A time-division correction method for adaptive optics system

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Abstract. An adaptive optics system can measure and compensate the wavefront distortion caused by dynamic disturbance in real time. It is usually used for astronomical observation and other occasions. According to the current technology, it is only suitable for small field of view optical system or point target, but not for ground extended target detection. In order to solve this problem, a correction method is proposed: firstly, the sub aperture image of wavefront sensor is divided into several sub regions, each sub region corresponds to a certain light direction or field angle range; secondly, calculate the offset of the image feature points in each sub region, and an image with good correction effect in a field of view in this direction is obtained; the last step is to measure each sub region one by one and combine these images into a full frame image. Through comparison, it is found that the method proposed in this paper is essentially to divide the extended target into multiple point light sources for correction.

1. Introduction
Adaptive Optics (AO) is a new optical technology which integrates optics, mechanics, electronics, computer and automatic control. It uses optoelectronic devices to measure the dynamic wavefront error in real time, and uses fast electronic system to calculate and control, and uses active devices to correct the wavefront in real time. So that the optical system has the ability to adapt to the changes of external conditions and always maintain a good working state, which has important applications in high-resolution imaging observation and high-concentration laser energy transmission[1].

The concept of adaptive optics is first derived from an atmospheric turbulent flow problem encountered in an astronomical telescope. The actual resolution of an optical telescope is often far less than the expected theoretical diffraction limit. When the light waves emanating from an object through the atmosphere reaches the Earth's surface, turbulence of the atmosphere causes a nonuniform refractive index of air. The amplitude and phase of the wavefront have been severely disturbed, which deteriorates the imaging quality of the telescope. Atmospheric turbulence has become an important factor limiting the resolving power of the ground-based telescopes[2-3].

The coherence length is usually used to express the intensity of atmospheric turbulence. Atmospheric turbulence has no obvious influence under the observation aperture smaller than the coherence length. The coherence length of the Earth's atmospheric turbulence generally only about 5-20 cm, Even though the construction of several meters diameter or larger ground-based telescope system, The imaging resolution of a large telescope will not exceed that of a small telescope with a diameter of 10-20 cm in the astronomers. It has serious consequences for astronomical observation or
space monitoring. It reduces the ability to detect the target, makes the morphological details of the target unclear, and reduces the accuracy of observation and positioning. Even it always has such disturbances in the seemingly peaceful atmosphere, the phenomenon that the actual observation resolution of the telescope is greatly reduced due to the influence of atmospheric turbulence has been discovered after mankind invented the telescope. This phenomenon has plagued the researchers for hundreds of years. It was only after the real development of adaptive optics that this problem was gradually solved[4].

But in the 1950s, there was no technical basis to realize this idea. In the 1970s, the demand for high-resolution optical observation and high-concentration laser energy transmission became more urgent, and related technologies have also developed better, and adaptive optics has can be used. Therefore, adaptive optics did not really start until the mid-1970s, and it has developed rapidly in the past 20 years.

2. Basic principles of adaptive optics

In 1953, American astronomer Babcock proposed the idea of using real-time measurement of wavefront errors and real-time compensation to solve dynamic disturbances such as atmospheric turbulence. The core of the idea is to introduce a reflection element whose surface shape can be changed (called wavefront corrector) and a wavefront error sensor into the optical system[5-6]. The wavefront sensor is used to measure the wavefront error, and a set of control system is used to control the wavefront corrector and compensate the wavefront error. If the amount of the wavefront correction process is fast enough, it can be used to compensate for the changing dynamic wavefront error corrected, that the optical system has the ability to adapt to environmental changes, overcome dynamic disturbances, and maintain ideal performance. This is the basic idea of adaptive optics. It changes the limitation of traditional optical technology that only pursues static accuracy, and makes the optical system have the characteristics of dynamic and variable, thus providing a way to solve the problem of dynamic interference that has plagued the optical industry for hundreds of years[2].

Due to different task requirements in different application fields, various forms of AO systems are different, but classic AO systems generally include three basic parts: wavefront sensors, wavefront controller, and wavefront correction. These three parts constitute a real-time control system, the wavefront sensors is used to measure dynamic wavefront errors. The wavefront controller is a kind of fast electronic system for calculation and control. Wavefront correction is used as an active device for real-time wavefront correction. The principle of adaptive optics is shown in Figure 1.

The adaptive optics system can measure and compensate the wavefront distortion caused by dynamic disturbance in real time, so that the optical telescope can obtain a target image close to the diffraction limit, or the laser emitting system can effectively focus the laser beam on the target. Adaptive optics technology makes the optical system have the ability to automatically adapt to changes in external conditions and maintain the best working state. It has improved the performance of the optical system[5]. The huge application potential of adaptive optics in space observation and laser beam atmospheric transmission has made it highly valued all over the world since its birth, and it has achieved great success. In recent years, with the emergence some new types of device, adaptive optics technology has been vigorously pushed to civilian fields. AO technology has begun to be widely used in laser processing, laser transmission, laser beam quality improvement, laser-driven nuclear fusion, laser communications, biomedicine and many other fields, and various AO systems have been developed. However, it is only useful in small field of view optical system or point target, but not suitable for the detection of ground extended target[1].
3. The Method of time-division-correction

In order to solve the problem of detecting extended targets with adaptive optics system, a time-division correction method proposed in this paper.

As shown in Figure 2 below, the Hartmann-Shack wavefront sensor with M sub apertures is used, and each sub aperture image is divided into N sub regions, the jth (1 ≤ j ≤ N) sub region of the ith (1 ≤ i ≤ M) sub aperture is called $Z_{ij}$. Since each sub aperture is divided into N sub regions, the corresponding optical system field of view and the output image of the AO system is also divided into N parts.

![Figure 1. Principle of adaptive optics.](image1)

![Figure 2. Sub aperture image and sub region.](image2)
The schematic diagram of time-division correction is shown in Figure 3. We can see that the extended target is divided into 3 parts (marked as \( X_1, X_2, X_3 \)), and is imaged on sub region \( Z_i \) through the \( i \)th sub aperture, \( Z_{i2}, Z_{i3} \). Since the light from \( X_1, X_2 \) and \( X_3 \) go through different paths, they have different disturbance wavefront, so it will be useless if we correct the wavefront from different direction at the same time. However, we can detect each sub region and correct the wavefront from different direction one by one, and then put these images together to make a full frame image.

![Figure 3. Schematic diagram of time-division correction.](image)

The process of time-division correction is shown in Figure 4. Firstly, the offset of image feature points in the same sub region in each sub aperture is calculated, and the wavefront disturbance of light from the direction corresponding to the sub region is obtained. And then according to the result, the wavefront corrector is controlled to corrected image in this direction. Repeat the above steps to obtain the corresponding corrected image of each direction, and assemble it into a full frame image. Using this method, the wavefront from different directions in the large field of view can be corrected, and clear imaging of ground extended targets can be achieved.
4. Conclusion
As shown in Table 1, we compare the method proposed in this paper with the basic method of adaptive optics technology.

|                  | Time-division method | Basic method |
|------------------|----------------------|--------------|
| View of field    | Large                | Small        |
| Target type      | Extended target      | Point target |
| Correction times | Number of sub regions | 1           |

The method proposed in this paper spend more time to correct the wavefront than the basic method. The reason is that one correction is divided into several corrections, so it is called “time-division”. By comparison, it is found that the time-division method essentially divides the extended target into multiple point light sources for time-division correction.

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