Aperture masking observations in binary stars detection with 1.56-m telescope

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ABSTRACT

By placing a mask over the pupil of the optical telescope, the aperture masking technique transforms the telescope into a Fizeau interferometry telescope.Thanks to reasonable aperture configuration and baseline rotation techniques, it is possible to achieve almost the same imaging quality as a full aperture telescope.This technique has shown great potential in astrometry and astrophysics research, such as: exoplanet detection, protoplanetary disk, brown dwarf, etc. In order to verify the image restoration algorithm,we carried out binary stars observations on 1.56-m telescope.We presented the numerical simulation of aperture configuration and baseline rotation, and designed the mask and the experimental system.We select some binary stars with magnitude from 5 to 7 and angular distance from 0.2 to 2arcsec as observation targets. Combined with the short exposure observation, a two-step image restoration method is proposed, the results of high-resolution image reconstruction and angular distance measurement are verified. The above results will be applied to the first generation Fizeau interferometry prototype at the Shanghai Astronomical Observatory(SHAO).
Keywords: aperture masking, image restoration, numerical simulation, binary stars, observation

1. INTRODUCTION

Aperture masking interferometry is a high-resolution and high contrast imaging technique based on optical interference theory, that allows diffraction limited imaging from ground-based telescopes. This technique replaces a traditional full-aperture telescope with a multi-aperture array by placing a customized mask in front of the secondary mirror or placed in a re-imaged aperture plane[1-2]. Most ground-based telescopes around the world at 5-10 meters are equipped with aperture masking observation equipment, such as Keck[2] and VLT[3]. As early as 1987, Haniff conducted binary stars observations using aperture masking on a 2.5-meter telescope and successfully obtained the angular distance and position angle[1]. With the development of large telescope technique, the application of aperture masking is becoming increasingly widespread, such as planetary systems, protoplanetary disks, brown dwarfs, low-mass stars, and more. Especially in recent years, the detection of exoplanets has received widespread attention, and aperture masking technique has been well developed as an effective observation mode[4].The JWST space telescope is also equipped with aperture masking observation mode, which can be combined with AO to obtain high-resolution imaging through multi-band observations and to probe the inner structure of nearby Active Galactic Nuclei (AGN),and it is also used as one of the coarse co-phasing schemes for JWST[5-8].

Aperture masking observation can also provide useful experimental and technical support for the development of Fizeau interferometry telescope. We hope to test the relative piston fluctuations of atmospheric turbulence at Sheshan station and verify the image restoration algorithm by conducting aperture masking design and observations on a 1.56-m telescope. It can also provide some technical verification for the first prototype of the Fizeau interferometry telescope at SHAO.

2. NUMERICAL SIMULATION AND DESIGN OF EXPERIMENTAL SYSTEM

2.1 Numerical simulation

Given the purpose of the observation experiment described in this article, we look forward to high-resolution observation, image restoration, and parameter measurement of binary stars. Therefore, we need to use a mask with at least three apertures and verify it through numerical simulation to make it almost equivalent to the resolution of a full aperture telescope.

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In this paper, we will briefly introduce the basic formula of multi-aperture interference and develop numerical simulation software.

Referring to Mennesson's article[9],the intensity of a multi-aperture array is as follows:

$$I \propto \left|\frac{\pi D(1+\cos(r))}{\lambda}\right|^2 \left|\frac{J_1(\pi D\sin(r)/\lambda)}{\pi D\sin(r)/\lambda}\right|^2 \left|\sum_{k=1}^{n} e^{j2\pi(L_k r/\lambda)\cos(\delta_k-\theta)} e^{j\phi_k}\right|^2 \qquad (1)$$

The first term of Equation 1 is practically constant over a small range of r. The second term is the intensity pattern of a single aperture and the third term is an array interference factor. Some of the parameters are shown in Figure 1.

In this paper, a symmetrically distributed aperture configuration is adopted (shown in Figure 1) and baseline rotation technique is used to achieve more adequate coverage of spacial frequency (so-called UV coverage). For this array configuration , the third term is described in equation 2:

$$I_{interference} = \left|e^{j2\pi(Lr/\lambda)\cos\theta} e^{j\phi_1} + e^{j2\pi(Lr/\lambda)\cos(2\pi/3-\theta)} e^{j\phi_2} + e^{j2\pi(Lr/\lambda)\cos(4\pi/3-\theta)} e^{j\phi_3}\right|^2 \qquad (2)$$

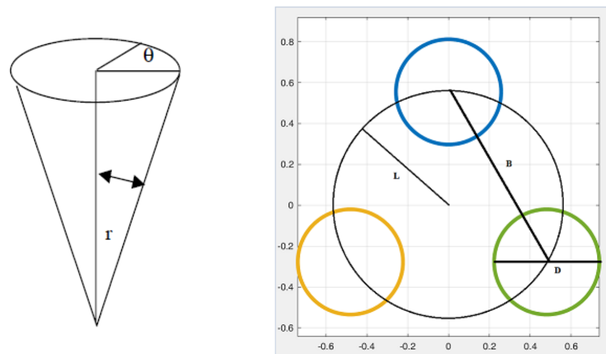

Figure 1 The aperture configuration and parameters in equation 1

The mask will be placed in front of the secondary mirror of the telescope. The parameters of the mask and the equivalent parameters of the primary mirror are shown in Table 1.

Table 1. parameters of the mask

Plane of secondary mirror		Plane of primary mirror	
diameter (d)	150mm	diameter (D)	515mm
baseline (b)	280mm	baseline (B)	961mm

In order to verify whether the current aperture arrangement can reach the diffraction limit of a full aperture telescope, we developed a software. Aiming to different aperture arrangements, baseline rotation, observation bands, and detector parameters, this software can calculate and evaluate point spread function(PSF), optical transfer function, UV coverage,etc.The UV coverage and MTF without baseline rotation are shown in Figure 2.

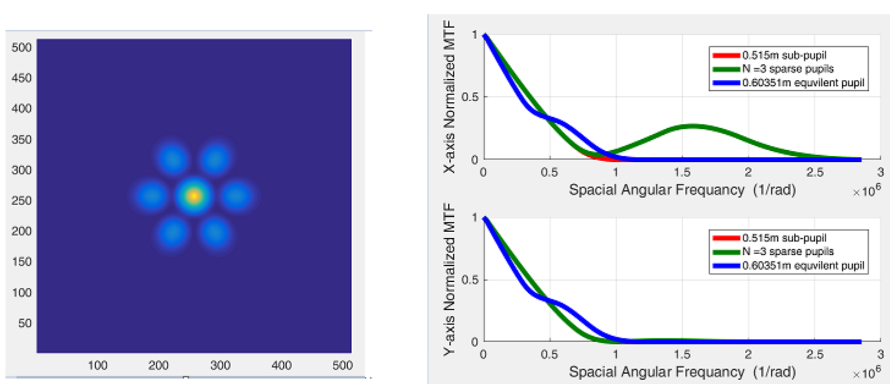

Figure 2 UV coverage and MTF without baseline rotation

It can be seen in Figure 2 that due to sparse UV coverage, the equivalent aperture of this array is much lower than the full aperture. Considering the characteristics of baseline rotation, we introduced a 30 step angle baseline rotation to increase UV coverage. The corresponding UV coverage is significantly increased, the numerical simulation is shown in Figure 3. Theoretically,with the help of image restoration technique, it can almost reach the limit resolution of 0.1arcsec.

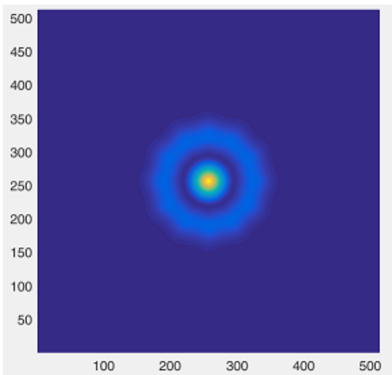
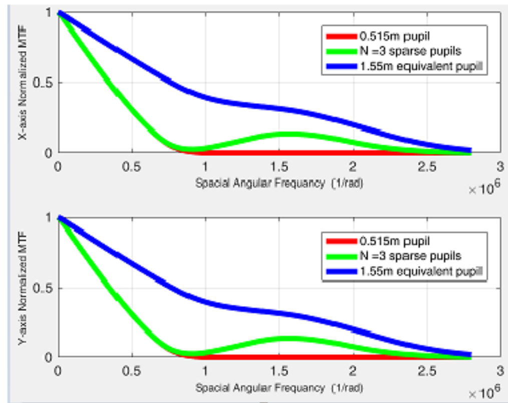

Figure 3 UV coverage and MTF with baseline rotation of 30 step angle

2.2 Introduction to Experimental System

In theory, based on the above discussion and the array configuration, we designed an image acquisition system to the terminal of the 1.56-m telescope, including an optical amplification unit and image acquisition equipment.The system has a magnification of five in order to meet the requirements of the sampling theorem and achieve the diffraction limit of the telescope. The optical structure is shown in Figure 4. The mask is placed in front of the secondary mirror and driven by a stepper motor. For this purpose, we developed a software that controls the motion of the stepper motor through the ECAT bus protocol; The acquisition, storage, and parameter settings of the camera are controlled through the CameraLink bus. The driving system structure is shown in Figure 5.

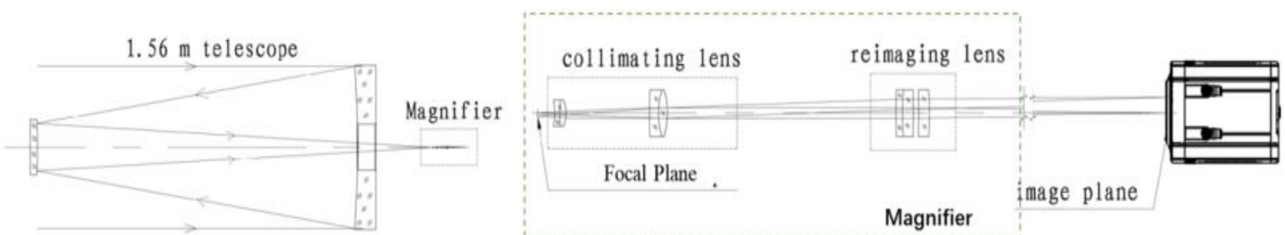

Figure 4 The optical system

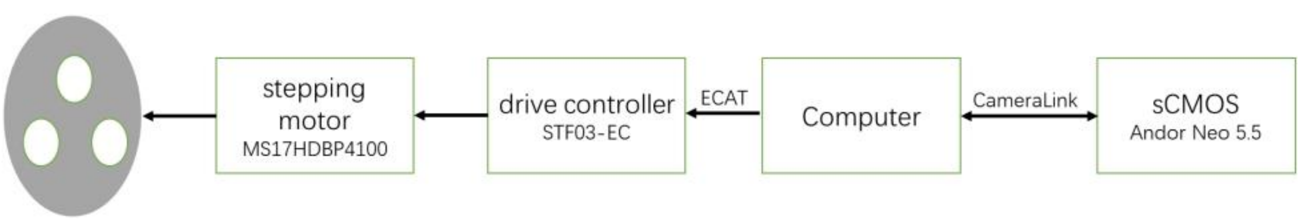

Figure 5 The driving system of mask and detector (sCMOS)

3. OBSERVATION AND DATA PROCESSING

3.1 Observations

We conducted binary stars observations on a 1.56-m telescope, with magnitudes ranging from 5 to 7 and angular distances ranging from 0.2 to 30arcsec. The experimental equipment and conditions are shown in Figure 6, and the list of targets are shown in Table 2. Based on the purpose of the observation experiment, we designed two observation modes: One mode is dual-aperture interferometry observation, which collects some 35ms short exposure images of the targets, and then obtained the relative piston fluctuations of atmosphere at Sheshan station through post-processing; In order to verify the image restoration algorithm and the impact of turbulence on imaging, a three-aperture interferometry observation was selected as another mode. The exposure time is 100ms, and the mask was rotated with 30° step angle . At each directional angle position, the reference stars and binary stars were alternately observed, and 100 samples were collected for each observation.

Figure 6 The experimental equipment and conditions

Table 2. The list of binary stars and reference stars

Name	right ascension	Declination	Separation （WDS）	Magnitude （WDS）	Separation （measured）
A 1377	18h 33m 56s	+52° 21' 12"	0.2"|0.2"	6.20|6.40	**0.22"**
HEI 568	19h 06m 58s	+11° 04' 15"	0.3"|0.3"	5.44|6.39	**0.25"**
STF 2583	19h 48m 42s	+11° 48' 56"	1.4"|1.4"	6.34|6.75	**1.44"**
STT 395	20h 02m 01s	+24° 56' 17"	0.5"|0.8"	5.83|6.19	**0.74"**
STF 2751	21h 02m 09s	+56° 40' 10"	1.5"|1.3"	6.23|6.89	**1.60"**
BU 989	21h 44m 38s	+25° 38' 42"	0.3"|0.2"	4.94|5.04	**0.21"**
STF 2909	22h 28m 50s	-00° 01' 12"	3.0"|2.1"	4.34|4.49	**2.40"**

3.2 Data processing

The main purpose of three-aperture observation is to obtain high-resolution image of binary stars, measure the angular distance, and verify the effectiveness of image processing algorithms. In theory,according to the aperture size of the mask, even using short exposure observations is insufficient to overcome the influence of atmosphere turbulence. We propose a two-step hybrid processing method for high-resolution image restoration of targets.The first step is preprocessing algorithm, including image denoising and background processing; Then convert images to the frequency domain for deconvolution; Finally, After post-processing, a binary image without phase information was obtained, but there is still a problem of image quality degradation caused by sidelobe effect in this image.The second step is the Fizeau interferometry image restoration algorithm, which minimizes the degradation of image quality caused by frequency loss. In this paper we adopt OS-EM[10] to the problem of restoring the above images.This method was originally designed for CT imaging and was later applied to LBT image restoration. The algorithm description can be found in reference 10. The measurement results of the angular distance of some observed targets are shown in the last column of Table 2.We use

STT395 as an example to demonstrate the high-resolution restored image of the target and analyze the results, as shown in Figure 7.

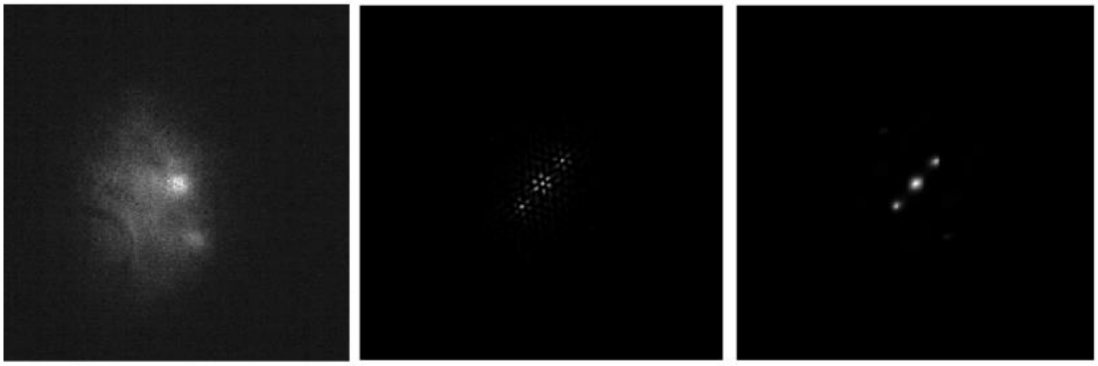

Figure 7 The results of STT395（Left: observation image Middle: image after step one Right:image after step two）

By analyzing the observation images and results, we can see that there are obvious speckle characteristics in the images. After processing with step one, the blurring caused by turbulence has been effectively improved; However, there is still image quality degradation caused by incomplete UV coverage in the image, as shown in the middle of Figure 7. Compared to full aperture telescopes, the sidelobes of the point spread function in aperture masking significantly increase, resulting in mid to high frequency attenuation. And after step two described above, a high-resolution binary image is obtained, and the measured angular distance is 0.74", which is basically equivalent to the given value in the catalog. There is a symmetrical image in the restored image because we does not consider phase information during the first step, but this does not affect the final parameter calculation results.

4. CONCLUSIONS

We conducted aperture masking observations on some binary stars using a 1.56-m telescope. After image restoration and calculation, we successfully got the angular distance of the target and obtained high-resolution binary images (angular distance greater than 0.2", magnitude between 6 and 7). During the observations,we did not calibrate the CCD, so we can not calculate the position angle information of the binary stars, and further calculations can be conducted through experiments in the future. In the process of data processing, we found that there was still turbulence effect on images, so we proposed a two-step image restoration method to suppress turbulence effect and improve the image degradation, which achieved good results. The experimental results of this article provide a preliminary technical foundation and validation for the co-phasing strategies of the first generation of the Fizeau interferometry telescope prototype, and also provide algorithm support for image restoration.

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