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First light for the sodium laser guide star adaptive optics system on the Lijiang 1.8 m telescope

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Abstract A first generation sodium Laser Guide Star Adaptive Optics System (LGS-AOS) was developed and integrated into the Lijiang 1.8 m telescope in 2013. The LGS-AOS has three sub-systems: (1) a 20 W long pulsed sodium laser, (2) a 300-millimeter-diameter laser launch telescope, and (3) a 37-element compact adaptive optics system. On 2014 January 25, we obtained high resolution images of an m_V 8.18 star, HIP 43963, during the first light of the LGS-AOS. In this paper, the sodium laser, the laser launch telescope, the compact adaptive optics system and the first light results will be presented.

Key words: instrumentation: adaptive optics — turbulence — atmospheric effects

1 INTRODUCTION

Adaptive optics (AO) was first proposed by Horace Babcock in 1953 (Babcock 1953), and was first demonstrated for correcting atmospheric turbulence on a ground-based astronomical telescope in 1989 (Rousset et al. 1990). The limited sky coverage of an AO system (AOS) has been recognized due to the demand of having relatively bright stars to measure the wavefront distortion induced by Earth's atmosphere. To increase the sky coverage of an AOS, using a laser to create an artificial guide star was proposed. An artificial laser guide star (LGS) can be generated by exciting either the sodium atoms in the mesosphere using a sodium-wavelength laser or molecules in the atmosphere using their Rayleigh back-scattered signals (Foy & Labeyrie 1985; Thompson & Gardner 1987). Since a sodium LGS is produced at an altitude of 90–110 km in the mesospheric sodium layer, it has less focal anisoplanatism than a Rayleigh LGS (with typical altitude around 20 km), and therefore is a better choice for large telescopes.

A number of observatories have performed sodium LGS experiments. However, only a few papers about LGS-AOS with science observation results had been published till 2010. The first light of a sodium LGS-AOS was achieved at the Lick 3-m telescope (Max et al. 1997).

In late 2004, the Lick system with an operational sodium LGS system was installed on the Keck II telescope (Wizinowich et al. 2006). By now, nearly all 8+ meter telescopes are using or planning to use sodium LGS for their AOS, including the planned European Extremely Large Telescope (E-ELT) and the Thirty Meter Telescope (TMT) (D'Orgeville et al. 1999; Takami et al. 2004; Wizinowich et al. 2006; Amico et al. 2010; Ellerbroek et al. 2012).

In China, a 127-element AOS (Rao et al. 2008; Wei et al. 2010) was integrated onto the Lijiang 1.8 m telescope at the Gaomeigu Observatory site in Yunnan Province, and the first scientific results obtained by the AOS were

Table 1 Main Parameters of the 20 W Prototype Laser

Average Power	20 W
Line Width	0.4 GHz
Pulsed Length	$\sim$ 110 microsecond
Repetition Frequency	500 Hz$\sim$800 Hz Tunable
Beam Linear polarization ratio	>99%

Table 2 Main Parameters of the 300 mm Laser Launch Telescope

Location	Paraxial emission
Throughput	0.93
Focusing	90 km $\sim$ 210 km
Beam Quality	Strehl ratio > 0.98
Field of View	$\pm$ 2.5′
Outer Diameter	300 mm
Beam Diameter	240 mm @ $1/e^2$

achieved in September 2009. The Institute of Optics and Electronics has collaborated with the Technical Institute of Physics and Chemistry (TICP), National Astronomical Observatories, and other institutes to develop the first generation sodium LGS-AOS mounted on the Lijiang 1.8 m telescope since the end of 2012. In January 2014, first light from the LGS-AOS was acquired, with the first high resolution image of a dim science object (HIP 43963 $m_V = 8.18$). The breakthrough of the LGS-AOS has significantly improved the capabilities of the telescope. Many different kinds of science observations, such as variable star observations of the inner part of globular clusters, are made possible by the LGS-AOS.

2 A DESCRIPTION OF THE THREE SUB SYSTEMS

The first generation sodium LGS-AOS consists of three sub-systems: (i) a 20 W long pulsed sodium laser, (ii) a 300-millimeter-diameter laser launch telescope, and (iii) a 37-element AOS. All the sub-systems are mounted on the 1.8 m telescope. The sodium laser system rotates with the azimuthal base of the telescope. The laser beam is transferred from the laser head to the Laser Launch Telescope (LLT) entrance pupil through the Beam Transfer Optics (BTO), and is then launched into the sky. The LLT and the 37-element low-order AOS are mounted at the Cassegrain focus which is bent by a fold mirror and rotate at a different elevation angle. The position and structure of the three sub-systems are shown in Figure 1.

2.1 Long Pulsed Sodium Laser

From 2002, the TIPC began began its systematic research on the technology related to a sodium laser (Bo et al. 2006; Geng et al. 2006). The first generation 20 W prototype laser was developed and laboratory tests were completed in 2010. On-sky test of the laser was conducted in 2011 (Wei et al. 2012; Jin et al. 2014) at the Gaomeigu site with the Lijiang 1.8 m telescope.

In 2013, an updated second prototype of the sodium laser was developed by TIPC. The output power reached 33 W (Wang et al. 2014) in the lab. Table 1 shows its performance after being mounted on the Lijiang 1.8 m telescope.

2.2 The LLT and BTO

A new 300-millimeter-diameter LLT with a larger field of view and excellent image quality was built to update the original one. The LLT expands the laser beam from 10 mm to 240 mm. The performance of the new LLT is shown in Table 2. To stabilize the sodium LGS in the wavefront sensor (WFS) of the 37-element AOS, a fast steering mirror is placed near the LLT entrance pupil and controlled using the LGS-WFS tip/tilt measurements. The BTO transfers the laser beam from the laser head output part to the entrance pupil of the LLT. The total throughput of the BTO is around 80%. Figure 2 shows a photo of the sodium laser at the Gaomeigu site.

2.3 37-element Compact AOS

The 1.8 m telescope has two secondary mirrors which can be switched easily. One of the secondary mirrors is used to generate a long F/89 path for the Coudé focus, and the other is used for the Cassegrain focus that is F/11.8. A 127-element natural guide star AOS is installed in the Coudé room. Considering the low throughput of the long Coudé optical path, a more compact LGS-AOS is installed on one Cassegrain focus which is bent by a fold mirror and rotates at a different elevation angle.

The layout of the compact 37-element AOS is shown in Figure 3. There is a pick-off mirror to "pick" the beam from the 1.8 m telescope into the first pupil relay element – an off-axis paraboloid (OAP1) reflector, which reimages the telescope primary mirror onto a 37-element deformable mirror (DM). Between OAP1 and the DM, two optical elements are included. One is a 40 mm diameter tip/tilt mirror; and the other one is a beam splitter (BS1) which transmits the light between 450 nm and 550 nm onto an order 3×3 natural guide star WFS and reflects the light longer than 550 nm to the DM.

After the DM, the beam size is changed from 40 mm to 16 mm by a pair of OAPS (OAP2 and OAP3). Another beam splitter (BS2) then transmits the 589 nm light to the 6×6 sodium laser guide star WFS (LGS-WFS), and reflects the rest to BS3. Then BS3 divides the light into two paths for cameras that are sensitive to different wavelengths. One camera is for the J-band which covers the wavelength from 900 nm to 1600 nm, while the other cam-

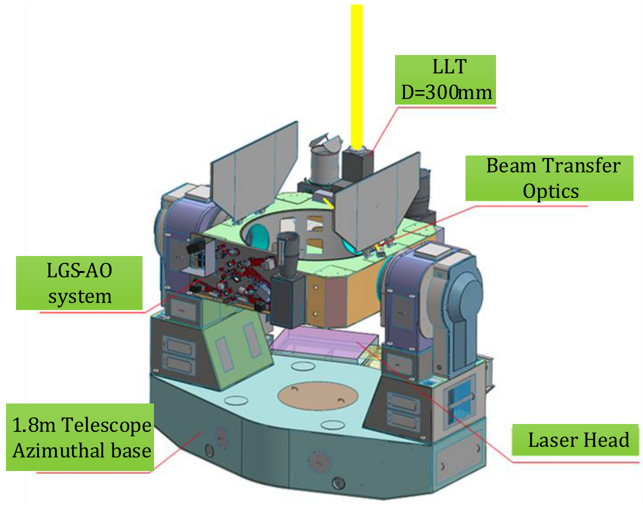


Fig. 1 Layout of the 1.8 m telescope and the sodium LGS-AOS.

Fig. 2 A photo showing the sodium laser being launched into the sky.

era is for the K-band from 1600 nm to 2500 nm. Only the J-band is used in the first light experiment.

One benefit of using a pulsed sodium laser is that a low altitude Rayleigh signal can be suppressed by range gating: a typical Rayleigh scatter signal is less than 30 km while the sodium return signal is between 90–120 km at zenith. Also, a beam launched from the side-mounted laser results in an angular difference between the Rayleigh signal and sodium signal of about $8''$ in the LGS-AOS. To reduce the effect of Rayleigh scattering in the signal from LGS-WFS, a spatial gate (field stop) is added in the focal plane of LGS-WFS and a time gate (optical chopper) is placed next to the field stop and controlled synchronously with the pulsed laser.

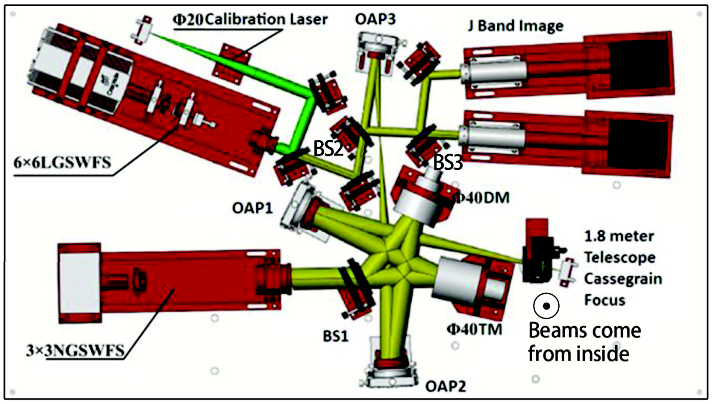
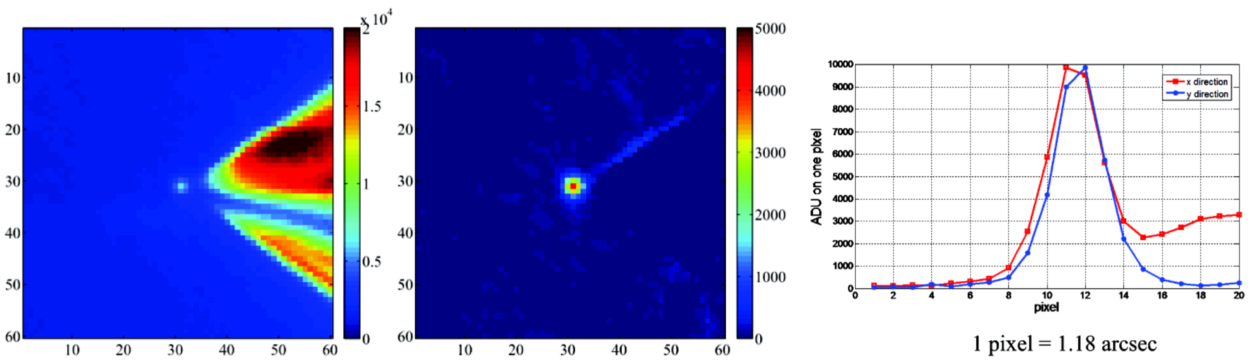
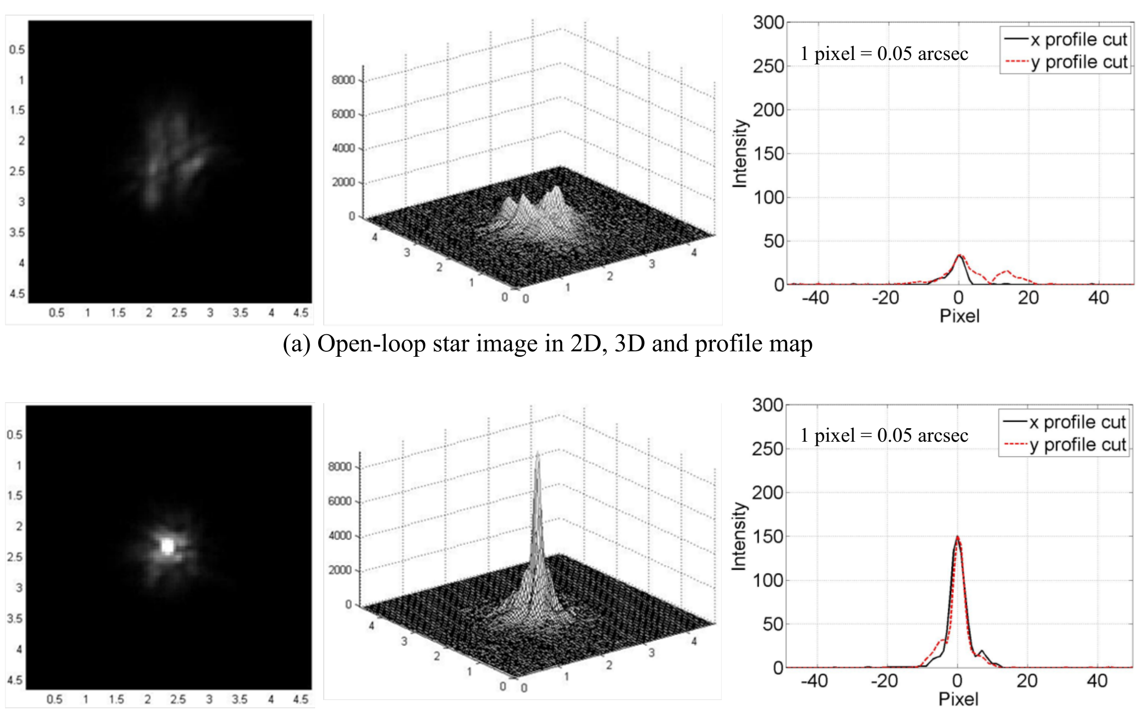


Fig. 3 Optical assembly of the sodium LGS-AOS.



(a) Initial data (b) After subtracting the Rayleigh background (c) 2-D cross-section of the sodium LGS

Fig. 4 An image of the sodium LGS.



(a) Open-loop star image in 2D, 3D and profile map

(b) Closed-loop star image in 2D, 3D and profile map

Fig. 5 The open-loop and closed-loop star images of the first generation LGS-AOS. The imaging wavelength of the star is the J-band.

3 FIRST LIGHT

An image of the sodium LGS is illustrated in Figure 4(a)–(b). The full width at half maximum (FWHM) of the LGS spot on the CCD is around 3.5 arcsec as shown in Figure 4(c). After removing the effect of laser jitter ($0.15''$ rms in our measurement), $1.5''$ local seeing and optical transfer function of the imaging system, the actual spot size in the sodium layer should be around $2.0'' - 2.3''$, which is suitable for AOS to measure the wavefront distortion.

The first light of high resolution imaging was achieved on 2014 January 25. The open and closed loop results of star HIP 43963 ($m_V = 8.18$) in the J-band are shown in Figure 5. The closed loop image FWHM is about 1.7 times the diffraction limit of the 1.8 m telescope. The peak power increased by more than three times when compared to open loop results.

4 CONCLUSIONS

The first generation sodium LGS-AOS, with a 20 W pulsed sodium laser, a 300-mm-diameter laser launch telescope and a 37-element compact AOS, was installed on the Lijiang 1.8 m telescope in 2013. The first light of high resolution imaging was achieved on 2014 January 25. The LGS-AOS can achieve a resolution of 1.7 times the diffraction limit of the 1.8 m telescope in the J-band.

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