Design and Performance of a Laser Guide Star System for the Keck II Telescope

H. W. Friedman, J. B. Cooke, P. M. Danforth, G. V. Erbert, M. Feldman,
D. T. Gavel, S. L. Jenkins, H. E. Jones, V. K. Kanz, T. Kuklo, M. J. Newman,
E. L. Pierce, R. W. Presta, J. T. Salmon, G. R. Thompson, N. J. Wong

This paper was prepared for submittal to the
Adaptive Optical System Technologies

Kona, HI

March 20-28, 1998

March 18, 1998

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

Design and performance of a laser guide star system for the Keck II telescope

H. W. Friedman, J. B. Cooke, P.M. Danforth, G. V. Erbert, M. Feldman, D. T. Gavel, S. L. Jenkins, H.E. Jones, V. K. Kanz, T. Kuklo, M. J. Newman, E. L. Pierce, R. W. Presta, J. T. Salmon, G. R. Thompson, N. J. Wong

LLNL, Box 808, L-464, Livermore, CA, 94551

ABSTRACT

A laser system to generate sodium-layer guide stars has been designed, built and delivered to the Keck Observatory in Hawaii. The system uses frequency doubled YAG lasers to pump liquid dye lasers and produces 20 W of average power. The design and performance results of this laser system are presented.

Keywords: sodium laser, guide star, adaptive optics

1. INTRODUCTION

A laser guide star system similar to that deployed at the Lick Observatory¹ has been designed and built for the Keck II, 10 m telescope on Mauna Kea, Hawaii. A conceptual drawing of the system showing the laser room on the dome floor and the laser mounted on the telescope is shown in Fig. 1. The subaperture size on the primary is comparable to that at Lick, and at the same observational wavelength centered about the K band. Thus the average power requirements of the laser system are also comparable, at about 20 W. One major difference is that the seeing at Mauna Kea is about a factor of two better than at Lick so that the spot diameter requirements are smaller and this can give rise to reduced back scatter resulting from saturation effects in the sodium layer. To reduce the peak flux in the sodium layer and obtain a smaller spot diameter, the output beam diameter on the telescope has been increased along with the repetition rate of the laser.

As with the Lick laser system, a dye laser is pumped by a series of frequency doubled YAG lasers which are remotely located and coupled to the dye laser on the telescope by optical fibers. The laser system has a full set of beam control optics as well as launch telescope and safety systems. A computer system couples the laser system to the User Interface and Supervisory Control system of the main telescope.

2. LASER SYSTEM SPECIFICATIONS

The laser system specifications are all based upon the requirement on the return flux and the spot size in the mesosphere. For the Keck adaptive optics system with sub aperture size of 55 cm and the Lincoln Laboratory/Adaptive Optics Associates camera with 64 x 64 pixel array and 6 noise electrons, the requirements for the return flux is 0.3 ph/cm²/ms and the spot diameter is 0.6 arcsec. These return flux requirement pertain to a median seeing conditions of $r_0 = 20$ cm at 500 nm. The laser system requirements to meet these parameters are the following: Average power ≥ 20 W, pulse repetition rate ≥ 26 kHz, pulse duration ≥ 125 ns, beam quality ≤ 1.5 times the diffraction limit and beam size ≥ 50 cm. A facilities requirement is that no more than 100 W shall be released into the dome for this instrument which means that the laser system is divided into two parts, one on the dome floor in a thermally insulated room and the the other on the telescope with waste heat removal. The two subsystems are connected by conventional wire and fiber optics.

3. OVERALL LAYOUT OF THE LASER SYSTEM

The overall conceptual layout of the laser system is shown in Fig. 2. A thermally insulated room located on the dome floor houses much of the laser system to minimize the waste heat rejection within the dome. Located in this enclosure are the 5 frequency doubled YAG pump lasers. These lasers are fiber optically coupled to the dye master oscillator also located in this room and the dye laser amplifiers located on the elevation ring of the telescope. In this room are the electronics racks which provide the closed loop control, safety system and computer system which operates the laser system. Facility systems such as the transformer, circuit breaker board, dye pump system and Programmable Logic Controller (PLC) are also located here.

Figure 2 Layout of the laser guide star system

The dye Wave Form Generator, (WFG) consisting of the dye master oscillator, mode and wavelength diagnostics, modulators and the Single Mode Polarization Maintaining (SMPM) fiber launch are thermally controlled since a constant temperature is vital to the wavelength stability of the system. The SMPM fiber as well as the pump fibers from the YAG lasers exit the room and travel about 80 m through both the azimuth and elevation bearings to reach the rest of the laser system on the elevation ring of the telescope.

The package on the elevation ring consists of three parts, the dye amplifier table, the diagnostic table and the launch telescope. A visualization of the elevation ring package and its relation to the launch telescope and thermal enclosure is shown in Fig. 1. The laser and diagnostic package both are housed on a 4' x 6' optics table with the final lens of the launch telescope attached to the upper ring. The laser package consists of dye preamplifier and power amplifier both pumped by fibers from the YAG laser pump system. The preamplifier restores the power of the dye master oscillator lost in the SMPM fiber while the power amplifier boosts the signal to the 20 W required to achieve the desired back scatter flux return. Interspersed on the laser table are relay telescopes which format the beam in terms of a circular aperture and relay that aperture from preamplifier to amplifier onto the final aperture of the laser system which is the large lens of the launch telescope.

The diagnostic package has a suite of diagnostics including a closed loop pointing and centering system, a high speed tip/tilt mirror fed by the adaptive optic wave front sensor to control up-link jitter, an encircled power camera and a Hartmann sensor for wave front determination. In addition, there is wide field of view camera for "nodding" and a camera to look back up through the launch telescope for alignment.

The launch telescope is a two element, refractive, Newtonian telescope which expands the beam to a full 50 cm round profile. The final lens of this telescope is placed "backwards" with the plane surface facing the sky and the curved surface, an asphere, ground to give a 1/10 wave (RMS) transmitted wave front. A back reflection from this last surface is used in the Hartmann sensor to monitor the quality of the wave front before it leaves the dome.

4. FREQUENCY DOUBLED YAG PUMP LASERS

A set of 5 frequency doubled YAG laser are used to pump the dye master oscillator, preamplifier and power amplifier as shown in Fig. 3. The YAG lasers are built from commercially available arclamp-rod blocks, acoustic-optic Q switches and KTP doubling crystals². Some of the mirror mounts and crystal holders are custom but by in large, the laser is essentially commercial. The cavity configurations are an "L" and "Z" shape for the dye master oscillator/preamplifier and power amplifier as shown in Fig. 4. The "L" cavity runs at the full system repetition rate of 26 KHz while the "Z" cavity runs at half the full system rate. The "L" system has less power than the "Z" but essentially the same pulse duration at double the repetition rate so in that sense, the two are matched. The 4 "Z" lasers are arranged in two time sets and interleaved in the amplifier dye cell to form the full system repetition rate.

Figure 3. Laser pumping configuration

Figure 4. YAG laser cavity configurations

1. Rear HR mirror	6. Output beam	11. Shutter
2. Q switch	7. Power measurement splitter	12. Shutter
3. Lamp/rod assembly	8. Integrating sphere	13. Shutter
4. 45° mirror turning block	9. Wave plate	14. Fiber launch lens
5. KTP/rear mirror assembly	10. Wave plate	15. Fiber launch lens
		16. Fiber launch lens

Figure 5. "L" Cavity YAG

1. Rear HR mirror	6. KTP/rear mirror assembly
2. Lamp/rod assembly	7. Integrating sphere power measurement
3. 200 mm mirror assembly	8. Power measuring splitter
4. Q switch	9. Mechanical shutter
5. 300 mm mirror assembly	10. Fiber launch lens

The 5 YAGs are housed in two electronics racks together with their power supplies, Q switch drivers, timing circuits, and cooling system. The arclamps are about 8 KW each. There is room for 4 YAGs in each rack and with some rearrangement of the supplies, up to 6 can be housed in a rack. The output power of the "Z" lasers is presently about 60-80 W (in the green) while the power of the "L" laser is about 40-50 W.

Diode pumped, frequency doubled YAG lasers do exist at this power level but at present, are more expensive than lamp pumped YAGs. These lasers have better beam quality due to the more efficient match of diode emission and YAG absorption wavelengths but this feature is of no importance for this fiber coupled application.

5. WAVEFORM GENERATOR

Diagram of the wave form generator are shown in Fig. 7 and 8. A Grazing Incidence Dye Master Oscillator³ shown in Figs. 9 and 10 is used for the sodium source beam. The basic advantage of the GI-DMO is the lack of prisms to spread the beam on the grating while the main disadvantage is the pointing of the output beam if the oscillator is tuned unless careful attention is paid to the mechanical design. In this application, however, where the wavelength is fixed, wavelength associated pointing is not a problem.

Figure 7. Layout of the Waveform Generator

1. Sodium hollow cathode cell	8. Isolator
2. Sodium cell/oven	9. Pinhole
3. Scanning Fabry-Perot interferometer	10. Spatial filtering lens
4. Fiber launch	11. Grazing incidence dye master oscillator
5. 300 MHz modulator	12. Scanning Fabry-Perot interferometer
6. 125 MHz modulator	13. Spectrometer
7. Power measurement	14. CCD camera

Figure 8. Waveform Generator Table

Figure 9. Layout of the Grazing Incidence Dye Master Oscillator

1. Pump fibers	5. Output beam hole
2. Grating	6. Etalon drive
3. Etalon	7. Tuning mirror drive
4. Tuning mirror	8. HR mirror

Figure 10. Photograph of the Grazing Incidence Dye Master Oscillator in the Waveform Generator

The GI-DMO output is first split and diagnosed with 30 GHz and 7.5 GHz scanning interferometers to determine its mode content. The rest of the beam is passed through two electro-optics modulators which spread the spectral content to match the absorption profile of the mesospheric sodium. The absorption profile is about 3 GHz wide and is double peaked due to the fine structure and the low temperature. The beam is then diagnosed with another 7.5 GHz scanning interferometer to determine that the correct spectral profile is obtained.

Two diagnostics make up the wavelength acquisition and tracking system. A hollow cathode lamp containing a buffer gas of neon and sodium emits a spectrum containing the D₁ and D₂ sodium lines along with adjacent neon lines. A simple fixed spectrometer superimposes the laser beam with this spectrum and the grating is tuned to put the laser line on the D₂ position. Fine tuning is obtained by observing the fluorescence from the vacuum sodium cell using both a TV camera and a photo diode.

Two control loops ensure that the laser stays single mode (before the modulators) and on wavelength. The first control loop dithers the etalon via a piezoelectric drive, senses the peak of the signal to maintain and adjusts the etalon peak to maintain maximum output. Since the cavity modes are only 1 GHz apart and the etalon free spectral range is about 34 GHz it is relatively easy to maintain the single mode condition. The second control loop monitors the fluorescence of the vacuum sodium cell and adjusts the cavity mirror to stay on wavelength.

6. LASER/DIAGNOSTICS TABLE

The dye laser amplifiers and diagnostic package share space on a 4' x 6' table mounted on the elevation ring of the telescope. The laser portion consists of a fiber receiver optic, a preamplifier and a power amplifier as shown in Figs. 11 and 12. The receiver optic places a waist of the beam at the center of the preamplifier which is pumped by the "L" YAG laser via a 600 micron, multimode optical fiber. The signal input to the preamp is of the order of a few milliwatts and exits the preamp at several hundred milliwatts. The beam is then clipped by a circular aperture which results in a flat wave front and an amplitude variation of no greater than 2:1. The dye relay telescope images this aperture into the center of the amplifier which is pumped by 4 fibers from the "Z" YAGs arranged in two time sets of half the repetition rate. The output of this amplifier is of the order of 20 W. The post amplifier telescope collimates the beam and relays the image of the aperture to one of the turning mirrors on the diagnostic table.

Figure 11. Schematic layout of the laser portion of the table

1. Heat exchange	9. Amp surveillance camera
2. Fiber launch	10. Alcohol monitor
3. Preamp	11. Fire sensor
4. Signal conditioning electronics	12. Amplifier with L1 lens
5. Collimating telescope	13. Dye relay telescope
6. Signal interface block	14. FTAR
7. High bandwidth tilt mirror	15. Pump fibers
8. L2 lens	16. Isolator

Figure 12. Photograph of the laser table

The optics train of the diagnostics portion of the table is shown in Figs. 13 and 14. The main beam on the diagnostic table is directed to the high bandwidth, tip-tilt mirror by mirror M_1 . The signal to the tilt mirror is derived from the wave front sensor of the adaptive optics system on the main telescope and removes uplink jitter which can move the Hartmann spots on the wave front sensor. After the splitters for the diagnostics, the main beam enters the launch telescope where it is expanded to 50 cm and propagated alongside of the main telescope

Figure 13. Layout of the diagnostics portion of the table

1. L4 camera	8. Centering camera	15. Narrow angle pointing camera
2. Wide angle pointing camera	9. Cross-polarizer controls	16. Amplifier power measurement
3. L3 lens	10. Hartmann telescope	17. Tilt surveillance camera
4. Fast shutter/power meter	11. PIB telescope	18. High bandwidth tilt mirror
5. Nodding mirror	12. PIB camera	19. Wiring harnesses
6. Reference beam shutter	13. Hartmann WFS camera	20. Wiring harnesses
7. Reference beam collimator	14. Turning mirror	21. Wiring harnesses

Figure 14. Photograph of the diagnostics package

There are several cameras in the diagnostic legs. The first camera is placed at the focal point of the beam and serves as the narrow angle pointing sensor. Another camera on the opposite side of the table is placed at the image of the beam and serves as the centering diagnostic. Using a cross coupled matrix controller, the outputs of these cameras control the translation of the L2 lens and the M1 mirror to make coordinated pointing and centering motions of the main beam on the sky. There is another camera in parallel with the narrow angle pointing camera used for wide angle moves such as in the nodding application for near IR astronomy. This camera is not controlled but serves just as a diagnostic for wide angle moves. The narrow and wide angle cameras could be combined into one except for the fact that the algorithms developed for the narrow angle pointing system require a relatively large beam thereby reducing the field of view of this camera.

Another camera next to the centering camera is used for encircled power measurements, called Power-in-the-Bucket or PIB. This is an alternate approach to the traditional method of measuring the power passed through a pinhole of a size corresponding to the central lobe of a diffraction limited beam but does not suffer from pointing errors. The camera should be at least a 12 bit or greater digital camera in order to get sufficient dynamic range for an accurate measurement but a standard 8 bit camera with absolute calibration or multiple images can also work. The 16 bit camera approach has worked well but the 8 bit camera has also given satisfactory results and was supplied with the system.

The most sophisticated beam quality measurement is the wave front sensor based upon a Hartmann technique. This diagnostic serves two purposes, first to adjust the launch telescope and second, to monitor the wave front of the outgoing beam even during the day with the dome closed thereby saving valuable time at night. The beam coming out of the laser is sampled by a beam splitter and directed into the Hartmann sensor. Using shutters, the outgoing beam is blocked and the return from the flat side of the final lens of the launch telescope is then sampled by another beam splitter. The first beam has all the aberration minus those of the launch telescope while the retro beam has all those aberrations plus twice that of the launch telescope. Adding both beams gives exactly twice the aberrations of the entire system so that simply dividing the sum by two gives the correct wave front aberration of the entire system. There is also an on-board wave front reference calibrator made by a fiber coupled yellow HeNe at 594 nm and a invar stabilized expander-collimator.

7. LAUNCH TELESCOPE

Several concepts were investigated for the Keck telescope including launching from behind the secondary to reflective designs. The off axis configuration was chosen because although it does require about twice the laser power as the on axis case, the implementation is so much easier. For example, getting the beam behind the secondary requires transmitting the beam across the primary mirror in the shadow of the one of the secondary support struts. If the beam is not shadowed either because it is too large or not well controlled, scattering may disrupt the control loop and force a reboot of the adaptive optic system. Encasing the beam in a tube will increase the IR emissivity of the background and trying to keep a small diameter beam behind a secondary strut will probably require a separate pointing and centering loop. Also, going behind the secondary will cause a redesign of the secondary cage with regard to both weight and location of secondary mirror control apparatus. If the telescope has not yet been designed, then this task is much easier but for Keck, which is a working telescope, this redesign effort was prohibitive. Finally the transmission losses in going propagating from behind the secondary are higher than those of the off axis beam train making the comparison less clear.

Reflective designs may be significantly cheaper than refractive designs but there is always the problem of aligning the reflective primary or inserting a flat to retro the beam. With reflective designs, tilt or jitter of the mirror will result directly in a tilt or jitter of the beam. Refractive designs can be made with a flat surface as the last surface and tilt of the lens does not tilt the beam, at least to first order. Granted, placing the flat facing the sky does force one to use an aspheric surface for the curve and that does increase the cost but it does eliminate the need for a large flat and gimbal mount to hold the flat. Finally, going to the off axis configuration does allow the use of the entire telescope barrel to get a large expansion ratio without too complex of an asphere.

The design chosen for Keck is a small plano-convex, positive lens, L3, which relays the circular aperture image to the large lens at the top of the telescope. The large lens, L4, is also a plano-convex with the convex surface being an asphere and the flat facing out to the sky. The radius of curvature for L4 is 6676.8 mm with a conic constant of -2.30. The curved surface is coated for lowest reflection while the flat surface is coated for a reflection of about 1%. In practice, the L3 lens is motorized in three axis, two in the transverse direction for the one time alignment of the launch telescope with the main telescope axis and the third as a focus adjustment to the mesosphere. In addition, there is also a manual adjustment on the tilt of the L3 lens to correct any residual astigmatism in the laser beam. The L4 lens is fixed in position but has a gimbal mount to adjust the retro back into the diagnostic system.

The alignment procedure for the launch telescope is to set the main telescope to zenith and then hang the L4 lens also plumb. Dropping a plumb line then locates the position of the L3 lens. Pointing the telescope to a bright star and adjusting the main telescope so that the star is in the middle of the acquisition camera, the L3 lens is then adjusted using the transverse axes to get the same star in the middle of L3. Looking back at the sky with the PIB camera, the L3 lens is then carefully adjusted to get the star in the middle of the camera field of view. From this point, the transverse axes of the L3 is not touched and the small parallax adjustment to get the laser beam crossing the mesosphere at the same point as the main telescope axis is a small adjustment of the pointing and centering loop. After this small adjustment, the laser axis may no longer be in the center of the L3-L4 combination but the aberrations are very small.

8. TEST RESULTS

Prior to shipment of the laser system to Hawaii in February, 1998, an 8 hour test was conducted. The major results of that test are shown in Figs. 13. The laser was turned on with all 4 YAG lasers pumping the amplifier resulting in an output power of almost 30 W which was about 50% higher than the nominal design in terms of window loading. In order to reduce the risk to the window during this test, one YAG laser was shuttered and the laser operated above 16 watts for the duration of the test. At the end, the fourth YAG was shuttered in and the power rose to 23 W. This test was conducted with the full lengths of pump fibers, 110 m as compared to the final length which is estimated to be about 70 m. Hence it appears

that there is ample reserve power in needed. There are several ways to effectively use this excess, as a backup should one YAG fail, for more power at a higher window loading or for more power at the same window loading by extending the amplifier gap. Operation at Keck will define which one of these options is best.

Figure 15. Power levels for the 8 hour test.

The beam quality of the laser is summarized in Figures 16-18. In Fig. 16, the encircled power from the 16 bit Photometrics PIB camera is shown. Approximately 71% of the power is contained within the first Airy ring out of a possible 83% giving a beam quality of less than 1.4 times diffraction limited or a Strehl of 0.6. The wavefront diagram from the Hartmann sensor is shown in Fig. 17 with its measured Strehl of 0.8. The Hartmann sensor does not have sufficient ^{of} lenslets to resolve higher spatial order losses and thus overpredicts the Strehl. A summary of the beam quality data during the run is shown in Fig. 18.

Figure 16. Encircled power measurements from a 16 bit Photometrics camera.

P-V= 0.30 waves, RMS= 0.07 waves, Strehl= 0.832 Power= 16.4

Figure 17. Beam quality as measured by the Hartmann sensor.

Figure. 18. Beam quality results during the 8 hour test.

9. ACKNOWLEDGEMENTS

Work performed partially under the auspices of the U. S Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-ENG-48 and funds provided by the W. M. Keck Observatory, California Association for Research in Astronomy.

10. REFERENCES

1. H. W. Friedman et. al. "Sodium Laser Guide Star Results at the Lick Observatory", *Proc. OSA Topical Meeting on Adaptive Optics*, Technical University of Munich, Garching, Germany, October 1995, paper TuA 28. Also, S. Olivier et.al., "First Significant Image Improvement from a Sodium-Layer Laser Guide Star Adaptive Optical System at Lick Observatory", *Science*, Vol 277, P1649-1652, 1997
2. M. V. Ortiz et al. "High average power second harmonic generation with KTiOPO_4 " *OSA Proc. on Advanced Solid State Lasers*, Vol 13, Feb. 1992, NM and G. V. Erbert, K. Kanz and I. Bass, "Lamp pumped Nd:YAG laser oscillator with 170 W green output", *Proc. IEEE Lasers and Electro-Optics Soc. Ann Mtg.*, PD2.6 Nov. 1997
3. M. Littman, "Single-mode pulsed tunable dye laser" *J. Appl. Phys.* 1984

Technical Information Department • Lawrence Livermore National Laboratory
University of California • Livermore, California 94551