The Laboratory Results of a 595-unit Adaptive Optical System

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Abstract. A 595-unit adaptive optical system is designed for the 4-meter diameter high resolution astronomical telescope. The deformable mirror adopts PZT actuators with 300mm diameter reflecting surface. A debugging system is established in laboratory and closed loop results are obtained. The scheme of the system, the design of the wavefront sensor, the wavefront processing system and the control software are described in this paper. Special influence matrix measuring methods are for the first time used on this debugging system and show better results than the classic actuator by actuator method. The system is successfully closed loop to correct the simulated static aberration. Using FWHM as the merit, the corrected PSF equals less than 1.1 times of that of the diffraction limit. A 913-unit adaptive optical system has been developed and will be closed loop in laboratory based on the experiments of this 595-unit system.

1. Introduction

Adaptive optics (AO) technique [1-16] is used to correct the aberration in large aperture telescopes, including the distortion induced by atmospheric turbulence and the optical aberration of the telescopes. Without the benefit from AO system, the large telescopes cannot acquire the resolution better than a telescope with several-centimeter diameter. AO system has been an indispensable part of the large aperture optical telescopes. The AO group from the Institute of Optics and Electronics, Chinese Academy of Sciences, has developed several tens of AO system for the applications in high resolution astronomical imaging [1-11], laser propagation through atmosphere [17], Inertial Fusion Confinement [18], and human eye imaging [19]. In the area of high resolution astronomical imaging, the first 21-unit adaptive optical system was successfully set up at the 1.2m telescope of Yunnan Astronomical Observatory in 1990[1]. And an upgraded one was installed at the 2.16m telescope of Beijing Astronomical Observatory for the infrared K-band high-resolution observation in 1996[2,3]. With the breaking through of the technical problems, a 61-unit adaptive optical system was equipped to the 1.2m telescope of Yunnan Astronomical Observatory, which is designed for I band observation, in 2000[4,5]. A 127-unit adaptive optical system was developed for the 1.8m astronomical telescope [8].

The 595-unit AO system described in this paper is developed for a 4-meter aperture telescope. Considering the atmospheric condition, this AO system can be used to correct the turbulence when observing in the K band. In order to understand the engineer problems, an integrated system was established and test in our laboratory.
2. Description of the laboratory setup

The laboratory setup of the 595-unit adaptive optics system is shown in Fig. 1. The whole system consists of collimating source, turbulence simulator, calibration reflector, off axis parabolic (OAP) mirror, deformable mirror, Hartmann-Shack (HS) wavefront sensor, imaging system, wavefront processor, high voltage amplifier and other relay optics. The whole system is set up on an optical platform with size of 2m*3m.

2.1. Collimating Source

The collimating source provides aberration-free optical beam for the system. In our first-stage laboratory test, single field of view and single wavelength laser (He-Ne) is used. The diameter of the beam is 15 millimeter. As planned, the source will be switched to extended object (multiple fields of view) and wide spectral range (multiple wavelengths) to compatible with our future multi-conjugate AO (MCAO) experiments.

2.2. Turbulence Simulator

We proposed two methods to simulate turbulence, the rotated phase screen or ventilator. Phase screen is made of an aberration plane. The rotation speed of the phase screen can be adjusted according to the turbulence simulated. The design of the aberration plane and its rotating rate lie on the model of Kolmogorov. As alternating, a ventilator is used to model turbulence with more intensity. In our first phase of closed loop debugging, the system only completes the correcting of static aberration comes from fixed aberration plan (which can be obtained by only stop the motor of the turbulence simulator).

2.3. Calibration Reflector

Calibration reflector is used to calibrate the HS wavefront sensor. The calibration process can eliminate the static aberration exists in the OAP and deformable mirror branch, including the surface error and position error. Calibration reflector is pushed out of the optical train except for during the calibrating. As shown in Fig 1, the calibration reflector is inserted into the optical path and the optical bream is reflected back to HS wavefront sensor and imaging system. The most possible error source, the OAP and deformable mirror, are then excluded from the optical train.
2.4. Deformable Mirror
The AO system is designed for a 4-meter astronomical telescope. The top level restriction of the deformable mirror is diameter should equals 294mm. The distances between actuators should be between 10mm to 15mm.

Given the restrictions, the distribution of the actuators is based on the analysis of aberration fitting error. Two projects, actuators distributed on square grids and triangle grids, are proposed under the restrictions.

Parameters for the square distributed project are as following:
(1) Distribution grids: square
(2) Total number of actuators: 552
(3) Distance between actuators: 10mm
(4) Effective diameter: 294mm

Parameters for the triangle distributed project are as following:
(1) Distribution grids: triangle
(2) Total number of actuators: 595
(3) Distance between actuators: 12mm
(4) Effective diameter: 294mm

![Fig. 2 Schematic show of the square distributed (left) and triangle distributed (right) actuators for the deformable mirror, the effective actuators are 552 and 595 respectively](image)

The distribution schemes are shown in Fig. 2. The coordinates are normalized to ±1 for aberration fitting analysis. In our calculation, the first 65 Zernike polynomials are input to the deformable mirror, the portion between the residuals and the input ones are used as merit for fitting error analysis. The results are shown in Fig. 3, the residual error of square distribution is as twice much as that of the triangle distribution one. In our deformable mirror, the triangle distribution one is selected, and the effective actuator number is 595.
Fig. 3 Fitting error of the first 65 Zernike Polynomials, the residual error of square distribution one (left) is much higher than the triangle distribution one.

PZT actuator is proposed for the 595 unit deformable mirror, the finite element model is shown in Fig. 4, the actuator and mirror surface parameters are optimized in this step.

Fig. 4 The finite element model of 595 unit deformable mirror

Fig. 5 The 595 unit deformable mirror under testing (left) and the surface error tested by Zygo interferometer without actuating (right).

As shown in Fig. 5, the deformable mirror was assembled and tested, the results shows the surface error is less than the parameter requirements and can ben remained for long lasting.

2.5. HS Wavefront Sensor

Lens array and camera are indispensable parts for HS wavefront sensor. The parameters for the HS wavefront sensor are as following:

Subapertures: 30x30, square
Frame rate: 500Hz, 1000Hz, and 2000Hz selectable

The subaperture number of the lens array is decided after residual error diagnosing. Fig. 6 shows the residual error using a Hartmann wavefront sensor with 30*30 subapertures. For the first 55 terms of
Zernike polynomials, the residual error is under 15%. But for the higher order aberrations, the correcting efficiency decreases. Comparing with the fitting error shown in Fig. 3, the value increases because of the Hartmann wavefront inducts detecting error.

![Residual Fitting Error (%)](image)

**Fig. 6** Systematic correcting error of the AO system

In our experiments, the beam diameter from collimation source equals that of the lens array, but is larger than that of the detecting area of the camera. A matching lens is designed to solve the problem. The test results from Zygo interferometer show that the Strehl Ratio is 0.97, as shown in Fig. 7, which provides perfect optical quality for the wavefront sensing.

![Test results of the matching lens using Zygo interferometer](image)

**Fig. 7** The test results of the matching lens using Zygo interferometer

### 2.6. Imaging System

The imaging system consists of a lens and a CCD detector. The effective focal length of the lens is 716mm, which can provide diffraction limited point for the CCD satisfying the Nyquist theory. Considering the future experiments, the lens is designed to work at the 500nm to 1000nm spectrum.

The parameters of the imaging system are as following:

- Wavelength: 500nm-1000nm
- Focal length: 716mm
- Detector: EMCCD
- Pixel number: 1004×1002

### 2.7. Wavefront Processor

As the heart of AO system, the wavefront processor should do: collecting and processing the images from Hartmann Shack wavefront sensor, calculating the wavefront slopes, reconstructing the wavefront and control the deformable mirror. Fig. 8 shows the block diagram of the wavefront processor. The H-S spot centroid computation and the wavefront reconstruction are completed in 1 FPGA chip. 1 TMS320C6701 DSP chip is used for the control algorithms. The outputs of the processor are the signal inputs to the high voltage amplifiers for controlling the actuators of deformable mirror. Parallel and pipeline architectures are used for the processor.
In our experimental system, the wavefront processor should complete 9.8 billion multiple and add calculation per second. We adopt Compact PCI framework with multi-FPGA and DSP array to accumulate this requirement. Different tasks are carried out in respective processing elements by time interleaving. And at the same time, the task is simultaneously implemented in multiple processing elements, and course concurrency is realized by hardware resource sharing. Multiple Instruction Stream Multiple Data Stream (MIMD) is used for wavefront reconstruction. The manufactured wavefront processor is as fast as 12.5 billion circles per second, which can provide enough processing for our system and is expansible and reconfigurable. The manufactured wavefront processor is shown in Fig. 9.

Fig. 8 Block diagram of the digital wavefront processor

2.8. Experimental System

Fig. 10 shows the picture of the optical bench of the system. It is put in a dark room for protecting CCD detector. The wavefront processor, high voltage amplifier and control system are not included in the picture.

Fig. 9 The manufactured wavefront sensor for our experimental system

3 The AO loop performance

The 595 unit AO system is assembled and the first closed loop result has been obtained. The image of point source is shown in Fig. 11. The FWHM value of its center section is 5.1 pixels.
In the experiments, static aberration with RMS value of $1.67 \lambda$ ($\lambda = 632.8$nm) is inserted into the optical train. Fig. 12 shows the far field image of the point source when the aberration is inserted. Fig. 13 shows the AO correcting result, the FWHM of the center section is 5.5 pixels.

**4 Conclusions**

We constructed a 595 unit AO system for a 4 meter astronomical telescope. The deformable mirror, the wavefront sensor, the wavefront processor, the high voltage amplifier and the control system are designed and manufactured by our group. The first step experiments have obtained closed loop results for static aberration. We will focus on turbulence correcting and multi field of view correcting experiments for this system. The performance of the system will be improved for further debugging. Finally, the system will be equipped to telescope.
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6 References