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Recent Science and Engineering Results with the Laser Guidestar Adaptive Optics System at Lick Observatory

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ABSTRACT

The Lick Observatory laser guide star adaptive optics system has undergone continual improvement and testing as it is being integrated as a facility science instrument on the Shane 3 meter telescope. Both Natural Guide Star (NGS) and Laser Guide Star (LGS) modes are now used in science observing programs. We report on system performance results as derived from data taken on both science and engineering nights and also describe the newly developed on-line techniques for seeing and system performance characterization. We also describe the future enhancements to the Lick system that will enable additional science goals such as long-exposure spectroscopy.

Keywords: Adaptive Optics, Laser Guide Star, Lick Observatory, Astronomy

1. INTRODUCTION

The adaptive optic system and laser were first mounted on the Lick Observatory 3-meter Shane telescope in 1995 with the goals of achieving the first sodium guide star corrected adaptive optics images and of being a prototype for the Keck AO system. In 1996, the LGS corrected image was demonstrated[1]. Since then, we have been striving to make the Lick AO system an efficient facility instrument for science observation.

In 1998-1999, we made significant changes to the AO optical bench, motor system, and software in order to make the system more efficient, stable, and functional for science observing in both natural guide star (NGS) and laser guide star (LGS) modes. Also, in November 1998, the new infrared camera, IRCAL, was commissioned. This camera has plate scale and pupil matched to the f/28 AO system output beam.

The AO has been used routinely for science observations in NGS mode for about three years. Typical science projects include detection of dim binary star companions to stars known to have planets and characterization of galaxies with active cores. These programs take advantage of the AO system's ability to repeatedly produce Strehl ratios > 0.5 in K band (in good seeing sometimes as high as 0.8) with reasonable observing efficiency.

During the 2000 and 2001 seasons we made significant automation upgrades, improved the observing procedures, and tested the efficiency of LGS observing mode using typical science observing sequences and target lists. The system can now consistently produce images with greater than 0.5 Strehl in K band using tip/tilt guide stars as far as 50 arcseconds off axis and as faint as 16'th magnitude[2]. Since the tip/tilt guidestar in LGS mode can be much dimmer than the wavefront sensing natural guidestar in NGS mode, and, in addition, the tip/tilt isokinetic angle is much lager than the wavefront isoplanatic angle, the resulting sky coverage is much larger in LGS mode, approximately 50%, as compared to less than 1% in NGS mode.

Regular, "facility-mode," science LGS observing began in 2001 and continues through the 2002 season, in addition to the engineering test observing. During engineering nights we tested new procedures for quickly acquiring the laser guide star into the AO wavefront sensor and also implemented an efficient procedure for focusing the launch telescope on the sodium layer.

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The main impediment to LGS science observing in 2001 was the constant (every 15 minutes or so) shutdown for satellite overcrossings. In early 2002, Space Command seems to have relaxed its laser illumination criteria. Since then they have not required a single satellite shutdown, although they still require that we clear our targets 2 days in advance. Freedom from this hindrance has made all the difference in allowing LGS science observations to be feasible and productive.

There is an ongoing project to mitigate the flexure in the AO system caused by changing gravity vector (the AO system is mounted on the cassegrain focus). The flexure causes a slow drift of the closed loop image on the science camera as the reference point (the tip/tilt sensor) and the science camera sag with respect to each other. Compensating for this will enable long-exposure imaging and spectroscopy. Tests in 2001 demonstrated that the flexure is reasonably repeatable and predictable, so we plan to follow up by adding an encoder-based compensation scheme using the field-steering mirrors later this year.

2. SYSTEM DESCRIPTION

The Lick AO system uses a Hartmann sensor and piezo-actuator deformable mirror. The wavefront sensor is a Lincoln Laboratories 64x64 pixel CCD built into an Adaptive Optics Associates camera which has 6 electrons/pixel read noise and frame rates to 500 Hz. The Hartmann grid samples the 3-meter primary with 80cm secondary obscuration with 40 illuminated subabertures, with subaperture diameter d=43cm. This sampling enables high bright-guidestar Strehls in the K band under normal seeing conditions at Lick. The wavefront reconstruction is based on the least-squares algorithm which is implemented on a parallel processor board. The deformable mirror has 61 active actuators arranged in a hexagonal grid. The AO system produces an f/28.6 output beam which is sent to an infrared science camera, IRCAL[3]. This camera has a 256x256 pixel HgCdTe PICNIC array sampled at 0.076 arcsec/pixel, which is adequate for Nyquist sampling in the K band.

The system layout allows for field guidestar selection and nodding during science observations without moving any optical surfaces in front of the science camera, an important feature for minimizing changes in the IR background. Field selection is accomplished with a pair of field-steering mirrors in the "diagnostic" arm, i.e. the path of the visible light to the wavefront sensor. Since there are non-common path optics after the diagnostic split (most notably the powered optics in the IR camera dewar), the system must be "image-sharpened" to eliminate the non-common path aberrations. The procedure consists putting a diffraction-limited fiber source (artificial stimulus) at the telescope focus in front of the AO system and tuning 10 Zernike modes in closed-loop to maximize Strehl ratio at the science image plane. Typical internal Strehl of greater than 0.9 in the BrG filter (2.16 microns) is attained.

The laser guidestar beacon is generated using resonant fluorescence from the mesospheric sodium layer at 90 km altitude. A dye laser tuned to the 589 nm Sodium D_2 line projects a beam from the side of the Shane telescope. The laser has averaged about 11 Watts output power (measured just before the final lens of the projector telescope) during the recent science observation runs. The beam quality is diffraction limited, Strehl ~0.8, and produces a beacon of about 1.8 arcseconds full-width-half-max, as seen in the telescope guider.

3. SUMMARY OF AO RUNS, 2001-2002

Table 1 summarizes the AO run statistics over the past two years. The night is deemed successful if astronomers take home sufficient data for science analysis, i.e. images of at least one science target and associated calibration stars. Equipment breakdowns or weather conditions can circumvent this. We haven't categorized bad seeing conditions bad weather as this is a grey area open for interpretation; even 0.1 Strehl can sometimes be useful. Low laser power however, is an equipment problem. Weather at Mt. Hamilton is generally cooperative in the summer so we found that astronomers took home data 86% of NGS nights, and 56% of LGS nights. We were somewhat plagued by equipment problems. Loss of observing time was minimized however through heroic last-minute scrambling by the Observatory to reschedule observing nights. Six LGS nights in Mar 2001 (4 engineering, 2 science) were "lost" due to the laser control computer breaking down; NGS nights were substituted in their place. The April 2002 AO run rescheduled to May when the AO system real-time control computer broke down. We are having to reschedule the August 2002 run because this same computer has broken down again. Plans are to upgrade this problematic computer with new equipment this winter.

Table 1. Summary of AO runs, 2001-2002

		total	took data home	lost to weather	lost to equipment problems
2001	NGS eng	0	0	0	0
	NGS sci	34	27	7	0
	LGS eng	10	3	1	6
	LGS sci	16	8	3	5
	Total 2001	60	38	11	11
2002	NGS eng	3	2	0	1
	NGS sci	19	19	0	0
	LGS eng	2	2	0	0
	LGS sci	16	10	3	3
	Total 2002	40	33	3	4
Total 2001, 2002	NGS eng	3	2	0	1
	NGS sci	53	46	7	0
	LGS eng	12	5	1	6
	LGS sci	32	18	6	8
	Total 2001, 2002	100	71	14	15

During regular LGS observations, the AO system is operated by an instrument specialist (Ellie Gates) and the laser system is operated by a laser technician (Kostas Chloros). NGS operations are routine enough that an AO knowledgeable observer can take care of both the AO system and IR camera operation, after initial setup in the early evening by the instrument specialist.

4. SCIENCE OBSERVATIONS

2001 saw the first regular science observing in LGS mode. A number of papers have been published or are in print reporting NGS science observing results. Typical science projects include detection of dusty nebula around young stars[4], detection of dim binary star companions to stars known to have planets[5], analyzing the composition of Neptune's tropospheric clouds[6], detection of host galaxies associated with quasars[7], and asteroid moon orbit determination[8]. Along the lines of AO engineering research, Steinbring et. al. have observed star clusters and binary pairs to study the anisoplanatic effect on PSFs[9].

5. STATISTICS OF SEEING AND AO CORRECTION

Since 2000, we have been routinely collecting AO performance data to continue to formulate observation planning tools for astronomers. From this data we've started to build up a statistics database for AO system performance and seeing conditions.

Seeing is characterized by Fried's transverse coherence length, r_0. Seeing is measured using the diagnostic data from the AO system during closed loop operation, since the closed-loop DM actuator commands are indicative of the phase aberrations. Actuator voltage was previously calibrated to wavefront phase (in microns) by correlating the DM data to open-loop full-width-half-max measurements, taken near the time that the closed-loop diagnostic data was recorded. These full-width-half-max data were taken with the primary mirror aberrations statically corrected by the AO and the atmospheric tip/tilt loop closed to remove wind shake. About 200 datasets were correlated. Data collected over two years show the statistical spread of r_0 shown in Fig 1. The histogram shows what appears to be a log-normal distribution with a maximum likelihood seeing of 7 cm but a median of 10 cm (r_0 at $\lambda = 0.55$ microns). Using a $\lambda^{6/5}$ scaling of r_0 with wavelength, the r_0 in K-band (λ=2 microns) has a median of 47 cm, compared with the 43 cm Hartmann sensor sampling, implying a median bright-star Strehl of about 0.4. Fig 2 shows the seasonal variation of seeing conditions (bars indicating the median for each month) with a general trend toward better seeing in the late summer and fall.

Greenwood frequency (Fig 3) can be determined by detecting a break in the temporal power spectrum of closed-loop actuator data at a frequency that is indicative of the wind clearing time of the 3-meter aperture. This measurement is really only valid when there is a single layer of turbulence, which occurs in about 50% of our measurements. The histogram of Greenwood frequencies shows roughly even distribution between 5 and 20 Hz. With a bright guidestar, the AO system can operate at a frame rate of 500 Hz and achieve a closed-loop correction bandwidth of 50 Hz. Thus for bright stars the bandwidth error is small, but for dimmer stars and lower frame rates this can be a limiting factor.

NGS Strehl performance vs seeing is shown in Fig 4 for data taken from 2000 to 2002. Strehl generally improves with seeing, but there is of course variation due to other factors, most notably, brightness of guide star. The open diamonds indicate a set of dim guidestar cases, where photocounts were less than 100 photons/subaperture/frame. Fig 5 plots Strehl vs Greenwood frequency, showing the general trend of Strehls improving as Greenwood frequency decreases. Again, the dim guidestar cases are at the low end, indicating that wavefront measurement error dominates performance in these cases.

Fig 6 shows the LGS Strehl data from 2001-2002. We note that for conditions where r_0 >~15 cm, the LGS population is distributed similarly to the NGS population, but as r_0 decreases below 15 cm the LGS performance appears to degrade rapidly. This can be explained by a number of factors. Decreased r_0 will broaden the full-width-half-max of the laser spot in the mesosphere, since the laser beam must traverse up through the atmosphere. A 1.8 arcsecond spot size is obtained in good seeing conditions. Blurring the guidestar spot is equivalent to reducing the laser power, since Hartmann centroiding accuracy is proportional to spot radiance. Furthermore, upgoing beam wander is increased as seeing degrades. Although an uplink tip/tilt loop acts to keep the average Hartmann centroids centered in quad-cells, the loop performance degrades with seeing, again further blurring the spot as it appears on the Hartmann sensor. A combination of these factors all act to more rapidly degrade LGS performance than NGS. Since the median seeing at Lick is 10 cm (and if this trend is borne out by additional data) we can see that the LGS mode may only be capable of producing corrected AO images in about half the observation nights, favoring the late summer and fall. An increase of output laser power could improve this percentage.

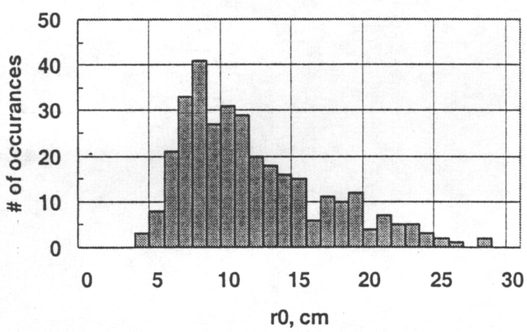

Fig 1. Histogram of seeing conditions 2000-2002. r_0 is referenced to λ=0.55μm

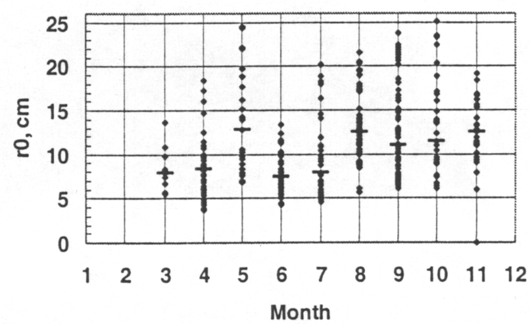

Fig 2. Seasonal variation of seeing, 2000-2002. Horizontal bars indicate monthly median r_0.

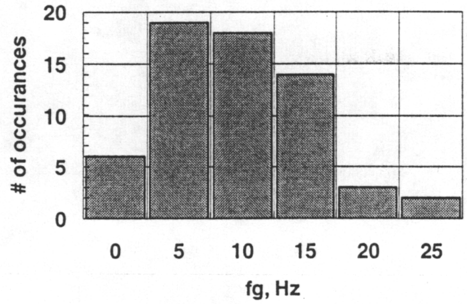

Fig 3. Histogram of Greenwood frequencies (referenced to λ=0.55μm).

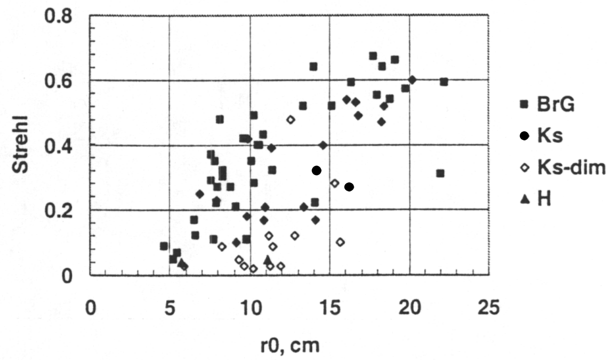

Fig 4. Strehl performance vs seeing conditions (NGS mode).

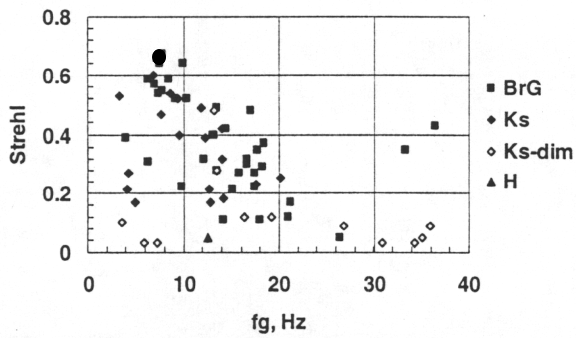

Fig 5. Strehl performance vs Greenwood frequency.

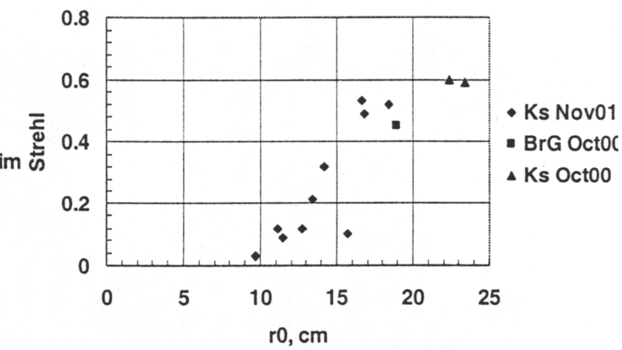

Fig 6. Laser guidestar AO Strehl performance vs seeing conditions.

6. FUTURE UPGRADE PLANS

In 2001 and 2002 we collected data to measure flexure within the AO system, the AO system with respect to the guider, and the AO system with respect to the laser. Since efficient astronomy observations, particularly in laser guide star mode, require that alignments be restored quickly at each new observation target, we hope to develop a predictable model of the flexures so they can be compensated semi-automatically. Flexure mitigation is an important component of the effort to enable long-exposure AO spectroscopy. Without such compensation, there is long-term drift in the position of the wavefront sensor with respect to the science camera that will drive the science object out of spectrograph slit (~2 diffraction limits wide) in about 15-20 minutes. Necessary hardware for the flexure compensation will include external position encoders on the field steering mirrors.

We plan to replace the aging real-time AO control computer that has caused significant down time during the 2002 season. By 1994 standards, this was a state-of-the-art specialized high speed parallel processor. Today, off-the-shelf computer hardware (Pentium PCs) can handle this same control task. Over the past several years, the adaptive optics group at LLNL has developed a generic approach to AO real-time controller hardware/software design using commercial off-the-shelf hardware and a modular object-oriented software which has been utilized in a number of diverse adaptive optics applications. We plan to leverage this experience to refurbish the Lick real-time controller and at the same time take advantage of extra CPU processing power to incorporate enhanced on-line diagnostics that will provide useful information simultaneous to the science observations. The laboratory integration of the new controller will take place in the winter of 2002/2003.

7. CONCLUSION

The AO has been used routinely for science observations in NGS mode for about three years and in LGS mode for about one year. The AO system routinely produces Strehl ratios > 0.5 in K band (in good seeing sometimes as high as 0.8) with reasonable observing efficiency. We have collected statistics on the seeing and system performance in both NGS and LGS mode. NGS mode is generally useful year round but LGS mode seems to require that seeing conditions be better than the median in order to produce diffraction-limited images. These conditions occur most often in the late summer and fall. Near-term upgrade to the system includes a new real-time control processor that will enable simultaneous PSF estimation and other real-time diagnostics useful to data reduction. Sodium laser power greater than 11 Watts would help improve the LGS success percentage but such lasers are not yet available.

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