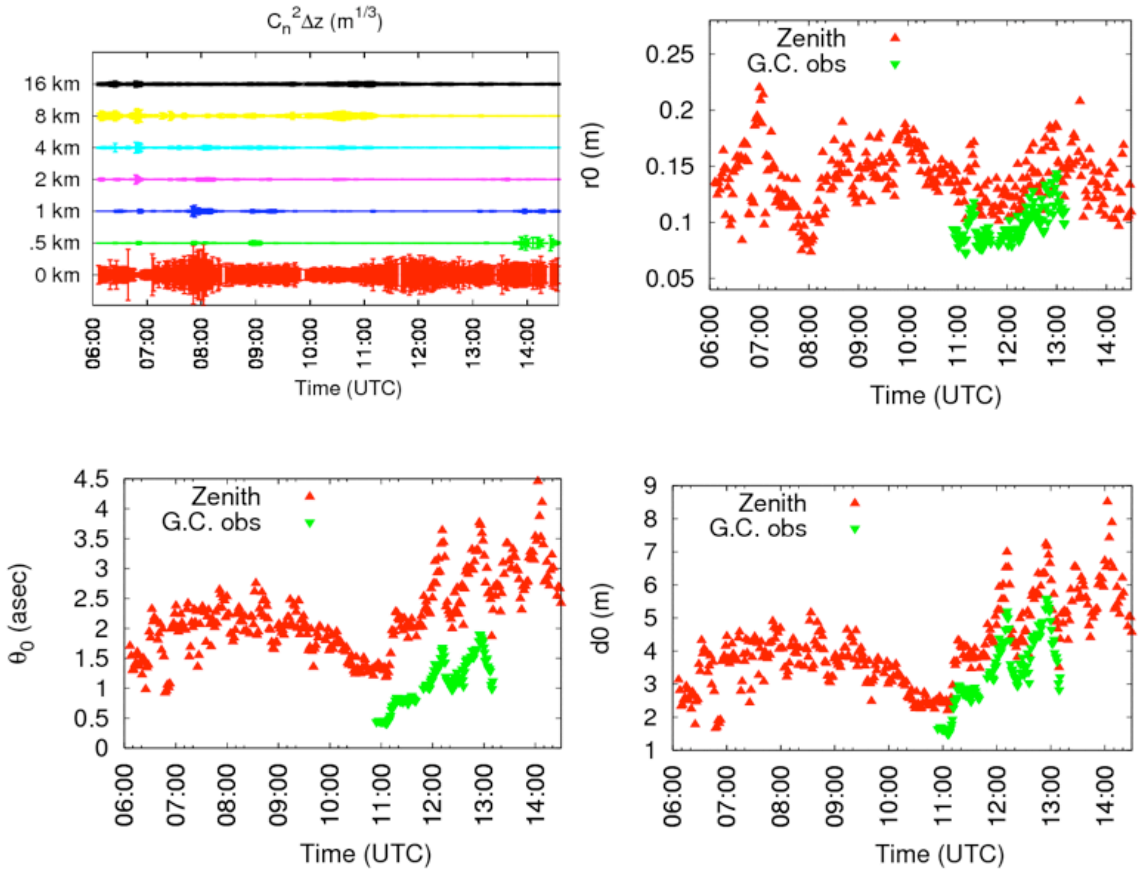

Figure 2: Variations in turbulence strength during observations of the Galactic Center. The red points indicate measurements at zenith while the green data points are from Galactic Center images.

4.1.3 Update summary on current PSF calibration techniques

The knowledge and calibration of the PSF is a key input for precision photometry and astrometry and can be retrieved from real-time diagnostic from the AO telemetry, from turbulence profile data, star images or other sources. There have been a number of publications and efforts dedicated to this topic, most of them partially or totally funded by the CfAO:

- Simultaneous (or a-posteriori) differential imaging techniques (e.g, Marois 2000 & 2006).
- Simultaneous (or a-posteriori) observations of a calibration field to estimate on-axis PSF and anisoplanatism (e.g., Melbourne et al. 2007, Steinbring et al. 2005)
- Modeling the modulation transfer function and estimating the corrections for the aperture photometry (e.g., Sheehy et al. 2006)
- Direct model fitting and blind deconvolution techniques (e.g., Diolaiti et al. 2000, Barnaby et al. 2000, Christou et al. 2004)
- Anisoplanatic deconvolution of AO PSF, as one proposed method for recovering photometric and astrometric accuracy starting from a good PSF estimate, in the presence of strong anisoplanatism (Flicker & Rigaut, JOSAA 2005).
- Use of measured guide star point spread functions and measured Cn2 profiles to estimate field dependent PSF (e.g., Britton et al. 2006, van Dam et al 2006).
- PSF reconstruction from wavefront controller data (e.g., Veran 1997, for CFHT, Jolissaint et al. 2005 for Gemini, Fitzgerald et al. 2004 for Lick, Clenet et al. 2006 for VLT/NACO, Marino et al. 2006 for the Dunn Solar Telescope).

These methods have demonstrated various degrees of success in their ability to estimate the PSF and recover the photometry with accuracy (see Véran 2007 for a review of PSF reconstruction, OSA AO conference, Vancouver). The Véran method for PSF reconstruction was implemented at CFHT and is still used with the AO instrument; the widespread StarFinder model fitting tool (Diolaiti et al. 2000) routinely provides the photometry for crowded stellar field (over a small field of view). Each of these methods is strongly dependent on the implementation context: the telescope, the AO mode and instrument where the method has been tested (e.g., curvature vs. Shack-Hartman wavefront sensors, low vs. high deformable mirror actuator density, actuator spatial response) and the nature of the observations (e.g., high contrast on-axis stellar object vs. crowded stellar field or off-axis faint galaxy). Their utilization also requires a high-level of expertise with AO data.

The observatory teams have been focusing on getting the NGS and LGS AO instruments to work in a more reliable way, while trying to cope with the extra load of operations. Hence, many of these previous PSF calibration development studies did not get adequate attention from the observatories or their user communities. This strongly limited their application and the resources to turn a prototype method and tool into a general user tool. As instruments become capable of delivering more consistent raw data and in order to serve a broader user community, the focus needs to shift to the science-quality of the calibrated data product.

For this project, we will take advantage and learn from previous works on PSF reconstruction at the CfAO and other observatories, as well as leverage from our own experience at developing the next generation wavefront controller (NGWFC) at Keck for NGS and LGS, working on next-generation adaptive optics (NGAO) design studies and developing algorithms for PSF estimation from turbulence profiles.

4.1.4 Tools for monitoring the atmospheric turbulence

A turbulence monitor/profiler provides one solution to both the time-variability problem of the PSF and the field-variability (with the Cn2 profile – see Britton et al. 2006). The Véran 2007 PSF reconstruction review emphasizes that need for turbulence profile measurements to complement the telemetry-based PSF reconstruction, and allow the overall method to take into account the various terms of anisoplanatism.

We now have access to this data from the TMT site monitor. Continued access to this data is critical for this project. We also plan to initiate talks among the various parties interested by the use of a DIMM/MASS instrument atop Mauna Kea and secure access to such instrument.

4.1.5 Developing, implementing and validating a prototype PSF reconstruction tool for the Keck AO systems

A PSF reconstruction technique for the Keck AO system will require us to look into very specific issues: the effect of the segmented pupil, the pupil rotation as seen by the AO sensors, the low-order WFS and the combination of multiple WFS information, the LGS spot information, the spot-size effect for under-sampled sensors, etc.

These issues will require the development of particular and novel solutions that we plan to investigate: dedicated turbulence profiling, novel spot size estimation methods by using the slope discrepancy method (van Dam, JOSA 2005), use of interferometer for measuring the mirror modes, use of models and low order sensors for calibrating WFS spot-size effects (Clare et al., Opt. Exp. 2007), extensive use of the full-rate telemetry from the NGWFC, etc.

The following sections illustrate the roadmap we propose and provide more details on the specific issues that this project may address.

4.1.5.1 Review and learn from the previous works on PSF reconstruction with their authors

A review of PSF reconstruction algorithms and implementations was provided in Véran 2007. While the Véran method was first implemented at CFHT and has been in routine use the longest on a curvature AO system, the method has been proven to work also on Shack-Hartmann AO systems, as demonstrated by Jolissaint (2005) and others. Yet, routine operation has not yet been implemented at any telescope.
We would, as a starting point, look at how the commonly employed (Véran 1997) "mean structure function" (also referred to as the "Uij") method of computing PSFs from WFS telemetry can be adapted to Keck. We would make use of recent improvements on this method (e.g. Gendron 2006 - diagonalized mode covariance matrix) to economize on computations, and incorporate the Keck-specific solutions that we think will be needed (e.g. slope discrepancy or other ways to data mine the redundant WFS telemetry information).

4.1.5.2 Develop and review a subset of algorithms to simulate PSF reconstruction using simulated Keck telemetry data for both NGS and LGS

We would also look into novel reconstruction methods that do not rely on computing the mean structure function, and which may be extensible to very-high-order systems (e.g. NGAO, ELT) for which the "Uij" method becomes computationally intractable. We may for instance investigate if the problem can be formulated as a sparse linear system, utilizing sparse matrix representations of the DM influence function and DM-to-WFS interaction matrices and employing an iterative numerical solver (e.g. PCG). This is a representation that lends itself well to high-order systems.

There is one exception where the "Uij" method is actually an exact solution, as opposed to an approximation, in the sense that the mean structure function is actually isoplanatic, and that is the case of tilt errors. A LOWFS that measures and reconstructs only tip/tilt may employ a slimmed-down version of the “Uij” algorithm that is very simple to implement. Such a reconstruction scheme has already been presented (Flicker, Rigaut & Ellerbroek, A&A 2003). This can be regarded as both an element of putting together a composite algorithm for off-axis LGS PSF reconstruction, and as another component verification for NGAO PSF reconstruction.
We will also use simulations to investigate the sensitivity to noisy measurements, as well as quantify the requirements for the temporal and the vertical resolution of the turbulence profiler data.

In the following sections, we highlight the goals, priors and challenges for each of the critical technical milestones for our project:

- Goal:
    - Simulate a subset of algorithms to reconstruct the PSF using NGWFC telemetry data (based on Veran 1997, Gendron 2006, etc.)
- Priors:
    - Review bibliography + experienced at other observatories
    - Develop & review candidate algorithms
    - Establish inputs and calibrations
- Challenges:
    - Modular approach for NGS/LGS, on-axis/off-axis
    - Sensitivity to noise

4.1.5.3 Select one or two algorithms for implementation with the Keck AO telemetry data

The NGWFC has demonstrated significant performance improvements for the Keck AO systems: Kp-band Strehl ratio of 66% on bright NGS, ability to close the loop on m_V=15 mag., and Kp-band of 50% in LGS mode (M. van Dam, E. Johansson et al. 2007). It also provides access to full-frame-rate telemetry data. This data will be used as input for the simulated algorithms to verify their functionality on the sky. We plan to start with the simple case of the on-axis bright NGS:

- Goal:
    - Prototype a subset of algorithms to reconstruct the PSF using NGWFC telemetry data (based on Veran 1997, Gendron 2006, etc.)
- Priors:
    - Establish and agree on requirements
    - Develop and review candidate algorithms
    - Work on centroid gain estimator
    - Full access to NGWFC data
- Challenges:
    - Segmented primary mirror and a rotating pupil on the WFS
    - Computational load
    - Data archiving schema
    - Observatory support
    - Software implementation

Once the main error terms are analyzed, we will move forward to the LGS cases. Our decision to proceed forward will be based on requirements for the main error terms that will be valid for the LGS case (e.g., the error term from the primary mirror segment figures will not be a show-stopper if this appears not to be a dominant term for the LGS cases). We anticipate the following plan for the reconstructing the on-axis “bright” LGS:

- Goal:

  - Prototype PSF reconstruction tool for LGS
- Priors:
  - Establish, agree on requirements
  - Develop and review candidate algorithms
  - Low order modeling and characterization
  - Collect turbulence profile data to support error term analysis
- Challenges:
  - Laser spot elongation term & variations (though it is calibrated by the LBWFS)
  - Centroid gain on quad-cell TT sensor (STRAP)
  - Low order WFS calibrations and modeling on fainter stars

We will implement and validate methods to measure the centroid gain for the tip-tilt sensor and the high order sensor. The candidate techniques are the tip-tilt dithering method (Véran and Herriot, 2000), the slope discrepancy method (van Dam, JOSA 2005), by fitting the power spectrum of the noise (van Dam et al., App. Op. 2004) and using the low bandwidth wavefront sensor (Clare et al., Opt. Exp. 2007).

The following steps will be to extend our model to fainter cases and off-axis cases. The fainter cases will be limited by our ability to understand the error terms and the effect of the noisy measurements for the PSF prediction.

- Goal:
  - Prototype PSF reconstruction tool for NGS and LGS on fainter guide stars
- Priors:
  - Establish, agree on requirements
  - Develop & review candidate algorithms
  - Error budget for faint stars
  - Collect turbulence profile data to support error term analysis
  - Simulate noisy measurements & investigate alternate control laws
- Challenges:
  - LGS spot modeling on fainter stars (Clare et al. 2007)
  - Additional source of noise for the TT (more sensitive to wind, vibrations?)

The off-axis NGS case is pretty straightforward and has been demonstrated when the on-axis PSF is known using turbulence profile data:

- Goal:
  - Prototype off-axis PSF reconstruction tool for NGS
- Priors:
  - Establish, agree on requirements
  - Develop and review candidate algorithms
  - Collect turbulence profile data to support error term analysis
- Challenges:

  - Calibrations of optical distortion in the focal plan
  - Requirements for the temporal and vertical resolution for the turbulence profile data.

The off-axis LGS case has not been demonstrated, and may present new challenges:

- Goal:
  - Prototype off-axis PSF reconstruction tool for LGS
- Priors:
  - Establish, agree on requirements
  - Develop & review candidate algorithms
  - Collect turbulence profile data to support error term analysis
  - Estimate/allocate contribution in error budget by each sensor
- Challenges:
  - Calibrations of optical distortion in the focal plan
  - Requirements for the temporal and vertical resolution for the turbulence profile data.

4.1.5.4 Characterize and optimize the algorithms depending on AO mode, science use cases and noise regimes

Once these methods are implemented, we will characterize them, compare the results to our error budget for each AO system mode (NGS, NGS-STRAP and LGS) and review these results with the experts. We will very likely re-iterate on some aspects of our overall plan and objectives.

Particularly, we will investigate how the turbulence profile data may complement the AO telemetry data to further constrain the PSF reconstruction method. We will investigate the limitations for each method, review our PSF reconstruction goals, and share them with the science teams.

4.1.5.5 Demonstrate and validate the method by collaborating with science teams

We will encourage astronomers to collaborate with us to develop use cases for recovering astrometry and photometry from PSF reconstruction. Similar collaborations were already initiated during the development of the science cases for NGAO.
We plan to select use-cases for PSF reconstruction and request Keck LGS engineering time to collect data for these cases. We already anticipate teaming up with M. Britton on science cases as part of the CATS proposal (Koo et al.). We are planning to work with the astronomy community and engage undergraduate or graduate students to work with us on science projects.

4.1.5.6 Implement the PSF reconstruction tools for routine science operations

When the PSF reconstruction is demonstrated for various science cases, we will start implementing for routine operations.

- Goal:
  - Implement PSF reconstruction for routine operations
- Priors:
  - Establish, agree on requirements with community and observatory
  - Review algorithms and results for use-cases
  - Review modular implementation for general purpose
  - Establish development & operation costs
- Challenges:
  - Computational load
  - Data archiving schema
  - Observatory support
  - Software implementation

4.1.5.7 Publish the methods and results

The results from the project will be reviewed by the experts on our proposal, published and shared with the CfAO community as we proceed. We anticipate that any general purpose tools will be available for members of our community. We will attempt to build modules within the PSF reconstruction tools that can be used on other telescopes, if possible.

4.1.5.8 Develop a larger proposal to study and prototype PSF reconstruction and calibrations tools for multi-WFS, tomography-based AO systems on large and extremely large telescopes.

Though this proposal will not address the case of PSF reconstruction and other techniques for precision astrometry and photometry with tomography-based AO systems, we see an implicit connection to a longer-term goal with PSF reconstruction for future AO systems, and NGAO particularly.

It is also crucial for the astronomers to be able to use current PSF reconstruction on current telescopes, assess the results and establish realistic science requirements for the ELTs .

Based on the experience collected and demonstrated during this proposal, we believe we will be in a position to submit a proposal to NSF-ATI for advanced PSF reconstruction tools for the future AO instrumentation. We expect to collaborate very closely with the AO user community to lay the science cases for this future project, and collaborate with the US observatories to develop the tools to demonstrate our goals.

4.2 Nature of Collaborations

This PSF reconstruction project for a versatile and multi-mode instrument like Keck will encourage sharing concepts and lessons learned from previous CfAO-funded PSF reconstruction projects. Algorithms and software (e.g., OPERA) have been produced, tested and published; and we will use them when it is relevant. We will also develop tools that will rely on the turbulence profile measurements, that the TMT is now collecting for their site monitoring.

The bulk of the work will be performed at Keck, yet we anticipate many opportunities for presenting and reviewing our progresses with PSF reconstruction experts. Our core team has been working with the CfAO for a long time and this team is very aware of the benefits of working in center mode. We will have regular monthly telecons, and specific meetings during each CfAO retreat. We also plan for at least one dedicated workshop at Keck, at a critical time during the project. We see the post-doctoral researcher as the key in making these collaborations happen.

This PSF reconstruction project is also crucial to lead the way for PSF reconstruction for tomography-based, multi-WFS LGS-AO instruments. P. Wizinowich is the chair of the executive committee for the Keck NGAO instrument, and D. Le Mignant is leading the science operations portion of this project, and we plan to develop very strong collaboration with the NGAO during the development of the algorithms. We will collaborate with the NGAO team at Keck, Caltech and UC (Don Gavel, who is also on the NGAO EC, is director of the LAO).

4.3 Role of participants

David Le Mignant will supervise the post-doctoral researcher R. Flicker, providing general direction to the project. He will also spend a small but significant fraction of his time in carrying out the technical work. D. Le Mignant’s role will be to help the post-doc to implement the experiments and improvements to operations at WMKO. R. Flicker will lead the technical side of the project in consultation with D. Le Mignant. Erik Johansson will make any necessary modifications to the wavefront controller. Marcos van Dam will contribute by helping the post-doc understand how to characterize the performance of the AO system at WMKO. Peter Wizinowich will consult on technical issues relating to optics and other hardware, and, will consult with D. Le Mignant for the overall management of the WMKO staff for this project.
M. Britton is submitting a sub-proposal to work on PSF estimation from turbulence profile in the context of the CATS science. Again, we anticipate working very closely with M. Britton as soon as we will be able to reconstruct the PSF on-axis using AO telemetry data (NGS first then LGS case). We will also collaborate with M. Britton, JP

Véran, L. Jolissaint and D. Gavel to present, review and discuss our progresses during the simulation phase and the implementation/demonstration phase.

5 SCHEDULE AND MILESTONES

Specific Year 9 and Multi-year Schedule and Milestones:

We propose three large phases in this project.

- The first phase which will roughly cover the first 8 months of the project. We will begin work in October 2007, with R. Flicker, the post-doctoral researcher starting immediately. By 1 May 2008 we intend to have completed the following tasks: 1.a) review and learn from the previous works on PSF reconstruction with their authors; 1.b) develop and review a subset of algorithms to simulate PSF reconstruction using simulated Keck telemetry data for both NGS and LGS.

- The second phase will last about 12 months and focus on the application to real data. By 1 May 2009 we intend to have completed the following tasks: 2.a) select one or two algorithms for implementation with the Keck AO telemetry data; 2.b) characterize and optimize the algorithms depending on AO mode, science use cases and noise regimes; 2.c) demonstrate and validate the method by collaborating with science teams.
- The third and last phase of the project will be to 3.a) implement the PSF reconstruction tools for routine science operations; 3.b) publish the methods and results; and finally 3.c) develop a larger proposal to study and prototype PSF reconstruction and calibrations tools for multi-WFS, tomography-based AO systems on large and extremely large telescopes.

6 PREVIOUSLY FUNDED CFAO PROPOSALS AND CENTER ACTIVITIES

In this section, we summarize previous CfAO-funded projects at Keck Observatory and list the relevant publications:

Y5-6: Demonstration and optimization of LGSAO science. PI David Le Mignant; post-doctoral researcher Antonin Bouchez.

This project was a key-collaboration to enable Keck to demonstrate and pave the way of LGS AO science on a large telescope.

- P. L. Wizinowich, D. Le Mignant, A. H. Bouchez et al., "The W.M. Keck Laser Guide Star Adaptive Optics System: Overview," Publications of the Astronomical Society of the Pacific 118, 297-309 (2006).
- M. A. van Dam, A. H. Bouchez, D. Le Mignant et al., "The W.M. Keck Laser Guide Star Adaptive Optics System: Performance Characterization," PASP, 118, 310-318 (2006).

- A. H. Bouchez et al., "Keck laser guide star adaptive optics: science verification results," Proc. SPIE 5490, 321-330 (2004).
- M. A. van Dam, A. H. Bouchez and D. Le Mignant, "Aberrations induced by laser guide stars in adaptive optics," OSA Topical Meeting on Adaptive Optics: Analysis and Methods, (2005).
- D. Le Mignant, R. D. Campbell, A. H. Bouchez et al, "LGS AO Operations at W.M. Keck Observatory" Proc. SPIE 6270 (2006).
- D. Le Mignant, M. A. van Dam, A. H. Bouchez et al, "LGS AO at W.M. Keck Observatory: routine operations and remaining challenges," Proc. SPIE 6272 (2006).

Y7-8: Optimal low-order wave-front measurements in LGS AO system. PI Marcos van Dam, post-doctoral researcher Richard Clare.

- R. M. Clare, Marcos A. van Dam, A. H. Bouchez, "Modeling low order aberrations in laser guide star adaptive optics systems," Optics Express 15, 4711-4725 (2007).

Y3-4: Evaluation and improvement of the performance of AO Systems. PI Bruce Macintosh, coI David Le Mignant, post-doctoral researcher Marcos van Dam.

This work has been an enormous benefit for our community in terms of better characterization of the Keck NGS AO and optimization of the system.

- M. A. van Dam, D. Le Mignant and B. A. Macintosh, "Performance of the Keck Observatory adaptive-optics system," Applied Optics 43, 5458-5467 (2004).
- M. A. van Dam, D. Le Mignant and B. A. Macintosh, "Characterization of adaptive optics at Keck Observatory: part II," Proc. SPIE 5490, 174-183 (2004).

CfAO Service other than HER:

- David Le Mignant organized meetings for AO users:
  - AO science and AO users' meeting at the 2006 fall retreat.[3]
  - Workshop on Quantitative AO Science at the 2007 spring retreat.[4]
- Marcos van Dam collaborated with the vision science theme through Mini-Grant projects[5] and contributed to the Vision Theme legacy AO book:
  - Marcos A. van Dam, "System Performance Characterization," Adaptive Optics for Vision Science, Jason Porter et al., eds (2006).

[3] http://lao.ucolick.org/twiki/bin/view/CfAO/CfAORetreatContrib
[4] http://lao.ucolick.org/twiki/bin/view/CfAO/QuantitativeAOScience
[5] http://cfao.ucolick.org/EO/Minigrants/pastprojects.php

7 Education and Human Resources Activities

The team for this proposal has interacted strongly with the CfAO in the area of Education and Human Resources Activities. D. Le Mignant has been an active member and an advocate for the CfAO education activities. We intend to continue this collaboration in the future, by hosting and supervising interns, teaching at the CfAO summer school, participating in the Professional Development Course and other appropriate activities.

- Our main achievement is the great collaboration with the CfAO associate Director Lisa Hunter to organize the Akamai Observatory Internship Program & Short Course (AOSC) for undergraduate students. The AOSC is a major educational event between the observatories and the educational partners on the Big Island. David Le Mignant is the lead instructor for the AOSC, while Sarah Anderson is the AOSC coordinator for the Big Island. We host part of the AOSC at the Observatory and more than 10 employees worked with the students during the June 2004-2005 and 2006 AOSC. The AOSC will take place again on the Big Island in 2007.
- Following the mission statement of the CfAO Education & Human Resources, we have been working more closely with the University of Hawai'i in Hilo and help increase interest and participation in science. The CfAO summer intern from Maui Community College we hosted for 2003, Kawailehua Kuluhiwa transferred to UH Hilo. Since then we have hosted more students from Maui and the Big Island. By continuing our work with these Hawaii resident students, we have built strong connections and foster collaborations with UH Hilo, and most major observatories at the summit of Mauna Kea. Randy Campbell, Al Conrad, Marcos van Dam, Jason Chin hosted CfAO interns in 2005 and 2006.
- CfAO members at Keck Observatory always participate actively and report on AO activities and results at the CfAO retreats, workshops and other activities.
- Keck Observatory staff participate in the Professional Development Workshop each year.
- David Le Mignant and Marcos van Dam have taught at the CfAO summer school in 2004 and 2006 and have given lectures on Adaptive Optics in Community Colleges on various occasions.