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Sodium-Layer Laser Guide Stars

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SODIUM-LAYER LASER GUIDE STARS

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ABSTRACT. The requirements and design of a laser system to generate a sodium-layer beacon is presented. Early results of photometry and wavefront sensing are given.

1. Introduction

Sodium-layer laser guide stars^{1,2} have the potential to allow adaptive optics systems to accomplish high-order wavefront corrections of atmospheric turbulence even for the largest ground-based telescopes. We have initiated a program whose long-term goal is to demonstrate the feasibility of closed-loop adaptive optics with sodium laser guide stars, using existing lasers at LLNL developed for the Department of Energy's Atomic Vapor Laser Isotope Separation (AVLIS) program. These copper-vapor-laser pumped dye lasers are considerably larger and more powerful than will be ultimately needed at an observatory site, but they have several immediate advantages for a feasibility experiment: they are available *now*, they have been engineered for high reliability, and the dye lasers are highly tunable and controllable in terms of line shape.

2. System Concept

Adaptive optics systems using laser guide stars must filter out the Rayleigh scattered light from the lower atmosphere. This can be accomplished by either temporal gating or spatial discrimination. In the temporal gating method, the pulse repetition frequency must be about 1 kHz which excludes many interesting laser configurations. We have chosen the spatial discrimination method in which the laser is propagated from a separate beam director and a field stop in the optical train then rejects the lower-altitude Rayleigh scattered light, as shown in Fig. 1.

Measurements at our site suggest that the parameter, r_0 , is approximately 5 cm at a wavelength of 0.5 μ . For our half-meter telescope, the parameter $D / r_0 \approx 10$ at a wavelength $\lambda = 0.5 \mu$, dropping to $D / r_0 \approx 6$ at a wavelength $\lambda = 0.8 \mu$. Based on these values, a zonal adaptive optics system optimized for operation at a wavelength of $\lambda = 0.8 \mu$ would have 9 cm subapertures, so that our half-meter telescope would require about 20 subapertures in all.

3. Site Layout

The Laser Guide Star site is located approximately 100 m from the laser building. The dye laser beam is propagated through an underground, evacuated pipe to a vacuum chamber directly under the guide star site where a pointing and centering control loop, beam diagnostics, communication equipment and safety shutters are located. The final mirror turns the beam upwards into a vertical beam tube. At the top of the beam tube is an exit window which is the final vacuum interface into the atmosphere. The laser beam shape is rectangular with dimensions of $4\text{ cm} \times 8\text{ cm}$, commensurate with a value of $r_0 \approx 5\text{ cm}$ at LLNL. At present the beam propagates to zenith with no positioning or tracking capability, as shown in Fig. 2. The experiments we report on here concern creating the guide star, performing imaging and photometry measurements on it, and recording open-loop wavefronts. A beam director was installed in the summer of 1993 but no results are available at this time.

4. Laser Requirements

The laser power required to produce a sodium beacon bright enough to close a control loop at the telescope depends upon the parameters of the sodium laser and upon the components of the control system, e.g., telescope optical efficiency, sensor quantum efficiency and noise characteristics. The *maximum* emission rate for a column of sodium atoms, assuming an illuminating laser pulse duration longer than the spontaneous lifetime (CW limit) is given by the column density divided by the emission lifetime. The

Fig. 1. Laser and beam-director configuration.

Fig. 2. LLNL Laser Guide Star site with 1100 W sodium beacon laser.

Table 1: Properties of the atmospheric sodium layer and the LLNL site.

Atomic Parameters

Sodium D2 line wavelength	λ_{Na}	589 nm
Spontaneous emission lifetime	τ_n	16 ns
Degeneracy correction factor	$g_u/(g_l + g_u)$	0.67

Atmospheric Sodium Layer Parameters

Mean column density at zenith (annual variation of factor of two)	N	$5 \times 10^{13} \text{ m}^{-2}$
Mean altitude	z	95 km
Vertical depth	Δz	10 km
Optical depth at zenith (3 GHz bandwidth)		2.5%
Emission cross section (averaged over 3 GHz bandwidth)	σ	$4 \times 10^{-12} \text{ cm}^2$

Atmospheric Propagation Parameters (for LLNL site)

Transmission coefficient, ground to sodium layer	X	0.60
Turbulence coherence length, at 500 nm (typical)	r_0	5 cm
Illuminated spot area at the Na layer	A_s	3.14 m^2
Radiating spot area at the Na layer*	A_{rad}	7.1 m^2

Wavefront Sensor (LLNL experiment)

Subaperture area	A_{wfs}	55 cm^2
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* For saturated sodium emission, A_{rad} is larger than A_s because the wings as well as the core of the illuminating profile begin to saturate.

photon rate, dN_{ph}/dt , at a detector on the ground with area equal to the wavefront sensor sub-aperture area A_{wfs} , is then given by:

$$dN_{\text{ph}} / dt \leq (A_{\text{rad}} N / \tau_n) (g_u / g_l + g_u) (A_{\text{wfs}} / 4\pi z^2) f_d X \quad (1)$$

where f_d is the duty factor of the laser and the rest of the symbols are defined in Table 1. For the values quoted in Table 1, typical of the LLNL site, the maximum photon rate at the ground based detector is $dN_{\text{ph}} / dt \leq 3.6 \times 10^8 f_d$ photons per second per subaperture.

The minimum number of photons per integration time needed to close a control loop is a function of the detector quantum efficiency and the noise floor. For a typical intensified fast-framing camera with quantum efficiency of about 5%, the minimum number of photons needed for high performance is of the order of one or two thousand. (Bare CCD's with high quantum efficiency would need far fewer photons.) For a typical atmospheric change frequency of 100 Hz, and a wavefront sampling rate of 10x that or 1 kHz, the integration time is of the order of a millisecond. Assuming an optical train efficiency of 30%, the laser duty factor, f_d , must be at least 2%.

For the experiments described in this paper, the AVLIS laser's duty factor f_d is about 10^{-3} . Hence the flux of photons per second will be lower by the corresponding ratio. These lower photon fluxes can be utilized for closed-loop operation if the integration time is made longer than one millisecond, as would pertain to atmospheric conditions characterized by lower values of the atmospheric change frequency and wind speed, or if a higher wavefront error due to a lower closed-loop bandwidth can be tolerated. An optical

pulse stretcher has been built to extend the duty factor by a factor of 16. This pulse stretcher will be used in upcoming experiments to close the control loop with 1 ms integration time.

The average laser power is determined by the laser flux required to generate approximately 1000 photons in the subaperture in the integration time of 1 ms, i.e.:

$$P_L = \frac{1000 \text{ ph}}{1 \text{ ms}} \times h\nu \times \frac{4\pi z^2}{A_{\text{WFS}}} \times \frac{1}{X^2 N \sigma} \quad (2)$$

For the values listed in Table 1, P_L @ 1000 W.

The pulse duration of the AVLIS laser is a few τ_n and a simple rate equation approach argument is sufficient to highlight the issue of saturation of the sodium layer. If the peak power at the sodium layer exceeds the saturation value, $I_{\text{sat}} = h\nu / \sigma \tau_n$, the radiation switches from the spontaneous isotropic mode to stimulated emission, and the re-radiation is in a dominantly forward direction, away from the ground-based detector. The efficiency of creating sodium backscatter therefore drops. Thus the pulse duration τ_p should satisfy the relation:

$$\tau_p / \tau_n \geq (P_L / \text{PRF}) (\sigma / h\nu) A_s^{-1} \geq (P_L / \text{PRF}) (\sigma / h\nu) r_0^2 / (\lambda z)^2 \quad (3)$$

where P_L is the average power of the laser, PRF is the laser's pulse repetition frequency, $h\nu$ is the photon energy at 589 nm, and λ is the wavelength. The second relation arises because the spot diameter at the sodium layer should be about equal to the resolution limit for a subaperture of diameter r_0 . The LLNL approach uses a high PRF laser at 26 kHz, with pulse duration of 32 nsec. Equation 3 then shows that in this case the maximum average laser power which avoids saturation is approximately 130 W. Hence, in order to avoid saturation with the 1100 W LLNL laser system, the pulse length should be stretched by at least a factor of $1100/130 = 8.5$. More detailed considerations which include accounting for the wings of the pulse shape will modify the details of this pulse-stretching requirement, but the general point is clear: to avoid saturation and obtain the highest signal return with the AVLIS laser at 1100 W average power, the laser pulse length should be stretched by at least a factor of 10.

The spectral profile of the sodium D2 line complex at the 200 K temperature in the sodium layer consists of two Doppler broadened lines each about a gigahertz wide, whose line centers are separated by 1.7 GHz. For optimum sodium excitation and re-emission efficiency, the width of the laser line profile should be comparable to 3 GHz. The transform limited pulse duration for such a spectral profile is a few tenths of a nanosecond, which is effective providing many such pulses are stacked to satisfy the pulse duration requirement discussed above. A mode locked train with such characteristics is used by Lincoln Laboratory and is an acceptable format. For longer laser pulses such as we use, the transform limited spectral profile is narrower than the sodium line-shape and phase modulation must be used to broaden the bandwidth for efficient operation. Phase modulation can be tailored to produce a spectral profile which matches the double peaked sodium distribution, thus increasing the effective backscatter cross section.

For optimum performance from a Shack-Hartmann wave front sensor, the spot diameter at the sodium layer must be comparable to the resolution limit of a subaperture with diameter r_0 . To accomplish this with the smallest beam director, a flat wavefront is needed. According to the theory of beam propagation in turbulent atmospheres, a beam of diameter r_0 with flat wavefront will not be broadened significantly beyond its diffraction limit but will wander in position at the sodium layer, relative to the background stars. This uncertainty in the position of the beacon is well known, and astronomical laser guide star adaptive optics systems must use a natural guide star to correct for this tip-tilt effect of the atmosphere. If the laser's outgoing wavefront is not perfectly flat, the spot will be larger as well as having an unpredictable position. The spot can be made smaller by increasing the diameter of the beam at the beam director, and this remedy works up to a beam diameter of about $2 r_0$. Above a beam diameter of about $2 r_0$, the spot size at the sodium layer will never be smaller than $(\lambda / r_0) z$ because of the effects of turbulence on the propagating wavefront.

Thus, laser beam qualities of about $2\times$ the diffraction limit can be tolerated at the expense of a larger beam director, but beyond that figure, the system performance will suffer.

5. The AVLIS Laser System

The AVLIS laser system presently delivers over a kilowatt of average power tuned to 589 nm at a PRF of 26 kHz. The bandwidth of the unstretched laser pulse is of the order of 50 MHz which is near the transform limit of the 32 ns (FWHM) pulse duration. The center frequency is stabilized to a few tens of megahertz for indefinite periods and using phase modulation, a spectral profile is broadened and shaped to closely match that of the mesospheric sodium atoms. The laser system contains closed-loop control systems to (1) point and track the beam, (2) correct the wavefront at low spatial and temporal frequencies, and (3) remove high speed jitter. Using these control loops within the laser, beams of 1400 W at 589 nm with corrected wavefronts (RMS wavefront error $\leq 1/30$ wave) and stabilized jitter (RMS jitter $\leq 5 \mu\text{rad}$) have been routinely delivered. With transmission losses, we currently transmit 1100 W into the atmosphere.

The AVLIS laser system is shown schematically in Fig. 3. It consists of twelve chains of copper vapor lasers (CVL's) pumping three chains of dye lasers. For the laser guide star application, one of the dye laser chains is tuned to the sodium wavelength and diverted underground to the telescope site located 100 m from the laser building. The output of the twelve-laser CVL system routinely exceeds 9000 W and the dye laser system delivers over 2 kW of tuned light with over a kilowatt in the highest power chain.

6. Pulse Stretcher

To operate the AVLIS laser at the 1100 W power level and avoid saturation, a multi-pass optical system consisting of multiple White cells has been designed and is currently undergoing laser tests in the laboratory. The concept consists of a series of four optical delay lines and 50/50 beam splitters which create a series of 16 sub-pulses stacked head-to-tail for each input pulse. Each sub-pulse in the stack is of equal magnitude, neglecting mirror losses, so that the net effect is to lower the peak power by a factor of 16. The pulse stretcher will be used in the fall of 1993 to increase the signal levels but all results shown in this report are with unstretched pulses. At astronomical sites, where the seeing is better and the laser power requirements lower, pulse stretching should not be required.

7. Beam Propagation and Photometry of the Laser Guide Star

The first laser beam propagation occurred on July 15, 1992. The event was highly visible as shown in Fig. 4. Figure 5 is a photograph of the guide star taken at a distance of four miles from the LLNL site. The length of the streak corresponds to the published thickness of the sodium layer of approximately 10 km. Figure 6 shows a visualization of data from a CCD image of the Rayleigh scattered light (right) and the sodium-layer laser guide star (round peak towards the center), taken with a laser power of 32 W. At this low power, the laser guide star is well separated from the lower-altitude Rayleigh-scattered light, and has a full width at half maximum of approximately 5 arc seconds, corresponding to a laser irradiance spot size of roughly 2 m at the sodium layer. For comparison, the diffraction limited beam spread for the 4 cm beam dimension is $\lambda/d = 1.3$ m at the sodium layer. The seeing measured on a natural star near the time this image was obtained was 3.3 arc seconds.

Fig. 3. Design of AVLIS laser system.

Fig. 4. Photograph of the laser beam overlooking Livermore Valley taken from a nearby ridge.

Fig. 5. Image of the laser guide star taken four miles from the LLNL site.

Fig. 6. Visualization of the Rayleigh scattered light (right) and sodium laser guide star (towards the center of the frame).

At higher laser powers, the width of the sodium guide star increased, reaching a FWHM of about 7 arc seconds at a power of 1100 W. We attribute this effect to the saturation of the sodium transition; as the laser power is raised, even the wings of the incident laser intensity distribution become saturated at the sodium layer. Computational models show that for a constant laser *irradiance* spot size of 2 m FWHM incident on the sodium layer, the guide star *emission* should indeed grow in diameter as the laser power is increased.

Figure 7 shows the photon flux from the sodium-layer laser guide star at the telescope aperture, as a function of the broadcast laser power. The photometric standard star Vega (α Lyr) was used as a reference, with a bandpass filter centered at 550 nm and a bandwidth of 40 nm FWHM. The solid curve represents the predictions of a detailed 24-level Bloch equation model for these conditions. At the 1100 W level the guide star is about fifth magnitude (m_V), consistent with many reports from visual observers that the guide star could be seen with the naked eye once one was 30–50 m away from the beam director.

8. Open-Loop Wavefront Sensor Measurements

We used a Shack-Hartmann wavefront sensor with the lenslet spacing corresponding to 8.4 cm. The data in Fig. 8 shows an example of the power spectrum of subaperture tilts as a function of temporal frequency, for the laser guide star ($m_V = 5.1$) and a natural star, Capella, $m_V = 0.1$. These spectra were obtained by averaging Fourier transforms of the tilts over all of the unvignetted subapertures of the Hartmann sensor. At low frequencies, both power spectra show approximately the $\nu^{-2/3}$ scaling predicted for Kolmogorov turbulence. The data for the natural star have sufficient dynamic range to also see the break in slope at about 20 Hz due to the finite size of the subapertures. In the region $20 \text{ Hz} < \nu < 100 \text{ Hz}$, the scaling is approximately $\nu^{-8/3}$ in agreement with several other researchers.

The laser guide star data only extend to 60 Hz, consistent with the use of a slower sample rate necessitated by the lower laser signal level. Nevertheless, even using the data up to 60 Hz, it appears that the noise floor for the laser guide star measurement is a little higher than that for the natural star, as expected, because of the laser star's lower signal-to-noise ratio and larger spot size.

We have used the measured wavefront slope data to reconstruct the wavefront phase. To our knowledge this is the first time that a sodium-layer laser guide star has been used for a wavefront reconstruction. Figure 9 compares three consecutive reconstructed laser guide star wavefronts (bottom row of three frames) to three reconstructed wavefronts from a natural star at the same 8 msec sample interval (top row of three

Fig. 7. Photon flux observed at the aperture of the half-meter telescope.

Fig. 8. Superposition of tilt power spectra from the laser guide star (shaded line) and the natural star (solid black line).

Figure 9. Sequence of three consecutive reconstructed wavefronts from a natural star (top row) and a laser guide star (bottom row)

Figure 10. Predicted Strehl improvement for the LENS experiment

frames). The laser and natural star wavefronts were not measured simultaneously, so they correspond to two different realizations of the turbulence spectrum. However, the average atmospheric turbulence conditions were quite similar in the two case.

The average wavefront tilt was removed from the slope data before reconstruction, by subtracting the average centroid position. Thus, the reconstructions shown in Fig. 9 portray only higher order wavefront

errors. Qualitatively the spatial and temporal scales of the wavefront distortions are similar for the laser guide star (bottom row) and the natural star (top row) although, of course, since the measurements were not simultaneous, the details of the wavefronts are quite different.

9. Implications for Closed-Loop Adaptive Optics Performance

The long-term goal of our experiment is to demonstrate the feasibility of closed-loop adaptive optics using sodium layer laser guide stars. We have used the photometry and open-loop wavefront sensor data presented to predict the performance of our planned closed-loop system using a model of the expected wavefront errors derived from statistical expressions for all the root-mean-square errors.

Figure 10 shows the Strehl ratio expected for closed-loop operation using the sodium laser guide star, as a function of the laser power, at an observing wavelength of 0.8 microns. Strehl ratios for both stretched and unstretched laser pulses are shown. The wavefront sensor is assumed to be a Hartmann sensor based on our Kodak intensified motion analysis camera, better results are predicted for a low noise, bare CCD detector. The Greenwood frequency, f_g , was assumed to be 38.2 Hz. At the 600 W power level, Strehls of about 0.3 are predicted at an observing wavelength of $\lambda = 0.8 \mu$ for the stretched laser pulse. At the same laser power, Strehls of about 0.15 at $\lambda = 0.8 \mu$ are predicted for the unstretched pulse. Thus, even for unstretched laser pulses, the Strehl should be high enough with 600 W of laser power to distinguish a diffraction-limited core in the point-spread function, for observations of objects with a sufficiently high signal to noise ratio.

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