Piston error detection and closed-loop control based on fringe contrast measurement applied to a kind of interferometric imaging telescope with four apertures

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ABSTRACT

Accurate piston error detection and closed-loop control are one of the key technologies to ensure the imaging quality of the interferometric imaging telescope.In this paper,we proposed a piston error detection and control scheme based on three computers and multithreading,which has been successfully applied to a four 0.1-m apertures interferometric telescope.This scheme adopts a kind of fringe contrast measurement and climbing method to achieve closed-loop control. The results implied that the fringe contrast can be raised through piston closed-loop correction.Compared with a single telescope with 0.1-m aperture,we can get a 2.63x improvement in resolution for the new interferometric telescope.It is proved that the feasibility and effectiveness of this scheme.We will further carry out astronomical observation experiments and improve the piston error detection and control scheme, in order to provide technical guarantees for the implementation of interferometric imaging telescopes.

Keywords: interferometric telescope, co-phasing, piston error detection, contrast, climbing method

1. INTRODUCTION

High resolution astronomical observation is the goal pursued by astronomers. In order to detect distant and weaker celestial targets, optical telescopes with a diameter of tens of meters are often required, which puts higher requirements on the rigidity, material, assembly, and transportation of the primary mirror.The Fizeau interferometric telescope is one of the solutions for high-resolution imaging. It uses several independent apertures on a common frame, and with the help of baseline rotation, we can obtain sufficient UV coverage.In this case, as long as the apertures are positioned with an accuracy of a fraction of a wavelength based on co-phasing error detection and control technology, it is possible to achieve the similar imaging quality to those single monolithic mirror after image processing.

Therefore, co-phasing error detection and closed-loop control of the interferometric telescope is one of the most important tasks for improving the imaging quality.

At present, there have been many studies on co-phasing error detection methods, such as: fringe contrast method[1], dispersed fringe method[2-4], Shack-Hartmann wave-front sensor[5],and so on.The fringe contrast method has the advantages of low difficulty and real-time performance.On the basis of this algorithm, we proposed a solution that includes piston calibration, real-time piston error detection and closed-loop control.We have successfully applied this solution to a kind of interferometric telescope prototype with four 0.1-m apertures and obtained experimental results.

Shanghai Astronomical Observatory has been committed to the research of the optical interferometric telescope for many years and has achieved fruitful results[6-12].We have completed the development of the new interferometric telescope prototype with four 0.1-m apertures.And the optical debugging and experimental observation are currently underway.This paper is organized as follows:In section 2 we present a brief overview of the strategies and methods of piston error detection and closed-loop control; In section 3 we introduce the new interferometric telescope with four apertures and the experiment of the prototype under the condition of laboratory which uses a NKT light source; In section 4, we summarize the results.

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2. PISTON ERROR DETECTION AND CLOSED-LOOP CONTROL SCHEME

2.1 Piston error detection method

Piston error is caused by the optical path difference of each beam along the z-axis of the exit pupil, and is one of the key technologies for high-resolution imaging of the interferometric telescope.When the tip/tilt error is well controlled ,the imaging quality will be directly determined by piston error.

Generally, The PSF of two apertures is made of fringes that are alternatively bright or dark.The bright fringes are features located on to a side-lobe in the PSF profile, where the high irradiance mitigates the achievable contrast.The dark fringes are located into a valley (between two side-lobes), where the low irradiance enables locally a high contrast.

In theory, The contrast of fringes can be used to measure the quality of an interferometric image, it is defined as follows:

$$C = (I_{max} - I_{min})/(I_{max} + I_{min})$$

Where, C represents the contrast of fringes, I_{max} and I_{min} are the peak values of the central bright fringe and the valley value of adjacent dark regions, respectively.

The simulated result shows that as the piston error increases,the contrast of interferometric fringes significantly decreases. And the relationship between them is related to the bandwidth of the light source[6], the simulation result is shown in Figure 1.

Therefore, we can establish a look-up table with the relationship between the fringe contrast and the 'best' position with the minimum piston error to achieve high-resolution imaging.

2.2 Piston error detection and closed-loop control scheme

In this paper, we proposed a piston error detection and closed-loop control scheme, it is achieved through a multi-computer collaboration (piston error detection computer,tip/tilt error detection computer and control computer), multithreading acquisition and calculation.The schematic diagram and optical path diagram of the piston error detection and control system are shown in the Figure 2 and Figure 3.

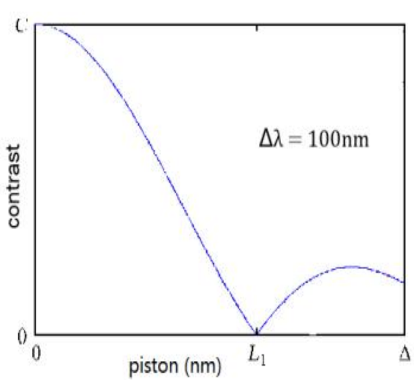


Figure 1 The relationship between piston error and contrast

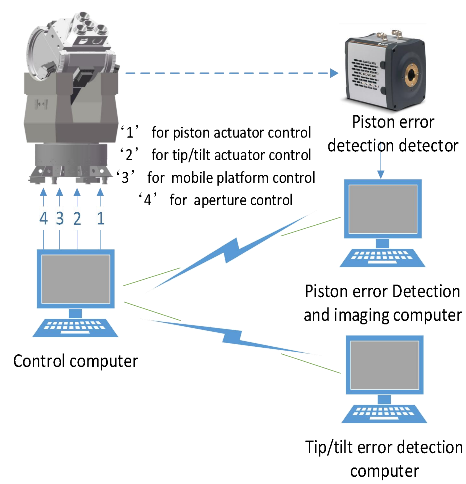


Figure 2 The schematic of piston error detection and control system

The piston error detection computer adopts a multithreading approach, including communication thread, collection and calculation thread, and logic control threads.The main task is to process the collected images, including noise suppression, one-dimensional sampling in particular direction, fringe contrast calculation and displacement adjustment calculation, and sending control and data commands to the control computer through TCP/IP protocol.The control computer communicates with two detection computers separately and controls three apertures except for the center one, including PI actuators,electronic shutter and so on.The control mode includes automatic scanning, manual scanning, open-loop, and closed-loop modes.

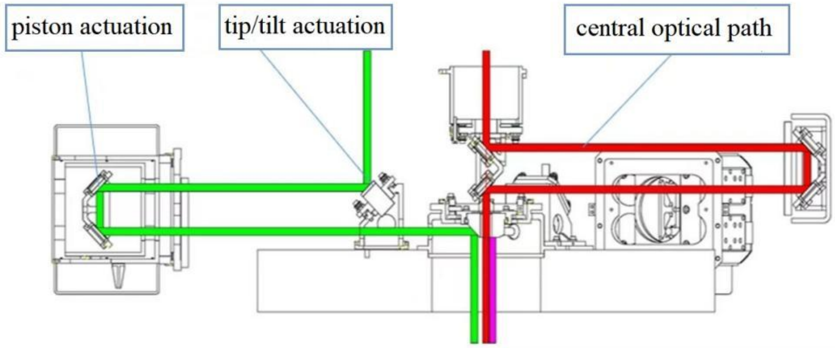
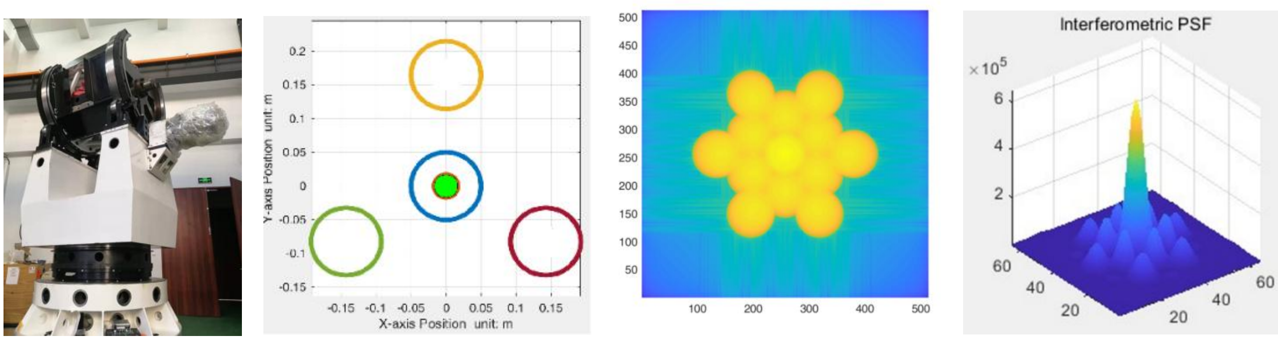


Figure 3 The optical path diagram of interferometric telescope

3. EXPERMENT AND RESULTS

3.1 An interferometric Telescope with four apertures

After years of research, we proposed a new interferometric telescope with four apertures on a common frame which provides a theoretical contrast exceeding the one of a single 0.1-m telescope and reaching the one of a 0.28-m telescope in some areas of the PSF.The apertures are arranged in Y-type.The design, manufacturing, installation, and laboratory debugging of the prototype (based on NKT light source) have been completed. At present, it has been moved to the observation site for debugging and experimental observation.The new interferometric telescope, the arrangement of apertures,the simulation result of UV coverage and interferometric PSF are shown in Figure 4.



a b c d

Figure 4 a. The interferometric telescope b. aperture arrangement c. UV coverage d. The interferometric PSF

3.2 Piston error detection experiment and Data processing

The Piston error detection experiment was conducted with the interferometric telescope in an optical laboratory, using an NKT continuous spectrum light source and incident on each aperture of the telescope through a collimator.

Experimental hardware: interferometric telescope prototype with four apertures + NKT light source + 800mm collimator.

Experimental software: Piston error detection program, tip/tilt error detection program, co-phasing control program, calibration data processing program.

Experimental steps:

1. Calibration (usually conducted once a day before observation):

(1) Calibration data collection : Perform piston scans on three pairs of apertures (0# & 1#, 0# & 2#, and 0# & 3#) , record the fringe image and corresponding actuator positions;

(2) Calculation the sampling angle: Calculate the sampling angle for all fringe data obtained from scanning, and take the average value as the sampling angle;

(3) Fringe contrast Calculation and generate a calibration table:one-dimensional sampling along the sampling angle direction, calculate the fringe contrast and their corresponding actuator positions.Record and generate a piston calibration lookup table.

2. Piston error detection and closed-loop control

(1) Tip/tilt error real-time detection and closed-loop control, spot overlap;

(2) Real time fringe image collection, and calculate the fringe contrast based on the sampling angle;

(3) Compare the contrast with the calibration lookup table and get a position correction value B after interpolation calculation;

(4) Send the position correction B to the control computer and wait for the next detection calculation;

(5) Adjust the position of the piston actuator using the climbing method. Specific operations: activate the forward movement by one correction value B, If the contrast moves towards the maximum direction, the adjustment is successful; Otherwise, it will move in the opposite direction with 2×B. If the adjustment is still unsuccessful, the actuator will return to its initial position;

Repeat steps (2) to (5) to achieve real-time piston error detection and closed-loop control.

Taking the test data collected on April 5th as an example, Figure 5 shows the calculation results of calibration data,and Figure 6 shows the results and statistical chart of piston correction.

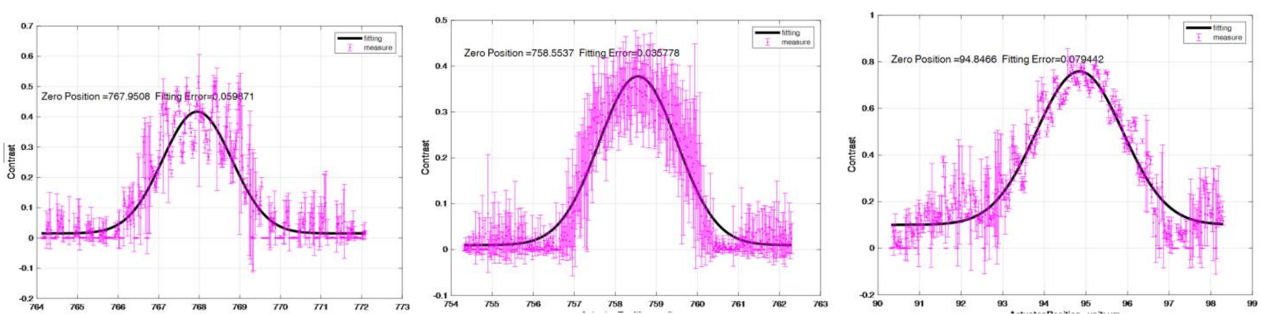


Figure 5 calibration data and results (from left to right: 0# & 1#, 0# & 2#, 0# & 3#)

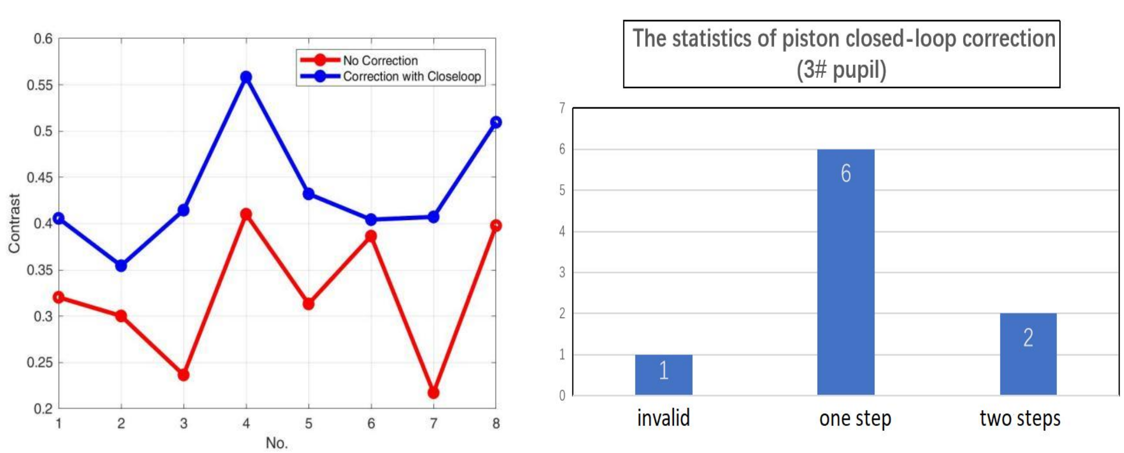


Figure 6 The results and statistical chart of piston error correction

By applying the piston error measurement and closed-loop control proposed in this article, we obtained the image of PSF and calculated the FWMH.It is implied that the FWHM of a single 0.1-m telescope was measured to be approximately

1.13 arc-seconds, while the FWHM of the new interferometric telescope is approximately 0.43 arc-seconds, achieving a 2.63x improvement in resolution, which is basically consistent with the theoretical value.

4. CONCULUSION

We proposed a piston error detection and control scheme, which has been successfully applied to a four-aperture interferometric telescope prototype. And completed verification experiments in the laboratory.The experimental results show that this method has the advantages of low computational cost and good real-time performance, but its anti-noise performance needs to be further improved.

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