Preliminary use of nematic liquid crystal adaptive optics with a 2.16-meter reflecting telescope

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Abstract A nematic liquid crystal adaptive optics system (NLC AOS) was assembled for a 2.16-m telescope to correct for atmospheric turbulence. LC AOS was designed and optimized with Zemax optical software. Second, an adaptive correction experiment was performed in the laboratory to test the performance of the NLC AOS. After the correction, the peak to valley (PV) and root mean square (RMS) of the wavefront were down to 0.2 λ (λ=633 nm) and 0.05 λ, respectively. Finally, the star of Pollux (β Gem) was tracked using the 2.16-m Reflecting Telescope, and real time correction of the atmospheric turbulence was performed with the NLC AOS. After the adaptive correction, the average PV and RMS of the wavefront were reduced from 11 λ and 2.5 λ to 2.3 λ and 0.6 λ, respectively. Although the intensity distribution of the β Gem was converged and its peak was sharp, a halo still existed around the peak. These results indicated that the NLC AOS only partially corrected the vertical atmospheric turbulence. The limitations of our NLC AOS are discussed and some proposals are made.

OCIS codes: (010.1080) Adaptive optics; (230.3720) Liquid-crystal devices; (010.1330) Atmospheric turbulence; (110.6770) Telescopes.

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1. Introduction

Adaptive optics systems (AOSs) have been widely applied to large aperture telescopes to overcome the effects of atmospheric turbulence [1-4]. A wavefront corrector (WFC) is a key element of the AOS, and, universally, deformable mirrors (DMs) are used for this purpose. To correct for atmospheric turbulence, the actuator number of the DM must be at least the approximate square of (D/r_0) [5]. Here, D is the aperture of the telescope, and r_0 is the atmospheric coherence length. When the telescope aperture D is increased, more actuators are needed. Currently, a 42-meter telescope (E-ELT) is being developed by the European Southern Observatory (ESO) [6], and it needs more than ten thousand actuators. However, the actuator number of the DM is only up to 1377 [7], which does not satisfy the requirements of larger aperture telescopes such as the E-ELT. Furthermore, the DM is very expensive and difficult to fabricate. Therefore, with their advantages of millions actuators and low price, liquid crystal wavefront correctors (LC WFCs) are being considered to solve the shortcomings of DMs [8-10].

Although the LC WFC has enough spatial resolution, it has the fatal shortcomings of slow response and polarization dependence. Love has utilized a quarter-wave plate and a mirror to make the LC WFC work with unpolarized light [11]. To improve the frame rate of the LC WFC, ferroelectric and dual-frequency LC materials were used [12, 13]. However, due to its high voltage requirement and the complexity of controlling it, the dual-frequency LC WFC has difficulty in handling millions of active elements. The binary phase modulation of ferroelectric LCs limits their effectiveness in WFCs. Since the response speed of the nematic liquid crystal (NLC) has been improved, the use of NLC WFCs for correcting horizontal atmospheric turbulence has become feasible [9]. Therefore, we adapted an NLC AOS to match a large aperture telescope for the correction of atmospheric turbulence. To the best of our knowledge, this work has not been previously performed.

2. An NLC AOS for a 2.16-m Reflecting Telescope

2.1 Optical layout

A 2.16-m Reflecting Telescope is located at the Xinglong Station of the Beijing Astronomical Observatory. The NLC AOS is to be situated in the Coude room. Designed according to the requirements of the telescope, the optical layout of the NLC AOS is shown Fig. 1. The entire optical system was designed to be placed on a 900×1200 mm optical platform. The divergent beam from the Coude optical setup provides the incident light of the NLC AOS. This beam is

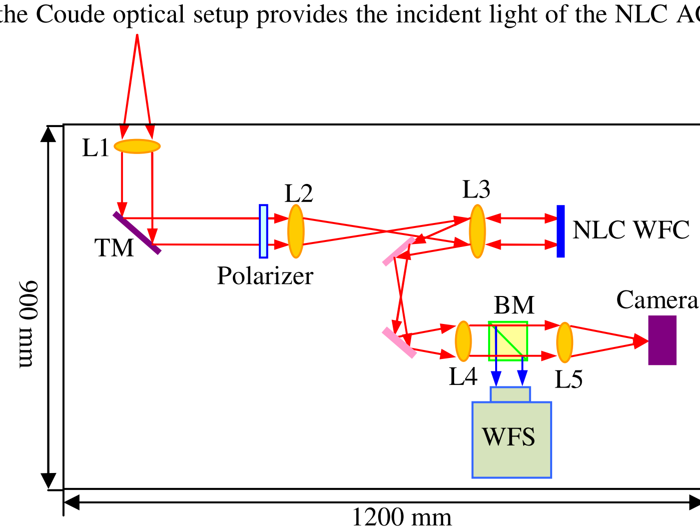

Fig. 1. Design of the optical layout of the NLC AOS for a 2.16 m telescope. L1–L5: achromatic lenses. TM represents the tip-tilt mirror.

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collimated by a lens (L1) and reflected by a tip-tilt mirror (TM). The reflected light goes through a polarizer, and magnified by the L2 and L3 lens combination. The magnified light goes to the NLC WFC with a small incident angle, which separates the reflected light from the incident light. Then, the light is reflected and goes to a beam splitter (BM), which divides it into two beams. One beam is used to measure the distortion with a wavefront sensor (WFS) and the other goes to a CCD camera.

The designed optical system was optimized with Zemax optical software. The optimal results are expressed by the modulation transfer function (MTF) and optical path difference (OPD) curves shown in Fig. 2 and Fig. 3. Figure 2 indicates that the MTF of the NLC AOS design suited our diffraction-limited MTF application very well. The optical system can optimally transfer the optical information. The OPD curve in Fig. 3 shows that the aberration of the NLC AOS was less than 0.1 λ (λ = 588 nm), which can be ignored for our corrective application. The results suggest that our optical system design is suitable for adaptive correction.

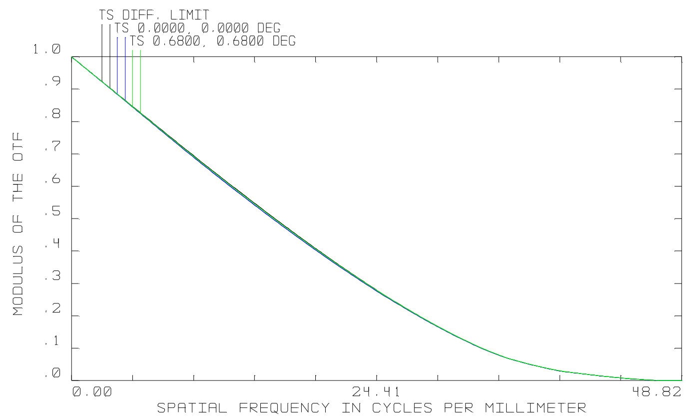

Fig. 2. The diffraction limited MTF design of the NLC AOS at the field of view of 0° and 0.68°.

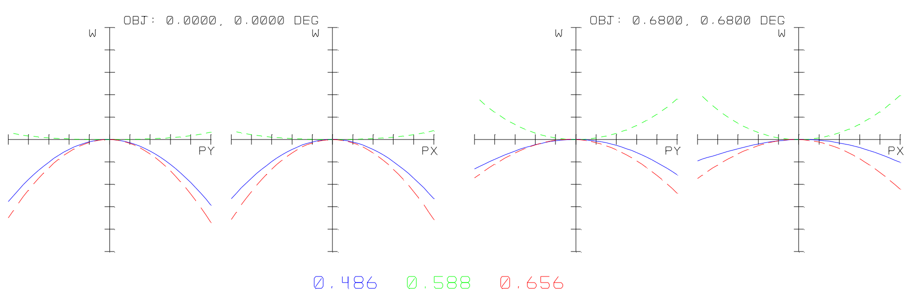

Fig. 3. PD curve at wavelengths, 486 nm, 588 nm, and 656 nm. Fields of view, 0° and 0.68°. Range of y-axis, ± 0.1λ, λ = 588 nm.

2.2 Adaptive correction experiment in laboratory

First, the NLC AOS was tested in the laboratory with adaptive correction experiment. A white light source outputted from a fiber bundle was placed at the focus of lens L1 as an object. A narrow-band colored filter with the wavelength of 633 nm was used to obtain the quasi-monochromic light. The NLC WFC had 512×512 pixels, a 200 Hz frame rate, and a 1 λ (λ = 633 nm) phase modulation depth [9]. The WFS had 400 microlenses, a 3 mm aperture, and a 500 Hz frame rate. An EM-CCD camera (DV897, Andor) was used to obtain the image of the

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fiber bundle. It had 512 × 512 pixels and an acquisition frequency of 34 Hz. A tip-tilt mirror (S-330, PI) with a resonant frequency of 2.4 kHz was used to correct the tilt aberration.

The NLC AOS was controlled by a real time computer, and its closed loop frequency could reach 60 Hz. Without the correction, the peak to valley (PV) and root mean square (RMS) of the wavefront were 1.6 λ and 0.4 λ respectively (Fig. 4(a)). The image of the fiber bundle was obscured, as shown in Fig. 4(b). Next, the closed loop correction was performed; the corrected results are shown in Figs. 4(c) and 4(d). The PV and RMS of the wavefront were down to 0.2 λ and 0.05 λ, respectively. The core of each fiber was resolved clearly. This demonstrated that the NLC AOS worked normally.

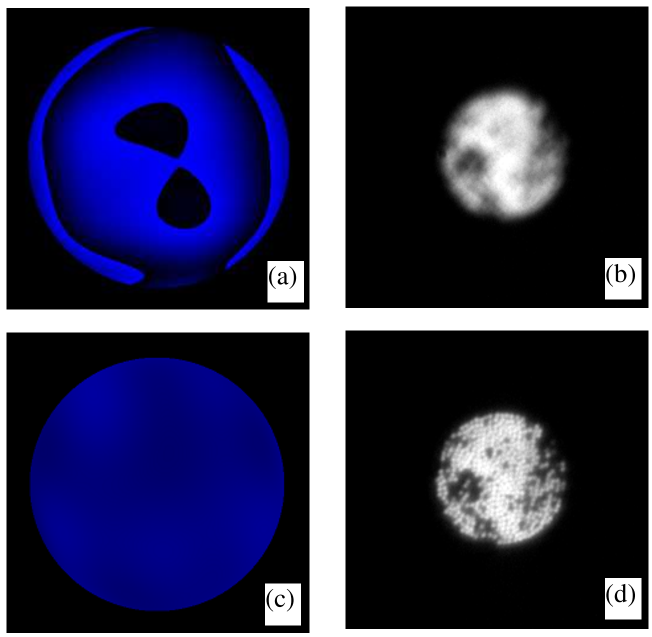

Fig. 4. Results without and with adaptive correction: (a) wavefront without the correction; (b) image of fiber bundle before the correction; (c) corrected wavefront; (d) image of fiber bundle with the correction.

3. Observation of the star (Pollux (β Gem)) with adaptive correction

3.1 The NLC AOS Joined to a 2.16-m telescope

The NLC AOS was carried to Xinglong Station and located in the Coude room of the 2.16 m Reflecting Telescope. The optical juncture of the NLC AOS and 2.16-m telescope is shown in Fig. 5. Light from the telescope is reflected horizontally by a mirror, where the dashed line represents the light from the upper optical setup. To reflect this light to the NLC AOS, a mirror was inserted into the Coude optical layout. The experimental setup of the NLC AOS is shown in Fig. 6. The incident light is reflected by a TM and goes to the NLC WFC with a small incident angle. Then, the light is reflected from the NLC WFC and separated from the incident light by a mirror. The reflected light goes to a BM and is split into two beams. One goes to an EM-CCD camera, and the other to the WFS.

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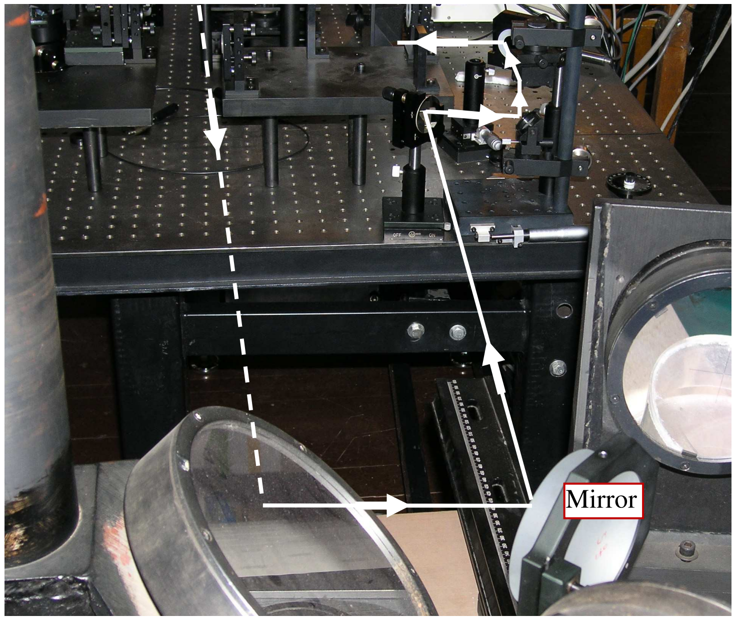

Fig. 5. Connection of the optical setup between the telescope and the NLC AOS in the Coude room, a mirror is inserted into the optical layout to reflect incident light to the NLC AOS.

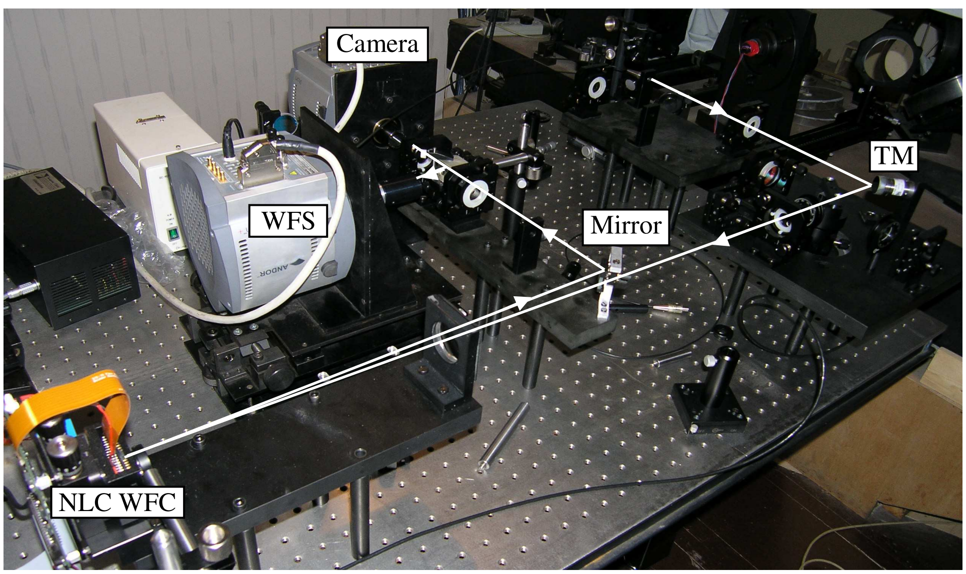

Fig. 6. Experimental layout of the NLC AOS.

3.2 Tracking Pollux (β Gem) with real-time correction

Pollux (β Gem), which has a visual magnitude of 1.14 and a distance of 35 light-years, was selected as the observation object. On the night of March 30th, 2008, β Gem was tracked with the 2.16-m telescope and the distortions were corrected in real time with the following NLC AOS. It can be seen from Fig. 7 that, with the closed loop correction, the average PV and RMS of the wavefront changed from 11 λ and 2.5 λ to 2.3 λ and 0.6 λ, respectively. Although

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the distortion was apparently suppressed, the residual error was larger than expected. The images of the β Gem achieved without and with the correction are shown in Fig. 8. After correction, the dispersive energy converged to a sharp peak and the image of the β Gem changed from a blurry disc to a tiny spot. Although the intensity peak was sharp, a halo still existed around it. These results indicate that only partial correction was achieved for the 2.16-m telescope. We think that this was caused by the following two factors: (a) stronger atmospheric turbulence–because of the heavy snow before we did the experiment, the turbulence was stronger than on an ordinary day, and (b) a slower loop frequency–due to the low temperature of ambience. The temperature of the NLC WFC was kept at 40 °C by using a heating configuration on the back of the liquid crystal (LC) panel. Since the LC panel did not have the heat insulation device, the ambient temperature seriously affected its temperature. In our laboratory, there was only a little difference between the ambient and the NLC WFC temperature. Therefore, the temperature of the NLC WFC could be controlled. However, because the temperature of the Coude room was just 9 °C that day, the temperature of the NLC WFC should have been reduced drastically. Since the response speed of the NLC WFC is sensitive to temperature, the need for temperature control is crucial. With our NLC AOS, the response time of the NLC WFC mainly occupied the system's time delay. Therefore, the loop frequency of the NLC AOS should be slowed under the cold ambient conditions. In order to achieve a fast response from the NLC WFC, the effects of temperature on response speed must be studied and a constant temperature configuration added to the NLC WFC's operational specifications in the future.

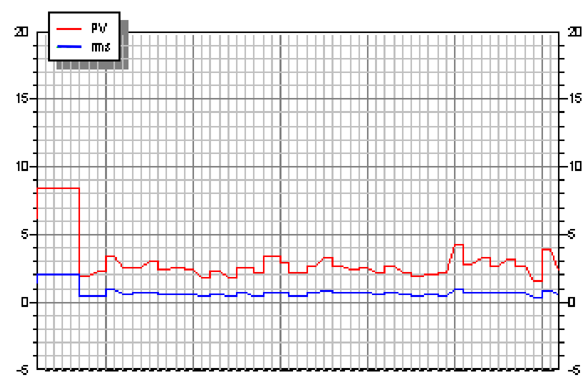

Fig. 7. Dynamic variation of PV and RMS of the wavefront before and after the correction; y-axis graduated in microns (μm).

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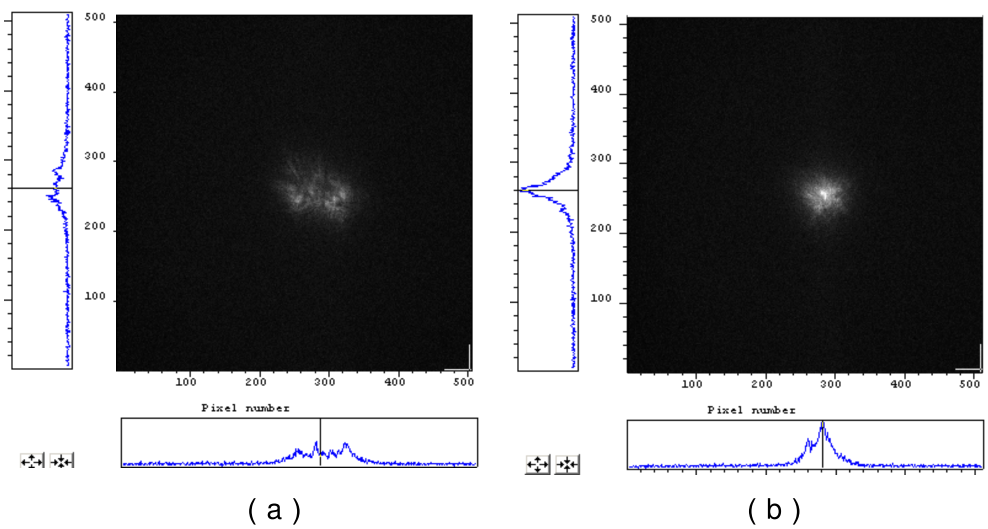

Fig. 8. Image of Pollux (β Gem) captured with a CCD camera (a) without and (b) with the correction.

3.3 Effects of the temperature on the response speed of the NLC WFC

The response time of the NLC WFC was measured by the method presented in Ref. 9. Specifically, this was done by using two grey maps on the LC WFC to change the phase retardation to between 0 and 2π radians, respectively. In the experiment, we toggled all the pixels of the NLC WFC between the grey levels of 255 and 0. An intensity detector was used to measure the change in brightness, and the detected signal was recorded by an oscilloscope. The response time of the NLC WFC was computed from the brightness curve. By controlling the temperature of the NLC WFC, the response time as a function of temperature was measured, as shown in Fig. 9. The rise time represents the response time of the NLC WFC when the voltage changed from low to high, the fall time, was the inverse of that. Observe that the variation trend from rise time was similar to that from fall time, the response speed was faster at higher temperature, and the fall time took longer than the rise time. Therefore, the response speed of the NLC WFC should be evaluated in terms of the fall time. Figure 9(b) shows that the response speed can be up to 200 Hz with a temperature of 40 °C, but as low as 77 Hz at 9 °C. This indicates that, in the Coude room at 9 °C, the response speed of the NLC WFC would be decreased drastically, and the loop frequency of the AOS reduced to 38 Hz.

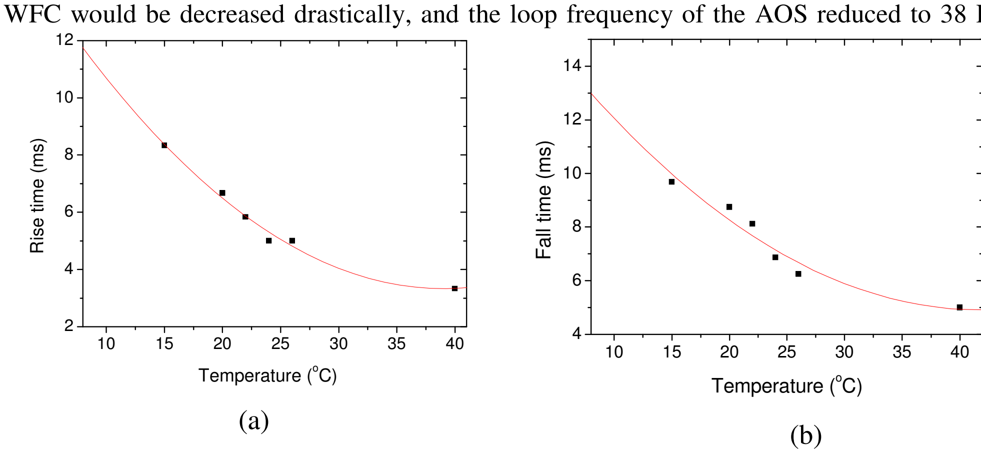

Fig. 9. Response time as a function of the temperature: (a) rise time; (b) fall time.

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This lower correction frequency cannot manage the stronger turbulence well. Consequently, the temperature of the NLC WFC should be held to 40 °C in the future to achieve a higher response speed. Furthermore, a good weather day is also a desirable condition for adaptive correction experiments.

4. Discussions and conclusions

We demonstrated that the NLC AOS potentially has the ability to be applied to large aperture telescopes to correct for atmospheric turbulence. First, the NLC AOS was designed, fabricated, and tested in the laboratory. The corrected results showed that the NLC AOS performed well. Second, the Pollux (β Gem) was tracked in real time, making adaptive corrections. By using the NLC AOS, the distortions were partially corrected. Compared to its blurry image without the correction, the intensity of β Gem image was centralized to a sharp peak using the NLC AOS. However, it must be noted that, as an effect of the larger residual error, there was still a halo around the intensity peak.

Finally, the causes of the partial correction were found to be the stronger turbulence and the slower correction frequency. Due to the lower temperature of the Coude room, the closed loop frequency decreased drastically. Therefore, we will strictly control the temperature of the NLC WFC in the future. According to our experimental results, even if the NLC WFC is kept at 40 °C, the correction frequency of 60 Hz might not meet the correction demands of atmospheric turbulence.

In the future, we will improve the correction frequency in terms of the following:

(1) WFS acquisition frequency: The frame rate of the WFS can be improved from 500 Hz to 1500 Hz by using a multichannel parallel output CCD camera.

(2) NLC WFC response speed: We are developing new LC materials with faster response times. The frame rate of the NLC WFC will be increased to 500–1000 Hz soon.

(3) Data transfer: Corrected with millions of pixels, the data transfer speed also limits the correction frequency of the AOS. We are developing the electric interface with a data transfer rate of 512 × 512 pixels from the computer to the LC panel that is estimated to be less than 1 ms.

(4) Open loop control: We have demonstrated that open loop control is suitable for the LC AOS [14]. With the open loop control, the loop frequency can be up to two times that of the closed loop.

With these improvements, we estimate that the loop frequency of the NLC AOS may be improved to 300 Hz or so, and the atmospheric turbulence may be corrected as well. Thus, the NLC AOS can solve the spatial resolution limitations of the DMs and lower financial costs.

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