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Co-phasing method for sparse aperture optical systems based on multichannel fringe tracking

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Abstract: To realize effective co-phasing adjustment in large-aperture sparse-aperture telescopes, a multichannel stripe tracking approach is employed, allowing simultaneous interferometric measurements of multiple optical paths and circumventing the need for pairwise measurements along the mirror boundaries in traditional interferometric methods. This approach enhances detection efficiency and reduces system complexity. Here, the principles of the multibeam interference process and construction of a co-phasing detection module based on direct optical fiber connections were analyzed using wavefront optics theory. Error analysis was conducted on the system surface obtained through multipath interference. Potential applications of the interferometric method were explored. Finally, the principle was verified by experiment, an interferometric fringe contrast better than 0.4 is achieved through flat field calibration and incoherent digital synthesis. The dynamic range of the measurement exceeds 10 times of the center wavelength of the working band (1 550 nm). Moreover, a resolution better than one-tenth of the working center wavelength (1 550 nm) was achieved. Simultaneous three-beam interference can be achieved, leading to a 50% improvement in detection efficiency. This method can effectively enhance the efficiency of sparse aperture telescope co-phasing, meeting the requirements for observations of 8–10 m telescopes. This study provides a technological foundation for observing distant and faint celestial objects.

Key words: stripe tracking; wavefront aberration; sparse aperture telescope; co-phasing adjustment

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基于多路条纹跟踪的稀疏孔径光学系统共相方法

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摘要: 本文提出采用多通道条纹跟踪方法以实现大口径稀疏孔径望远镜的有效共相调整, 该方法允许同时进行多个光路的干涉测量, 避免了传统干涉方法中沿镜面边界进行成对测量的需要, 从而提高了检测效率并降低了系统复杂性。使用光学波前理论分析了多光束干涉过程的原理和基于光纤直接连接的共相检测模块构造, 并对通过多路径干涉获得的系统面型进行了误差分析, 探索了干涉方法的潜在应用。最后, 通过实验验证实现了原理贯通, 通过平场校准和非相干数字合成, 实现了优于 0.4 的干涉条纹对比度, 并且动态测量范围优于工作中心波长(1550 nm)的 10 倍以上, 实现了比工作中心波长(1550 nm)更优的分辨率。实现三光束干涉的同时检测效率提高了 50%, 从而有效提高了稀疏孔径望远镜的共相效率, 满足 8~10 m 望远镜的观测要求, 为观察遥远和暗淡的天体提供了技术基础。

关键词: 条纹跟踪; 波相差; 稀疏孔径望远镜; 共相调整

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1 Introduction

Large-aperture sparse-aperture telescopes (LASAT) represent a sparse aperture high-resolution optical system, usually with wavelength-level measurement and driving capabilities. They have high resolution and light-gathering capacity, and have been expected to achieve breakthroughs in fields, such as observations of the first cosmic light and near-Earth asteroid detection^[1-3]. In ground-based observations, each mirror of the LASAT can independently perform observation mission. This approach reduces the technological risk and shortens the number of scientific output cycles. The Giant Magellan Telescope in the United States comprises seven individual mirrors, each with a diameter of 8.4 m. These mirrors were combined to form the final telescopic system with an effective aperture of 30 m. By sequentially adding seven primary mirrors to the telescope, the total detection time of the system was effectively increased. Moreover, independent observations have been conducted without utilizing all seven primary mirrors. The Large Bin-

ocular Telescope comprises two telescopes, each with an aperture of 8 m. Based on the principles of planetary interferometry, celestial objects can be detected with high resolution and sensitivity in terms of single dimension angular radius measurements^[4-7].

In space exploration, sparse-aperture telescopes are advantageous owing to their volume and weight. By launching the telescope independently into orbit, the sparse-aperture telescope can achieve independent observations before the on-orbit assembly for over-all observations (by synthesizing multiple telescopes into an equivalent single telescope). This will largely enhance mission safety. The Gaia space telescope consists of two optical systems^[8], which can be regarded as generalized sparse-aperture systems. Each optical system comprises five reflective mirrors, with the rear mirror serving as a beam-combining system. Gaia enables large-scale imaging surveys of the Milky Way galaxy through precise alignment of the two systems. Similar space-based optical survey instruments, such as the Chinese Space Station Telescope, can contribute to the elucidation of physical laws under extreme conditions by considering multimes-

senger observations. These instruments are critical for various applications, including multiband photometric surveys, multiband variability, spectral signal analysis, and the discovery of novel transient sources, such as supernovae, intermediate-mass black holes, and tidal disruption events involving binary black holes.

To achieve the equivalence of a single continuous mirror in the LASAT, the following two adjustments are required: co-focus and co-phase. The co-focus adjustment process can be treated as a coupling movement between the defocused and focal plane spots. For a spherical mirror, because of the infinite number of optical axes, the co-focus position of the primary mirror is selected to be within the adjustment range of the secondary mirror or corrective mirror group. For aspheric segmented mirrors, the inclination of the optical axes between the segments introduces additional off-axis aberrations, such as astigmatism and coma. Moreover, for a multisegmented mirror with multiple annular zones, a partial compensatory relationship exists between the variation in the radius of curvature of each annular zone and defocus. Although this may have a relatively minor impact on the energy detection, it is critical for precise astronomical observations. In these cases, adjustments can be made by measuring high-order spherical aberrations to achieve fine-tuning and enhance the accuracy of the observations. With the achievement of a common focus as a foundation, LASAT requires the implementation of co-phase maintenance, which involves the following two stages: (1) adjustment of errors to within one wavelength (coarse co-phase), and (2) further adjustment of these errors within one wavelength to meet the imaging requirements of the system. Currently, dispersion fringe sensors are primarily used as coarse sensors in LASAT. However, these sensors not only involve non-common path aberrations but also be faced up with challenges in effectively integrating owing to the volume and mass of the interferometric optical path using bulk optical elements^[9-12].

Narrowband interference methods are often employed for fine co-phase adjustments utilizing the interference fringes created by the mask templates at the junctions of the segments. Currently, the Keck telescope uses a two-point interference method to generate one-dimensional interference fringes. Conventional geometric shape measurement methods typically do not satisfy the accuracy requirements for phase detection. Therefore, optical interference methods should be employed to detect submicrometer-level step errors between the mirror surfaces.

Compared to ground-based telescopes such as Keck, the James Webb Telescope, despite its fewer mirrors and wider wavelength band, utilizes a universal iterative measurement based on focal-plane image assessments. This system requires an optical path that utilizes significant space in the backend^[13]. Unlike the phased iterative measurement method of the James Webb Telescope, which employs numerous bulk optical elements, this approach enhances the light throughput of the system. This paves the way for universal phase measurements in the forthcoming generation of 20-m space telescopes. Although these telescopes have more mirrors, current methods are not sufficiently efficient^[14].

Ground-based telescopes, such as the European Extremely Large Telescope and the American Thirty Meter Telescope, utilize interferometry with free-space-combined optical elements by employing pairwise interference. Because only two channels of measurement can be performed at a time, this method has a lower measurement efficiency than ours. In addition, uniform calibration is required to address errors between channels, including intensity attenuation, phase distortion, visibility differences, detector response, and noise. The proposed technique employs multi-channel interference, which significantly enhances both efficiency and accuracy^[15].

Furthermore, a multiwavelength channel spectral method was used to achieve an accurate alignment between the coarse- and fine-phase processes,

and the step errors between the submirrors near the working center wavelength were reduced. A multi-beam interference approach was used for cooperative phase detection in sparse-aperture systems. A multipath fringe-tracking technique was employed to simultaneously acquire the phase differences between different paths, and aperture coding was used to achieve phase detection for different submirrors and positions. This approach enables rapid, accurate, and high-throughput phase sensing and control.

This paper introduces an innovative approach for the co-phasing detection of LASAT using methods based on astronomical photonics^[16-18]. These methods can significantly reduce the volume and weight of a system while enhancing its environmental adaptability. Furthermore, the high integration of astronomical photonics and precise alignment of the system also find the way for multipath interference and fringe tracking measurement techniques. This approach minimizes non-common optical path aberrations from various parallel path measurements. Consequently, it boosts detector's utilization and effectively reduces the complexity and cost of co-phasing systems. This leads to an improved measurement efficiency and a decreased launch weight.

Section 2 presents the fundamental principles of fringe tracking, followed by an analysis of the phase-detection accuracy using interferometry in

Section 3, along with a description of the detection architecture and process. Section 4 presents the verification of the phase-detection process in various modes, thereby providing a comprehensive understanding of the principles.

2 Materials and methods

2.1 Basic principles of multichannel fringe tracking

The fundamental principle of fringe tracking involves the extraction of the actual phase information of a system by analyzing the interference fringes and rapidly adjusting the phase to maintain the stability of large-aperture segmented mirrors. Hence, for both sensing and control, the sampling frequency must be higher than the changes in the fringe positions caused by external disturbances. The basic principles of fringe sampling and perception are illustrated in Fig. 1 (color online). In this figure, A , B , C , D represents the sampling position intensity. The difference in the light intensity between A and D represents the visibility of the system fringes. The light intensities at different sampling positions were determined using the two input light intensities and phases of the system. Between the maximum and minimum light intensities, there must be a special intermediate point to suppress sampling noise and build a light intensity benchmark.

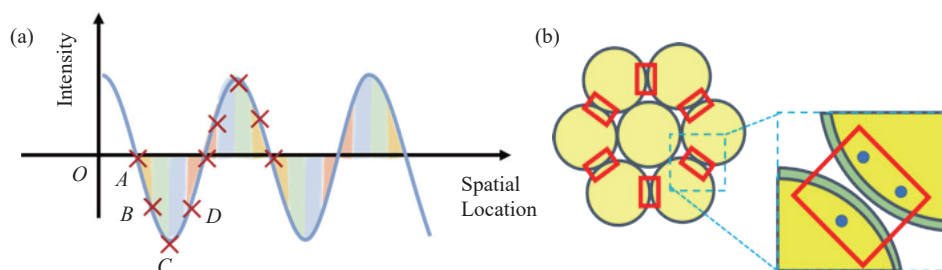


Fig. 1 Fundamental principles of fringe sampling. (a) System light-intensity sampling position and (b) sparse-aperture boundary multi-point sampling position

The direct extraction of fringe positions is affected by local variations in light intensity and noise, especially in the case of multibeam interfer-

ence. The envelopes generated by multiple beams are complex and impact fringe tracking. Here, a theoretical analysis was employed to construct an inter-

ference intensity model using the example of three beams, for a detailed expansion. Simultaneously, the overall wavefront information was constructed by acquiring the local height differences at the boundaries and sampling the spatial frequency. Subsequently, the position (Tip, Tilt Piston, TTP) of the individual segment in a sparse aperture were obtained through plane fitting.

In the actual detection process, stable interference is formed through a photon transmission path constructed using optical fibers and spatial filters^[19-20]. The intensities generated from the three-path interference are represented by Eq. (1).

$$I_i^N = \left[\sum_{j=1}^N |E_{ij}|^2 - \sum_{k,l=1}^N 2|E_{ik}||E_{il}| \sin\left(\frac{2\pi}{\lambda_i}(\delta_{kli})\right) \right], \quad (1)$$

where $|E_{ij}|^2$ represents the respective light intensity of each path; λ is the wavelength of the channel spectral center; j denotes the interfering beams of light; N is the total, δ_{kj} is the optical path difference (OPD) between the two paths of the system; and λ_i is a known value. Optical fiber connections enable aperture reconfiguration, facilitating integrated interferometry without altering the optical path of the original imaging system. This integration is achieved using an aperture coding system. Flexibility in adjusting the interference in each path is accomplished, and the final interferogram of the three-path interference is processed using phase coherence to determine its circularity. The architecture of the coherent interference detection system of LASAT is illustrated in Fig. 2 (color online).

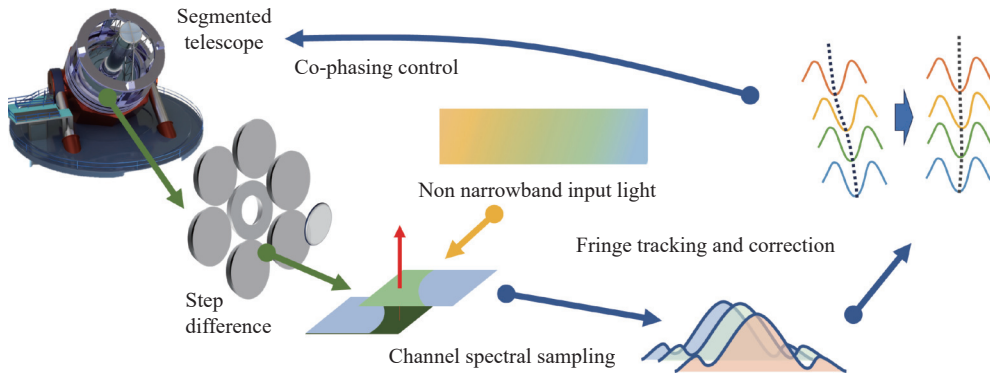


Fig. 2 Schematic diagram of fringe tracking sensing and control for the LASAT system

In this study, a theoretical analysis was performed for the synthesis of three beams. The expression of beam intensity under a single-channel spectrum was obtained, and the system error was smoothly suppressed through beam phase closure.

System detection throughput can be effectively

$$I_i^3 = \left[|E_{i1}|^2 + |E_{i2}|^2 + |E_{i3}|^2 - 2|E_{i1}||E_{i2}| \sin\left(\frac{2\pi}{\lambda_i}(\delta_{12i})\right) - 2|E_{i3}||E_{i1}| \sin\left(\frac{2\pi}{\lambda_i}(\delta_{13i})\right) - 2|E_{i3}||E_{i2}| \sin\left(\frac{2\pi}{\lambda_i}(\delta_{23i})\right) \right], \quad (2)$$

where $|E_{i1}|^2$, $|E_{i2}|^2$, and $|E_{i3}|^2$ are the light intensities of each of the three channels; λ_i is the wavelength of the channel spectral center; and $i1$, $i2$, and $i3$ denote the interfering beams. Because of the phase-closure property of three-channel light interference, three-channel light rays can be assumed to oscillate

enhanced by employing a multilevel fringe-tracking system. Based on this, the efficiency of wavefront sampling and the resulting final pixel resolution of the target surface were analyzed. By selecting three channels and substituting in Eq. (1) yields

in trace amounts near their common average position. Using small-angle approximation and intensity $|E_i|$ for each channel, the expression can be simplified as follows:

$$I_i^3 = \left[3|E_i|^2 - 2|E_i|^2 \frac{2\pi}{\lambda_i} (\delta_{12i} + \delta_{13i} + \delta_{23i}) \right]. \quad (3)$$

By performing interference synthesis on the three beams, the phase difference between the two beams can be obtained, whereas the average phase difference among the three beams can be determined. Finally, the absolute phase difference is obtained using the phase-closure principle. Assuming that route 3 measures its phase difference relative to routes 1 and 2, whereas routes 1 and 2 remain unchanged, the interference phase measurement error introduced by the baseline changes can be eliminated by subtracting the measured phase differences of routes 1 and 2 from the obtained results. Two beams of interfering light were used to establish a reference for calculating the phase in multilevel interferometry.

Using a single wavelength, the dynamic detection range of the system can be expanded using the channel spectrum. Astronomical photonic devices are placed near the rear end of the pupil plane. As shown in Fig. 2, the two beams on different mirrors finally enter the rear end through the astronomical photonics device for synthesis, thereby realizing the perception of a coherent state. The multiwavelength sampling process is shown in Fig. 2, where the system acquires beams of multiple wavelengths that ultimately converge on the focal plane. Photonic devices were used on the focal plane for collection, and integrated interference was applied to the backend.

The interference fringes in the two narrow bandwidths eventually form a periodic light-intensity distribution. This period can be used to effectively expand the dynamic range of the measurements. According to trigonometric function theory, the synthesis of any periodic sine wave corresponds to a sine wave with a certain period. Hence, it cannot have a unique phase difference center, as in the case of continuous spectrum band measurement. Therefore, it was necessary to mix multiple wavelengths and constrain the final common phase errors. The fringe pattern formed by the dual wavelengths exhibited irregularities at the boundaries, which were difficult to distinguish from stray

fringes. Therefore, using combinations of multiple wavelengths, a prominent Gaussian distribution envelope can be formed to realize coarse co-phasing.

The analysis conducted in this study revealed that using dual wavelengths for light-intensity superposition and carrier waves can effectively enhance the measurement range. However, when the number of cycles is high, fluctuations in the light intensity may occur. As the optical frequencies become closer, the measurement range that can be covered increases. Based on the multiwavelength broadband measurement method and physical models, the effects of differences in multiwavelength envelopes and boundary blurriness on the center fringe positioning error were addressed. This was realized by considering factors such as the pixel resolution, fringe period, and other relevant parameters. Simultaneously, the sampling error owing to discontinuities in the light intensity was reduced, that is, the density of the fringes directly influenced the accuracy of the phase detection.

3 Results

3.1 Analysis of the system wavefront detection accuracy

The entire wavefront of the system can be effectively reconstructed by fitting the rigid displacements at each subaperture position.

First, numerical simulations were performed to establish sparse aperture data with varying wavefront phase errors. The data were obtained based on the slope of the system. Considering the systematic wavefront reconstruction, the system adopted a limited number of edge measurements owing to its practical arrangement, resulting in a relatively low sampling rate.

Slope measurement is advantageous over absolute-height measurement because it offers a variable range, good accuracy compatibility, and high reconstruction robustness. The aperture sampling pattern adopted is shown in Fig.1(b). In this pattern, one

subaperture uses two sampling points, whereas the other uses a single sampling point. Each sampling point was used to detect the step difference between two adjacent points on the opposite side and calculate the average step difference between them. A

common reference can be established based on slope measurements, enabling a balance between accuracy and range. The relationship between the scale span and detection accuracy is illustrated in Fig. 3 (color online).

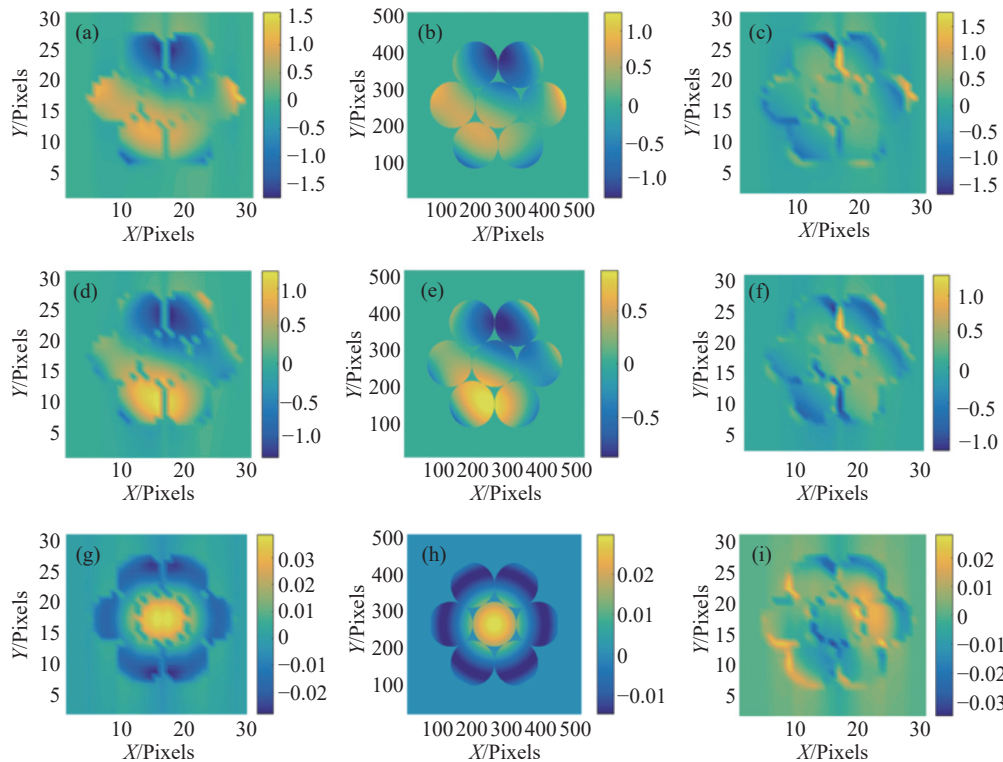


Fig. 3 Verification of the accuracy of the sparse aperture wavefront reconstruction. (a)–(c) Large aberration, (d)–(f) medium aberration, and (g)–(i) small aberration (The three columns correspond to the reconstructed wavefront, the original wavefront and the residuals, respectively)

Edge detection error and detection noise must be superimposed to obtain the co-phase detection accuracy of the system. The final wavefront detection accuracy of the system directly affect the correction accuracy of the subsequent low-order aberrations of the system. For low-order phase differences, the co-phase errors obtained at all the measurement points, can be fitted to reduce the random error of a single point.

Consequently, the absolute accuracy requirements of these systems were reduced. Moreover, for wavefront sensing, the larger the scale mapped onto the primary mirror, the lower are the absolute measurement accuracy requirements. Thus, the obtained residual of the wavefront detection (reconstruction algorithm error) was better than 0.02λ ($\lambda =$

$1\ 550\ \text{nm}$), the peak and valley of the larger aberrations were approximately three operating wavelengths, and the smaller aberrations were approximately 0.05 wavelengths. Larger wavefront aberrations are dominated by low-order aberrations, such as coma and astigmatism, whereas smaller aberrations are dominated by spherical aberrations that are more difficult to correct in the system.

3.2 Experiment for feasibility verification

A coarse phase adjustment was achieved using the white-light interference principle based on broadband light interference. This study focused on a parallel multichannel high-throughput detection and resolution theory with the aim of reducing the modulation of fringe center positions introduced by the nonuniformity of various spectral channels. Con-

sidering dual-wavelength detection, the phase-parameter fitting method and the relationship between the combination of wavelengths, fringe period, and uniqueness of the central position were analyzed. For wavelength switching, the precise synchronization mechanism of the high-throughput multimodal detection must be known.

The experimental setup is shown in Fig. 4 (color online). Light is initially coupled to optical fibers via a coupler, and multiple light paths are synthesized using lenses. A camera is used to capture images of the multipath fringes. The ultimate objective is to reduce the side lobes and blurring in the point spread function, while avoiding degradation of contrast and resolution. The system has an aperture of 450 mm and a focal length of 4.5 m ($F = 10$), which can effectively simulate long-focus systems. In

the experiment, this system utilized 14 integrated interference modules (limited by the size of the fiber coupler and the caliber of the parallel light tube) and a camera at the back end to perform the parallel detection of its fringes. Compared with traditional physical optical components, the volume and weight of this system are significantly reduced. The total space occupied by the 14-beam integrated interference is less than $600 \text{ mm} \times 300 \text{ mm} \times 300 \text{ mm}$, which is more suitable for the tense focal plane space of future large-aperture telescopes, and can significantly reduce the launch weight of space telescopes.

In the generation of incident light, a parallel light tube simulator can be used, where the main mirror of the parallel light tube is in the form of a parabolic mirror. Finally, a 14-channel system is built on the system pupil plane.

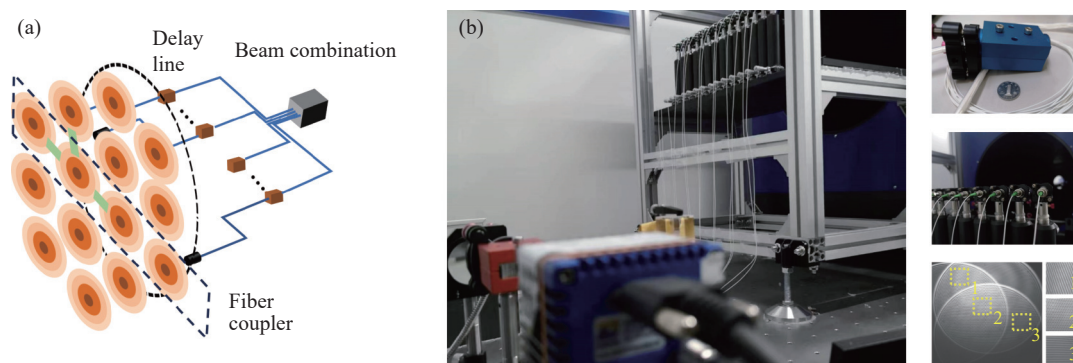


Fig. 4 Multi-fringe testing verification experiment. (a) System architecture diagram; (b) experiment field diagram including beam combination (top), fiber coupler (middle) and fringe (bottom)

According to the projection calculation of existing telescopes, this architecture can achieve the co-phase measurement of an 8-m telescope (14 apertures, single aperture 2-m in diameter; passive support for diameters below 2 m is very mature and only requires adjusting the position of the sub-mirror). This is merely a principal demonstration of the verification system. By further improving the integration, the same function can be achieved within a smaller range ($100 \text{ mm} \times 30 \text{ mm} \times 30 \text{ mm}$). The traceability of measurement accuracy was derived from the accuracy of the single mirror used. According to the test report provided by the supplier, the emission accuracy of the light tube wavefront was

better than 100 nm. Therefore, it was more suitable for detecting the common phase measurement process. In Fig. 4, the boxes in the figure represent the sampling locations for the 14 apertures.

The interference fringes formed by narrow-band light at 1 530 and 1 560 nm are shown in Fig. 5 (color online). Evidently, upon flat-field calibration and incoherent digital synthesis, the fringe contrast exceeded 0.4, its dynamic range exceeded 10 wavelengths at the operating center (1 550 nm), and the resolution outperformed one-tenth of the operating center wavelength (1 550 nm). The filters were used to generate narrowband beams at 1 530 and 1 560 nm. Through flat-field correction and beam combination

of the two light intensities, a wide range of common phase adjustments can be realized. For the same physical interval δ , the fringe phases corresponding to different wavelengths have a certain difference $\Delta\Phi$, thereby achieving differential measurement in different channel spectra. The interference fringes generated in the different wavelength bands exhibit a phase difference.

$$2\pi\frac{\delta}{\lambda_1} - 2\pi\frac{\delta}{\lambda_2} = \Delta\Phi \quad (4)$$

In special cases, when the fringes show the maximum change in the light and dark contrast, the relationship between the wavelength and actual physical interval can be directly obtained. Therefore, the channel spectrum method can be tested using broadband light or frequency sweeps.

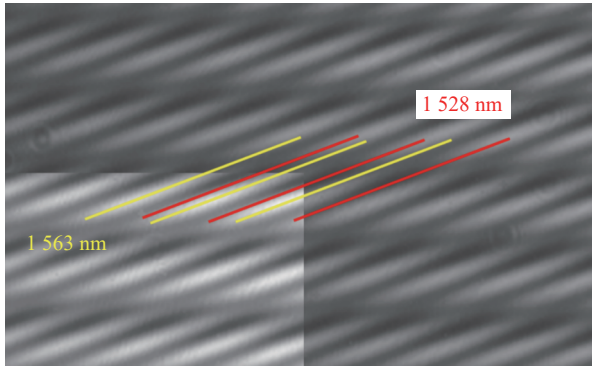


Fig. 5 Three-beam interference principle and its fringes in different wavelength ranges

According to Eq. (3), the intensity distribution of the system's fringes can be obtained, where the intensity distribution after wavelength phase shifting represents the situation along a certain interference direction.

$$I_1 = I_0 + A \cos \phi \quad (5)$$

$$I_2 = I_0 + A \cos(\phi - \Delta\Phi) = I_0 + A \cos \phi \sin \Delta\Phi - A \sin \phi \cos \Delta\Phi \quad (6)$$

$$I_3 = I_0 + A \cos(\phi + \Delta\Phi) = I_0 + A \cos \phi \sin \Delta\Phi + A \sin \phi \cos \Delta\Phi \quad (7)$$

where I is the intrinsic light intensity, representing the sum of the light intensities of all paths, which can be obtained by measuring each path separately,

and A is the amplitude of the fringes. The phase shift difference can be obtained by combining Eq. (5) ~ (7), as shown in Eq. (8).

$$\frac{I_2 + I_3}{2} = I_0 + A \cos \phi \sin \Delta\Phi = I_0 + (I_1 - I_0) \sin \Delta\Phi \quad (8)$$

By transforming Eq. (8), we can get Eq. (9), and by combining it with Eq. (3), we can obtain the final step phase difference.

$$\Delta\Phi = \arcsin \left[\frac{I_2 + I_3 - 2I_0}{2(I_1 - I_0)} \right] \quad (9)$$

When the light and dark states of the system are reversed, the actual physical interval of the system can be directly obtained as follows:

$$\delta = \frac{1}{2} \frac{\lambda_2 \lambda_1}{\lambda_2 - \lambda_1} \quad (10)$$

where λ_1 and λ_2 are correspond to the minimum and maximum wavelengths in the measured spectral band. Using the device depicted in Fig. 4, it was possible to achieve a spectral dispersion of varying widths, generating interference fringes within these different wavelength bands. The use of a detector array allows the acquisition of two-dimensional interference fringes. These interference fringes enable the derivation of slopes at the edges of the system, facilitating the inversion of the mirror pose and alignment conditions of the system. In addition, the two-dimensional variation in the light intensity of the system can be used to obtain the phase differences between each pair of the three light intensities and simultaneously achieve the co-phasing measurement of the three paths. For sparse aperture boundaries, the phase differences between the three subapertures can be obtained simultaneously, and the overall control matrix can be constructed using the middle subaperture as a reference. Combined with the analysis results of Fig. 5, based on measuring the edge phase difference, equal-interval phase sampling was conducted at the main mirror position, which was used as the data source for the slope measurement. Using the overall solution model constructed in the theoretical analysis, we obtained the

wavefront information of the entire system and achieved high-precision reconstruction. This further demonstrates the high integration and high-throughput advantages of astronomical photonics devices (for traditional physical optics measurement methods) in achieving high-density sampling of the system. It is necessary to enlarge the system pupil and place a corresponding number of collection optical

paths. Simultaneously, for the system interference synthesis architecture, it is necessary to rearrange the optical path. According to Eq. (4), δ is 13.64 μm , and the bandwidth of a single wavelength is less than 0.2 nm. The interference fringes in the lower-left corner of the image are the result of another acquisition. The two are combined for ease of observation and comparison, as show in Fig. 6.

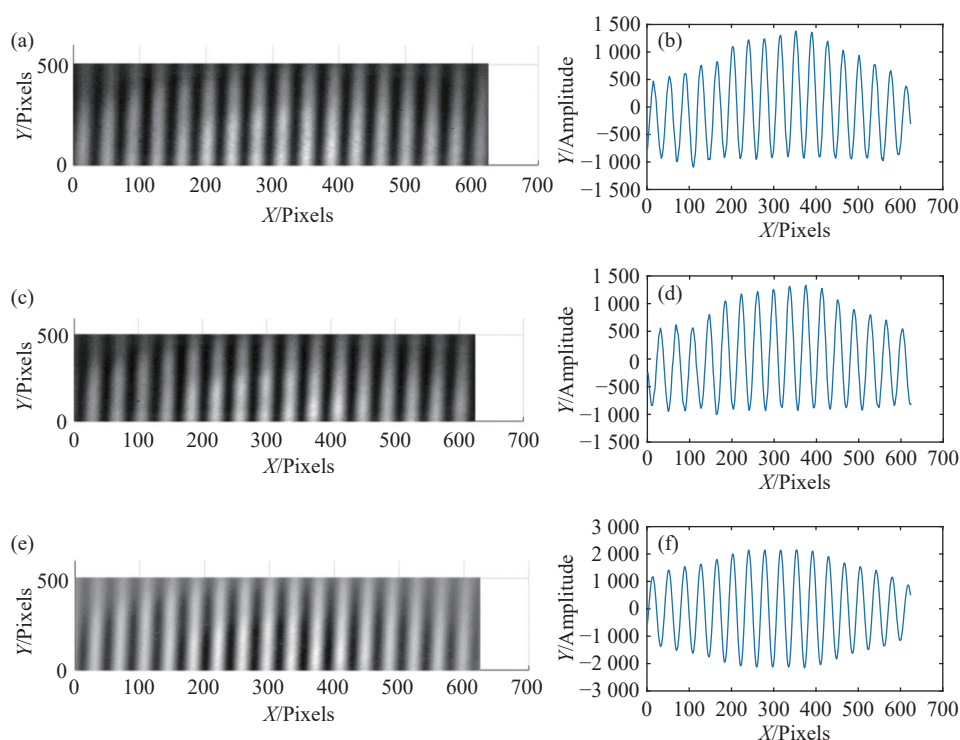


Fig. 6 Validation results of the dual-wavelength fringe tracking. (a), (b) Interference fringes formed by the narrowband light at 1530 nm and their average cross-section; (c), (d) interference fringes formed by the narrowband light at 1560 nm and their average cross-section; (e), (f) incoherent synthesis of the dual wavelength and average cross-section

To utilize the fringes formed by white-light interference for coarse co-phase detection, the interference envelope of the dual wavelength was leveraged. This ultimately achieves coarse co-phase detection. Moreover, channel spectrum facilitates comparative measurements across various spectral channels, thus suppressing co-phase errors. Finally, for precise co-phase control of the system, experimental validation was conducted using two distinct approaches: (1) larger tilt angles and (2) smaller tilt angles. The outcomes of these approaches were experimentally demonstrated.

For the segmented telescope, the co-phase of

three mirrors was implemented in a laboratory environment. The segmented mirror multipath interference fringe tracking experiment is shown in Fig. 7. The co-phase error between the three paths can be obtained using the origin position. In this study, three hexagonal sparsely segmented mirrors with masks were used to simulate circular sparsely segmented mirrors.

By employing frequency-sweep measurements in both the C and L bands, the visibility of individual measurements can be enhanced, leading to an increased signal-to-noise ratio. This approach leverages the shifting and variation of the characteristic

peak intervals corresponding to different frequency bands. After increasing the modulation speed, external noise can be effectively suppressed, and alternating carrier modulation can be employed to mitigate interference from the external environment. During the actual measurement process, a broad-

band approach was necessary to enhance the measurement range. Therefore, a frequency-sweep laser was used to generate the reference wavelength. Each interference cycle contained five pixels, resulting in a detection accuracy of 0.2 wavelengths.

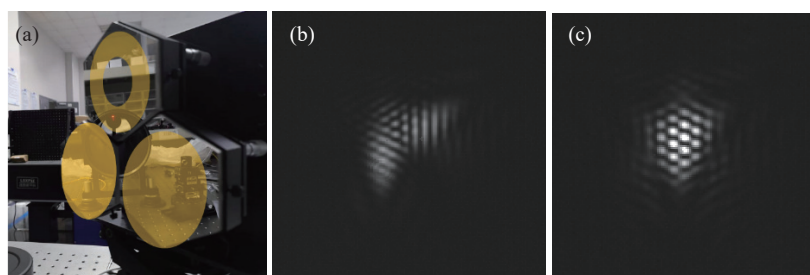


Fig. 7 Segmented mirror multipath interference fringe tracking experiment. (a) Experimental system; (b) three-path interference pattern before correction; (c) three-path interference pattern after correction

4 Discussion

The proposed approach involves an optical fiber interconnect architecture that utilizes optical waveguides for photon collection and transmission, thereby overcoming the drawbacks of large spatial footprints and heavy weights associated with large-span optical apertures.

Here, the boundary measurement was experimentally verified, and the application effect of the existing technology was analyzed by taking advantage of the aperture rearrangement of optical waveguides. In terms of flux calculation, traditional interferometry requires the construction of spectroscopic and beam-synthesis optical paths, and it is necessary to ensure that the distance between different optical paths is greater than the coherence distance. Photons are confined in waveguides by using photon astronomy methods, thereby achieving high-flux beam propagation and synthesis^[21].

When the positions of the components shift, the optical path is altered and influenced by changes in the optical surface morphology. Consequently, this induces corresponding changes in the interference fringes. Pertinent information regarding the position of the system can be obtained by interpreting

and tracking the interference fringes. Similarly, this method can be used in systems requiring high phase accuracy and stability, such as space remote sensing cameras and high-precision optical microscopy equipment.

5 Conclusions

High functional integration and stability are urgently required for high-resolution, high-sensitivity, and high-contrast imaging systems. Astronomical photonics provides innovative performance improvements in astronomical observations by leveraging the advanced technologies used in optical communications and interconnections. Through photon collection, synthesis, and modulation in waveguides, crosstalk between channels can be effectively reduced, and more complex optical path arrangements can be realized. The astronomical photonic devices used included photonic couplers, optical fibers, and arrayed waveguide gratings (AWG). This integration level will be further improved in the future. This setup facilitated a flexible combination of different sampling positions and multiple interference paths. High-precision common-phase measurements were performed using multipath interference fringe tracking. The acquired

wavefront detection residuals were superior to 0.02λ ($\lambda = 1550\text{ nm}$), and the co-phase range exceeded $7.9\text{ }\mu\text{m}$. This system can simultaneously achieve three interference paths, thus resulting in a 50% improvement in the detection efficiency, based on which a new mode of interference measurement was employed.

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