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Research on the compensation of laser launch optics to improve the performance of the LGS spot

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To improve the beam quality of the uplink laser, a 37 channel piezo-ceramic deformable mirror was inserted into the laser launch optics to compensate the static aberrations. An interferometer was used as the calibration light source as well as the wavefront sensor to perform closed-loop correction for the moment. About 0.38λ root mean square (rms) aberrations, including the deformable mirror's initial figure error, were compensated, and the residual error was less than 0.07λ rms. Field observations with a 2 m optical telescope demonstrated that the peak intensity value of the laser guide star (LGS) spot increased from 5650 to 7658, and the full width at half-maximum (FWHM) size reduced from 4.07 arcseconds to 3.52 arcseconds. With the compensation, an improved guide star spot can be obtained, which is crucial for the adaptive optics systems of ground-based large telescopes.

OCIS codes: (010.1080) Active or adaptive optics; (220.1000) Aberration compensation; (140.3300) Laser beam shaping.

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1. INTRODUCTION

A laser guide star (LGS) is essential for adaptive optics (AO) systems of modern ground-based large telescopes [1]. Since in many cases the target star is insufficiently bright to provide enough photons for the wavefront sensor (WFS) or worse, there is no available guide star within sight. To achieve good performance for AO, it is critical for the WFS to see a guide star spot as bright and small as possible. This requires not only a laser with good beam quality, but also an ideal beam transfer path.

Unfortunately, when the laser reaches the sodium layer, it is inevitably degenerated by many factors along the path, such as thermal distortions inside the laser cavity, aberrations of the launch optics, and atmospheric turbulence. The LGS spot will spread as the beam quality gets worse. Béchet *et al.* reported that the GeMS laser beam quality M^2 along the x direction degenerated to 2.23, which was caused by quasi-static distortions, even if frequent and time-consuming alignment procedures had been done [2]. A two deformable mirror (DM) beam shaping system was proposed since 2012 to correct both amplitude and phase distortions [3]. In 2014, Norton *et al.* corrected the uplink laser using a microelectromechanical system (MEMS) DM and found that a purposefully aberrated beam resulted in poorer performance of the ShaneAO system [4]. Early in 2004, to create a smaller spot in their tests, Drummond *et al.* at Starfire Optical Range corrected the laser for the upward leg with a 60 actuator AO system on a 50 cm telescope at the auxiliary beam director pointed at a natural guide star. The guide star produced from a closed-loop circularly polarized pump beam was about 50% of the width of either the open-loop beam or the linearly polarized closed-loop beam [5].

During our past field LGS observations, aberrations in launch optics also became a problem for long term operation. A launch telescope structure with an interface reserved for adaptive compensation was designed several years ago [6]. In this paper, we continue with our previous research with a 37 channel DM inserted in the beam launch optics. Aberrations in the main launch telescope, including the DM's initial figure error, were compensated, and the LGS spot was observed with a 2 m adaptive optical telescope. Preliminary results showed that the laser power distribution at the sodium layer was improved, producing a smaller LGS spot.

2. LGS TESTBED

A. Mode-Locked Laser

A macro-micro mode-locked laser is developed to excite the guide star at the sodium layer. The all-solid-state laser employs the popular sum-frequency scheme, which combines a 1064 nm laser and a 1319 nm laser nonlinearly to generate a 589.159 nm output. The power of the laser in use can reach more than 5 W. The linewidth is less than 0.4 pm to match the sodium atom's profile more efficiently. The beam quality M^2 is slightly less than 1.4 at present. For conveniently gating out the unwanted Rayleigh backscatter, the macro-pulse frequency is set to 500 Hz. More efforts are being made to upgrade the laser with higher output power and better beam quality.

B. Beam Launch Optics

The main laser launch telescope (LLT) is installed on an optical table and consists of two Galilean beam refractors to reduce the whole size. A commercial pre-expander is placed after the laser to provide an appropriate input aperture for the LLT. A general view of the beam launch optics is illustrated in Fig. 1. The last reflecting mirror (RM) responsible for directing the laser beam into the sky does not appear here.

The two refractors are cascaded with a RM, which can be replaced with a DM. For laboratory use, most components are designed and assembled with commercial optomechanics, such as kinematic mirror mounts, multi-axis platforms, and so on. In addition to aberrations that could not be eliminated during the assembly procedure, new aberrations induced by slow mechanical displacements of the very flexible structure also become a significant problem during long time experiments. The beam quality as well as the LGS spot is degenerated by the launch optics. In the past, frequent calibrations and realignments were necessary to minimize the distortions and at least half a day would be wasted.

C. 2 m Adaptive Optical Telescope

A newly constructed optical telescope has been put into use recently. It has a 2 m SiC primary mirror, which is the largest one in China at present. The telescope is equipped with a 349 channel DM. The AO system can operate at a high frequency of up to 2000 Hz. All of these instruments are in the Coude room under the telescope. The newly constructed system has being performing well since its first light operation on 16 July 2017.

The telescope is now located within the institute, about 20 m away from the 589 nm launch beam. The camera for LGS observation has a detector of 128 × 128 pixels, corresponding to about a 64 arcseconds × 64 arcseconds field of view. A 6 nm narrow filter is placed before the detector to suppress the background light.

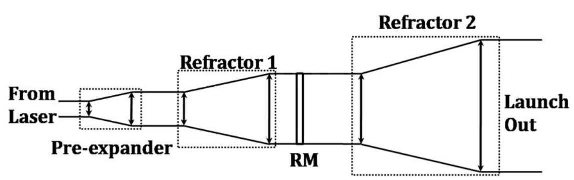

Fig. 1. Laser beam launch optics. The reflecting mirror (RM) is drawn as a transmissive one for convenience.

3. FIELD RESULTS

A. Compensation Setup

Instead of laborious realignments of the launch optics, we replace the RM in Fig. 1 with a 37 channel DM to compensate for the aberrations in the launch optics. Our initial setup used a 632.8 nm interferometer as the calibration light source and the WFS for closed-loop correction. Achromatic lenses are employed to ensure the performance consistency between different wavelengths. The modified structure of the launch optics is showed in Fig. 2.

A removable mirror, A, is placed between the pre-expander and the first refractor. When the mirror is shifted in, the calibration light is directed into the launch telescope. Another removable mirror, B, is placed behind the second refractor to reflect the light back into the interferometer. Both mirrors are shifted out when the compensation is completed; the 589 nm laser then passes through the path and launches into the sky.

A piezo-ceramic DM specially coated for the 589 nm operation works together with the interferometer to perform the compensation. The same dielectric coating is deposited on the mirrors in the laser cavity where the power density is extremely high. The very high reflectivity of the surface can effectively prevent the mirror from being damaged or distorted by heat dissipation. Hours of tests indicate that the 45 mm mirror can keep its state well under the current power level. Figure 3 shows the obvious yellow coating of the mirror's surface.

A Shack–Hartmann WFS is conjugated to the DM through a beam reducer. The pitch of the microlens array is 300 μm, and 9 × 9 subapertures are used to match the 2.7 mm incident beam. For now, it mainly functions as a monitor to watch the deformation of the mirror. In the next plan, more aberrations, including those caused by thermal effect, will be measured with the WFS directly, using the laser itself as the calibration source.

B. Procedure of Field Experiments

Each time before launching the laser beam out, mirrors A and B are shifted in to form a closed loop. Calibration light from the interferometer is reflected by mirror B and returns back, carrying the aberration information of the launch optics. According to the measured result, the height of the wavefront at each actuator is calculated. Then, the differences between the height at each actuator and the average height of the entire wavefront are figured out. Finally, the actuators are controlled to minimize the differences to approximate zero. Due to the hysteresis of the lead zirconate titanate (PZT) actuator, we usually have to

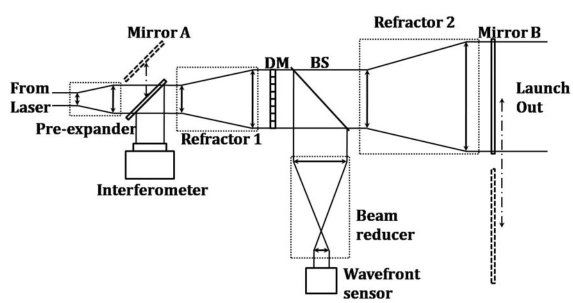

Fig. 2. Launch optics setup with the DM. The DM is drawn as a transmissive one for convenience.

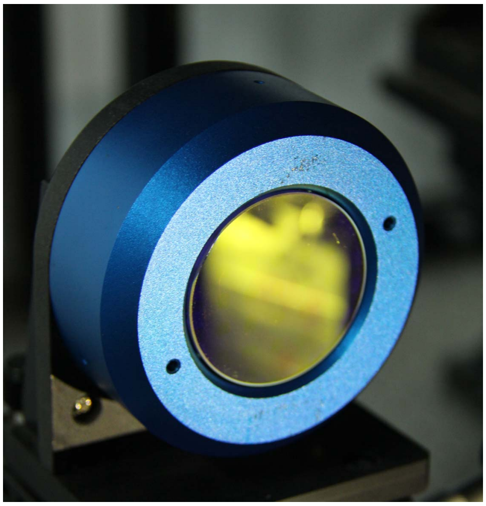

Fig. 3. 37 channel DM with yellow coating.

perform four to six iterative processes to reach the desired flatness. This method was applied in flattening and calibrating our DMs at first, and a flattened 137 channel mirror surface better than 0.02λ root mean square (rms) has been reported in 2012 [7]. After that, both mirrors are shifted out, and the laser is launched to the sky. The focus of the pre-expander as well as the secondary mirror of the 2 m telescope is adjusted to achieve a minimized LGS spot. After that, a set of LGS spot images is captured, while the DM maintains its compensation position. Finally, the DM is turned off, and another set of images is captured.

One thing that should be noted is that when the DM is turned off, its initial figure error is included in the launch optics rather than being flattened. After years of operation, considerable distortions are found when the DM is set to its initial state. One reason is that we cannot simply apply a fixed open-loop voltage every time to flatten the DM because of the hysteresis effect. Another reason will be discussed later in the next section.

C. Results With and Without Compensation

Several nights of field experiments were conducted since August in 2017. In these experiments, the elevation angle of the launched beam was set to about 82 deg. The data reported here was obtained on 16 October 2017.

Initial wavefront aberrations in the launch optics were measured to be 0.38λ rms. A portion of the aberrations was caused by the launch telescope, while the other portion came from the DM itself. Distribution of Zernike coefficients is illustrated in Fig. 4.

Most aberrations in launch optics were low order terms; thus, a 37 channel DM was capable of correcting them. After the aberrations were compensated for in several loops, the wavefront error dropped quickly to a low level, which was less than 0.07λ rms.

Typical images of LGS spot with and without compensation are displayed in Fig. 5. The gray stretch method is used to show some details clearly. The gray level range is 4000–7500 for both images.

The spot was obviously elongated, because the spot was observed from 20 m away, and the long axis corresponded to the thickness of the sodium layer. We evaluate the spot from two

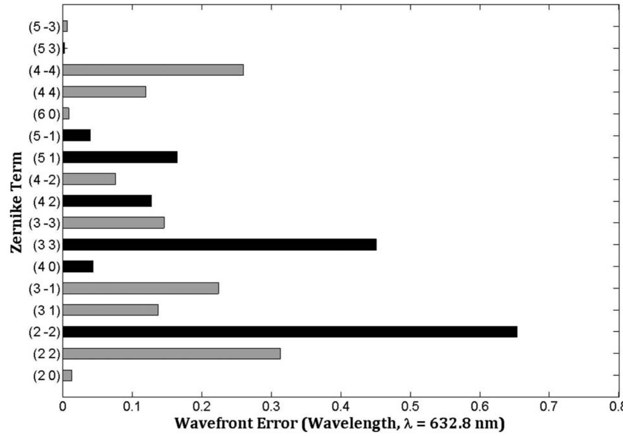

Fig. 4. Zernike coefficients of aberrations in launch optics. Dark color means a positive term, while gray color means a negative term.

aspects, the peak intensity value and the full width at half-maximum (FWHM) size of the short axis.

A set of ten images were averaged to calculate the two metrics, respectively. The peak intensity value with compensation was

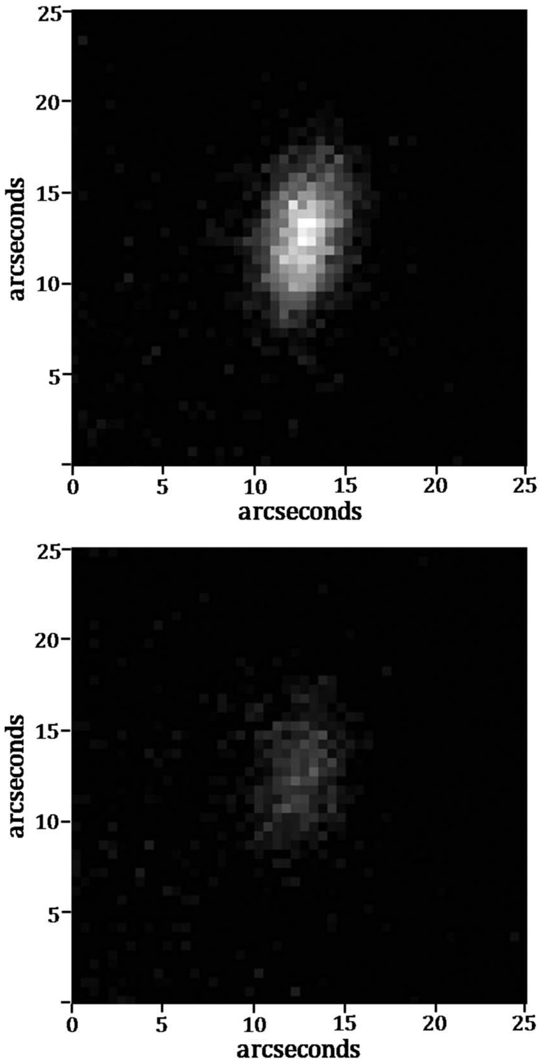

Fig. 5. LGS images with (top) and without (bottom) compensation.

about 7658 ± 276, and the FWHM size was about 3.52 ± 0.27 arcseconds. When the DM was turned off, the peak intensity value dropped to 5650 ± 172, and the FWHM size increased to 4.07 ± 0.30 arcseconds. The compensated spot was 13.5% smaller than the aberrated one. The profiles of the short axis in Fig. 6 explicitly show the degradation when the DM was turned off. Note that both images are average filtered to show the profiles smoothly.

A conclusion is that after the compensation, the spread laser power at the sodium layer was redistributed and focused to the Gaussian core, resulting in a brighter center. The FWHM size was reduced, but the whole spot size did not change too much. In other experiments, we found that the dominant factor that affected the whole spot size was defocus, which required careful optimization before the observation. In later experiments, therefore, the focus was tuned with only the pre-expander, and this term was eliminated from the launch telescope to keep the focus unchanged before and after compensation. This explains why almost no defocus term exists in Fig. 4.

We also find that the extent of the improvement is directly related to the atmospheric turbulence strength. During strong turbulence nights, which are very common in an urban area, the LGS spot shows much less improvement after the compensation. In such a case, aberrations in the launch optics are only a small fraction, and the laser beam was mainly destroyed by turbulence. This is in accordance with Andrew P. Norton's conclusion. Considering the poor viewing conditions and for research purposes, we did not flatten the DM and took its initial figure error as part of the launch telescope's aberrations. However, small amount of aberrations will affect the performance of the spot definitely under good seeing conditions.

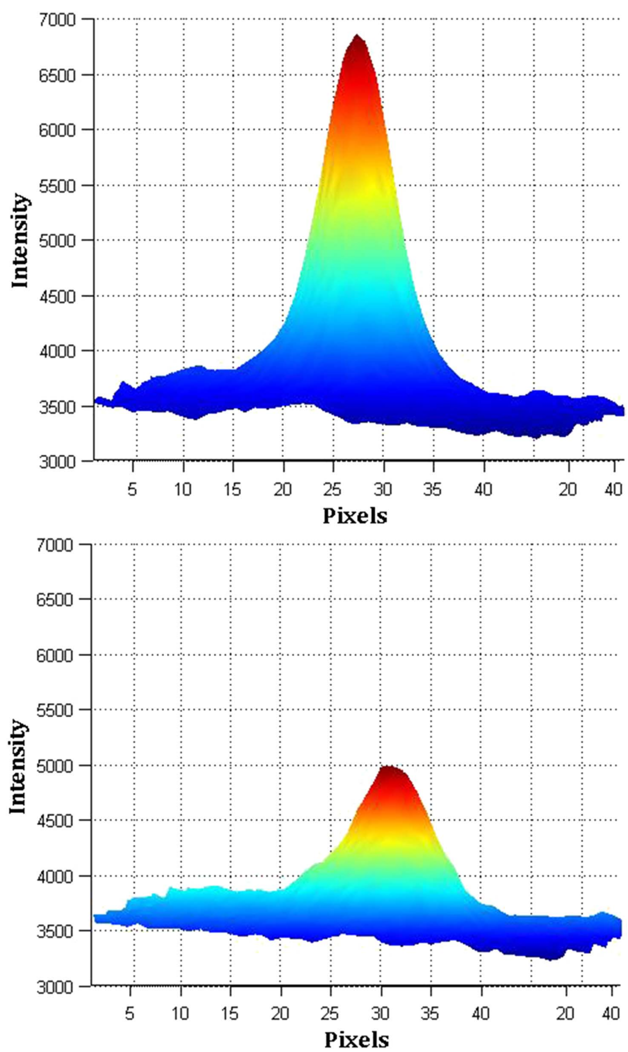

Fig. 6. Profile of the short axis with (top) and without (bottom) compensation.

4. CONCLUSIONS

We successfully demonstrate that the performance of the LGS spot can be improved by compensating for the static aberrations in laser launch optics.

For a Shack–Hartmann WFS, the standard deviation measurement error depends on the spot size and the received photons [2]:

$$\sigma_{\text{means}} \propto \frac{\theta_{\text{image}}}{\sqrt{N_{\text{ph}}}}. \tag{1}$$

From Eq. (1), a spot size 13.5% smaller is equivalent to increasing the number of received photons by 33.7% for a given σ_{means}. Once the laser is delivered to the observatory, it is more feasible to optimize the beam launch optics rather than to increase the laser power to get a better LGS spot.

In the near future, a new compensating structure will be implemented. The laser itself will become the calibration light source, and aberrations inside as well as outside the laser cavity should be measured and corrected. The interferometer will be removed; thus, the whole adaptive compensation system will become more compact and practicable. Moreover, the following of experiments as well as in-depth data analysis are needed to understand this issue better.

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