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High-resolution imaging of optical interferometric telescope

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ABSTRACT

High resolution observation of celestial objects has always been the goal of optical interferometry. In this paper, we concentrated on two aspects of image reconstruction for Fizeau interferometric telescope. 1. The influence of piston error on imaging quality was studied, which provides a basis for the technical specifications of telescopes. 2. We proposed to use speckle imaging technology in interferometric telescopes, this method can reduce the effect of atmospheric turbulence on the resolution. In summary, a method combining denoising algorithm and speckle imaging technology is used to suppress noise, remove turbulence and reconstruct high-resolution images of real objects. The simulation results show that speckle imaging technology is also applicable to the interferometric telescope, and got good image reconstruction effect. The research results can be further extended to other mosaic telescopes.

Keywords: high-resolution imaging, optical interferometry, piston, speckle imaging, image reconstruction

1. INTRODUCTION

In the process of the development of astronomy, high resolution observation of celestial objects has always been the goal of astronomers. The technique can provide some useful information for the research of celestial bodies, formation and evolution, it also can realize space target surveillance and tracking. In most cases, large-aperture optical telescopes are used for astronomical imaging research. In general, the larger a telescope aperture, the higher inherent resolution is. However, in practice, making extremely large telescope is confronted with some difficult problems: ultra-precision mirror grinding, Complex Mechanical Structure and high cost. At the same time, due to the influence of atmospheric turbulence, the actual resolution of optical telescope is far less than the theoretical resolution. Optical interferometric telescope which consists of several sub-apertures is one of the significant technique utilized to measure astronomical objects with high resolution. It can achieve the equivalent resolution of large-aperture telescopes through reasonable array configuration. It is one of the main research directions of ground and space telescopes in the future.

At present, this technology has become a research focus all over the world. There are two kinds of optical interferometric telescope arrays. One is Michelson interferometric array, such as Keck, NPOI, MROI and VLTI, they can provide super high spatial resolution which can reach millisecond resolution; the other is Fizeau interferometric telescope, such as LBT, this kind of telescope has the advantage of short baselines, common mount and multiple sub-apertures, so it is feasible for instantaneous direct imaging through focal plane combination.

The researchers of Shanghai Astronomical Observatory have developed the study of optical interferometric technique for a few years. We have made many achievements in imaging theory, array configuration, co-phasing detection and image restoration[1-3]. Image restoration is the last step in the optical interferometry imaging. This paper is mainly concerned the simulation of image restoration.

In the following sections, we will describe the structure of interferometric telescope. Section 2 gives the description of the simulation and the reconstruction of images with different piston error. Section 3 shows the influence of atmospheric turbulence on imaging, and introduces speckle interferometry into optical interferometric telescope. Finally, we get the conclusions and expectation.

1.1 The structure of interferometric telescope

Fizeau interferometric telescope is mainly composed of a primary mirror, a secondary mirror and a beam synthesizer. The primary mirror is a virtual parabolic surface composed of a central sub-aperture and six annular off-axis sub-apertures. The diameter of the sub-aperture is 40cm, and the centre-to-centre spacing is 15cm. The structure of the telescope is shown in Figure 1, and the corresponding parameters are shown in Table 1.

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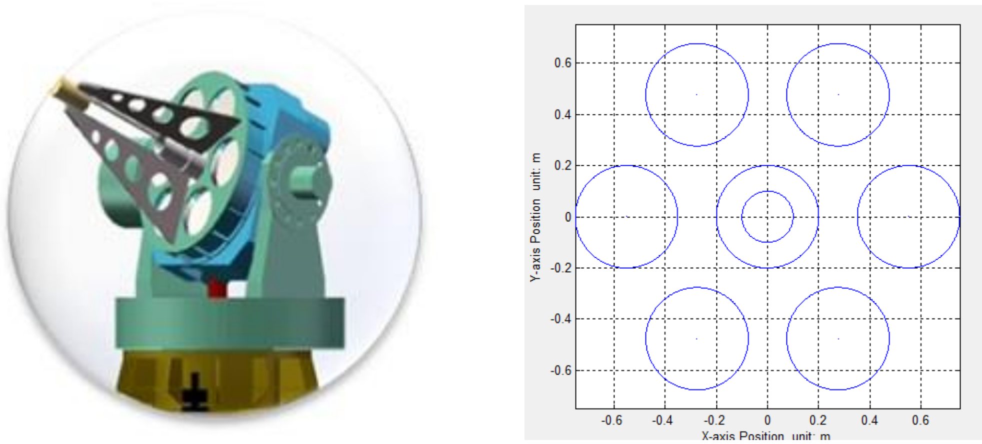

Figure 1.The structure of segmented mirrors telescope (L: concept map; R: array configuration diagram)

Table 1. The parameters of segmented mirrors telescope

parameters	**value**	**unit**
Sub-aperture diameter	40	cm
Obstacle of central mirror	20	cm
segments number	7	unit
equivalent aperture	124	cm
surface accuracy RMS	1/50	λ
surface accuracy P-V	1/6~1/8	λ

2. IMAGE RECONSTRUCTION WITH DIFFERENT PISTON ERROR

Compared with single-mirror telescopes, the biggest challenge for Fizeau optical interferometric telescopes is how to effectively maintain the common phase between sub-mirrors. Each sub-mirror may have six degrees of freedom, piston and tip/tilt error are the main factors which are affected imaging quality. The smaller the common phase error of the sub-mirror, the better the imaging quality of the telescope.

Because of the incomplete frequency coverage and the influence of errors, the image obtained by the interferometric telescope should be reconstructed by the restoration algorithm. The accelerated method OS-EM[4-6] which is based on ordered subsets of projection data are widely used in image restoration, especially in Computed Tomography (CT). It is also used for reconstruct the real image derived from optical interferometric telescope, for example: LBT adopted this method in their software. In this paper, the process of optical interferometric image reconstruction is shown in Figure 2.

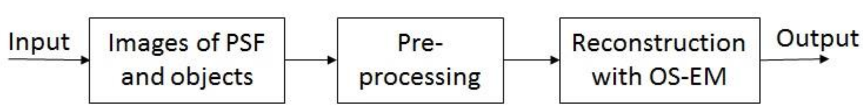

Figure 2. The process of optical interferometric image reconstruction

In the past few years, we did some experiments with different array configuration and image reconstruction algorithms, and OS-EM algorithm shows superior performance. We also carried out some experiments with different piston errors, the results of image restoration are compared and analyzed. We also analyzed the RMS error and the number of iteration and got some useful results. The results are shown in Table 2.

Table 2. The comparison under different piston

Piston error	Iteration number	Compute time	RE	MSE
0um	20	5s	0.0081	0.00136
±0.1um	20	5s	0.0106	0.00231
±0.2um	20	5s	0.0102	0.00349

3. SPECKLE IMAGING WITH OPTICAL INTERFEROMETRIC TELESCOPE

It is unavoidable to be affected by atmospheric turbulence when observing astronomical objects with ground based telescope, and the images would be degraded by blurring, jitter and so on. At present, most of the large-aperture optical telescopes are equipped with AO system to correct turbulence effects. For Fizeau interferometric telescope, because of the large number of sub-mirrors, each sub-mirror needs to be equipped with an AO system, the complexity of mechanical structure and the cost of construction will be increased. Therefore, we proposed the application of Speckle Interferometry to interferometric telescope. By taking a series of short exposure speckle images, and get high resolution imaging of the objects after post-processing.

In this paper, the PSF of Fizeau interferometric telescope is simulated by numerical simulation, and then convoluted with the real object to obtain a series of simulated speckle images. After denoising algorithm, DSA restoration and post-filtering, the high-resolution restored image of the object will be obtained. The process of reconstruction algorithm is shown in Figure 3.

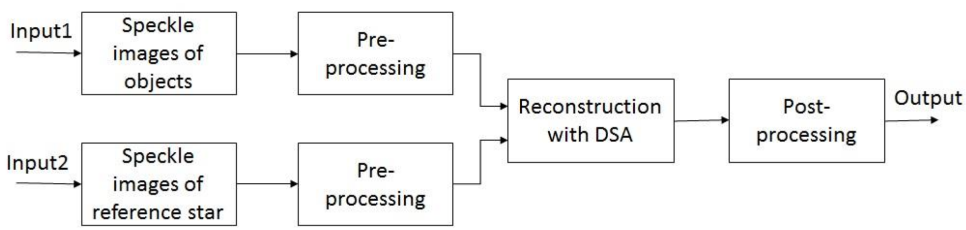

Figure 3. The process of reconstruction algorithm

3.1 Image pre-processing and post-processing

Astronomical images are mostly dim and sensitive to noise. This kind of image contains complex noise, including dark current noise, recording noise, detector noise, CCD read-out noise, photon noise, systematic error caused by the difference of atmospheric, other noises and so on. Because of these noises, it is very difficult to get high-resolution image of astronomical object. Therefore, it is necessary to use appropriate noise reduction methods to deal with these noises.

Wiener filtering is an adaptive filtering method, which can adjust the output of the filter according to the local variance of the image. The ultimate goal of this method is to minimize the mean square error between the original image and the restored image, and it is better to remain the edge information and the high frequency information. It is suitable to remove the white noise. Alpha-trimmed mean filter is a nonlinear spatial filter. It is widely used for the restoration of signals and images corrupted by additive non-Gaussian noise. In this paper, winner filter is adopted as pre-processing method, and alpha-trimmed mean value filter is adopted as the post-processing method.

3.2 Deconvoluted Shift-and-Add

DSA[7] is a spatial reconstruction method based on the statistics of the object diffraction image. It is more suitable for the restoration of extended objects. Firstly, we can get the initial estimation of the object based on ISA[8] algorithm; secondly, the initial estimation will be removed from the speckle image by deconvolution, and the maximum position of the remaining part is probably the position of the stronger pulses in the PSF of the integrated system; At last, speckle images of object will be shifted and added based on this position, and we will obtain the high resolution restoration image of the astronomical object.

3.3 The result of reconstruction

Numerical simulation experiments are carried out for 40 cm full-aperture telescope, 124cm full-aperture telescope and Fizeau interferometric telescope (equivalent aperture 124cm). The reconstruction results are shown in figure 4.

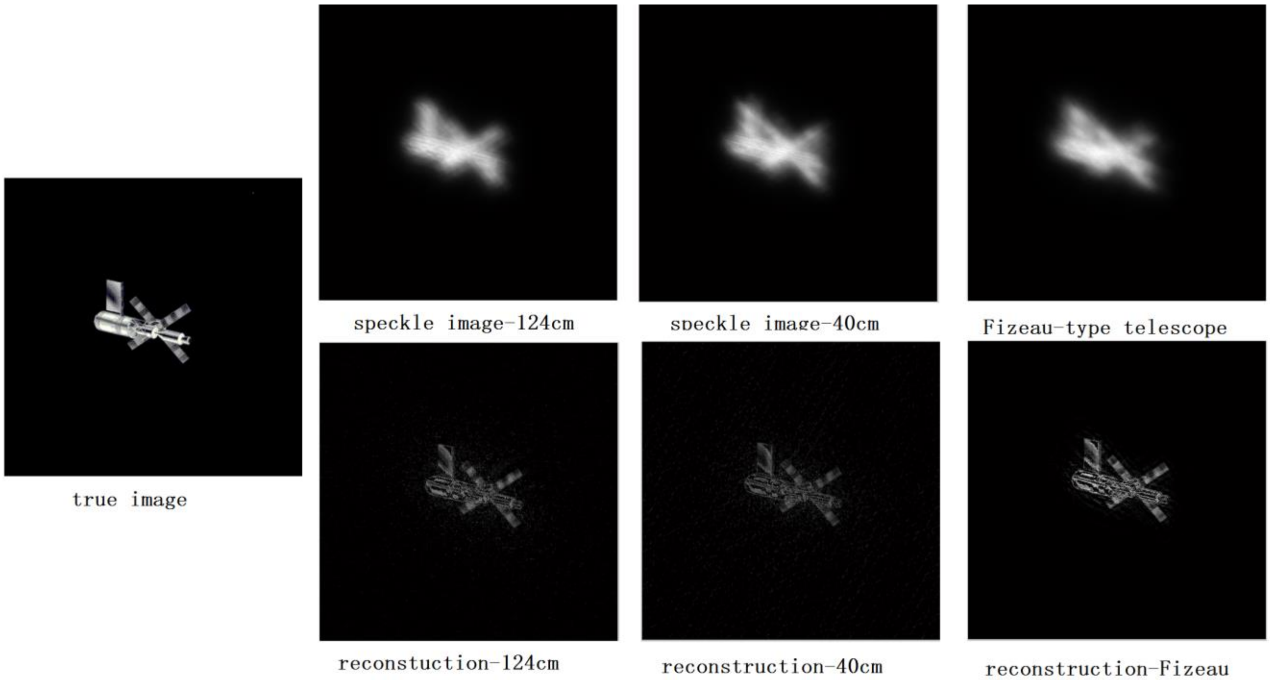

Figure 4. The results of reconstruction experiments

We also obtained some useful conclusions according to the experiments:

1. Speckle interferometry technique is also applicable to Fizeau interferometric telescope.
2. The comparison of image restoration effects: Fizeau telescope is the best, 124cm telescope is the second, and 40cm telescope is the last. Reasons for the above results: When the equivalent aperture of Fizeau telescope equals to a single aperture telescope, the effect of turbulence on the image quality becomes smaller because the size of sub-mirror decreases greatly. But for the telescope with 124cm and 40cm apertures, the imaging quality of the large one is better.

4. RESULTS AND DISCUSSION

In this paper, we did some research and experiments on the image reconstruction methods for Fizeau interferometric telescope, and the application of speckle interferometry in interferometric telescopes is verified by numerical simulation. In the future, we will carry out masking interferometry experiments on 1.56-m telescope to verify the image restoration method, and the application of speckle interferometry will be introduced into the masking interferometry technology.

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