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Adaptive optics for the free-space coherent optical communications

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ABSTRACT

We present the results that the performances of the atmospheric coherent optical communications improved by a real 127-element adaptive optics system operating in 1550 nm wavelength on a 1.8 m telescope. The mixing efficiency and the BER of the homodyne free-space optical coherent communications have been analyzed with the correction of the adaptive optics system. It is shown that, the AO can expand the scope of the atmospheric turbulence condition $D/r_0(1550)$ from 1 to around 6.5 in which the coherent optical communications can function well. In order to acquire favorable results, the mixing efficiency should be larger than 0.4 and the residual wavefront error after the AO correction should be smaller than $\lambda/6$. We also find that the mixing efficiency of the coherent homodyne receiver is approximate to the Strehl ratio of the far field of the signal light. In conclusion, we have shown that the adaptive optics is a very promising technique that can largely improve the performances of the free-space coherent optical communications degraded by the atmospheric turbulence.

1. Introduction

As the free-space coherent optical communications have much higher sensitivity (nearly 20 dB) than the traditional non-coherent optical communications, it has great potential to be used in the free-space communication links with long-range and high-data-rate property [1–3], e.g. the satellite to the ground links. Unfortunately, the atmospheric turbulence can greatly affect the performances of the free-space coherent optical communications links.

The adaptive optics (AO) technology is a powerful tool to overcome the effect of the random optical disturbance, and has been applied in many fields [4,5]. Up to now, it has been shown that the AO technology can largely improve the performance of the atmospheric non-coherent optical communications [6–9]. Some researchers also recommend the AO technology to improve the atmospheric coherent optical communications [10–14]. Belmonte and Kahn have analyzed theoretically the performances of the free-space coherent optical links when the AO technology is adopted [15]. However, a more detailed experimental report about the AO technology to improve the performance of the atmospheric coherent optical communications (ACOC) can seldom be found.

In this paper, we devote to the experimental performance evaluation of a real 127-element AO system to the ACOC links using the coherent optical communication parameters, such as the mixing efficiency and bit error rate (BER).

2. The theory

The idea of the coherent detection scheme is combining the received optical signal coherently with a continuous-wave optical field before it reaches the photodetector. The continuous-wave field is generated locally using a narrow linewidth laser, called the local oscillator (LO). The received optical signal and the LO field can be, respectively, expressed as

$$E_S = A_S \exp[-i(\omega_S t + \varphi_S)], \tag{1}$$

$$E_{LO} = A_{LO} \exp[-i(\omega_{LO} t + \varphi_{LO})], \tag{2}$$

where A_S and A_{LO} are the magnitudes, ω_S and ω_{LO} are the angular frequencies, φ_S and φ_{LO} are the phases of the received optical signal and the LO laser, respectively.

For the coherent detection, the mixing efficiency γ for the homodyne detection can be express as [16]

$$\gamma = \frac{[\int_U A_S A_{LO} \cos(\Delta\varphi) \mathrm{d}U]^2}{\int_U A_S^2 \mathrm{d}U \int_U A_{LO}^2 \mathrm{d}U} \tag{3}$$

where $\Delta\varphi = \varphi_S - \varphi_{LO}$, U is the coherent area between the optical signal and the LO laser. We assume that both the intensities of the

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optical signal and the LO laser are homogeneous, both of their polarization directions are the same, the sizes of the laser beams are the same and both beams coincident with each other well. We also assume that the amplitude distribution is homogeneous, then the mixing efficiency only depends on the spatial phase distribution difference (SPDD) between the signal laser and the LO laser. In this case, the mixing efficiency is also a function of the RMS of the phase difference $\Delta\varphi$.

The BER can be express as [16]

$$BER = \frac{1}{2} erfc(\sqrt{2\eta N_P \gamma}) \tag{4}$$

where the function $erfc(\cdot)$ is the complementary error function, η is quantum efficiency of the photodetector, N_P is the number of photons per bit of the received optical signal.

3. Discussion

The experiment is carried out with an AO system with 127 actuators incorporated with an 1.8 m telescope located on the Gaomeigu station of the Yunnan astronomical observatory, China [17–19]. The AO system uses the visible waveband with the central wavelength of 600 nm to detect the distorted wavefront, and uses the 1550 nm waveband to image the star observed. The full width at half maximum (FWHM) of the 1550 nm waveband is about 10 nm and the central wavelength is 1550 nm. The emission spectrum of stars we observed covers the visible and the 1550 nm waveband. In this case, we can easily acquire the star images of 1550 nm waveband with and without the AO correction.

At 14:33 (UT) on June 11, 2013, the star HIP72105 was observed. The altitude angle of the star was 87° and the Fried parameter r_0 was about 7.3 cm (600 nm in the oblique path). The D/r_0 for the 1550 nm wavelength is 7.1. The star images of the 1550 nm waveband without and with the correction of the adaptive optics are shown in Fig. 1. The image sequence recorded has 95 frames. The first to the twentieth frame are without adaptive optics correction. The twenty-first frame to the ninety-fifth frame are corrected by the adaptive optics. It is seen that the spread image of the star before AO correction becomes a tiny bright point after the AO correction, and the maximum intensity of the star reached nearly 8000 analog to digital unit (ADU) after the AO correction from several hundred ADU before correction. The diffraction ring can also be observed clearly.

The Strehl ratio (SR) of the star images are measured with the ratio of encircled energy curve of the images to the diffraction

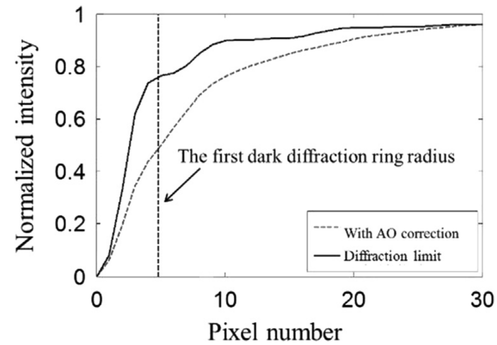

Fig. 2. The encircled energy curve of the star image with AO correction.

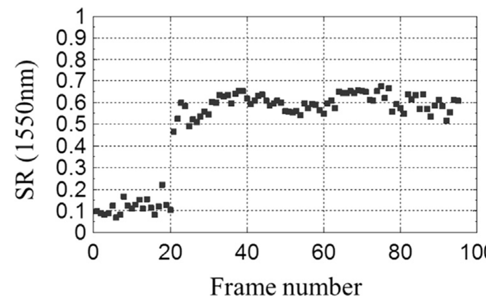

Fig. 3. The SR performance with and without the AO correction.

limit at the first dark diffraction ring. The encircled energy curve of the star HIP72105 is shown in Fig. 2 and the first dark diffraction ring radius is 4.8 pixels. Thus, the SR is measured. The SR for the sequence of the 95 frames of the star images is shown in Fig. 3. Before the AO correction, the SR is about 0.1 at the 1550 nm. However, after the AO correction, the SR reaches around 0.6, which is a satisfactory result.

In order to work in different turbulent conditions, we observed stars with different altitude angles. For the observation of each star, we recorded the SR with the AO correction and the Fried's parameters r_0 in the oblique path at 1550 nm. After 41 stars have been observed, the relationship between the SR and the normalized atmospheric turbulence strength D/r_0 is shown in Fig. 4. Each square point in Fig. 4 represents the result of the observation of a certain star.

All the observations were conducted between March 18, 2013 and June 11, 2013. The wind speed and the amplitude angle are different for each observation. The atmospheric turbulence

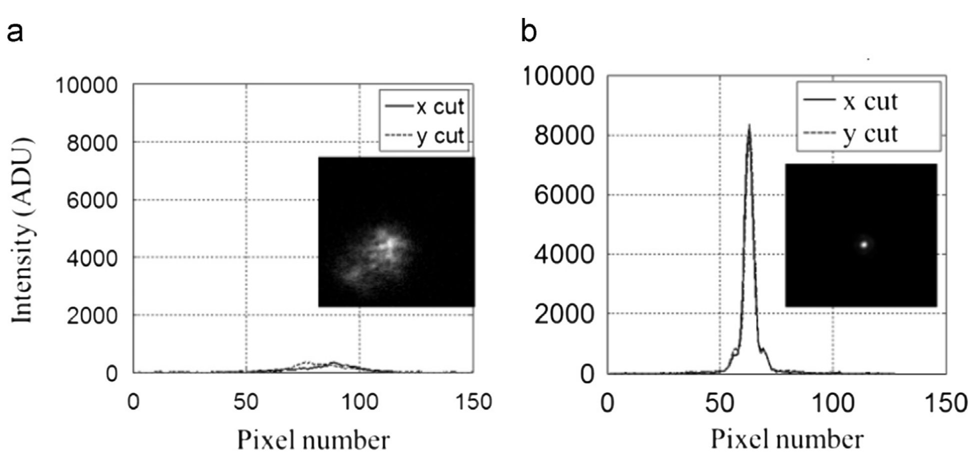

Fig. 1. The star images and its cut curves of HIP72105 at 1550 nm waveband without (a) and with (b) the correction of the adaptive optics at 14:33 (UT) on June 11, 2013. The image serial recorded has 95 frames. The first to the twentieth frame are without adaptive optics correction. The twenty-first frame to the ninety-fifth frame are corrected by the adaptive optics. The image shown in (a) is the fifth frame and the image shown in (b) is the sixty-sixth frame.