Optical Simulation Analysis of a Fizeau-type Y-4 Prototype

Chaoyan Wang*, Xinyang Chen, Congcong Zhang, Lixin Zheng, Yuanyuan Ding, Dan Zhou, Jianqing Cai, Lurun Shen, Qi Wang
Shanghai Astronomical Observatory,Chinese Academy of Sciences, 80 Nandan Road, Xuhui District, Shanghai, China, 200030

ABSTRACT

To achieve high-resolution image using optical synthesis aperture telescope, it's necessary to co-phase accurately of all the telescopes so as to reduce the effect of co-phase errors including piston error, tip/tilt error, and mapping error, etc. Though simulation analysis of the optical system, error sources can be identified and thus save time of alignment. This paper introduces the Fizeau-type Y-4 prototype under development, including the layout of the Y-4 prototype, the layout of the reflective mirrors in the delayed light paths and the beam combiner. With the optical transfer function as the evaluation index, the actual equivalent diameter of Y-4 prototype is calculated. Furthermore, the effect of polarization introduced by coating and polarization differences on the contrast of interference fringe is analyzed. At present, the installation and alignment of the prototype in laboratory have been completed, and the interference synthesis of 4 light paths has been realized. One aim of this paper is to share some experiences in optical design and detection for the development of optical synthetic aperture telescopes. Another aim is to expand these new techniques to the larger optical synthesis aperture telescope project in the future.

Keywords: Optical interferometry, Fizeau-type, optical simulation, equivalent diameter, polarization

1. INTRODUCTION

The imaging resolution of the telescope is limited by the size of aperture generally. At a certain wavelength, the larger aperture of the telescope, the higher resolution. However, the aperture of the telescope cannot increase infinitely because it's limited by the cost of the large telescope, the mirror processing capacity and the cost of the payload. Optical synthesis aperture telescope imaging technology is based on the distribution of multiple small single telescopes through a certain baselines to reach the equivalent resolution of a large single-aperture telescope and can be used for high-resolution astronomical observations. Many countries in the world have developed the technology of the optical synthesis aperture telescope. For example, GI2T[1][2](Grand Interferometer 2 Telescopes) in France is the earliest application of this technology. It used two telescopes to obtain the fringe. America has constructed some telescope arrays. CHARA[3] (the Center for High Angular Resolution Astronomy) located in Mount Wilson is consisted of 7 telescopes that diameter is 1m with the longest baseline up to 1100m. NPOI[4](Navy Precision Optical Interferometer) located in Lowell Observatory is consisted of 6 telescopes that diameter is 0.5m and 4 telescopes that diameter is 1.8m, the longest baseline up to 440m. MROI[5] (Magdalena Ridge Observatory Interferometer) located in New Mexico is consisted of 10 telescopes that diameter is 1.4m with the longest baseline up to 340m. The study was also conducted in European Southern Observatory. VLTI[6] (Very Large Telescope Interferometer) is consisted of 4 telescopes which diameter is 8.2m and the other 4 telescope which diameter is 1.8m with the longest baseline up to 200m.

This paper will introduce the Fizeau-type Y-4 prototype developed by the optical interference telescope team at Shanghai Astronomical Observatory. The optical layout of the prototype including delayed line systems and imaging systems is shown in the section 2 and the structure of the sub_telescope and the alignment method is also introduced. In the section 3, the PSF of three kinds of telescope array configuration are simulated. According to the cutoff frequency, the equivalent diameter of Y-4 prototype can be got. Because the polarization effect causes the contrast degradation, polarization effects induced by the coating of mirror and contrast decline with the polarization difference are simulated. We also give the experiments results in section 4. In the end of this paper, the development progress and the next work arrangement are summarized.

*superyan@shao.ac.cn;

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2. THE OPTICAL LAYOUT OF Y-4 PROTOTYPE

The optical system of Y-4 prototype consists of 3 parts: 4 sub-telescopes, 4 sets of delayed optical paths, detection and imaging optical systems. The overall appearance of the Y-4 prototype is shown in Figure 1.

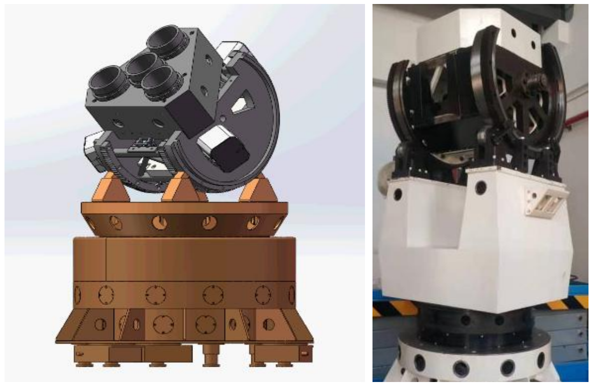

Figure 1. The overall appearance of the Y-4 type prototype.(left) design diagram; (right) device diagram.

The 4 sub-telescopes are Y-typed, with one sub-telescope in the center and three surrounding telescopes at 120 degrees each other. The relative position of the telescopes is shown in Figure 2. The distance between each three surrounding telescope (1#, 2#, 3#) and the central telescope (0#) is 164.5mm. The pupil diameter is about 100mm. About 10mm collimated beam can be got after collimator lens.

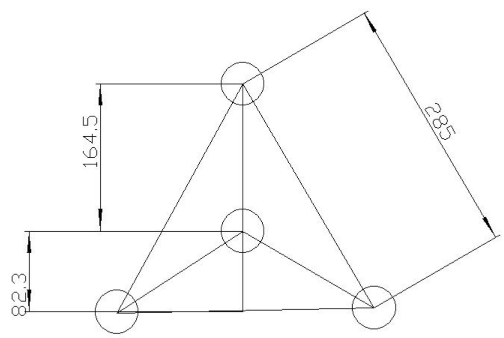

Figure 2. The relative position of the 4 telescopes.

2.1 The 4 sub_telescopes

The primary and secondary mirrors of a single telescope are still in the classic Cassegrain form combined with the collimator system that can get 10mm collimated beam. Each telescope can be accurately aligned using a ZYGO interferometer and the RMS value of each telescope is above λ/25 @ 632.8nm. The structure of telescope and the diagram of alignment scheme is shown in Figure 3.

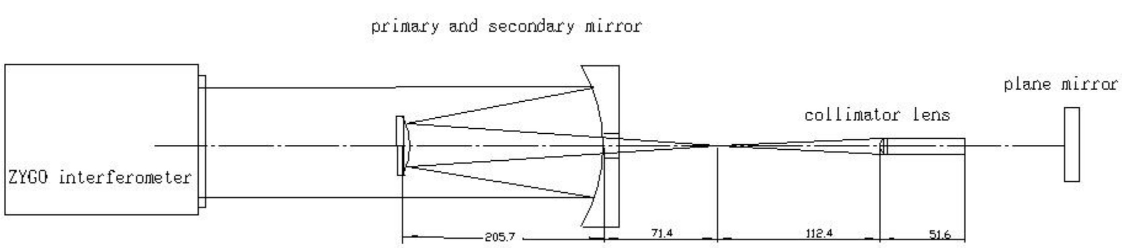

Figure 3. The structure of the telescope and the diagram of alignment scheme.

2.2 Delayed optical paths

There are some optical elements in the delayed optical paths such as the tip/tilt mirrors, the piston mirrors, and one beam combiner, as shown in Figure 4. Each sub-telescope is matched with a delayed light path. 4 beams are introduced into 4 delayed light paths through the tip/tilt mirrors. Right angle mirror is an important component of the delayed optical path, which is to compensate for the optical path difference also called piston error. The angles of right angle mirrors have been accurately aligned before inserted in the light path, and the angle error is no more than 2 arcsecond. The beam combiner is a corner cone prism that coated with a reflective film on the outer surface. The beam combiner has a through hole of the middle to allow beam of center sub-telescope (0#) pass through. The beam after reaching beam combiner is mapped onto the imaging lens and finally imaged on the camera.

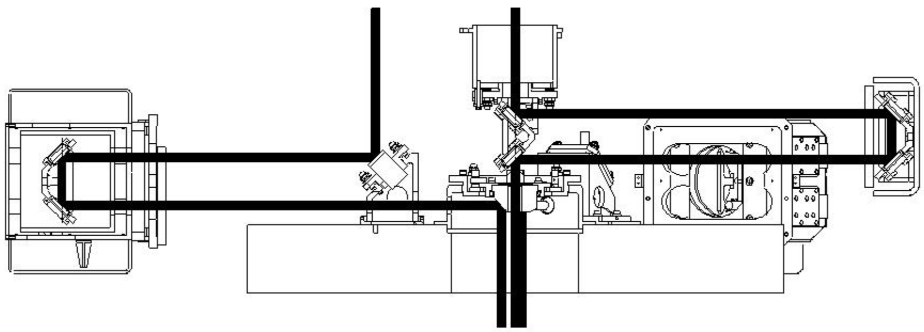

Figure 4. The diagrammatic sketch of delayed optical paths.

2.3 Tip/tilt/piston detection and imaging system

An imaging lens, which focal length is about 3.2m, is located behind beam combiner. In the focal plane, there is an camera to monitor the image. Tip/tilt mirrors and piston mirrors are both mounted on the PI actuators. Tip/tilt mirrors are used to correct the tip/tilt error so as to make two light beams overlap on the imaging plane. Piston mirrors are used to correct the piston error so as to compensate the Optical Path Difference(OPD). Fringe tracking system can be used to detect the OPD between two light beams. When the tip/tilt error and the piston error of two light beams are corrected to the minimum, the fringe is clearest. In this setup of prototype, there is no moveable tip/tilt mirror and moveable piston mirrors in the middle delayed light path (0#) only. So we can adjust the remaining three delayed lines with the middle delayed light path as a benchmark. When 4 piston errors are corrected, we can get the optimal resolution image.

3. SIMULATION

3.1 The simulation of PSF

According to the Fourier optics theory, the imaging performance of the optics system is usually evaluated in the spatial domain by the Point Spread Function(PSF) and in the time domain by the Optical Transfer Function(OTF). When we use a diffraction-limited imaging system to image the point target, we can receive the Fraunhofer diffraction images in the focal plane of the system. The PSF of the ideal imaging system can be represented as,

$$Z_k = \pi \cdot D \cdot \sqrt{(\frac{X}{\lambda f} + \frac{2\theta_{k\_tip}}{\lambda D})^2 + (\frac{Y}{\lambda f} + \frac{2\theta_{k\_tilt}}{\lambda D})^2} \quad (1)$$

$$E_{0k} = \frac{2J_1(Z_k)}{Z_k} \cdot \frac{\pi D^2}{4\lambda f} \quad (2)$$

$$E = \int_{\lambda_c - \frac{\Delta\lambda}{2}}^{\lambda_c + \frac{\Delta\lambda}{2}} \sum_{k=1}^{4} E_{0k} \cdot e^{-i\frac{2\pi}{\lambda f}(Xx_k + Yy_k)} \cdot e^{i\frac{2\pi}{\lambda}P_k}\, d\lambda \quad (3)$$

$$PSF = E \cdot E^* \quad (4)$$

where D is the diameter of the light beam mapped onto the imaging lens and f is the distance from the pupil to the imaging plane. J_1 is the Bessel function of the first kind. K is the number of the telescopes. Figure 5 shows the simulation results of the PSF under 3 kinds of the telescope array configurations.

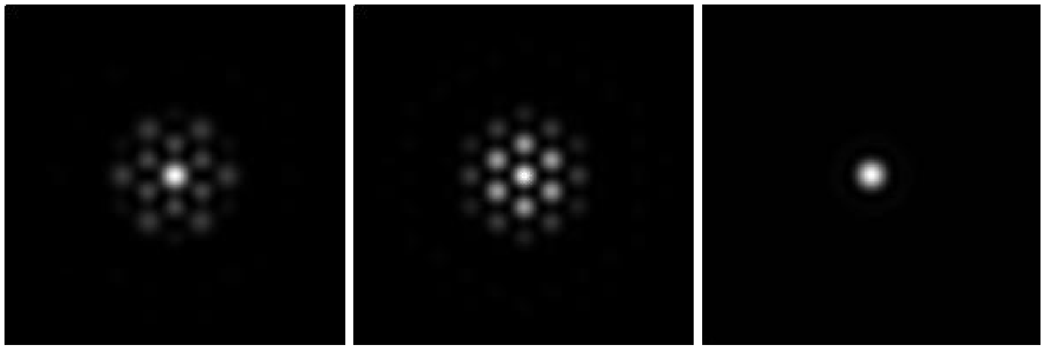

Figure 5. The simulation results of the PSF under the 3 kinds of the telescope array configuration: (left) Y-4 type; (middle) Golay3 type; (right) single aperture telescope with the equivalent diameter.

Comparing with the figure 5(left) and 5(middle), the more frequency information of Y-4 type in medium and high frequency domain can be obtained than Golay3 type, due to the contribution of the central telescope. Compared with the PSF of single telescope in figure 5(right), there are some side orders in Y-4 type and in Golay3 type.

3.2 Equivalent diameter calculation

The modulus of OTF is Modulation Transfer Function (MTF). The maximum cutoff frequency is one of the method for evaluating the actual spatial resolution capability of optical synthesis aperture imaging system. If the maximum cutoff frequency of Y-4 type telescope is coincided with that of the single telescope, the diameter of single telescope can be think as the equivalent diameter of Y-4 type telescope. Figure 6 shows the normalized MTF under the 3 kinds of telescope array configurations. Because the cutoff frequency of Y-4 type and Golay3 type both are not same in x direction and y direction, the normalized MTF changes with the cutoff frequency in both directions are calculated respectively. The simulation results show that the maximum cutoff frequency of Y-4 type in x direction is identical to a single telescope which diameter is 380mm and in y direction that is about 260mm.

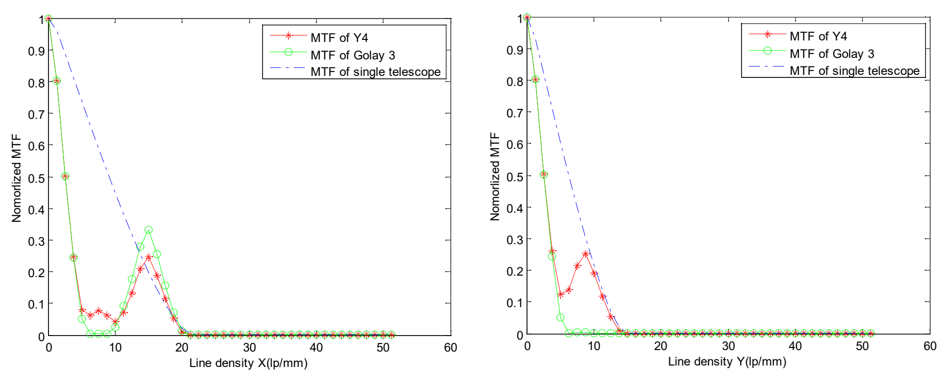

Figure 6. The plot of the normalized MTF under the 3 kinds of configuration: (left) x direction; (right) y direction.

3.3 The polarization effects

Fringe tracking system is the most important component in optical synthesis aperture telescope. Based on the method of fringe scanning, we can find the minimum OPD between different delayed optical paths. This requires higher contrast of fringe. The polarization effects in optical synthesis aperture telescope can reduce the contrast so that this effect can cause the image in focal plane blurring. Generally, there are two reasons for the polarization effect, one is mirror coating and the other is non-vertical incidence. Figure 7 shows that the polarization state before and after incidence at the mirror coated with Al_2O_3.

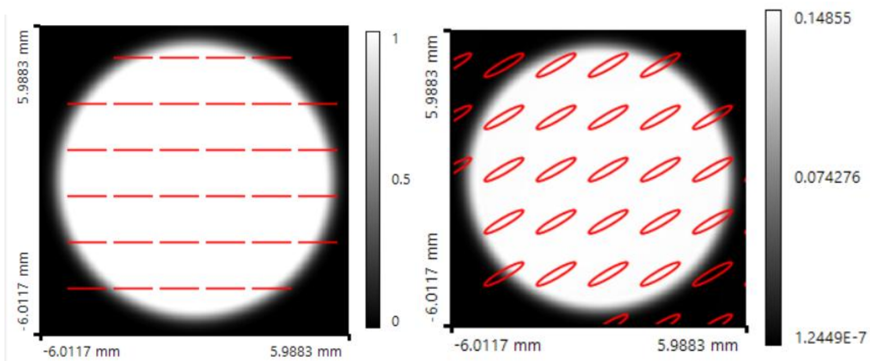

Figure 7. The polarization state before and after incidence at the mirror coated with Al_2O_3:(left) before ; (right) after.

If there is a different polarization states between two delayed paths, the contrast of fringe will be degraded as shown in Figure 8. As the polarization difference increased, the contrast of fringe declined from 0.99 to 0.53. Contrast of fringe is calculated from the intensity of brightest fringe and the adjacent dark fringe (the red dots as shown in figure 8) . The formula for calculating the contrast can be expressed as,

$$\text{contrast} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \qquad (5)$$

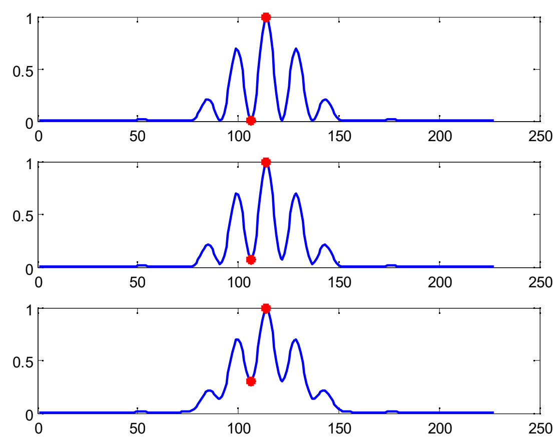

Figure 8. The profiles of fringes with different polarization degrees difference.

4. EXPERIMENT RESULTS

After a series of optical adjustment in laboratory, including the alignment and installation of 4 sub_telescopes, all the mirrors in delayed optical path, the combiner and imaging lens, we can obtain the image using four sub_telescopes simultaneously, as shown in Figure 9.