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Controlling the Laser Guide Star power density distribution at Sodium layer by combining Pre-correction and Beam-shaping

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ABSTRACT

The Sodium laser guide star (LGS) plays a key role in modern astronomical Adaptive Optics Systems (AOSs). The spot size and photon return of the Sodium LGS depend strongly on the laser power density distribution at the Sodium layer and thus affect the performance of the AOS. The power density distribution is degraded by turbulence in the uplink path, launch system aberrations, the beam quality of the laser, and so forth. Even without any aberrations, the TE_{00} Gaussian type is still not the optimal power density distribution to obtain the best balance between the measurement error and temporal error. To optimize and control the LGS power density distribution at the Sodium layer to an expected distribution type, a method that combines pre-correction and beam-shaping is proposed. A typical result shows that under strong turbulence (Fried parameter (r_0) of 5 cm) and for a quasi-continuous wave Sodium laser (power (P) of 15 W), in the best case, our method can effectively optimize the distribution from the Gaussian type to the "top-hat" type and enhance the photon return flux of the Sodium LGS; at the same time, the total error of the AOS is decreased by 36% with our technique for a high power laser and poor seeing.

1. Introduction

All astronomical Adaptive Optics Systems (AOSs) require one or several bright reference sources to measure the atmospheric turbulence and to improve the image quality and field of view [1]. Since bright natural stars are very limited over the sky, an artificial laser guide star (LGS) is generated by Rayleigh backscatter or resonance fluorescence of Sodium atoms to overcome this limitation [2]. As the altitude of the Sodium LGS is much higher than that of the Rayleigh LGS and approaches the top of the atmosphere, the focal anisoplanatism error is much smaller than that of the Rayleigh LGS, especially for large aperture telescopes [3]. Thus, most existing large ground-based telescopes, such as the Very Large Telescope (VLT) [4], Keck [5], and Subaru telescope [6], and next-generation extremely large telescopes, including the Thirty Meter Telescope (TMT) [7], European Extremely Large Telescope (E-ELT) [8] and Giant Magellan Telescope (GMT) [8], are all equipped with a Sodium LGS AOS.

Several papers have carefully analyzed the performance of an AOS in correcting higher order aberrations (excluding tip and tilt aberrations) with a single Sodium LGS [1,9,10]. For an AOS with a single Sodium LGS, Hardy has analyzed the proportions of the wavefront sensor (WFS) measurement error and temporal error, which account for nearly 70% of the entire error [1].

The measurement error is a function of the spot size and signal-to-noise ratio (SNR) determined by the photon return from the LGS; both of these quantities are determined by the power density distribution at the Sodium layer. The temporal error is a function of the sampling frequency, which is also determined by photon return. The ideal Sodium LGS should be adequately compact in spot size and bright enough for wavefront detection.

Decreasing the spot size usually requires good beam quality of the laser beam, and excellent optical performance of the beam transfer and launch system [11,12]; some papers have also proposed the use of pre-correction to compensate for turbulence in the up-link optical path and system aberrations and thus decrease the power density distribution at the Sodium layer [13–15]. To enhance the photon return or coupling efficiency of a Sodium LGS, it is usually necessary to change the polarization of the pump laser to circular [16], use Sodium D_{2b} line repumping [16,17], and switch the laser between left and right circular polarization at the Larmor frequency [18]. Both of the two aspects will influence or be influenced by the power density distribution of the Sodium LGS. In this paper, we focus on how to control the power density

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distribution of the Sodium LGS to obtain the smallest measurement and temporal errors for different levels of atmospheric turbulence, and propose to combine wavefront phase error compensation by pre-correction and wavefront amplitude redistribution by beam-shaping to obtain the required power density distribution at the Sodium layer.

Pre-correction of the dynamic aberrations of the turbulence in the uplink path and the system aberrations has generated a significant amount of interest during the last two decades in the fields of free space communications [13,19,20]. In 2003, a Sodium LGS produced with higher order atmospheric compensation was nearly 50% smaller than the uncompensated beam at Starfire Optical Range (SOR) [21]. In 2004, Roggemann et al. simulated applying pre-correction to the outgoing beam to concentrate most of the laser's power in a small area [13]. From 2008 to 2010, Lick Observatory used pre-correction in projecting the LGS to reduce the spot size, which results in a corresponding reduction in the required laser power [14,15]. In 2012, Guesalaga et al. (Gemini south) proposed applying pre-correction to compensate for the dynamic aberrations and system aberrations in order to decrease the size of the LGS spot [22], with the goal of obtaining a smaller spot and potentially regulating the pattern of irradiance. In 2013, Rampy et al. analyzed that the pre-correction could be used to reduce the spot size of the LGS by a factor of two; the WFS measurement error would also be reduced by a factor of two [23]. In 2014, Norton et al. (Shane Telescope) used a micro-electro-mechanical system (MEMS) deformable mirror (DM) to correct the system aberrations in the beam transfer optics to concentrate the laser light onto the Sodium layer [12]. In the same year, the multi-conjugate AOS of Gemini South demonstrated the correction of the system aberrations of the laser in both amplitude and phase, the spot size was estimated to be reduced by up to 15% owing to pre-correction [11].

All these previous works focus on decreasing the LGS spot size using only pre-correction to obtain a compact Sodium LGS. However, the key factor that affects the performance of an AOS is the LGS power density distribution at the Sodium layer. Because of the saturation of Sodium atoms, a trade-off exists between the spot size and the photon return in optimizing the LGS power density distribution.

In this paper, we are more concerned with optimizing and controlling the LGS power density distribution at the Sodium layer to an expected distribution type. Thus, we propose a method that combines pre-correction and beam-shaping. At the Gaomeigu Lijiang astronomical observation site, the mid-value of r_0 is nearly 9 cm; in the worst case, r_0 is approximately 5 cm, and the dynamic aberrations seriously affect the power density distribution at the Sodium layer. To achieve high quality observation in the worst case and increase the observation time of the telescope, the effectiveness of the Sodium LGS after using pre-correction to eliminate the influence of the dynamic aberrations was analyzed; to overcome the saturation, beam-shaping is introduced to convert the distribution of the power density at the Sodium layer from the Gaussian type to the "top-hat" type.

In Section 2, we state the methodology for combining pre-correction and beam-shaping to obtain the lowest total error. In Section 3, the proposed method is validated by a numerical simulation; the total error (the sum of measurement error and temporal error) is calculated to test the validity of the proposed method. In Section 4, the sampling frequency and the orders of pre-correction with beam-shaping are discussed to optimize the performance of the AOS in correcting higher order aberrations (excluding tip and tilt aberrations). In Section 5, conclusions and future works are presented.

2. Methodology overview

The coupling efficiency between Sodium atoms and our Sodium laser has an optimal value. The method combining pre-correction and beam-shaping to realize the optimal value in the spot is described. This method converts the power density distribution at the Sodium layer from the Gaussian type to the "top-hat" type; the coupling efficiency values in the "hat" are all optimal, so the saturation of the Sodium atoms can be mitigated, and the measurement error and temporal error can be controlled effectively.

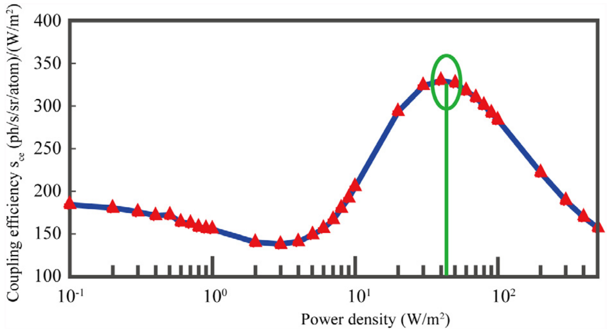

Fig. 1. Coupling efficiency of the QCW-TIPC laser. Symbols: simulation count. Line: fitting curve. Simulation conditions: repumping power fraction: 0.1, repumping frequency offset: 1.71 GHz, circular polarization, multi-mode with ideal square pulse. The green circle indicates the optimal coupling efficiency with a value of 335 photons/s/W/(atoms/m^2)/sr, the green line indicates the optimal power density of 44 W/m^2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.1. Approach of combining pre-correction and laser beam-shaping

The photon return and spot size of the Sodium LGS are determined by the power density distribution at the Sodium layer and the coupling efficiency between the Sodium atoms and the laser. The coupling efficiency is defined as follows according to Holzlöhner et al. [16]:

$$s_{ce} = \frac{\varphi \cdot L^2}{P \cdot \left(T_a\right)^X \cdot C_{Na} \cdot X} \tag{2.1}$$

where ϕ is the photon flux on the telescope (in units of photons/s/m^2); L is the vertical distance from the receiver telescope to the center of the Sodium layer; P is the laser power reaching the Sodium layer; T_a is the atmospheric transmission; $\mathrm{X} = \sec(\theta)$, where θ is the zenith angle of the launching beam; and C_{Na} is the column density of the Sodium atoms, which has a typical value of 3×10^{13} atoms/m^2. S_{ce} is in units of ph/s/W/(atoms/m^2) /sr.

In this paper, the laser is a quasi-continuous wave (QCW) solid state Sodium laser [17] made by the Technical Institute of Physics and Chemistry (TIPC), standard values of the atomic, atmospheric, and mesospheric are used [16]. Fig. 1 shows the coupling efficiency between the Sodium atoms and the laser [24]. It shows the same tendency as the results of the Bloch equations and shares the characteristic (e.g. [16]) that an optimal coupling efficiency exists. For our laser, the optimal coupling efficiency (green circle) has a value of 335 ph/s/W/(atoms/m^2)/sr, which corresponds an optimal power density (green line) of 44 W/m^2. Thus, Sodium atoms will radiate the most photons when the power density distribution at the Sodium layer corresponds to the optimal power density.

When the light passes the atmosphere in the uplink path, turbulence distorts the wavefront; strong turbulence would broaden the power density distribution at the Sodium layer and even make it more speckled [Fig. 2(a) and 2(d)], The values on the power density map do not all fall in the optimal power density range.

After the turbulence is pre-corrected by a method in which the outgoing beam is reflected off a DM prior to project into the atmosphere, the phase of the outgoing beam is adjusted by the DM, which is conjugated to the dynamic distorted wave-front ψ in the uplink path in real time; the power density distribution at the Sodium layer is the Gaussian type [Fig. 2(b) and 2(e)]. On the basis of the power of the laser ($P = 15$ W), the peak value of the power density around the center is higher than the optimal value of the coupling efficiency, but the power density near the skirts of the disk is less than the optimal value; therefore the power density values are not all optimal. These two situations cause the reduction of the photon return while the power is fixed.