Realization of a kind of interferometric imaging telescope with four apertures

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ABSTRACT

Abstract: The Fizeau type interferometric telescope forms an array of several sub telescopes for direct imaging on the image plane based on the principle of optical interferometry. Compared to the optical long baseline interferometer, this kind of telescope can be used for real time imaging of celestial body due to some excellent characteristics such as sufficient spatial frequencies coverage, single mounting avoiding outer optical delay lines and so on. We have built an interferometric imaging telescope with four apertures. Although each aperture size is 100mm, but this telescope can reach the higher angular resolution which is equivalent to a monolithic telescope of 280mm aperture size through optimal array configuration. Some novel opto-mechanical structure design and error control methods have been applied to this telescope successfully. For example, in order to enhance the rigidity of mechanical system, a unique C-shape structure to replace the traditional azimuth axis is adapted. Piston, tip/tilt errors between all apertures can be detected at the same time by extracting signals from Modulation Transfer Function (MTF), so some classical beam splitters can be removed which will reduce light loss significantly. At present, we have finished the final assembly, co-phasing calibration and verifying of dynamic co-phasing close-loop methods at laboratory. The FWHM of far field image spot is 0.43 arcsecond which is consistent with theoretical values. The out-door astronomical observation will be carried out soon.

Keywords: optical telescope, interferometric array, piston error, tip tilt error, imaging

1. INTRODUCTION

Astronomical interferometry is a unique technique for achieving high-resolution observations, which is different from large aperture telescopes. It forms a two-dimensional multi baseline array of several smaller sub-aperture telescopes, and achieves high-resolution observation through optical interferometry principles. Without considering atmospheric turbulences, the spatial resolution will extend the limitations of telescope aperture and be determined by the baseline length. In theory, the longer the baseline, the higher the resolution. The doubling of the spatial resolution of telescopes will undoubtedly have a strong promoting effect on many cutting-edge research topics in astrometry, astrophysics, and astrobiology.

The Fizeau type interferometric telescope forms an array of several sub telescopes for direct imaging on the image plane based on the principle of optical interferometry. Compared to the optical long baseline interferometer, this kind of telescope can be used for real time imaging of celestial body due to some excellent characteristics, such as sufficient spatial frequencies coverage, single mounting avoiding outer optical delay lines and so on.

We have built an interferometric imaging telescope with four apertures. Although each aperture size is 100mm, but this telescope can reach the higher angular resolution which is equivalent to a monolithic telescope of 280mm aperture size through optimal array configuration. A unique C-shape structure has been used to enhance the rigidity of mechanical system. Piston, tip/tilt errors between all apertures can be detected at the same time by extracting signals from Modulation Transfer Function (MTF), so some classical beam splitters can be removed which will reduce light loss significantly.

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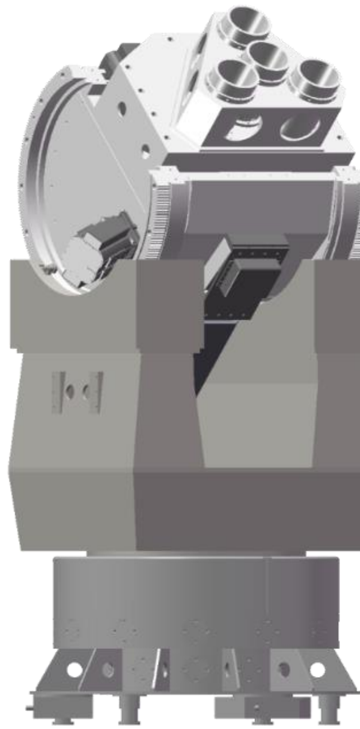

Figure 1. The 3D picture of Y-4 interferometric imaging telescope

2. DESIGN

We have designed and analysed two types of interferometric array configurations. The first type is a triangle configuration with three apertures, shown in figure 2. Three 100mm sub-apertures formed an equilateral triangle, while the center of the array is empty. This configuration has relatively high U-V coverage and point spread function(PSF), compared to single 100mm sub-aperture. The second type is a Y shape configuration with four apertures (Y-4 configuration) , shown in figure 2. Four 100mm sub-apertures formed a Y shape, one at the center of the array, the others evenly distributed around the center sub-aperture. The Y shape configuration has much higher U-V coverage and point spread function (PSF).

The goal of the Y-4 interferometric telescope is to achieve precise detection of co-phase errors and achieve interferometric imaging at visible band. This telescope can also be used for double star astronomy, near earth objects, and tracking of space targets in medium and low orbits. In order to achieve interferometric imaging, we should optimize array and structural design and maximize spatial frequency domain coverage. The precision requirement for co-phasing error should be better than 1/10 wavelength, and perform interferometric image restoration to get true image. Figure 3 shows the simulated PSF of interferometric image and un interferometric image. The PSF increased about three times after interference.

Some novel opto-mechanical structure design and error control methods have been applied to this telescope successfully.

- A unique C-shape mounting structure to replace the traditional azimuth axis is adapted in order to enhance the rigidity of mechanical body.

- Piston & tip/tilt errors between all apertures can be detected at real time by extracting signals common sensing unit avoiding extra beam splitters.
- Adopting the modular design concept for all Piston & tip/tilt correction units to improving telescope's stability and flexibility.

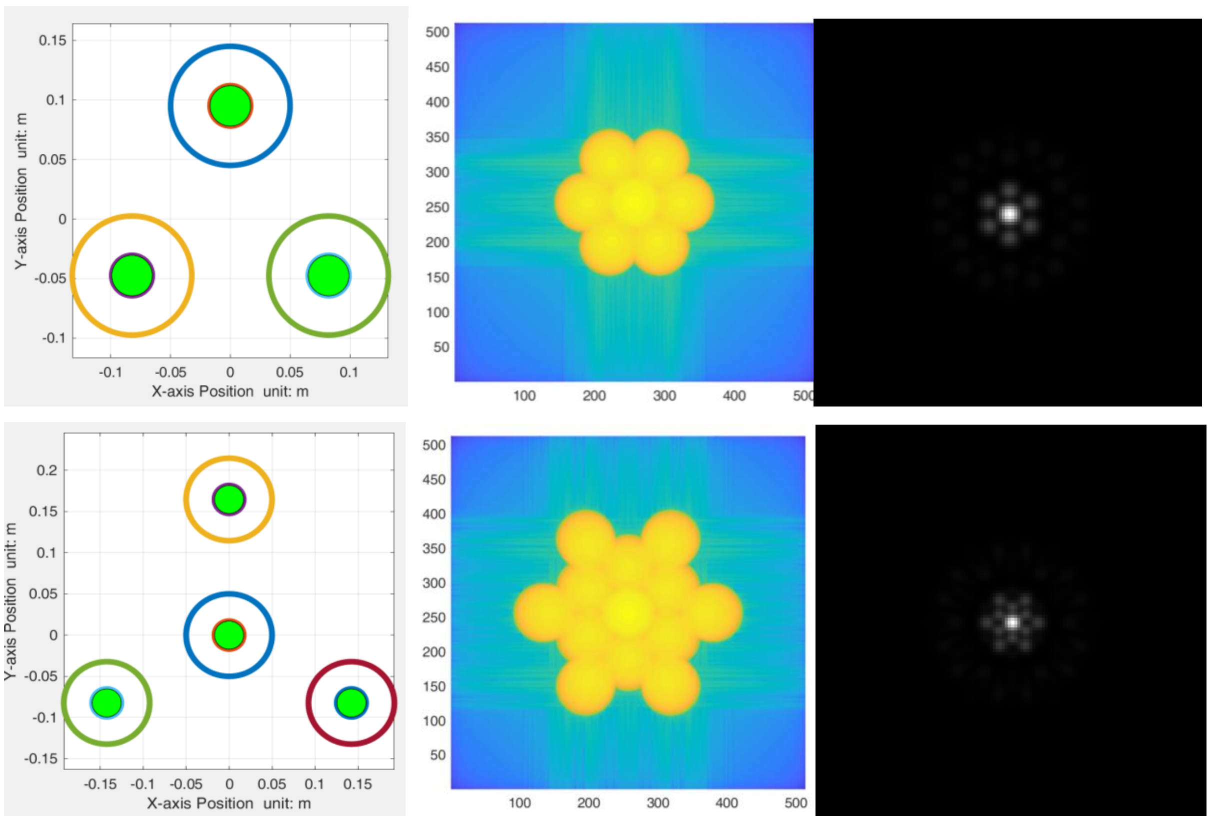

Figure 2. Comparation of triangle and Y-4 configuration at U-V coverage (middle image) and PSF (left image)

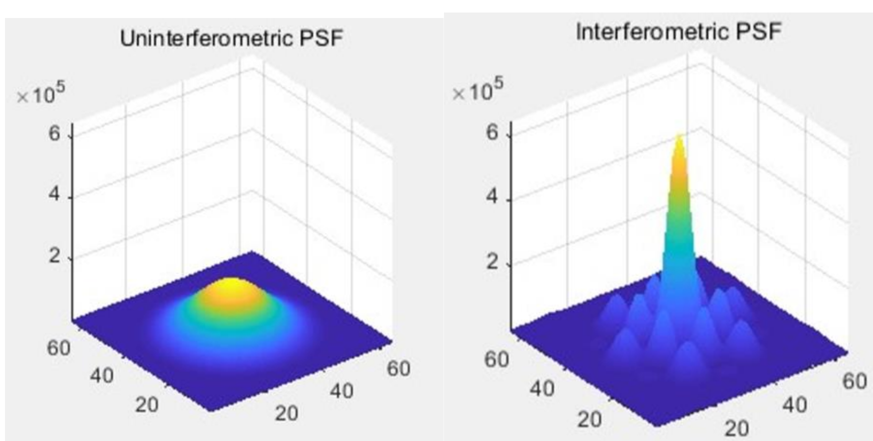

Figure 3. PSF of interferometric and un interferometric image

Optics of sub-aperture is RC primary and secondary mirror with a set of collimating mirrors, shown in figure 4. The entrance pupil is 100mm, the exit pupil is 10mm, so the magnification rate is 10. The collimators can be adjusted along optical axis to compensate temperature drift induced de-collimation.

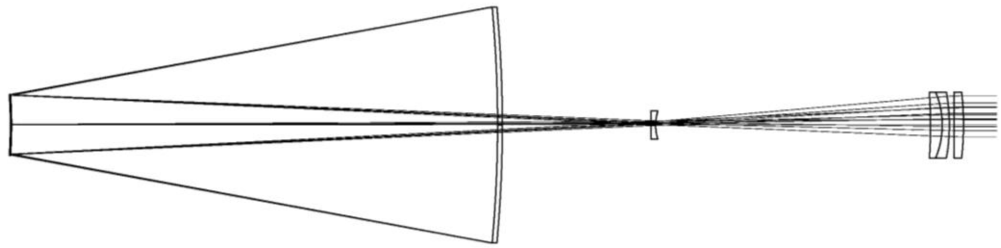

Figure 4. Optics layout of sub-aperture

When the light comes out of the pupil, it will entre the delay line system, also serves as co-phasing correction unit, shown in figure 5. Light from sub-aperture will be rapidly corrected by a fast tip/tilt mirror, then comes to a right angle mirror for piston error correction, finally the light will be turned to a trihedral cone, which can reconfigure the four beams parallelly. After reconfiguration, the 10mm beams form the same Y-4 shape as the entrance pupil, while the spacing size is reduced by 10 times. This arrangement satisfies the principle of proportional scaling, which ensures the interferometric imaging.

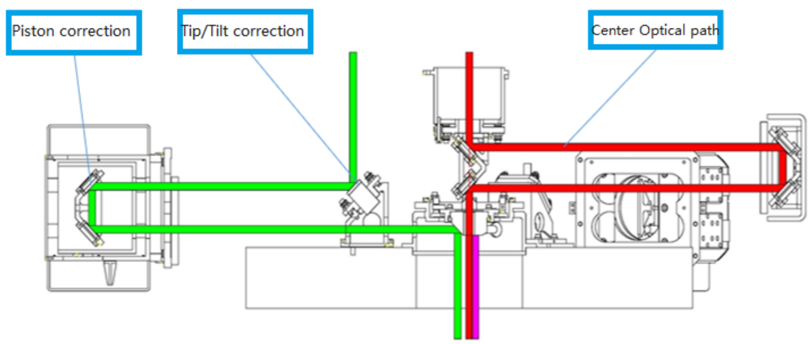

Figure 5. Co-phasing correction unit

The reconfigured beams finally entre beam combining system for interferometric imaging and co-phasing error detection. The beam combining system uses a double bonded lens, which has the disadvantages of color difference and narrow operating spectral range. The short focal length of the beam combining mirror results in insufficient stripe sampling and low resolution. The imaging terminal includes a common phase detection camera, a directional detection camera, and a scientific imaging camera, all of which have been used for many years, and the pixels show varying degrees of aging and increased noise; The optical components of the beam combining and imaging terminal can meet the random rotation requirement during observation.

The whole co-phasing correction unit is installed into a unique C-shape mounting structure. This structure can provide adequate space to install the piston and tip/tilt correction parts, and ensure the rigidness of the co-phasing correction unit. The telescope mount is an alt-azimuth structure, which has the advantages of compact structure, simple gravity deformation, and high pointing accuracy. Figure 1 is a schematic diagram of the structure of the telescope's mount system.

The mount consists of elevation axis system, azimuth axis system, and a ship type frame. The elevation axis system is composed of C-shaped frame. The outer circle of the C-frame and four supporting bearings form an elevation axis system. The elevation axis gear is installed on both sides of the C-shaped frame, and the elevation encoder and driving torque motor are installed on the right side of the C-shaped frame, The C-frame is supported by two sets of rolling bearings on both sides. Both radial and axial bearings are used to prevent displacement and overturning of the C-frame during rotation. This design can apply preload force on the elevation axis to eliminate radial shaking, also constrain the 5 degrees of freedom of the axis system to ensure the rotational accuracy in the pitch direction. The azimuth axis system of

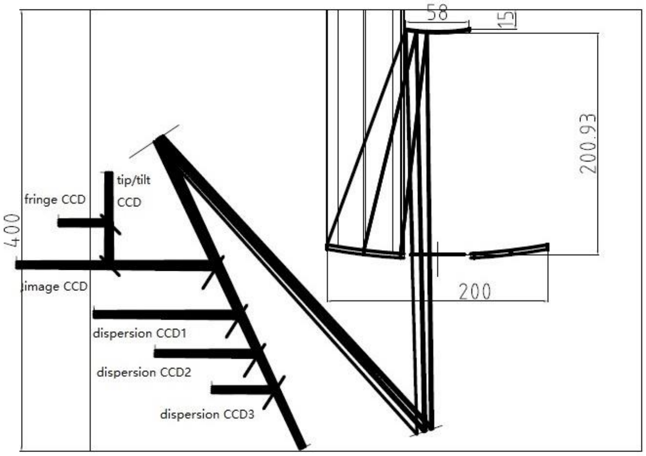

Figure 6. Beam combining optics

the interferometric telescope uses dense ball bearings, which are composed of upper and lower thrust bearing rings, steel balls, cages, and cage support mechanisms. The dense ball thrust bearing has the advantages of high load-bearing stiffness, flexible rotation, reduced shaking of the azimuth axis, improved accuracy, and simple maintenance.

3. ASSEMBLING & ALIGNMENT

We assembly and align the opto-mechanical system at laboratory. Optical alignment between primary, secondary and collimation mirrors of four sub-apertures has been down. Average wavefront PV is 1/4 wavelength, RMS is 1/25 wavelength. Maximum wavefront PV is 0.366 wavelength, RMS is 0.049 wavelength. Minimum wavefront PV is 0.22 wavelength, RMS is 0.026 wavelength. For interferometric imaging, consistency of four pupils should be ensured. Detailed data is shown in figure 7.

Image quality	1#	2#	3#	4#	Average
Wavefront PV/(λ)	0.262	0.366	0.28	0.22	0.28（1/4λ）
Wavefront RMS/(λ)	0.039	0.046	0.049	0.026	0.04（1/25λ）

Figure 7. Aligned pupil consistency of the telescope

Differences of pupil diameter and baseline between four sub-apertures are measured by a large CCD detector, Figure 8 shows the pupil image, and pupil number. Maximum pupil diameter is 10.91mm, minimum pupil diameter is 10.08mm, average pupil diameter is 10.67mm. Maximum baseline length is 16.47mm, minimum baseline length is 16.39mm, average baseline length is 16.45mm. Maximum baseline angle is 121.2 degree, minimum baseline angle is 118.84 degree, average baseline angle is 120 degree.

Inconsistent sub-aperture energy will affect. The measured values (energy ratio ⩾ 0.94, diameter ratio ⩽ 1.09) affect the fringe visibility by 0.98, figure 9 shows the degraded fringe visibility affected by energy and diameter differences. According to theoretical simulation, measured baseline length(maximum difference is 0.056mm) can meet the requirement of equivalent diameter of 28cm.

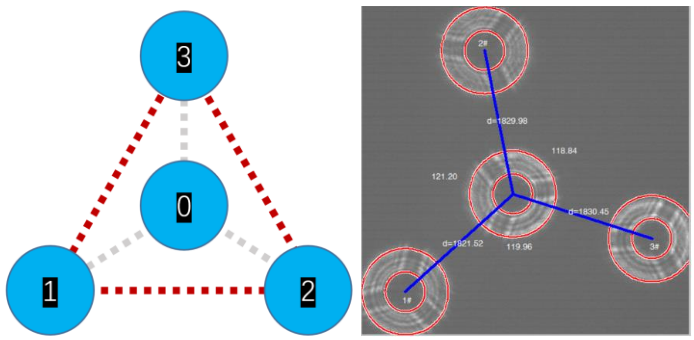

Figure 8. Measured pupil diameter and baseline

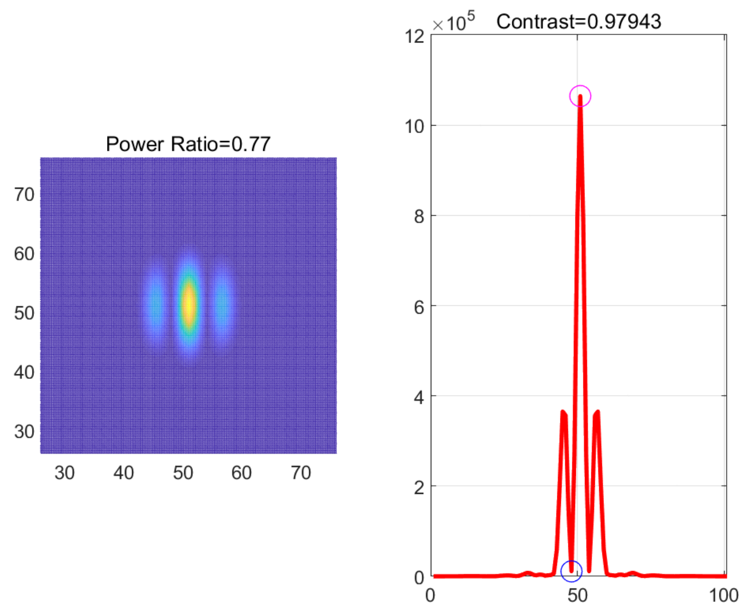

Figure 9. Degraded fringe visibility affected by energy and diameter differences

4. TEST RESULTS

We have finished the final assembly, co-phasing calibration and verifying of dynamic co-phasing close-loop methods at laboratory. Performance of closed loop tilt unit has been tested at laboratory. Manually apply a random two-dimensional tip/tilt to make sub-aperture image spot to move around its initial position, with an amplitude of 20 arcseconds. Achieved closed-loop tip/tilt accuracy within 0.3 arcseconds.

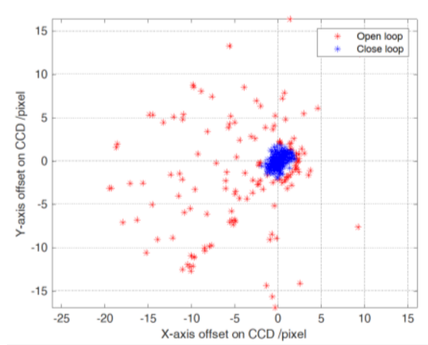

Figure 10. Closed loop tip/tilt test result

Piston error detection include aperture control, real time image acquisition, crop buffer image data, fast Fourier transform, row sampling, smooth filtering, MTF peak to peak ratio R (~400ms) calculate, calibration table query, the calibration value interpolate and calculate, interacting and communicating with the common phase control program TCP, sending and receiving signals and instructions, coordinating logical timing. Within the coherent length range (~4 μ m) , we can effectively achieve closed-loop correction of piston error. The closer the coherence length boundary is, the greater the probability of ineffective correction occurring. The MTF peak to peak ratio signal needs to be calculated through Fourier transform (256 * 256 matrix), which takes a lot of time (~400ms) and is much longer than the image frame transmission time (full frame~59ms). And it is not conducive to improving the closed-loop correction bandwidth. So we have to minimize the detection signal calculation time as much as possible, and improve the closed-loop correction bandwidth. We also measured piston error correction accuracy, piston correction error is less than 0.1 wavelength. Figure 11 shows piston error correction process and the interference fringes.

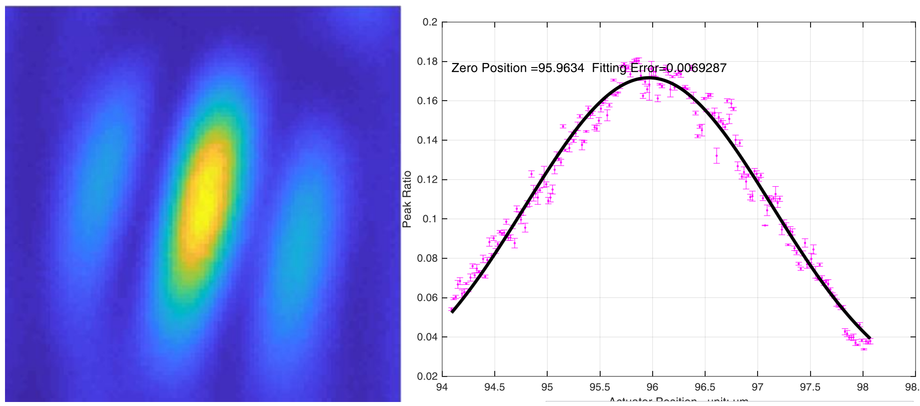

Figure 11 Piston error correction

At laboratory, we have got the interferometric image of Y-4 telescope. The FWHM of image spot is 0.43 arcsecond which is consistent with theoretical values.

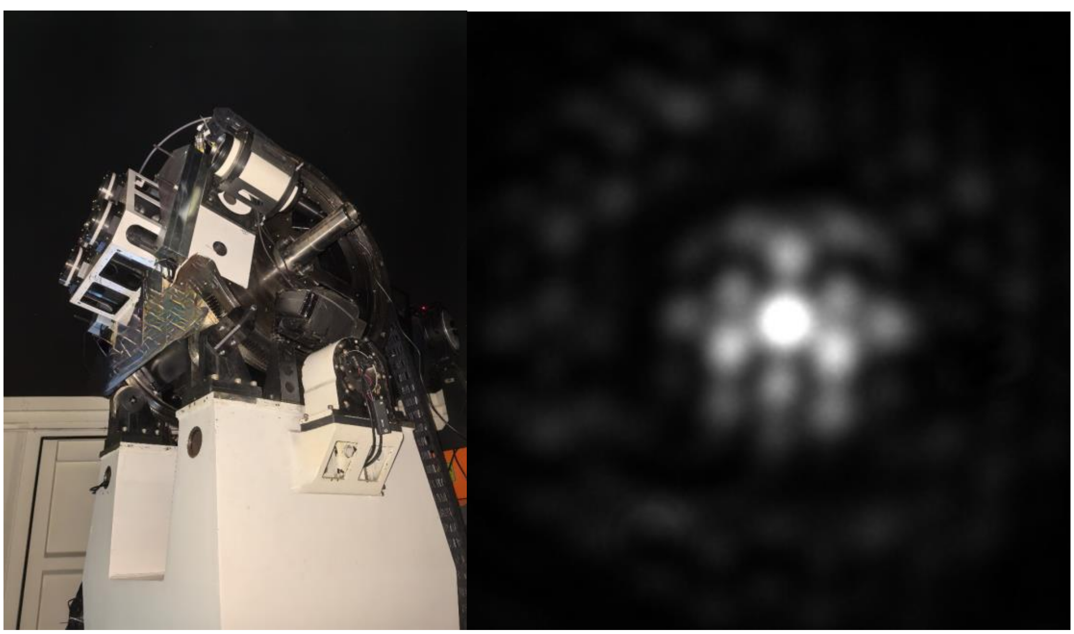

Figure 12 On-site photo of the telescope and far-field image with co-phasing correction

5. CONCLUSIONS

Several key techniques for Fizeau optical interferometry have been validated through building this telescope prototype successfully. This will provide valuable technical reserves for building larger aperture interferometric telescopes in the future.

This telescope prototype also can be used to observation of binary stars, near Earth objects, and space targets in medium and low orbits.

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