Proposed Multiconjugate Adaptive Optics Experiment at Lick Observatory
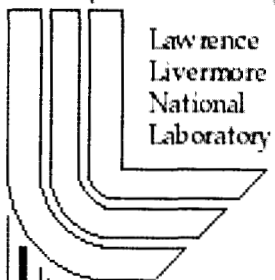
B.J. Bauman, D.T. Gavel, L.M. Flath, R.L. Hurd, C.E. Max, and S.S. Oliver

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

August 15, 2001

Proposed multiconjugate adaptive optics experiment at Lick Observatory

Brian J. Bauman, Donald T. Gavel, Laurence M. Flath, Randy L. Hurd,
Claire E. Max, Scot S. Olivier

Lawrence Livermore National Laboratory, L-290, Livermore, CA 94550

ABSTRACT

While the theory behind design of multiconjugate adaptive optics (MCAO) systems is growing, there is still a paucity of experience building and testing such instruments. We propose using the Lick adaptive optics (AO) system as a basis for demonstrating the feasibility/workability of MCAO systems, testing underlying assumptions, and experimenting with different approaches to solving MCAO system issues.

Keywords: Multi-conjugate adaptive optics, adaptive optics, laser guide star, sodium guide star, testbed, demonstration, Lick Observatory

1. INTRODUCTION

Since the first description of MCAO in 1975[1], a number of papers have expanded our understanding of how MCAO systems should operate[2-7]. However, only one on-sky experiment[8] and no in-lab experiments have been performed yet. The outpacing of theoretical papers relative to experimental ones suggests that MCAO is more easily said than done! It seems prudent to check that designed systems will perform as intended, using an on-sky demonstration system or testbed.

2. CONCEPT

Currently, Lick Observatory has an AO system which is working well as a facility-class instrument in natural guide star (NGS) mode and which is beginning to take science data in laser guide star (LGS) mode[9-11]. This existing capability, plus some fortunate circumstances to be discussed, makes the Lick AO system an excellent place to field an MCAO demonstration/testbed system. Of course, the decision to build an MCAO demonstration/testbed system, especially when it is to be built for the adaptive optics community, depends on factors other than the ease/expense of building a demonstration system alone. If the testbed is to be part of a larger plan to build a facility-class (or near facility-class) MCAO instrument, then other telescope/AO systems may be a better choice. However, if the goal is only to build an MCAO demonstration/testbed as quickly, easily, and cheaply as possible, then using the Lick AO system is probably the best choice. Note that while a facility-class MCAO instrument could be built at Lick, that prospect is beyond the scope of this paper. Certainly, key decisions about whether or not to alter components from the current Lick AO system would have to be made. It is generally not desirable to disassemble a working, useful instrument! If we did alter current components, then we would need a careful plan to minimize the time that Lick Observatory is without an AO system. In general, though, we can easily and reversibly convert the Lick AO system into a MCAO system.

3. MOTIVATION/GOALS

MCAO is an onerous undertaking. While the optical and optomechanical complexity are significant, the computational and control aspects are truly daunting. In short, a testbed is a risk reduction measure. It is highly desirable to try out (and hopefully prove) concepts in such areas as wavefront detection, reconstruction, and control; we want to identify the practical problems and design issues in MCAO systems.

Table 1 shows a list of MCAO risk areas and a non-exhaustive list of specific issues to be resolved.

Risk Area	Specific issues
Guide stars	Number/power/orientation of LGS configurations Number/brightness/orientation of NGS configurations Fratricide elimination Undesired Rayleigh scatter elimination
Deformable mirrors	How many DM's? How many actuators?
Wavefront sensing, tomography, reconstruction, controls	Pyramid vs. Shack-Hartmann vs. curvature Tomography vs. layer-oriented approach If tomography is to be used, how to handle heavy computing load? Develop control algorithms (especially for tomography) Develop practical results for error propagation
Optical layout	Undesired Rayleigh scatter elimination Practical layouts
Scientific usefulness	Does MCAO produce a higher scientific efficiency? Does MCAO produce higher quality science? Does MCAO allow science otherwise not possible?
System design	Evaluate complexity and degree of automation required Failure/availability analysis

Table 1: MCAO risk areas and some of the specific issues related to them.

While we want to establish on-sky feasibility and provide design guidance for MCAO on the current generation of telescopes, we also hope to illuminate these same issues for the next generation of extremely large ground-based telescopes. More precisely, we would want a Lick MCAO demonstration/testbed to reduce each of the risk areas to the point where there is a clear and achievable development path to MCAO systems on 30m telescopes.

4. REQUIREMENTS

Using the above goals, we can fashion a list of requirements that meets these goals as practically as possible. In order to accomplish this and to help isolate effects, we reduce the hardware requirements as much as possible. For example, we can show the improvement in Strehl ratio consistency by using two guide stars and evaluating the Strehl ratio in the field between the guide stars.

Risk Area	Requirement
Wavefront sensing, tomography, reconstruction, controls	Flexibility to implement either pyramid or Shack-Hartmann wavefront sensors Flexibility to implement either tomography or layer-oriented approach Ability to develop control algorithms (especially for tomography) Ability to develop practical results for error propagation
Guide stars	2 guide stars (GS's) will allow correction of a quasi-linear field, sufficient for demonstration; 3 GS's would be desirable in order to correct a more two-dimensional field. At least 1 LGS for flexibility in experimentation; multiple LGS's allow work on tilt anisolplanatism.
Deformable mirrors	At least 2 DM's, preferably one DM can be varied in correction height
Optical layout	Flexibility to try different methods to eliminate undesired Rayleigh scatter.
Scientific usefulness	Instrumentation allows evaluation of science questions listed above

Table 2: MCAO risk areas and the testbed requirements necessary to address them.

5. RATIONALE FOR USING LICK OBSERVATORY AO SYSTEM

There are several ways that one could develop an MCAO demonstration/testbed. One could set up a lab test, or piggyback off of a working AO system. Of course, the Lick AO system is not the only AO system in the world, but it does have a number of advantages:

- Availability: As only the third-rank telescope in the University of California telescopic armada, and the 29th largest telescope in the world, observing and engineering time are relatively easy to come by. It has not been difficult to get 10-15 engineering nights a year in developing the current Lick AO system, which allows for rapid progress. Most larger telescopes are too important scientifically and too "visible" for experiments.
- Accessible for CfAO and LLNL personnel: Lick Observatory is a convenient 1.5 hour trip away from UC Santa Cruz, UC Berkeley, or LLNL, which makes it possible to bring a large community to bear on the problems of MCAO.
- Working, reliable AO system already in place: This is key so that time is not spent on resolving the usual set of problems that arise when commissioning a new instrument.
- Lick's AO system is easily adapted to an MCAO testbed. This will be discussed in more detail below.
- Operational Sodium Laser Guide Star system already in place: The laser guide star is a flexible experimental tool, allowing us to create a guide star wherever we need one for an experiment. We are not limited to serendipitous natural asterisms. Further, it is clear that next-generation AO systems will have almost certainly have LGS's and it is not too soon to work on the tilt anisoplanatism problem. In order to field multiple LGS's, we are currently working on schemes that will allow us to divide the current 18W laser into multiple 6 or 9 W lasers. Since the nominal Lick LGS system produces an m_v=10.5 guide star in good sodium seasons, these lower power levels will allow us to generate an m_v=11.25-11.75 guide star during strong sodium seasons, easily within the usable range of the WFS.
- Estimate that we are only 1-1.5 man-year away from deploying a demonstration MCAO system—quick feedback!

Now we will discuss why the Lick AO system can be easily adapted to MCAO usage:

- Laser Guide Star Program already owns an operational 3" 127-actuator DM in addition to the DM in current use.
- The second DM can be inserted into an existing Offner relay system that "plugs in" just before the cassegrain focus—don't have to destroy the Lick AO system to do the experiment (see figures 1 & 2).
- Offner bench allows DM to be moved to various correction heights—5km is very easy/convenient to achieve (close to 4.5km in Gemini MCAO design) with 7 actuators across the 3m telescope "footprint" at any given field angle. This is the same actuator density as on our ground-layer DM. Other heights down to about 2km can be achieved within the existing Offner bench setup. Of course, we would want to measure the C_n^2 profile at Lick Observatory before designing the MCAO system so that we could choose the most effective arrangement of DM's.
- AO bench already has 2 wavefront sensors (although one is slow) and ability to steer to 2 guide stars anywhere within 2 arcmin diameter field
- Sodium LGS system exists; working on scheme to divide 18W laser into multiple 6-9W lasers—enough to produce sufficiently bright LGS's at strong sodium times of the year.

6. HARDWARE

Table 3 lists the hardware in the current Lick AO system, the hardware necessary to accomplish to tests mentioned above, and a plan for resolving shortfalls.

	Existing system	Requirement	Plan
Deformable mirror(s)	LLNL-built, 127 actuators, 61 actuators controlled, triangular pattern, electrorestrictive (PMN) actuators	Need one more DM	Program already owns Itek 109-acutator DM with 3" aperture
Wavefront sensor(s)	Shack-Hartmann wavefront sensor, 37 subapertures (44cm diameter on primary), Adaptive Optics Associates camera with Lincoln Lab 64x64 CCD, read noise 7e per pixel at 1200 frames/sec; 4x4 center-of-mass or quad-cell centroiding algorithm	Need one more fast WFS for 2 GS correction with quasi-linear field; two more for 3 GS correction. Need ability to use pyramid wavefront sensing.	A second WFS already exists with independently steerable path; need to upgrade to faster camera. Design for pyramid WFS need to be developed, but probably can fit within existing space at the cost of perhaps some disassembly of the current WFS.
Field steering	3 independently steerable paths: science (via telescope) plus 2 GS's within 1 arcmin radius of telescope axis	Have enough independently steerable paths for 1 NGS + 1 LGS or 3 NGS's. Need one more path for 2 LGS's	Can easily add one more steerable leg on "back side" of AO table.
Computation	160Mflop Mercury VME with 4 Intel i860 processors, operated at up to 500Hz sample rate, with 0db crossover up to 30Hz.	In layer-oriented scheme, the two real-time computers do not need to "talk" to each other, so an independent computer can run the 2nd wavefront sensor In tomographic scheme, the two real-time computers need to communicate so that all the wavefront data is "in the same place"	In-house PC-based wavefront control system already in use on another program. Should be adequate for this application. We estimate that bringing the data together will require 6-12 man months of programming effort.
Layout	See figures 1 & 2	Need to integrate second DM and additional WFS's into AO bench.	See text in section 5.

Table 3: Hardware in the current Lick AO system, the hardware necessary to accomplish to tests mentioned above, and a plan for resolving shortfalls.

7. TEST PLAN

The test plan given below focuses on the steps in getting MCAO working. Once the system is working, then one can try, for example, different WFS's schemes or different DM arrangements to find what works best. To the extent possible, we should measure C_n^2 profile on experiment nights so that we could compare MCAO predicted and measured performance.

- Use one guide star at a time and use with each of the WFS's, one at a time. Characterize performance of each SCAO system to establish "baseline".

These next steps would probably be first performed with a layer-oriented wavefront scheme since the real-time wavefront control computers do not necessarily need to talk to each other. In fact, starting with this configuration is desirable because if it can be made to work, then that eliminates the complexities of tomographic reconstruction. The

tests can be repeated using tomographic reconstruction once the software/hardware is complete to allow communication between the computers.

- Use 2 NGS's with about separation equal to 1-2x the isoplanatic angle. Examine Strehl ratio in field between the GS's as a function of GS magnitude and separation. Since our IR science camera has 20 arcsec field width, one cannot test the whole 1-2 arcmin field of interest simultaneously. However, by nodding the science field over the desired field (and counternodding the guide stars), one could stitch together the entire field.

- Repeat using one NGS and an LGS so that we can have arbitrary guide star separations and evaluate performance.

- Upgrade Lick AO system to handle 3 GS's—either 1 or 2 LGS's. Use a 3 guide star pattern to correct a larger, "more 2-dimensional" field.

8. FUTURE WORK

This project is in a conceptual phase. For the reasons listed in section 2, it makes sense to coordinate with other groups (e.g., CfAO, Palomar, Gemini). Certainly, future efforts will be aided by measurements of C_n^2 profiles at Lick.

9. CONCLUSION

An approach to developing an in-lab and on-sky MCAO testbed at Lick Observatory has been presented. It appears that an MCAO testbed can be quickly and fairly easily built at Lick Observatory by "piggybacking" off the current AO bench's capabilities without destroying the capacity to do single conjugate AO science.

10. ACKNOWLEDGMENTS

11. REFERENCES

1. R.H. Dicke, "Phase-contrast detection of telescope seeing errors and their correction", *Astrophysical Journal*, vol. 198, 605-615, 1975.
2. J.M. Beckers, "Increasing the size of the isoplanatic patch with multiconjugate adaptive optics", in *Proceedings of ESO Conf. On Very Large Telescope and their Instrumentation* (ESO, Garching bei Munchen, Germany, 1988), pp. 693-703, 1988.
3. M. Tallon and R. Foy, "Adaptive telescope with laser probe -- isoplanatism and cone effect", *Astron. Astrophys.*, vol. 235, p. 549, 1990.
4. D.C. Johnston and B.M. Welsh, "Analysis of multi-conjugate adaptive optics", *J. Opt. Soc. Am. A*, vol. 11, pp. 394-408, 1994.
5. B.L. Ellerbroek, "First-order performance evaluation of adaptive-optics systems for atmospheric turbulence compensation in extended filed of view astronomical telescopes", *J. Opt. Soc. Am. A*, vol. 11, p. 924, 1994.
6. T. Fusco, J.M. Conan, V. Michau, L.M. Mugnier, and G. Rousset, "Phase estimation for large field of view: application to multiconjugate adaptive optics," in *Proceedings of SPIE-The International Society for Optical Engineering, vol 3763* (Propagation through the Atmosphere II), pp.125-133, 1999.
7. A. Tokovinin, M. Le Louarn, and M. Sarazin, "Isoplanatism in a multiconjugate adaptive optics system", *J. Opt. Soc Am. A*, 2000.

8. R. Ragazzoni, E. Marchetti, and G. Valente, "Adaptive-optics corrections available for the whole sky", Nature, vol. 403, pp. 54-56, 2000.

9. Claire E. Max, Scot S. Olivier, Herbert W. Friedman, Jong An, Kenneth Avicola, Bart V. Beeman, Horst D. Bissinger, James M. Brase, Gaylen V. Erbert, Donald T. Gavel, Keith Kanz, M.C. Liu, Bruce Macintosh, Kurt P. Neeb, Jennifer Patience, Kenneth E. Waltjen, "Image improvement from a sodium-layer laser guide star adaptive optics system", Science, vol.277, pp.1649-52, 1997.

10. Donald T. Gavel, Scot S. Olivier, Brian J. Bauman, Claire E. Max, Bruce A. Macintosh, "Progress with the Lick adaptive optics system", Proceedings of the SPIE - The International Society for Optical Engineering, vol. 4007, (SPIE International Symposium on Astronomical Telescopes and Instrumentation 2000, Munich, Germany, March 2000), 2000.

11. Donald T. Gavel, Claire E. Max, Scot S. Olivier, Brian J. Bauman, Deanne M. Pennington, Bruce A. Macintosh, Jennifer Patience, Curtis G. Brown, Pamela M. Danforth, Randall L. Hurd, Elinor L. Gates, Scott A. Severson, James P. Lloyd, "Science with laser guide stars at Lick Observatory", Proceedings of the SPIE - The International Society for Optical Engineering, vol. 4494 (SPIE 2001 International Symposium on Optical Science, Engineering, and Instrumentation, San Diego, CA, July 2001), 2001.
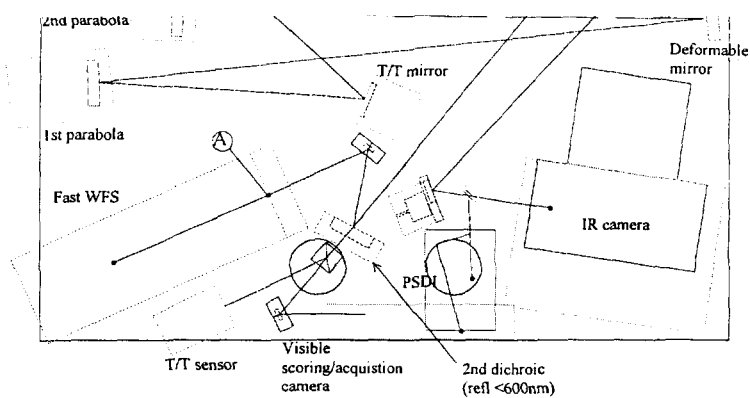
Figure 1: The Lick AO bench optical layout design at left. Light from the telescope enters from top center in the upper figure. Two unit-removable mirrors can turn the light into an Offner relay which contains the second DM (see figure 2). After these mirrors the light hits two turning mirrors, the t/t mirror, an off-axis parabolic collimating mirror, the deformable mirror, then an off-axis parabolic focusing mirror. The light is then split at a dichroic. The light longer than 900nm is transmitted through the 1st dichroic to a pair of turning mirrors that align the beam into the infrared camera. The light that is reflected off the "1st dichroic" (<900nm) is then sent to a "2nd dichroic" In LGS mode, the 2nd dichroic reflects <600nm light, which includes the LGS. In NGS mode, this optic is replaced by a mirror or beamsplitter. For MCAO, the "2nd dichroic" could be the same dichroic or a window with a reflective patch over a portion of the field.

The reflected light is reflected off the 2nd dichroic to a fold mirror and into the fast wavefront sensor. An iris, nominally located at the focus of the wavefront sensor beam rejects LGS Rayleigh scatter. The iris' diameter and position can be controlled remotely to maximize unwanted light rejection. The rest of the wavefront sensor leg consists of a collimating lens, lenslet array, relay optics, and AOA wavefront sensor camera. The light that is transmitted through the "2nd dichroic" then hits a beamsplitter cube. 10% of that light is transmitted to the scoring/acquisition camera (this position could be used for another wavefront sensor if the beamsplitter cube is replaced with, say, a 50/50 cube). The remaining 90% of the light is reflected towards the table, where in normal operation it strikes a second, smaller beamsplitter cube. 90% of that light is reflected into the APD t/t sensor, while the remaining 10% is transmitted through a hole in the table to a second wavefront sensor on the back side of the table (lower part of the figure), usually used to track telescope focus. In MCAO mode, this would be a fast NGS wavefront sensor. The small beamsplitter cube could be removed since the NGS wavefront sensor will provide the t/t information.