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Measurements of the Lick Observatory Sodium Laser Guide Star

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Abstract

The Lick Observatory guide star laser has provided a beacon sufficient to close the adaptive optics loop and produce corrected images during runs in 1996 and 1997. This report summarizes measurements of the wavefront quality of the outgoing beam, photoreturn signal from the sodium beacon, and radiance distribution of the guide star on the sky, and follows with an analysis of the impact of the laser on adaptive optics system performance.

1. Introduction

Corrected images using laser guide star based adaptive optics system have recently been demonstrated at Lick Observatory [1]. We have performed a number of measurements of the laser beam and the resulting guide star in order to characterize its brightness and intensity distribution

The Lick system is outfitted with a number of diagnostics to observe both near and far field characteristics of the laser. Also, by changing a dichroic in the AO system, we can obtain high resolution images of the guide star spot in the sodium layer. Here, we present the results of guide star measurements taken over the past two years, with an analysis of the guidestar's characteristics on the performance of the AO system. Some straightforward modifications to the laser system are currently planned that should improve the beam quality for this year's AO operations.

2. The Lick sodium guide star laser and diagnostics system

The Lick laser is a 20 Watts tuned dye laser having a pulse repetition frequency of 11 kHz and a pulse width of 150 ns that operates at a frequency in the middle of the sodium D_2 line at 0.589 microns. The laser is electro-optically phase modulated to broaden it to 1.5 GHz line width, producing a spectrum that attempts to address all of the atoms in the Doppler-broadened absorption line of mesospheric sodium, and thereby avoiding saturation effects due to the high peak power of the pulsed laser. We refer the reader to earlier work [2] for more details of this laser system.

The laser light is projected from a 30 cm diameter projection optic located off the side of the Shane 3 meter telescope, with 1 meter separation between the output optic and edge of the Shane aperture (Figure 1). The beam itself is square, the shape of the last dye amplifier channel, and has been measured at 14 cm on a side. This is somewhat smaller than can actually be accommodated by the last optic. The laser system contains a diagnostic package that samples some of the outgoing laser light for near and far-field quality, as well as establishes pointing and centering control. The near and far field intensity images are recorded with standard 8-bit digital cameras, and the wavefront phase is measured with a Hartmann sensor.

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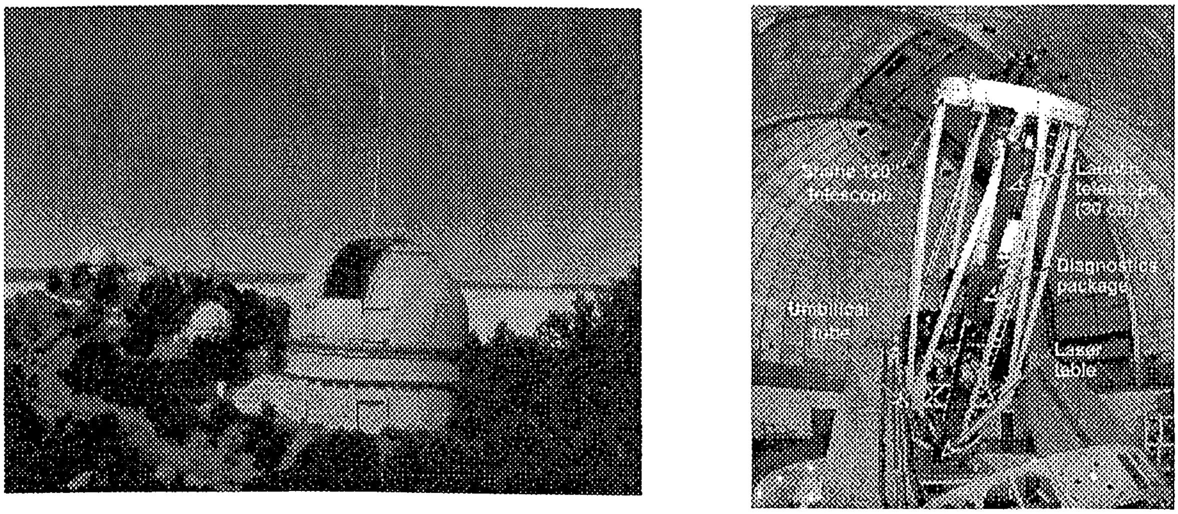

Figure 1 Left: Laser beam exiting the Shane telescope dome. Right: Laser mounted on the side of the 3 meter telescope.

3. Guide star return signal

Figure 2 shows measurements of laser guide star return flux from 1996 and 1997 laser guide star runs. The return flux shows the same variability with season that was observed in earlier lidar measurements of sodium abundance by Gardner [3]. The AO system control loop had enough signal to lock at 55 Hz sample rate in the periods of low sodium (May and July), and at 200 Hz in periods of high sodium (September, October, and November). Improved images of astronomical objects have been obtained only in the high seasons.

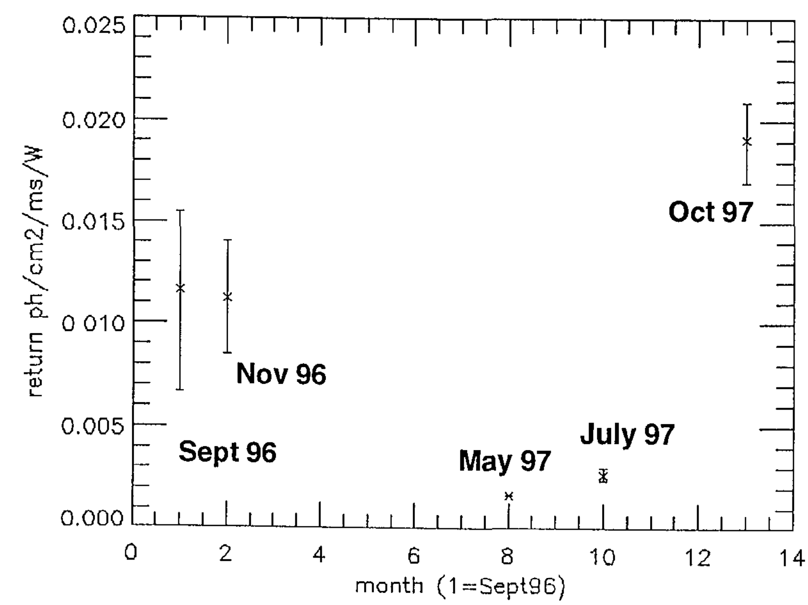

Figure 2 Normalized laser guidestar return signal over a two year campaign. Bars indicate variation night to night during a run. After accounting for system throughput, and assuming a linear sodium response model, the return signal of 0.015 photons/ms/cm^2/Watt corresponds to a sodium column density of 5×10^9 /cm^2.

4. Outgoing beam quality

Near and far-field images of the outgoing beam are shown in Figure 3. With the power amplifier turned off (preamp power level) the beam is fairly uniform, and the far field pattern resembles that of a diffraction-limited square beam pattern. The distance from the center to the first zero in the diffraction pattern is 0.87 arcseconds on the sky.

With the laser amplifier operating at 7 Watts, the far field shows some blurring of the central lobe and with some energy entering the next order, particularly in the x direction (this is the direction of the pump light in the amplifier). There is also light beginning to appear in a halo about 4 arcseconds in radius. (Note that the log scale exaggerates the low level intensities). At this power level, roughly 35% of the energy of the laser is within the central core of the far field spot. This is to be compared with 83% theoretical maximum in the diffraction-limited case.

At 18 Watts output power, the far field spot shows considerable light in the halo, with spot widening favoring the x direction. At this power level, 25 to 30% of the energy is in the central core. The near field beam shows a slight change to a trapezoidal shape, possibly due to non-uniform thermally induced focusing in the amplifier dye cell.

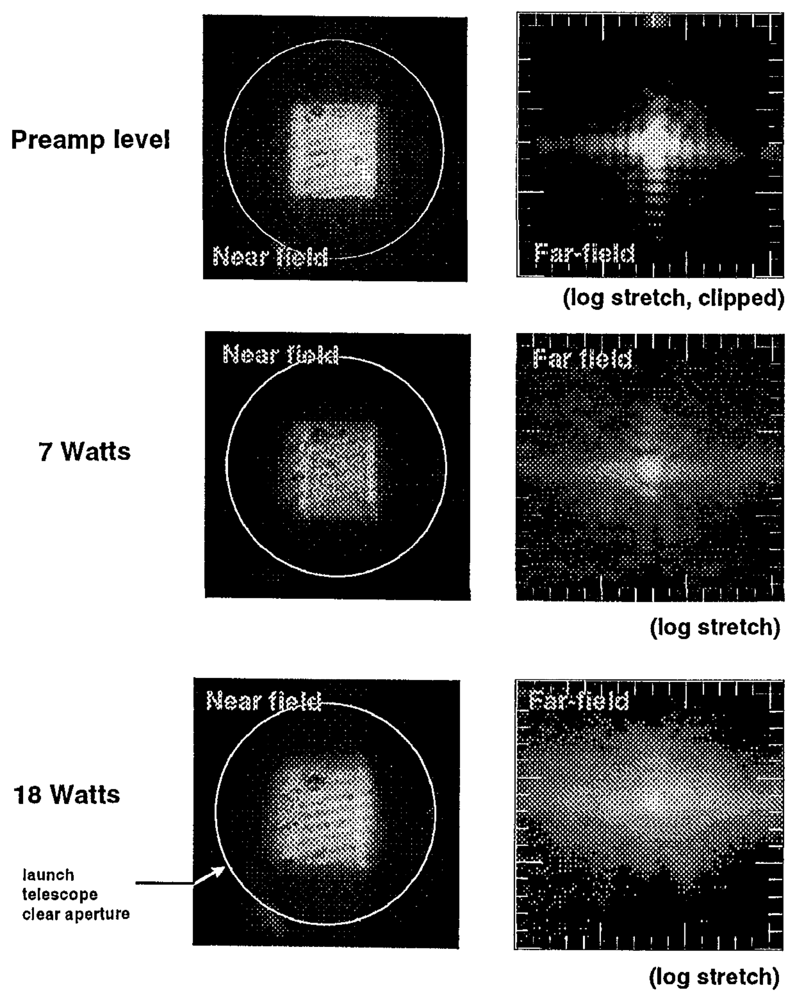

Figure 3 Near and far-field images of the exiting laser beam. Tick marks on the far-field images represent 1 arcsecond intervals on the sky. The circle on the near-field image indicates the 30 cm diameter of the final optic of the launch telescope

5. Images of the guidestar on the sky

One night in October, 1997 was dedicated to observing the laser guide star spot with the receiving telescope. With the dichroic splitter removed from the AO system, the guide star light travels down the science path of the system. A Photometrix visible light CCD was used to take long exposure images at 0.05 arcsecond resolution.

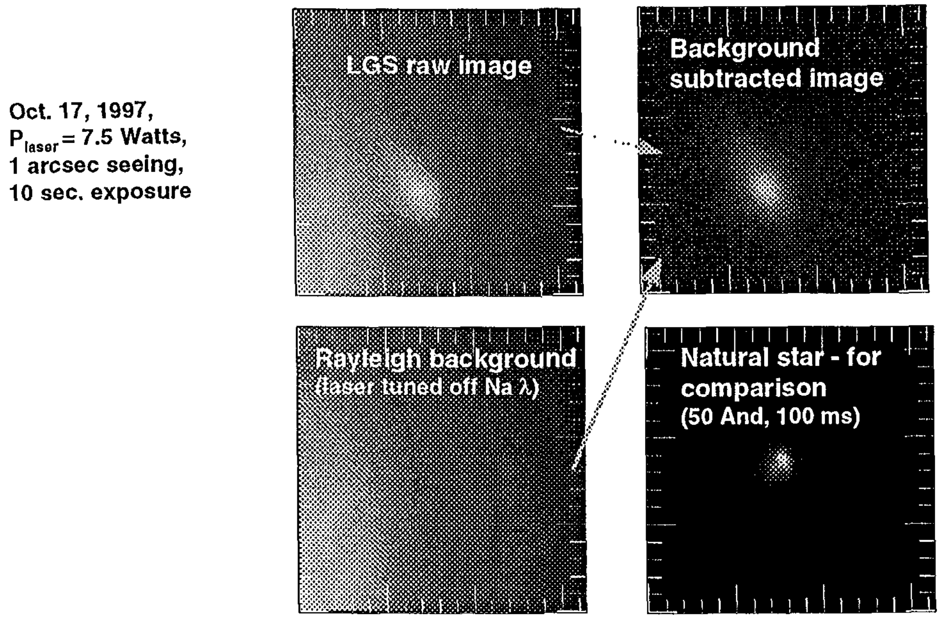

Figure 4 Images of the guide star and a natural star taken with the receiving camera (Photometrix CCD, 0.05 arcseconds/pixel plate scale). The tick marks indicate 1 arcsecond intervals on the sky.

We compare the encircled energies for the outgoing laser profile to that of the observed LGS spot in Figure 5. The energy curve of the 7.5 Watt laser guide star is in approximate agreement with the 7 Watt outgoing far-field spot convolved twice (once for upgoing path, once for downgoing path) with the atmospheric PSF.

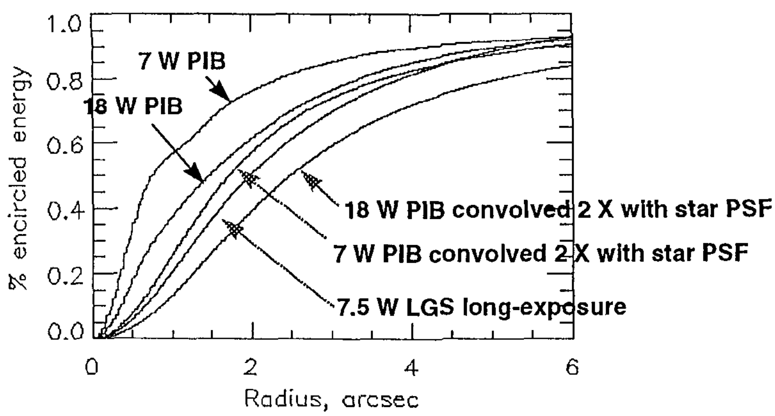

Figure 5 Encircled energy of the outgoing laser far field images (labeled PIB) compared with the long exposure image of the laser guidestar with the receiving telescope (LGS long-exposure).

6. Impact on system performance

Wavefront error depends on guide star spot intensity distribution according to:

$$\sigma_{\mathrm{SNR}} = \chi\, d\, \frac{\int_{\infty}^{\infty} dy \int_{\infty}^{\infty} dx\, f(x,y)}{2\int_{-\infty}^{\infty} dy\, f(0,y)} \times \frac{1}{\mathrm{SNR}} \tag{1}$$

where $f(x,y)$ is the distribution of light on the detector (x and y given in units of angle on the sky), SNR is the signal to noise ratio on the detector, d is the Hartmann subaperture size, and χ is a factor that accounts for AO control loop averaging. The factor in the middle, the ratio of integrals of the light distribution, is a measure of the spot size which has units of angle on the sky. The wavefront error (which is in distance units, depends linearly on the spot size factor and inversely on the brightness (through the signal-to-noise ratio).

There can be significant Strehl improvement by making the spot smaller, as shown in Table 1 where we calculate the spot size factor and error contribution for several guide star cases. A natural star has the smallest spot size error contribution. The measured far-field laser spot at each laser power was convolved with the seeing (star) to get an estimate of the contribution from laser guide star spot size. In the worst case at the 18 Watts level, the laser guidestar spot size factor is almost a factor of 3 larger than that of the natural star. A perfect laser guide star, one with a diffraction-limited square-beam far-field pattern, will have a spot size factor much closer to the ideal natural star case.

Table 1 Wavefront error contribution for several guide star cases

	Spot Size Factor	SNR	σ_{SNR}	Strehl Contribution at λ=2μm
Star	1.05 arcsec	20.8	123 nm	0.86
LGS 18 watts * star	2.97 arcsec	20.8	340 nm	0.32
LGS 7 Watts * star	1.74 arcsec	15.5	268 nm	0.49
"Perfect" 18 Watt LGS * star	1.28 arcsec	20.8	149 nm	0.80

The wavefront error contributions shown in Table 1 should be compared with the other dominant sources of wavefront error in the Lick AO system: the fitting error (due to the finite number of actuators on the deformable mirror), which is 130 nm rms, and the servo following error which is 180 nm rms (assuming a sampling frequency of fs=200 Hz, and a Greenwood frequency of fg=100 Hz).

7. Planned improvements to the Lick laser

Improvements to wavefront quality will result in a smaller guide star spot with reduced halo, thereby decreasing the wavefront measurement error term. Our plans are to incorporate what we have learned in developing a second-generation sodium guidestar laser (to be delivered to the Keck Observatory) back into the Lick system. In particular, wavefront quality will be significantly improved by implementing a better method of sending the light through the dye amplifiers. In the new configuration, the beam is reflected once off a wall of the amplifier dye cell rather than going straight through, with the result being that dye medium induced wavefront aberrations tend to average to zero. This geometry also allows a round instead of square beam to pass through the (rectangular shaped) dye cell, which gives a better fill factor on the final projecting optic.

Initial measurements of the Keck laser in the laboratory are quite encouraging. Enclosed energy fraction in the central lobe remained above 70% (compared to 30% for Lick and 83% for theoretical diffraction-limited) at full power for the duration of an 8 hour hands-off test run (Figure 6).

The straightforward conversion of the Lick laser to bounce-beam will take place before this summer's runs.

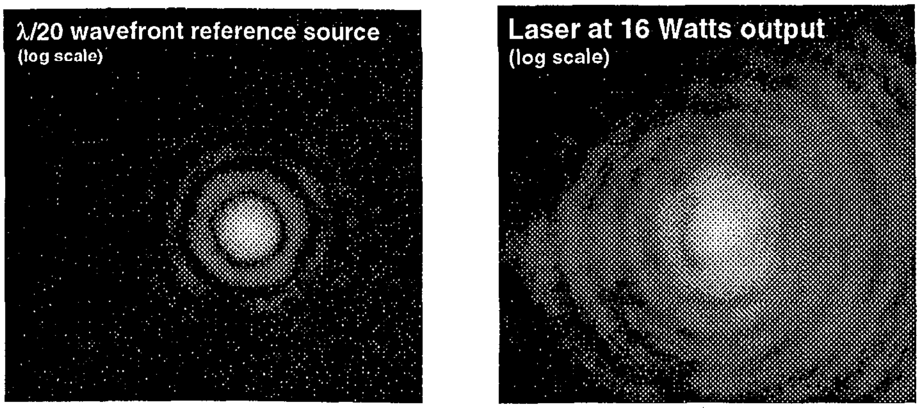

Figure 6 Laboratory test results from the Keck sodium guidestar laser. The far-field beam pattern has greater than 70% of the laser energy in the central diffraction-limited core.

8. Conclusions

During our observations in 1996-1997, we observed large seasonal variation in sodium guidestar return. The seasonal variation agrees well with sodium abundance variations observed by Gardner et. al. The Lick laser guide star system has operated closed loop at 55 Hz sample rate during the low season, and at 200 Hz in the high season. Improved images have been achieved only in the high season.

The Lick laser presently produces a $\theta_{50} = 4$ arcsecond, $\theta_{80} = 8$ arcsecond spot at 18 watts output power in 1 arcsecond seeing. 30% of the outgoing energy is in the diffraction-limited core (0.87 arcsecond radius). This yields a 340 nm rms wavefront measurement error contribution (compare to 130 nm of deformable mirror wavefront fitting error).

The new bounce-beam amplifier configuration should increase effective spot radiance by a factor of 2. This is due to both better beam quality and a larger, round instead of square, beam. This should result in a 150 nm rms wavefront measurement error contribution. Initial results from tests with the Keck laser at high power have demonstrated the ability to put 71% of the energy in the central core.

References

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2. Friedman, H.W., et. al., **SPIE**, Vol 2534, 150-160, 1995.
3. Gardner, Welsh, and Thompson, **Proceedings of the IEEE**, v78, 11, 1990.

Acknowledgment

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