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ABSTRACT

Recent results from the Laser Guide Star Project at Lawrence Livermore National Laboratory are presented. Photometry of the return signal has shown that the photon return is approximately 10 photons/cm²/ms at the pupil of the receiving telescope in agreement with a detailed model of the sodium interaction. Wavefronts of the laser guide star have also been measured with a Shack-Hartmann technique and power spectra have been shown to agree with those of nearby natural stars. Plans for closed loop demonstrations using the laser guide star at LLNL and nearby Lick Observatory are discussed.

1. INTRODUCTION

The use of a sodium-layer, laser generated guide star has been proposed as a key ingredient of an adaptive optics system to correct large astronomical telescopes.¹ Although several groups have measured the return signal from such guide stars,²⁻⁵ no tests with lasers sufficiently powerful to close a control loop have been reported. Lawrence Livermore National Laboratory is preparing a feasibility demonstration using a laser system developed for atomic vapor laser isotope separation (AVLIS) for this purpose. The laser system, described in more detail elsewhere,⁶ consists of a set of 12 chains of Copper Vapor Lasers which pump a chain of dye lasers to produce narrow bandwidth, tunable light in the visible region. Using this laser system, over 1200 W of 589 nm light has been propagated into the atmosphere with a repetition rate of 26 kHz and wavefront flatness error of less than 0.03 waves rms. The bandwidth of the laser, nominally 50 MHz, has been reshaped to match the double-bumped distribution of atmospheric sodium⁷ using a phase modulation scheme. The pulse duration of the dye lasers is about 40 ns full width at half-maximum (FWHM) which, for this power level and repetition rate, results in a peak laser flux which exceeds the saturation flux by an order of magnitude. An optical scheme⁶ to stretch the output pulse to avoid saturation is undergoing tests but the results described in this paper have not been generated using that apparatus.

2. EXPERIMENTAL ARRANGEMENT

The experimental arrangement for the results described in this paper is shown in Fig. 1. Light from the Rayleigh plume is filtered out of the cameras using a field stop at the Cassegrain focus of the 1/2 meter receiving telescope. A separation between the telescope and the beam director of 5 meters allows for a 10 arcsec pinhole to separate the guide star from the top of the Rayleigh plume while producing minimal elongation of the guide star. Two cameras record the data: (1) a Photometrics series 200 CCD camera for long integration times in the imaging mode and (2) a Kodak Motion Analysis System, model 1012 CID camera in conjunction with a lenslet array as a Shack-Hartmann wavefront sensor. The lenslet array, when referenced to the 50 cm pupil of the telescope, has a center-to-center spacing of 8.4 cm with a clear aperture of 7.6 cm.

Figure. 1. Configuration for the laser guide star experiment.

3. PHOTOMETRY OF THE LASER GUIDE STAR

The laser guide star and Rayleigh plume were recorded with the Photometrics camera as shown in Fig. 2. An illustration of the separation between the Rayleigh plume and the laser guide star is shown in the contour plot at a laser power of 32 W in Fig. 3. At higher laser power levels, the separation is not as well defined. Along with finer scale pinholes, the pulse stretcher will help since the contrast between the laser guide star and the Rayleigh plume will be increased. By measuring the return signal from the laser guide star and comparing it to the signal from various well known stars nearby, the photometric plot shown in Fig. 4 is generated. The model prediction is the result of a calculation using 24 level Bloch model for the sodium atom.⁸ At the highest laser power, the return signal corresponds to approximately 450 photons/ms for the subapertures represented by the lenslet array spacing and clear aperture. Since the Kodak camera which has a quantum efficiency of 5%, requires a minimum of a few thousand photons to obtain good accuracy for the centroid measurement of the Hartmann spots, the minimum sampling time for this laser configuration would be several milliseconds. Since sampling times for the wavefront measurement are anticipated to be of the order of one millisecond, it is evident that either the laser pulse must be stretched to reduce saturation effects or a more sensitive wavefront camera must be found. Efforts are underway to procure a backside illuminated, CCD camera based upon a Lincoln Laboratory chip, improve the quantum efficiency of the Kodak camera and stretch the pulse to reduce saturation effects. It is anticipated that one or more of these efforts will occur in the near term permitting a closed loop demonstration of an adaptive optics system.

Figure 2. Laser guide star and Rayleigh plume for laser powers ranging from 7 W to 1100 W.

Figure 3. Contour plot of the laser guide star and end of the Rayleigh plume for a laser power of 32 W.

Figure 4. Irradiance of the sodium-layer laser guide star at the pupil of the telescope for laser powers up to 1100 W. The atmospheric transmission during these tests was estimated to be 60% as determined from measurement of several natural "photometric" stars of well known irradiance.

4. WAVEFRONT MEASUREMENTS

An example of the wavefront data taken with the lenslet array and Kodak Motion Analysis camera is shown in Fig. 5. These data are used to correct for stray light which may not have been blocked by the pinhole. The photograph on the left is taken with the laser modulation on and the center wavelength tuned to the sodium resonance at 589 nm while the photograph on the right is taken with the modulation turned off and the center wavelength tuned off resonance by approximately 1 GHz. The Rayleigh plume is not affected by the off resonance situation while the sodium fluorescence is extinguished. In this case, the pinhole was effective in blocking stray light.

Figure 5. Hartmann spot array from the laser guide star at 1050 W. The photographs are of a single frame with exposure times of 1/125 sec with the laser tuned on (left side) and off (right side) the sodium wavelength.

In Fig. 6, a sequence of Hartmann exposures of laser and natural (beta Andromeda) guide stars are shown. The Hartmann spots for the natural guide star are considerably smaller than are those for the laser guide star indicating that the spot size of the laser guide star is resolved by the subaperture. This agrees with an image measurement of the laser guide star shown in Fig. 7 which shows the guide star to have an angular extent of about 6 arcsec, as compared to a resolution limit of a 7.6 cm subaperture of about half that amount.

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Figure 6. Hartmann exposures, both single frame and multiple frame averages, of laser guide stars at about 1000 W and a natural guide star (beta Andromeda). The images on the left are single frames and on the right are averages of all the frames. The top images are of a natural guide star, beta Andromeda, taken at 500 f/s. The middle and bottom images are of the laser guide star taken at 125 f/s and 250 f/s, respectively.

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Figure 7. Image of the laser guide star taken with the Photometrics camera showing the FWHM diameter to be approximately 6 arcsec.

The reason for the increased width of the laser guide star as compared to the FWHM width of the incident laser beam is the degree of saturation of the laser flux. For a highly saturated laser beam, the wings of the spatial distribution will also induce fluorescence in the sodium layer causing the FWHM emitted distribution to be larger than the FWHM of the incident beam. When the pulse stretcher is implemented, it is expected that the size of the laser guide star will be closer to the resolution limit of the subaperture.

From data such as that shown in Fig. 7, the power spectrum of the slopes of the Hartmann spots can be calculated and an example of such data is shown in Fig. 8. The power spectrum of the natural star follows the expected slope down to the sampling limit of half the frame rate or about 250 Hz. The power spectrum of the laser guide star also follows the expected value until the signal reaches a noise floor somewhat before the sampling limit of 60 Hz. The higher noise floor is due to centroiding errors introduced by the larger spot which is resolvable by the subaperture size. Again, reducing the peak laser flux by stretching the pulse will improve this situation.

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Figure 8. Slope power spectra for laser and natural guide stars. The power spectra for several Hartmann spots are calculated from the Kodak camera output and averaged to produce the data.

5. CONCLUSIONS AND FUTURE PLANS

Photometry of the laser guide star has shown that the photon return agrees with a detailed atomic physics model. When the pulse stretcher is implemented, the return signal should increase while the spot size decreases thereby improving the degree of atmospheric correction. Wavefront measurements of the laser guide star agree with those of natural sources to within the limitations of the spot size and sampling frequency. The goal of the demonstration at LLNL is to close an adaptive optics loop consisting of a tip-tilt mirror, deformable mirror and a sodium-layer laser guide star, on a one-half meter telescope within a year.

In addition to demonstrations at LLNL, the plan includes demonstrations at nearby Lick Observatory. The first demonstrations involve high speed wavefront measurements and speckle observations on the Lick one meter telescope. These will be followed by a demonstration of a closed loop tip-tilt mirror and deformable mirror, on the one meter all using natural guide stars as the reference source. Following a successful demonstration of the sodium-layer laser guide star system at LLNL, a laser system will be constructed at Lick for integration into the closed loop adaptive optics system. Eventually, the plan is to move all these systems onto the 3 meter telescope at Lick for astronomical observations. The final goal for this effort is to install an adaptive optics system based upon a sodium-layer laser guide star on the Keck 10 meter telescope at Mauna Kea, Hawaii. Discussions are underway with Keck personnel to define a phased approach similar to the plan for the Lick 3 meter telescope.

6. ACKNOWLEDGMENTS

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