# Aperture Masking imaging using a hybrid algorithm for binary stars with 1.56-m telescope

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## ABSTRACT

Aperture masking observations for binary stars have been done with a 1.56-m telescope at Shanghai Astronomical Observatory(SHAO) during 2019-2024. In order to ensure ample light available to restore the high resolution images even at short exposure times and reach the diffraction limit of the 1.56-m telescope,we select some binary stars and reference stars nearby with magnitude 5-8 and angular distance 0.2-4 arcsec in the WDS catalog as observation targets.This article achieved high-resolution restoration of binary stars using a hybrid data processing method, including data reduction, a spatial domain method named ISA or a frequency domain method named SI to suppress atmospheric turbulence, and OS-EM to reduce image degradation caused by multi-aperture interference.The results show that this method can effectively obtain high-resolution images of binary stars, and the measured angular distance is basically consistent with the given value in WDS catalog.

**Keywords:** aperture masking, image restoration, binary stars, observation,ISA,OSEM

## 1. INTRODUCTION

Aperture masking is an interferometry technique allowing direct imaging with ground based optical telescope. In order to use aperture masking, we must discard most of the pupil area, and lose most of the signal, but we can also remove some of the atmospheric noise, and this leads to dramatically enhanced SNR. Nowadays,This technique has scored some conspicuous successes[1-9],such as planetary systems, protoplanetary disks, brown dwarfs, low-mass stars, and more.Aperture masking has been added to the CONICA camera with VLT-UT4 telescope,and they observed two debris disk systems HD 92945 and HD 141569,and demonstrated the potential for SAM mode to contribute to studies of faint companions[1-2]. H. C. Woodruff presented results from a spectro-interferometric study of the Miras *o* Cet, R Leo[3]. M. Willson reported on a survey of transitional disc targets observed using with Keck-II/NIRC2 instrument, and found significant asymmetries in four targets,this is thanks to the unique observational window that SAM provides[4].In recent years, aperture masking technique has been well developed as an effective observation mode to detect the exoplanets[5].The JWST space telescope is also equipped with aperture masking observation mode,which can be combined with AO, and open studies of planetary systems as much as ten magnitudes fainter than their host star[6]. They also can obtain high-resolution imaging through multi-band observations and to probe the inner structure of nearby Active Galactic Nuclei (AGN)[7-8]. And this technique is also used as one of the coarse co-phasing schemes for JWST, by combining narrow band and medium band Nyquist-sampled images taken with a science camera, they can sense JWST primary mirror segment tip-tilt to 10mas, and piston to a few nm[9].

During 2019-2024,aperture masking observations have been done with a 1.56-m telescope at SHAO,including three observation modes:single aperture,dual apertures and multi apertures.The purpose is to establish and test a high-resolution imaging processing scheme without AO, which can provide technical support for the prototype of the Fizeau type optical interferometric telescope.The organization of this article is as follows: Section 1 is introduction of aperture masking; Section 2 describes the experimental system and observation; the detailed data processing method will be discussed in section 3, and we will get the conclusion in section 4.

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# 2. EXPERIMENTAL SYSTEM AND OBSERVATION

## 2.1 Introduction to Experimental System

We designed two masks with different configurations. Mask A with a configuration of 3-hole,and Mask B with four configurations, including 3-hole,4-hole,Goly 6 and 7-hole. The parameter of the masks are shown in table 1. The mask is constructed in front of the secondary mirror. And the system is equipped with a rotating control mechanism to drive the mask, resulting in more abundant UV coverage. We also developed an amplification with 5x magnification before the Andor sCMOS camera, in order to match the theoretical limit resolution of the telescope.The observation system is shown in Figure 1,the driving&acquisition system and the relevant software are shown in Figure 2.

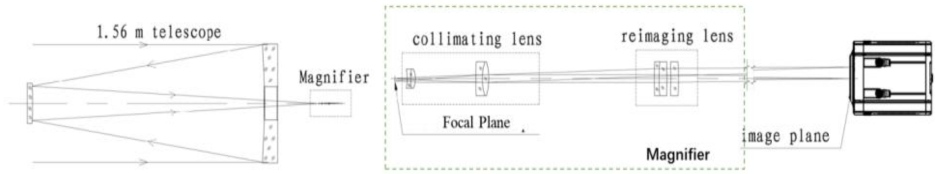


Figure 1 The observation system

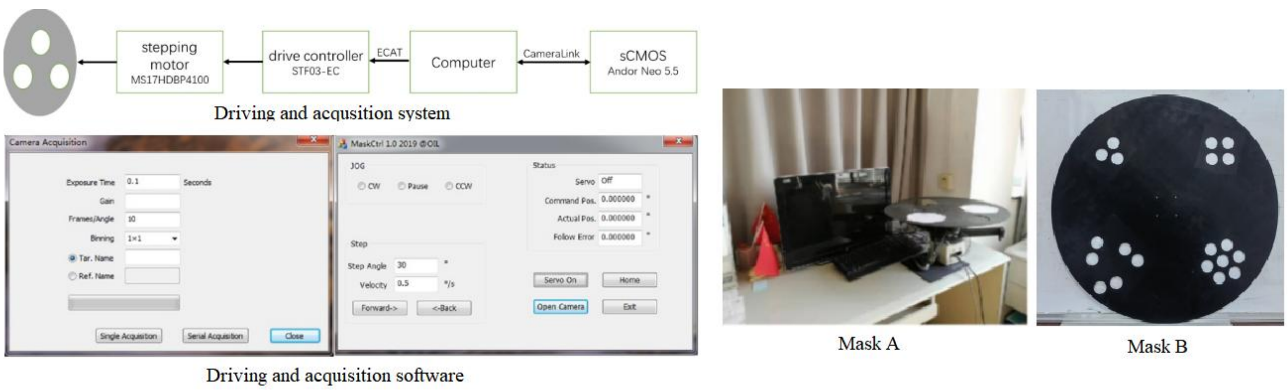


Figure 2 Driving&acquisition system, software and mask

Table 1 The parameter of the masks

| Configuration | Plane of secondary mirror | | Plane of primary mirror | |
|---|---|---|---|---|
| | **diameter (d)** | **baseline (b)** | **diameter (D)** | **baseline (B)** |
| (A)3-holes/4-holes/Goly6/7-holes | 300mm | 400mm | 1030mm | 1373mm |
| (B)3-holes | 150mm | 280mm | 515mm | 961mm |

## 2.2 Observations

Binary stars observation experiments were conducted with 1.56-m optical telescope at SHAO.The comprehensive system of the telescope has a focal length of 78 meters and a limited resolution of approximately 0.1 arcsec. Because the night sky background in Sheshan area is relatively bright, so we selected dozens of binary stars from the WDS star catalog as observation targets, with magnitudes ranging from 5 to 8 and angular distances ranging from 0.2 to 4 arcsec, while using nearby stellar as reference stars. The observation parameters and steps are as follows:

1) Dark acquisition: exposure time of 100ms, 100 frames;

2) In order to increase the UV coverage, Mask A is rotated at 15 degrees, 30 degrees, 45 degrees, and 60 degrees for every target; Mask B is not rotated;

a. Binary star data acquisition: exposure time of 100ms, 100 frames per angle, without binning;

b. Reference star data acquisition (located near binary star):exposure time of 100ms, 100 frames per angle, without binning;

3) Switch to the next set of binary and reference star;

In this article, we list some observation targets and the measurement results, as shown in Table 2.The specific data processing methods will be described in the next section.

Table 2 The observation list and measurement results

| **Name** | **right ascension** | **Declination** | **Separation (WDS)** | **Magnitude (WDS)** | **Separation (measured)** |
|---|---|---|---|---|---|
| STF1877 | 14h 45m 00s | +27° 04' 00" | 4.0"\|3.0" | 2.58\|4.81 | **2.92"** |
| 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"** |
| HU371 | 21h 35m 30s | +24° 27' 08" | 0.2"\|0.3" | 6.83\|7.27 | **0.16"** |
| BU 989 | 21h 44m 38s | +25° 38' 42" | 0.3"\|0.2" | 4.94\|5.04 | **0.21"** |
| COU14 | 21h 50m 06s | +17° 17' 09" | 0.4"\|0.2" | 5.74\|6.94 | **0.27"** |

## 3. DATA PROCESSING

Considering that the equivalent diameter of the sub-aperture of the mask is 515mm/961mm, which is greater than the atmospheric coherence length, it is still affected by atmospheric turbulence in imaging observations and resulting in speckle phenomenon.We adopted a hybrid processing method to get the high-resolution images of the binary stars, including data reduction, a spatial domain method named ISA or a frequency domain method named SI to suppress atmospheric turbulence, and OS-EM to reduce image degradation caused by multi-aperture interference.The process of restoration algorithm is shown in Figure 3.

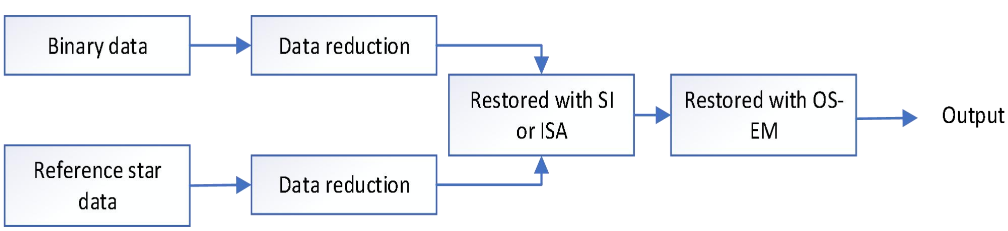


Figure 3 The hybrid processing method

- Data reduction

The image size captured by Andor sComos camera is 2160 * 2560, and we cropped them to 512 * 512 with the maximum value of the image as the center. And then dark correction, background correction and denosing for both binary data and reference data are done at this step.

- ISA

The Iterative shift-and-add (ISA) is an algorithm in spatial speckle imaging, which was proposed by Yaohui Qiu and zhong liu, it is based on a concept of "the region of the greatest diffraction limitted information of object"[10]. The steps of ISA are as follows:

1) Get the PSF using SAA with reference data;

2) Get the initial image using SAA with binary data;

3) Compute the correlation of the original data and the initial image;

4) Find the maximum pixel of the correlated image, and the point can be taken as the point for shifting;

5) Deconvolve and get the restored image.

We can also use the classic frequency domain processing method, speckle interferometry(SI)[11]. This method is simple and fast to calculate, with symmetrical ghost images, but it does not affect the measurement results such as angular distance.

- OS-EM

It is an acceleration algorithm based on ordered subsets of projection data.This method was originally designed for CT imaging and was later applied to LBT image restoration.The detailed algorithms can be found in the literature which is written by M. Bertero and P. Boccacci[12].

After processing followed the above steps shown in Figure3, we got the measurement results and the restored image, some of them are shown in the last column of Table 1.

We take STF1877 as an example to demonstrate the high-resolution restored image of the target and analyze the results, as shown in Figure 4.

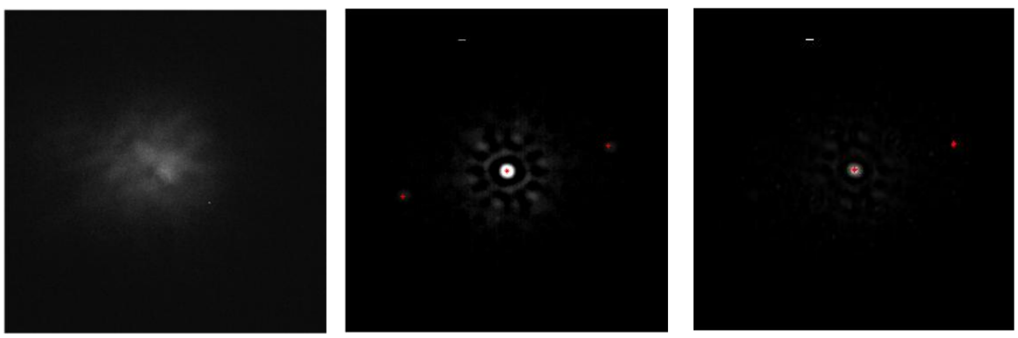

Figure 4 The results of STF1877

(Left: reduction data, Middle: the restored image with SI+OS-EM, Right: the restored image with ISA+OS-EM)

By analyzing the observation images and results, we can see that there are obvious speckle characteristics in the images without AO. After processing with ISA/SI, the blurring caused by turbulence has been effectively improved; and after processing with OS-EM, the sidelobes caused by multi-aperture has been moved, a high-resolution binary image was obtained, and the measured angular distance is 2.92", which is basically equivalent to the given value in the WDS catalog.

## 4. CONCLUSIONS

We conducted aperture masking observations on some binary stars and proposed a hybrid image restoration method with the ISA/SI and OS-EM. After image restoration and calculation, we successfully got the angular distance and obtained the high-resolution binary images. And the measured angular distance is basically consistent with the given value in WDS catalog.

## REFERENCES


[1] S. Lacour, P. Tuthill, P. Amico et al. "Sparse aperture masking at the VLT I. Faint companion detection limits for the two debris disk stars HD 92945 and HD 141569, " Astronomy & Astrophysics, 532, A72(2011).

[2] Peter Tuthill , Sylvestre Lacour , Paola Amico , Michael Ireland , Barnaby Norris , Paul Stewart , Tom Evans , Adam Kraus , Chris Lidman , Emanuela Pompei , Nicholas Kornweibel."Sparse Aperture Masking (SAM) at NAOS/ CONICA on the VLT, " Proc. SPIE 7735, Ground-based and Airborne Instrumentation for Astronomy III, 77351O (2010).

[3] H. C. Woodruff, M. J. Ireland, P. G. Tuthill, et al."THE KECK APERTURE MASKING EXPERIMENT: SPECTRO-INTERFEROMETRY OF THREE MIRA VARIABLES FROM 1.1 TO 3.8 μm," The Astrophysical Journal, 691:1328–1336, 2009.

[4] M. Willson , S. Kraus , J. Kluska et al."Sparse aperture masking interferometry survey of transitional discs* Search for substellar-mass companions and asymmetries in their parent discs, "A&A 595, A9 (2016) .

[5] Steph Sallum and Andy Skemer, "Comparing Non-Redundant Masking and Filled-Aperture Kernel Phase for Exoplanet Detection and Characterization," Journal of Astronomical Telescopes, Instruments, and Systems, 5(1), 018001(2019).

[6] A. Soulain, A. Sivaramakrishnan, P. Tuthill, D. Thatte et al."The James Webb Space Telescope Aperture Masking Interferometer,"Proc SPIE 11446, 1144611 (2020).

[7] K.E. Saavik Ford, Barry McKernan."AGN AND QUASAR SCIENCE WITH APERTURE MASKING INTERFEROMETRY ON THE JAMES WEBB SPACE TELESCOPE,"The Astrophysical Journal,, 783(2), 73(2014).

[8] Etienne Artigau, Anand Sivaramakrishnan, Alexandra Z. Greenbaum et al. "NIRISS aperture masking interferometry:an overview of science opportunities, "Proc SPIE 9143,914340(2014) .

[9] Anand Sivaramakrishnan, David Lafrenière, K. E. Saavik Ford et al., "Non-Redundant Aperture Masking Interferometry(AMI) and Segment Phasing with JWST-NIRISS," Proc SPIE 8442, 84422S, (2012).

[10] Qiu Yaohui, Liu Zhong ,Lu Ruwei et al."A New Method for Astronomical Image Reconstruction in Spatial Region:Iterative Shift-and-Add Technique," Acta Optica Sinica, 21(2),186-191,(2001).

[11] A Labeyrie."Attainment of diffraction limited resolution in large telescope by fourier analysing speckle patterns in star images," Astronomy and Astrophysics,6(1), 85－87(1970).

[12] M. Bertero and P. Boccacci. "Application of the OS-EM method to the restoration of LBT images," Astronomy & Astrophysics Supplement Series. 144, 181–186 (2000).