UCRL-JC-134970
PREPRINT

New Optical Design of Adaptive Optics System at Lick Observatory

Brian J. Bauman, Donald T. Gavel
Kenneth E. Waltjen, Gary J. Freeze
Kristian A. Keahi, Thomas C. Kuklo
Shordon K. Lopes, Michael J. Newman
Scot S. Olivier

This paper was prepared for submittal to the
44th Annual Meeting of the International Symposium on
Optical Science, Engineering, and Instrumentation
Denver, CO
July 18-23, 1999

July 22, 1999

Lawrence Livermore National Laboratory

DISCLAIMER

New Optical Design of Adaptive Optics System at Lick Observatory

Brian J. Bauman, Donald T. Gavel, Kenneth E. Waltjen, Gary J. Freeze, Kristian A. Keahi,
Thomas C. Kuklo, Shordon K. Lopes, Michael J. Newman, Scot S. Olivier

Lawrence Livermore National Laboratory, PO Box 808, Livermore, CA 94551

ABSTRACT

We present the requirements, design, and resulting new layout for the laser guide star/natural guide star (LGS/NGS) adaptive optics (AO) system on the 3-meter Shane telescope at Lick Observatory. This layout transforms our engineering prototype into a stable, reliable, maintainable end-user-oriented system, suitable for use as a facility instrument. Important new features include convenient calibration using proven phase-shifting diffraction interferometer or phase-diversity techniques[1]; a new wavefront sensor design that uses the science path's f/28.5 parabola; improved field stop mechanics for better Rayleigh-scatter rejection in LGS mode and better guide-star selection NGS mode; high-sensitivity, wide-field acquisition camera; and significant improvements in adjustment motorization and optomechanical stability.

Keywords: Adaptive optics, Lick Observatory, laser guide-star, natural guide-star, phase-shifting diffraction interferometer, phase-diversity, optical design, Bravais lens

1. INTRODUCTION

The laser guide star/adaptive optics system at the Lick Observatory Shane 3m telescope has been in operation since 1994, with the first significant sodium laser guide-star (LGS) correction occurring in 1996.[2] The adaptive optics bench and layout in use during 1996-1998 was an engineering prototypical/experimental unit. The LGS/AO system has performed well, setting records for LGS performance.[3] As we have gained experience in aligning, using and calibrating the instrument and adding calibration components such as the phase-shifting diffraction interferometer (described later), it has become apparent that a partial redesign and re-layout was required. Indeed, our goal of transferring the AO bench day-to-day operation/maintenance to Lick Observatory requires an easy-to-use, reliable, maintainable system with high observing efficiency on the sky. In particular, we needed to improve the optomechanical stability of key components such as the fast wavefront sensor (WFS), reduce noncommon path errors (particularly non-common powered optics), incorporate calibration techniques/instrumentation such as phase-diversity and PSDI into easy, fast, and nonintrusive equipment, wide-field-of-view acquisition camera to aid capturing NGS and natural tip/tilt stars in LGS mode.

2. SYSTEM DESCRIPTION

The Lick laser guide star/adaptive optics system is installed at the f/17 cassegrain focus of the 3m Shane Telescope. Most of the major components of the system are as given in reference 2 and are summarized in the following table:

Deformable mirror	LLNL-built, 127 actuators, 61 actuators controlled, triangular pattern, electrorestrictive (PMN) actuators
Tip/tilt mirror	3" mirror mounted on Physik Instrumente 2-axis tilt platform, 1200Hz bandwidth
Fast wavefront sensor	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
Tip-tilt sensor	Quad-cell photon-counting avalanche photodiode with ±2arcsec FOV, pupil imaged onto the fibers feeding APDs
Wavefront control computer	160Mflop Mercury VME with 4 Intel i860 processors, operated at up to 500Hz sample rate, with 0db crossover up to 30Hz.

Laser guide star	Sodium beacon--tunable dye laser, pumped by flash-lamp-pumped frequency doubled Nd:YAG lasers, launched by 30cm aperture refractive telescope, 18 W average power with 100ns pulse width and 11kHz repetition rate.
Infrared camera	PICNIC HgCdTe 256x256 CCD, 30e$^-$ read noise, .02e$^-$ per second dark current, 1.15x relay optics, 0.076 arcsec/pixel.,800-2550nm, 77K, QE>60%, speckle/subarray/coronagraph modes, 14 filters+blank+open (including grisms) [4]; this upgrades the LIRC-II camera described in reference 2.
Visible scoring camera	Photometrics CH250 (1035x1317, 6.8μ pixels, Kodak 0400 detector, thermoelectrically cooled)
Slow wavefront sensor	Similar to fast wavefront sensor, but using Photometrics CH250 CCD described above

In addition to the above components, we also have commissioned a PSDI system, described briefly below and in more detail in other papers in this conference.[5] This implementation of PSDI, which measures the wavefront error just before the infrared camera and thus is used to calibrate the fast wavefront sensor, is an adaptation of the instrumentation/techniques developed at LLNL by Gary Sommargren for use in measuring extreme ultraviolet (13nm) lithography optics. The technique has been shown to measure wavefront errors down to approximately 1 nm[6]. It is well-suited to this application because unlike many interferometers, it accepts converging light at an image plane, such as that at the infrared camera.

3. REQUIREMENTS

In addition to the requirements given in reference 2, we wanted to implement the following feature in the Lick AO bench:

- High-stability optomechanics, particularly in key paths such as the fast wavefront sensor.
- Capability to nod the image on the infrared camera without changing the path into it (i.e., by repointing the telescope)
- Fast, remotely-actuated calibration with PSDI or phase diversity techniques applied to science camera or infrared camera, suitable for use during the night.
- ±1 arcmin acquisition mode
- Tip/tilt star in LGS mode can be acquired on tip/tilt sensor and slow wavefront sensor over ±1 arcmin field
- Minimal changes to switch between LGS and NGS mode

4. LAYOUT/DESIGN

The new optical layout is as shown in figures 1 and 2. Light from the telescope enters from top center on figure 1 and hits two turning mirrors, the tip/tilt 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 (and also 1.5% of the light at 532nm, the PSDI wavelength) is transmitted through the 1st dichroic to a pair of turning mirrors that align the beam into the infrared camera. Just before IRCAL, a mirror may be driven into the light path to reflect the light into the phase-diffraction interferometer; this is used to calibrate the wavefront sensor. The light that is reflected off the "1st dichroic" (<900nm) is then sent to a "2nd dichroic" (in LGS mode; in NGS mode, the dichroic is replaced by a 90%R/10%T spectrally-flat beamsplitter-- this is planned to be a remotely-actuated replacement). The light that is <600nm is reflected off the 2nd dichroic to a fold mirror and into the fast wavefront sensor. An iris 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 (600-900nm in LGS mode; 10% of <900nm in NGS mode) then hits a beamsplitter cube. 10% of that light is transmitted to the scoring/acquisition camera. The remaining 90% of the light is reflected towards the table, where it strikes a second, smaller beamsplitter cube. 90% of that light is reflected into the APD tip/tilt sensor, while the remaining 10% is transmitted through a hole in the table to a slow wavefront sensor on the back side of the table. The purpose of the slow wavefront sensor is to monitor focus and other slowly varying aberrations introduced by the laser guide star. The tip/tilt sensor and the slow wavefront sensor look at the tip/tilt star in LGS mode—in NGS mode, they are ignored.

The next sections describe in more detail some of the more important changes in the Lick AO bench.

1. Acquisition camera

In order to acquire a tip/tilt star, we need to have a 2 arcmin diameter field of view. The tip/tilt sensor's high angular sensitivity means that its field of view is very small (approximately 2 arc sec diameter), so it is useful to have an acquisition camera that will allow the tip/tilt star to be captured on the tip/tilt sensor.

We are using our visible scoring camera, a Photometrics CH250, as an acquisition camera as well. In its normal f/28.6 configuration, the Photometrics camera has a plate scale of 0.017arcsec/pixel with approximately 20 arcsec field of view. In order to achieve a ±1 arcmin FOV, we must have f/5.8 optics. It is most convenient if the lens can be driven into the camera path so that focus of the camera does not have to be adjusted; this is a Bravais lens.[7] Since the tip/tilt mode will be off during acquisition, the performance of the lens does not need to be any better than the seeing.

The performance of this lens is limited by astigmatism, coma, and lateral color from the smaller relay lens. There is some distortion (approximately 5% at the corner), but this can calibrated out. The tolerances are lenient enough to allow this lens to be assembled with off-the-shelf optics and drop-in tube package. The performance of the lens in the corners of the field would be reduced dramatically by some of the outer pupil rays, so those rays have been vignetted out since they would only degrade the image. The vignetting affects only the extremes of the field and the only penalty is longer exposure if dim objects in the periphery need to be seen.

2. Fast wavefront sensor

The previous fast wavefront sensor used an f/6 off-axis parabola (OAP) that was uncommon with the science camera path. This tended to produce uncommon path errors since even small drifts in "upstream" mirror angles would change the static aberrations at the fast wavefront sensor, which would not be seen by the infrared camera. Since the OAP was finicky, as a corollary, our calibration would not stay "fresh" very long. Using the same slow (f/28.5) OAP for both wavefront sensor and infrared camera, combined with easy and quick calibration, would significantly reduce the noncommon path errors.

One of the benefits of changing to the f/28.5 wavefront sensor is that the distance between the LGS image at the focus of the f/28.5 parabola and the subsequent collimating lens has been lengthened to approximately 4 inches from 0.75 inches. Similarly, the distance between the collimating lens and the lenslet array has been lengthened to about 4 inches. This allows better adjustability of the background-blocking iris., since it can be on its own high-stability fiber-optic quality stage . Also, there is now room for atmospheric dispersion correctors to be deployed between the collimating lens and the lenslet array.

Our optomechanical/alignment scheme has been designed for stability and ease of alignment. Newport 462 and 562 series stages produce a rigid and repeatable wavefront sensor.

3. PSDI

The purpose of PSDI is to calibrate the wavefront sensor. A "perfect" point source is created at the cassegrain and is interfered with a coherent perfect point source at the infrared camera's input image plane. The resulting interference pattern is viewed with a megapixel 12-bit camera. Phase-shifting mechanisms within PSDI allow the interference fringes to be interpreted with conventional phase-shifting software. The resulting wavefront is then used to "tweak" the DM actuators to produce the flattest possible interference pattern at PSDI. The centroids of the fast wavefront sensor are recorded in this state; this is the set of "target centroids" during closed-loop operation.

More precisely, the PSDI system works in the following manner: a high-power/wavelength-stability Nd:YAG laser is injected into a single-mode fiber which is split via a variable fiber-based beamsplitter into 2 fibers. Each fiber is clamped in a fiber-based variable polarizer which is adjusted so that the two fibers output light of very similar polarization states (to maximize fringe contrast). One end is brought to the cassegrain focus of the AO bench and the light is propagated through the system from this "ideal point source" (6 micron core =>1.5 milliarcseconds). The other fiber is embedded in a substrate, super-polished, and coated with a partially-reflecting coating; this is commonly called "the back end" of the PSDI system.

The middle part of this fiber is wrapped around a PZT-actuated fiber spool which stretches the fiber in a controlled manner, producing a calibrated phase shift. The light emerging from this point source is interfered with the incoming light from the Cassegrain focus. The combined light is then propagated through a lens which relays the DM/pupil plane onto a Kodak ES1.0 camera.

Ideally, we wanted PSDI to be located as close as possible to the infrared camera so that there would be minimum noncommon path optics. Therefore, we wanted the PSDI laser to transmit through the 1st (900nm) dichroic. We selected the PSDI laser wavelength based on a small measured transmission "hole" at 532nm in our existing 900nm cut-off dichroic and the fact that very stable Nd:YAG lasers were readily available (high wavelength/power stability is required by phase-shifting algorithm). Since the transmission through the dichroic was only 1.5%, and we wished to use fairly inefficient coupling (by using "slow" coupling optics; this was so that the PSDI laser power would be insensitive to misalignments, hence lower maintainence), we selected a 50mW laser. A "drive-in" mirror, actuated by a high-speed long-throw motor, picks off the light just before the infrared camera and sends it to the PSDI. Motorized tip/tilt controls on the drive in mirror allow tilt fringes to be "fluffed out" and eliminates repeatability requirements on the drive-in mirror. A motorized focus stage on the back end removes the focus fringes. These motors are controlled "manually" by the AO system operator.

4. Phase-diversity calibration

Phase-diversity calibration is easily implemented in this system. Visible phase-diversity is done with the visible scoring camera (Photometrics) by moving the camera out of focus by approximately 1 wave rms (about 1mm). Infrared phase-diversity is done with the IR camera by moving it out of focus by approximately 1.5-4mm. Infrared phase-diversity is potentially very accurate since it is done with the science camera. The visible phase-diversity calibration path differs only by a few flat surfaces.

5. CONTROL SYSTEM

Several control mirrors are used in alignment procedures and NGS/LGS/nodding observing procedures. The motor moves required for a given operation (say, "move NGS on fast WFS by 1 arcsec in the x axis") are calculated according to a control matrix governed by the distances between the various control mirrors. The observing procedures are described below to aid understanding of the control system.

The operation in NGS mode is as follows: the science path pointing, since it has no reflective control optics, is constant. The NGS is acquired on the acquisition camera (with the Bravais lens in place) and the two control mirrors (1st dichroic and the fold mirror in front of the WFS) are tilted to "point and center" the NGS on the fast WFS according to a control matrix. Using the 1st dichroic as a control mirror allows the acquisition camera to monitor the move. A control mirror in front of the acquisition camera corrects the remaining deviation onto the acquisition camera, again according to a control matrix.

For LGS mode, the operation is more involved because of the additional sensors, but the procedure is similar. There is a choice to be made whether the tip/tilt star or the LGS should be aligned near the center of the 2nd dichroic. The tip/tilt path is aligned near the center so that the subsequent optics for the tip/tilt star (leading to the tip/tilt sensor and the slow wavefront sensor) can be smaller. A "control mirror" (the reflective surface of a beamsplitter cube) allows the pupil to be properly placed on the tip/tilt sensor. This mirror steers into two sensors looking at the tip/tilt star, so the same surface can be used to steer into both. Meanwhile, the LGS path is off the center of the 2nd dichroic, but is steered back onto the center of the subsequent mirror so that the LGS is pointed and centered on the fast WFS. There is a slight change in focus in the LGS path, but this can be calculated and removed by moving the focus of the fast WFS. This focussing capability of the fast WFS is necessary anyway because the LGS is imaged far from the NGS position (nominally, 71 mm).

For nodding operations, the telescope is re-pointed according to the desired nod, and the control mirrors then keep the LGS positioned near the science object and the tip/tilt star on the tip/tilt star sensors. The telescope pointing control is not terribly accurate ($\pm$ 0.5 arc sec), but this is acceptable since this is within the field-of-view of the tip/tilt sensor.

A control matrix is given in figure 3 showing what control mirrors are moved with each common operation.

6. CONCLUSION

The revised Lick AO bench design has been presented. The design has the potential for high-reliability, high-efficiency observing in NGS and LGS modes and is being fielded in mid '99.

ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48. It was supported by Laboratory Directed Research and Development funding within the University Relations Program and the Lasers Directorate. This support is gratefully acknowledged.

REFERENCES

1. Don Gavel, Brian Bauman, Eugene Campbell, and Carmen Carrano, "A Practical Comparison of Phase Diversity to Interferometry in Measuring the Aberrations in an Adaptive Optics System", SPIE 1999 International Symposium on Optical Science, Engineering, and Instrumentation, Denver, CO, July, 1999.
2. S.S. Olivier, C.E. Max, H.W. Friedman, J. An, K. Avicola, B.V. Beeman, H.D. Bissinger, J.M. Brase, G.V. Erbert, D.T. Gavel, IK. Kanz, B. Macintosh, K.P. Neeb, K.E. Waltjen, "First Significant Image Improvement from a Sodium-Layer Laser Guide Star Adaptive Optics System at Lick Observatory", SPIE 1997 International Symposium on Optical Science, Engineering, and Instrumentation, San Diego, 1997.
3. Scot S. Olivier, Donald T. Gavel, Herbert W. Friedman, Claire E. Max, Jong R.An, Kenneth Avicola, Brian J. Bauman, James M. Brase, Eugene W. Campbell, Carmen Carrano, Jeffrey B. Cooke, Gary J. Freeze, Elinor L. Gates, Vernon K.Kanz, Thomas C. Kuklo, Bruce A. Macintosh, Michael J. Newman, Edward L.Pierce, Kenneth E. Waltjen, James A. Watson , "Improved performance of the laser guide star adaptive optics system at Lick Observatory", this conference , Denver, CO, July, 1999.
4. James P. Lloyd, Michael A. Liu, Bruce A. Macintosh, William T. Deich, Scott A. Severson, James Graham, in preparation.
5. Eugene W. Campbell, Brian J. Bauman, Daren R. Sweider, and Scot S. Olivier , "Adaptive optics system calibration using phase-shifting diffraction interferometer", SPIE 1999 International Symposium on Optical Science, Engineering, and Instrumentation, Denver, 1999.
6. G.E. Sommargren, "Diffraction methods raise interferometer accuracy," *Laser Focus World* **32**, pp. 61-62, 64, 66, 70-71, 1996.
7. Rudolph Kingslake, *Optical System Design*, Academic Press, New York, 1983.

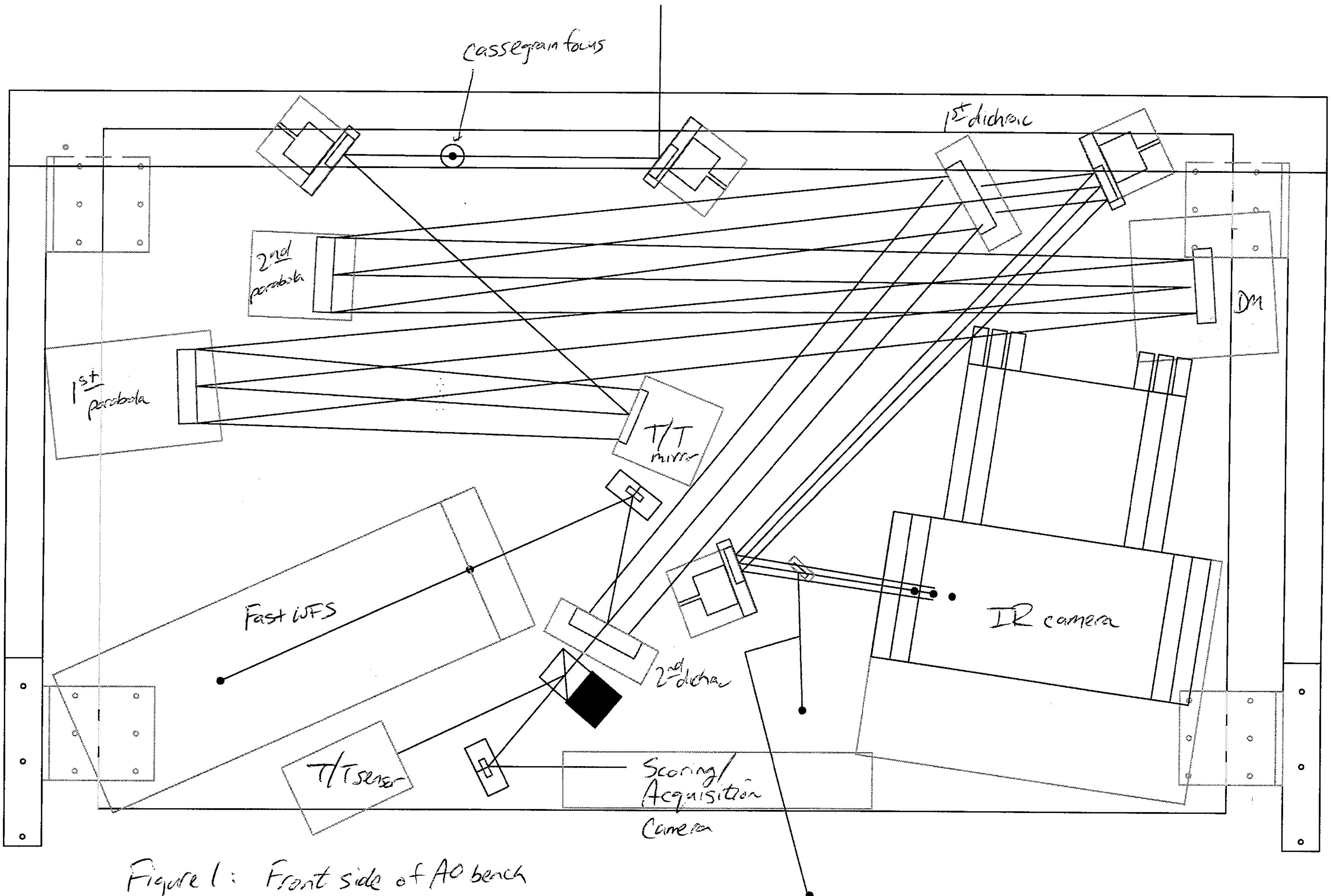

Figure 1: Front side of AO bench

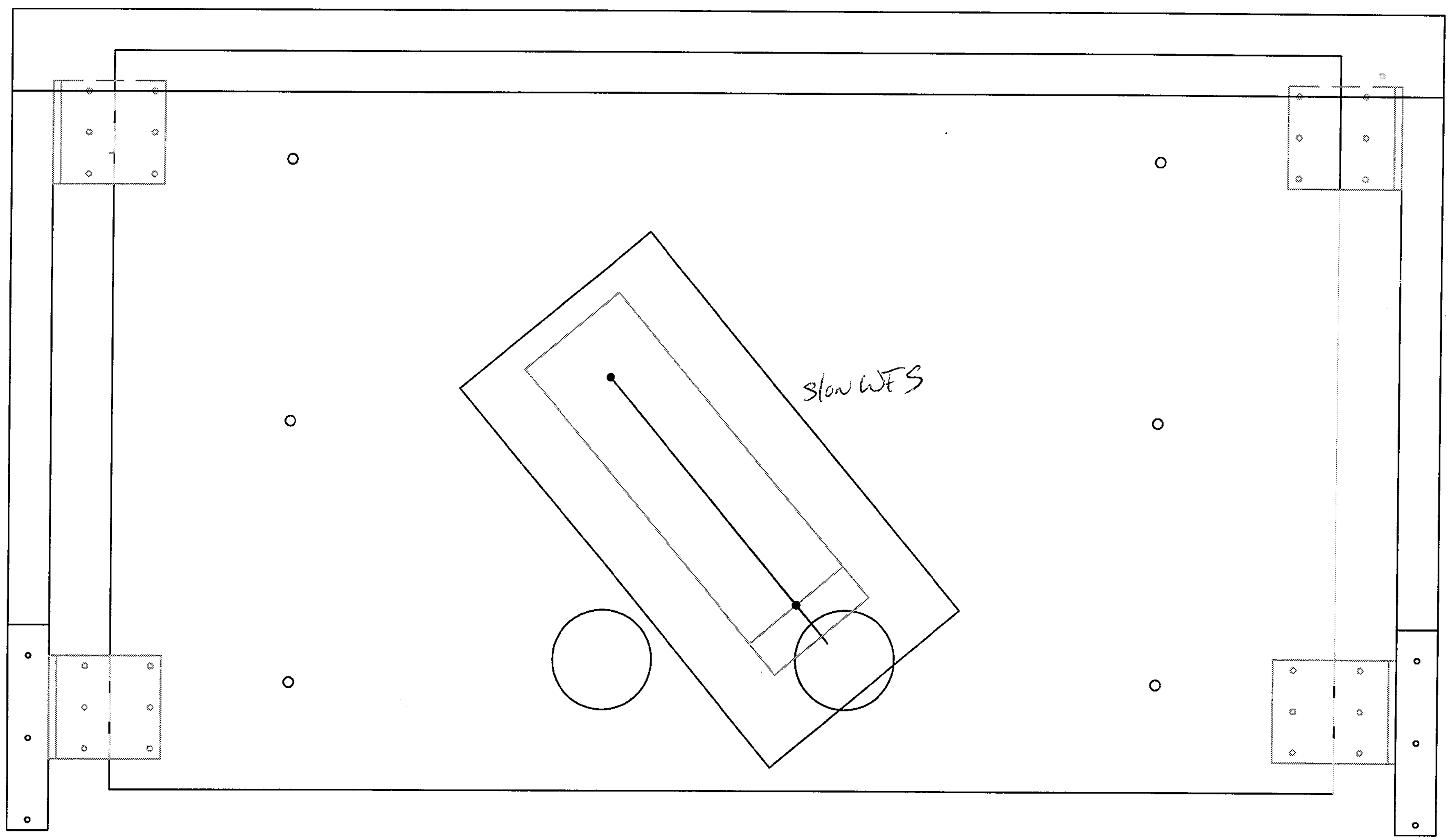

Figure 2: Backside of AO bench

		Operation											
		Nod science star	Move LGS on fast WFS	Move pupil on fast WFS	Move WFS iris	Move photometrics image	Move TT star on TT sensor	Move TT sensor pupil	Move TT star on slow WFS	Move slow WFS pupil	Acquisition mode	PSDI calibration	Phase-diversity calibration
Motor	1st dichroic (900nm)	X							X	X			
	2nd dichroic (600nm)	X	X	X					X	X			
	Fast WFS fold mirror	X	X	X					X	X			
	Fast WFS focus		X	X									
	iris displacement				X								
	TT sensor beamsplitter cube	X					X	X	X	X			
	TT sensor displacement	X					X	X	X	X			
	Slow WFS fold mirror	X							X	X			
	Photometrics fold mirror	X				X			X	X			
	Photometrics focus												X
	PSDI focus, tip/tilt											X	
	Bravais lens stage	out	out	out	out	out	out	out	out	out	in	out	out

Figure 3: Control matrix for several common alignment/observing operations. "X" indicates that the motor is used for this operation.