

DOI: 10.20098/j.cnki.1001-5132.2024.0120

Phasing sensing and alignment of telescopes with segmented primary mirrors based on astrophotonics

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Abstract: The sensitivity and resolution of survey observations can be effectively improved by increasing the aperture size of the system, resulting in high-quality deep-field survey data. However, an increase in aperture size not only increases the complexity of the system by introducing new influencing factors, but also alters the mode of operation and the effects of existing components, especially for survey telescopes with segmented primary mirrors. To address this problem, we combine subaperture mirror testing with curvature sensing. This strategy makes it possible to utilize the intensity difference before and after the focal plane. With this strategy, both the alignment tilt and phase differences in the system can be detected, enabling alignment adjustment and maintenance of wavefront stability. In addition, wavefront information across the subapertures was used to maintain continuity, and at the system interface, a fringe pattern was used to align the tilt adjustment direction. Eventually, the correlation coefficient with the original wavefront was >0.8 , the decrease in PV value in the segment edge region was $>40\%$, and a co-focus resolution of $2''$ was achieved, with a co-phasing resolution of $0.08\ \mu\text{m}$ over a $5\ \mu\text{m}$ range. The number of edge interferometric measurement channels (in each block) was reduced from 6 to 2, and the throughput was increased by a factor of 3. To ensure the final fringe resolution of future ultra-large-aperture splicing telescopes, the target size, volume, and weight of the system detector should be effectively reduced. In this regard, the use of astrophotonics devices can effectively increase the integration of the system, reducing the impact of the environment on ground-based systems, and reducing the launch costs and risks of space-based systems.

Key words: large telescope; active optics; single-shot curvature sensing; astrophotonics

CLC number: P111

Document code: A

Article ID: 1001-5132 (2024) 04-0001-11

1 Introduction

The resolution and light-gathering power of large-aperture wide-field optical survey telescopes are

directly proportional to their aperture size^[1-3]. Currently, global advanced survey projects mostly rely on telescopes of 2–8 m. These include the Sloan Digital sky survey telescope (with an aperture of 2.5 m), Pan-

收稿日期: 2024-01-14.

宁波大学学报(理工版)网址: <http://journallg.nbu.edu.cn/>

基金项目: 国家自然科学基金(62235018, 12373090); 中国科学院青年创新促进会项目(2020221).

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STARRS survey telescope (with an aperture of 1.8 m), Dark Energy Camera survey project (with a main mirror aperture of 4 m), Hyper Suprime-Cam for the Subaru telescope and the large synoptic survey telescope (with an aperture of 8.4 m) at the Vera C. Rubin observatory. These survey telescopes can be used to conduct time-domain astronomical research on active galactic nuclei, near-earth asteroids, and gravitational lenses in higher dimensional data^[4-7]. They can also be used to construct precise cosmological models to address fundamental scientific questions regarding black holes, dark matter, dark energy, and the origin of the universe, life, and consciousness.

However, as the demands for higher resolution and sensitivity in detecting deep space, exoplanets, and near-earth asteroids increase, the development of 10 m class survey telescopes is required. Moreover, the size limit for a single mirror is about 8 m (e.g., Subaru), and it is not feasible to manufacture a 10 m mirror in one piece. An alternative approach is to combine segmented mirrors to achieve the desired size. The segmented mirror approach can be categorized into two types: the sparse aperture form that aligns independent telescopes precisely to achieve co-phasing (e.g., the giant Magellan telescope), and the segmented mirror form that minimizes the stitching effect and approximates a continuous mirror surface (e.g., the thirty meter telescope and extremely large telescope)^[8-11]. The Maunakea spectroscopic explorer is a next-generation survey telescope developed by the University of Hawaii. It has a field of view of 1.5° square and a main mirror aperture of 11.25 m and utilizes a prime-focus configuration. The primary focus achieves aberration correction through a lens group in which the first lens has a diameter of 1.3 m. Compared to 10 m class segmented telescopes such as Keck, it has a larger field of view (degree level) and faster focal ratio (between $F/1$ and $F/2$), but it cannot rely on backend optics for correction. Moreover, the strong coupling of the spatial frequency characteristics of the mirror surfaces of the

system and the strong requirements for residual errors in active optical correction pose substantial challenges to the sensing and control capabilities of optical system aberrations^[12-13].

An increase in the aperture size not only increases the complexity of the system by introducing new influencing factors, but also changes the mode of operation and effects of existing components (e.g., amplifying the influence of mirror misalignments). Under the coupling of two factors, traditional relevant standards can no longer meet the calibration requirements of current large-aperture optical systems, which involve a “large span, multiple parameters, and common references”. To ensure maximum imaging capacity and efficiency of large-field active optical telescopes, real-time closed-loop correction of wavefront errors using wavefront sensing is required to ensure that the surface and relative positions of the components are as close to the theoretical design as possible. Active adjustment of large-aperture telescopes requires feedback from wavefront-sensing systems. Hartmann wavefront sensors that require complex relay optics are commonly used. However, for short focal ratios and wide-field (2° – 3°) imaging survey systems, achieving high-precision wavefront sensing in the pupil plane requires additional complex correction optics. The timeliness of the correction can be affected by replacing specialized wavefront-detection terminals. The James Webb space telescope primarily relies on dispersion fringes for coarse co-phasing and uses focal plane images for fine co-phasing. It mainly uses bulk optical elements to achieve beam deflection and dispersion. The use of astrophotonics devices can further reduce the weight of the system, laying the foundation for the co-focus and co-phasing of more segmented mirror systems in the future^[14-18].

In this study, the intensity difference before and after the focal plane was utilized by combining subaperture mirror testing with curvature sensing. This enabled the detection of alignment tilt and phase

differences in the system and the use of segmented mirrors inside the system to adjust and maintain wavefront stability. Wavefront information across the subapertures can be used to maintain continuity at the system interfaces. Simultaneously, curvature sensing was employed to maintain the alignment of the system motion actuators based on information from the full field of view. The imaging of guide stars in various fields allows for the detailed measurement of wavefront variations in the system. Mapping the different wavefront components to the misalignments of optical elements, combined with the symmetrical relationship of off-axis fields, enabled the measurement of system misalignments and stabilization during the observation process, ultimately achieving precise observations of dim targets (e.g., exoplanets) through long-term integration.

This paper is organized as follows: Section 2 describes and analyzes the alignment process of large-aperture and wide-field segmented telescopes. Section 3 analyzes the alignment and maintenance between segmented mirrors. Section 4 analyzes the adjustment of the primary focus terminal, and discusses the interaction effects between the primary focus terminal and segmented mirrors.

2 Experimental principle

In this section, the principle and process of measurement are explained, including the structure of detection and the method of data processing. As the aperture size of an optical system increases, the ultimate resolution improves. However, because of the increased spatial span, the ability of the system to maintain its original position decreases. Therefore, adjustment components are needed to address the fundamental contradiction between the span and stiffness. For large-aperture optical systems, aberrations introduced by misalignments of optical elements far exceed the limits imposed by the surface shape and diffraction. In this

study, calibration standards for adjustment components were established to provide calibration benchmarks for large-aperture optical systems with the aim of realizing fast and accurate adjustment. This is vital for ensuring the imaging quality of large-aperture optical systems. System calibration can effectively improve the accuracy of the adjustment components and reduce their manufacturing and debugging cycles. It is critical for achieving large-aperture optical systems with effective adjustment capabilities by using higher precision component equipment for the precise calibration and value transfer of adjustment components, as shown in Fig. 1. Here, based on the diffraction element, the intensity distributions before and after the focal plane were generated simultaneously, as shown in Fig. 1. Unlike free-space propagation, the waveguide defocusing method, which is based on the principle of temporal coherence, can achieve strict locking and energy sharing, avoiding positioning and angle errors caused by free-space defocusing.

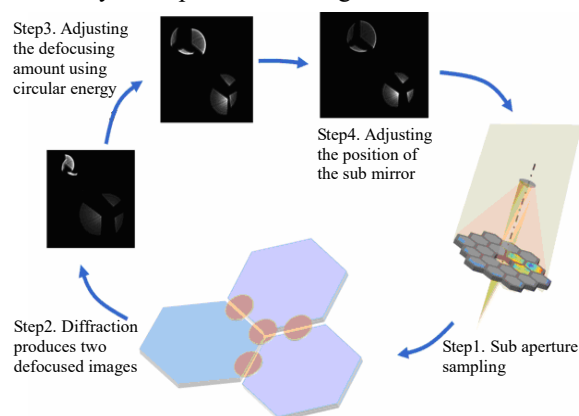


Fig. 1 Schematic of the detection and calibration of adjustment (curvature-sensing-based edge anomaly perception of the segmented mirror)

Based on the combination of standard spherical waves and Fourier optics theory, an analytical expression was obtained for the influence of non-pupil surface rigid body motion and surface shape variation on the wavefront aberration response. Based on this, an analytical model for the multi-mirror-system correction process was established. By using this method, wave-

front detection can be realized in a single exposure without separating the field of view. Simultaneously, the wavefront information at each subaperture was used to obtain the overall wavefront of the system.

Under a scalar electromagnetic field representation, the complex amplitude u produced by a spherical wave emitted by an off-axis approximate light source can be expressed by

$$u = A(x, y)e^{j\Phi(x, y)}, \quad (1)$$

where $\Phi(x, y)$ is the initial phase, A is the uniform amplitude distribution on the plane under the off-axis approximation, and x and y are the optical pupil coordinates. According to Fresnel's diffraction law, the complex optical field after the two mirror adjustments can be expressed by Eq. (2). During the calculation process, the higher-order cross terms were omitted, as well as the part where the light intensity distribution of the system changes over time.

$$u_{12} = A(x, y)e^{j\Phi(x, y)} \left[-j \frac{k}{2d_{12}\pi} e^{-j \frac{k(x^2 + y^2)}{2d_{12}}} \right], \quad (2)$$

where d_{12} is the distance between the two planes. It can be observed from Eq. (2) that the modulation of the pre-focus and post-focus energy distribution of the system can be achieved by adding a spherical wave propagation phase. Here, the spherical wave phase is added via a diffraction element to achieve simultaneous acquisition of pre-focus and post-focus information.

The final light intensity I of the detector can be obtained as the product of the complex optical field and its conjugate:

$$I = uu^*. \quad (3)$$

The curvature of the wavefront phase is proportional to the intensity difference along the optical axis, as given by

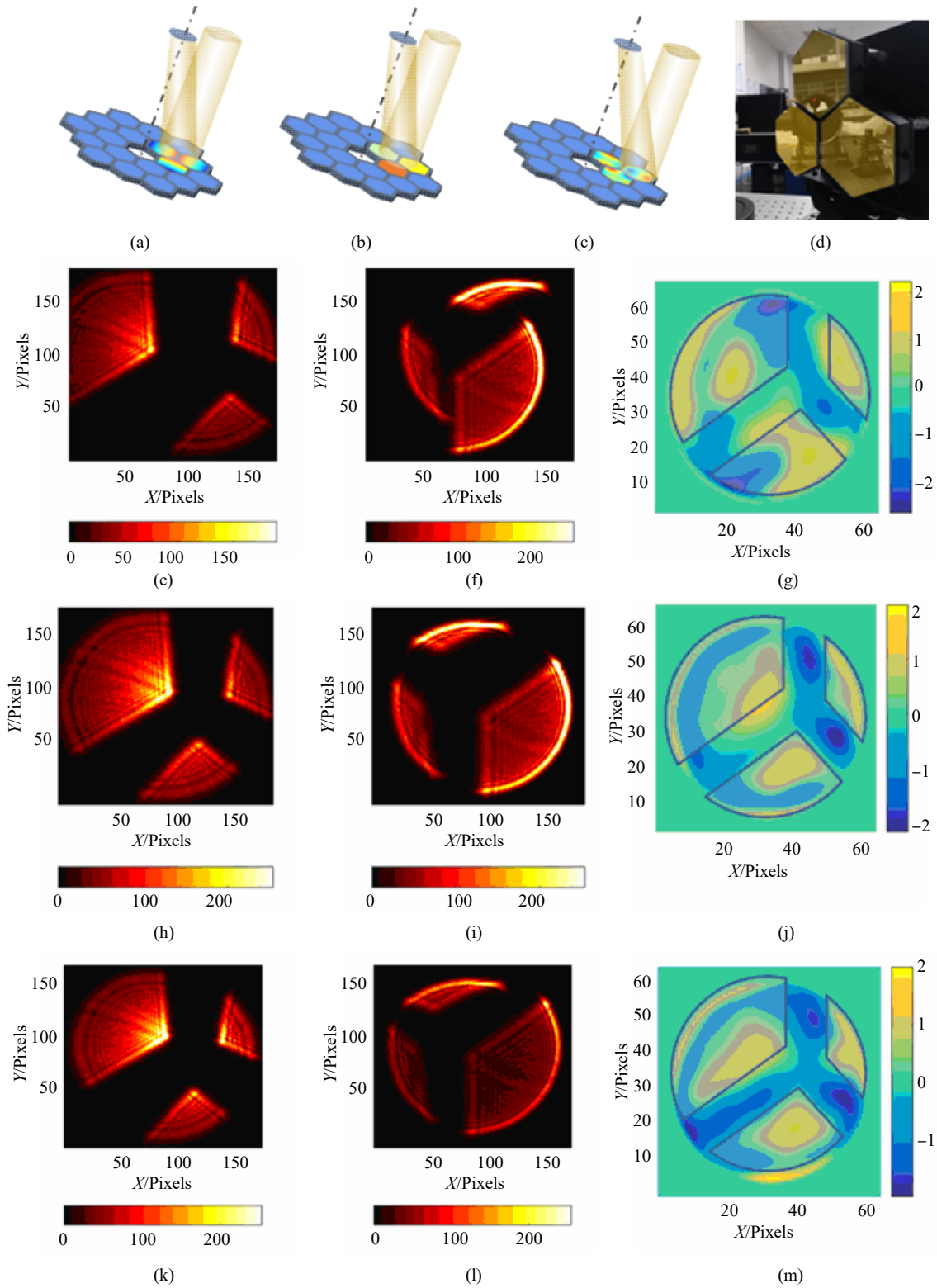
$$\frac{I_+ - I_-}{(I_+ + I_-)\Delta z_i} \approx -\nabla^2 g_0(x, y), \quad (4)$$

where I_+ and I_- are the energy distributions for defocus before and after the focal plane, respectively, and Δz_i is the defocus amount for the i -th field. Eq. (4) is the Riemann equation, and it uses a Fourier series as a

basis for subaperture curvature sensing.

The wavefront tilt and spherical waves were written onto a single waveguide. Finally, the light intensity distributions at the focus and equidistant defocus points were displayed on the focal plane. Based on this light-intensity distribution, a Poisson equation can be constructed, and the phase information of the submirror can be obtained by solving it. The average phase in the area was obtained by mapping the pupil position.

Simultaneously, based on the Fresnel diffraction plate, accurate measurement of the defocusing can be achieved, that is, by using the surrounding energy method to obtain the initial position of the focal plane. Owing to the strict locking of the pre- and post-focal defocusing star images generated by the zone plate, the energy difference was determined based on the curvature-sensing principle. According to this principle, the energy difference at an edge is called the amount of wavefront defocusing. Owing to system aberrations, the method of maintaining co-focus stability using the focal ring energy is substantially influenced by external factors. When the mirror surface is subjected to an uneven thermal load and airflow, the shape of the focal spot fluctuates. For defocused star images, accurate defocus values can be obtained through wavefront calculations that are unaffected by the coupling of other aberrations. Finally, the decrease in the PV value in the nonwavefront region was >40%. Defocused images formed by two mirrors were used to simulate wavefront sensing with the same main mirror but different guide stars. This enabled accurate calculation of the coma and astigmatism aberrations in the system. This information was then used to align the individual mirror elements of the primary focus, as shown in Fig. 2. Curvature-sensing measurements were performed for possible local tilt, local step difference, and local surface shape changes. The wavefront of the system was modulated using a zone plate. Furthermore, the spherical wavefront carried by the zone plate separately modulated the phase of the



(a)–(c) Types of local boundary anomalies, (d) Photograph of experimental site, (e)–(f) State 1 energy distribution before and after the focal point, (g) State 1 boundary wavefront, (h)–(i) State 2 energy distribution before and after the focal point, (j) State 2 boundary wavefront, (k)–(l) State 3 energy distribution before and after the focal point, (m) State 3 boundary wavefront.

Fig. 2 Perception of boundary aberrations based on curvature sensing

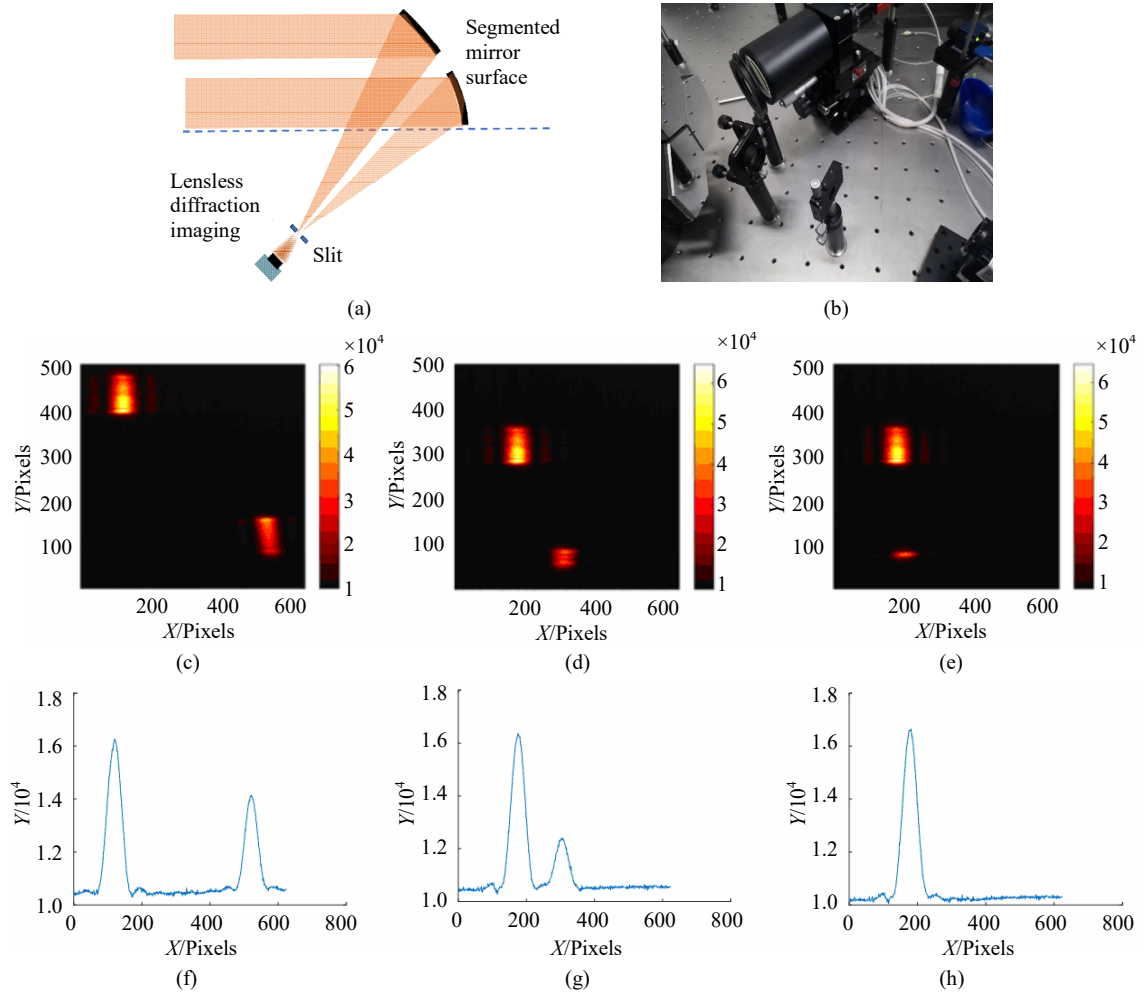
wavefront propagating in free space, causing it to shift forward and backward. Finally, the energy distributions before and after the focus were simultaneously formed on the focal plane, achieving a fixed amount of defocus and lock distance. By using the energy distribution in the corresponding area, the co-focus or co-phase states can be mapped.

3 Narrowband interferometry analysis

Experimental tests were conducted on the process of testing and precision traceability using deformable mirrors to generate specific aberrations and existing algorithms to solve them.

Narrowband interferometry analysis utilizes pupil projection techniques to perform shearing interferometry on the edges of the submirrors, thereby enabling system alignment. By constructing a closed-size chain, precise alignment of the system can be ensured. A slit was used for spatial filtering to separate the influence of aberrations, thereby achieving co-focus measurement. Ultimately, the co-focus accuracy was $<10 \mu\text{rad}$, as shown in Fig. 3. The co-focus accuracy is obtained through the positioning accuracy and the focal length. Here, the positioning accuracy is $10 \mu\text{m}$, the focal length is 200 mm , and the corresponding confocal accuracy can be obtained through simple calculation.

Narrowband measurements utilize a small portion

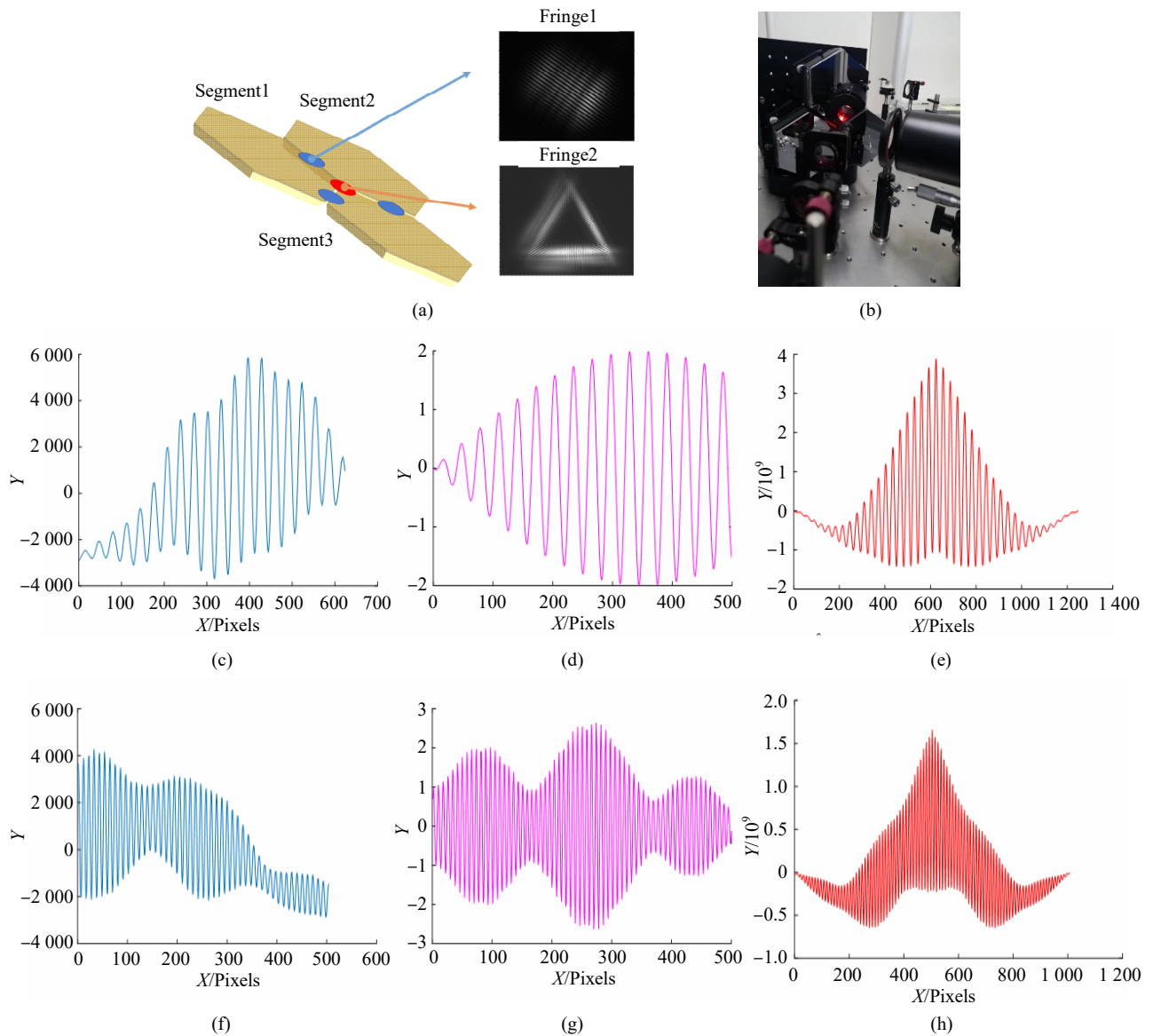


(a) Measurement principal diagram, (b) Experimental site photograph, (c)–(e) Co-focus sensing process based on a slit, (f)–(h) Energy distribution cross-sectional diagram.

Fig. 3 Principle and adjustment process based on shearing interferometry

of the observed spectrum that does not affect the overall observation of the system. They facilitate real-time detection and offer high detection accuracy and are currently used in many telescopes. Obtaining the relative positions of the submirrors using the narrowband method requires overcoming the effect of aperture diffraction on the narrowband testing process. As shown in Fig. 4, crosstalk exists between the

diffraction patterns of the aperture itself and the interference patterns between the apertures. However, the energy of the narrowband method is weak and cannot be further reduced through the aperture. Consequently, far-field spot variations were introduced by the system and the aperture will also affect the narrowband interference pattern. Therefore, analysis of the aperture shape is required. The characteristic



(a) Measurement principal diagram, (b) Experimental site photograph, (c) Measurement diagram of the interference stripe energy distribution interface under a large bandwidth, (d) Theoretical distribution diagram, (e) Positioning diagram based on a correlation calculation, (f) Measurement diagram of the interference stripe energy distribution interface under a small bandwidth, (g) Theoretical distribution diagram, (h) Positioning diagram based on a correlation calculation.

Fig. 4 Perception of boundary variations based on the narrowband method

diffraction pattern of the circular aperture (Airy disk) is the least similar to the straight interference pattern formed by equal-tilt interference. However, under the same light flux, the energy is concentrated in the case of a circular aperture, making it prone to saturation and contrast reduction. By contrast, the straight-edge diffraction pattern introduced by a rectangular aperture is highly similar to the interference pattern. Therefore, an elliptical sampling aperture can be used to measure boundary stability and co-phasing error. In this case, a tilted carrier is used to modulate the interference pattern by slightly tilting the submirrors. The interference and diffraction patterns can be identified and separated. When a hexagonal mosaic was used, the weights of the step differences at each edge were the same. For the fan-shaped mosaic, the adjustment weight in the radial direction was lower than that in the circumferential direction. Therefore, the adjustment weights must be modified or damping terms must be added to the adjustment matrix to ensure effective adjustment of the system, so that the control matrix does not become singular.

Based on the narrowband interference method and wavelength-division multiplexing devices, preliminary adjustments were made using the center wavelengths of 1 610 nm and 1 530 nm with a bandwidth of 40 nm. Subsequently, wideband light sources with a wavelength of 1 050 nm and bandwidth of 80 nm were used to ensure that the interference pattern was aligned with the tilt adjustment direction.

In this case, the correlation coefficient was used to determine the maximum value of the system interference clause. By solving the test stripes, the position of the maximum correlation coefficient can be obtained. The positioning resolution was found to be superior to that of a single pixel. The co-phasing measurement resolution was obtained based on the interference stripe period. Finally, a co-phasing resolution of 0.08 μm over a 5 μm range was achieved. The actual edge interference path requires precise

alignment using aperture diffraction followed by subsequent interference measurements, as shown in Fig. 4(c)–(h). Moreover, the direction of the interference pattern can be used for precise co-focus measurements.

By constructing a high-throughput sensing architecture, the number of edge interferometric measurement channels (in each block) was reduced from 6 to 2 and the throughput was increased by a factor of 3. To ensure the final fringe resolution of future ultra-large-aperture splicing telescopes, the target size, volume, and weight of the system detector can be effectively reduced.

4 Overall low-order preservation

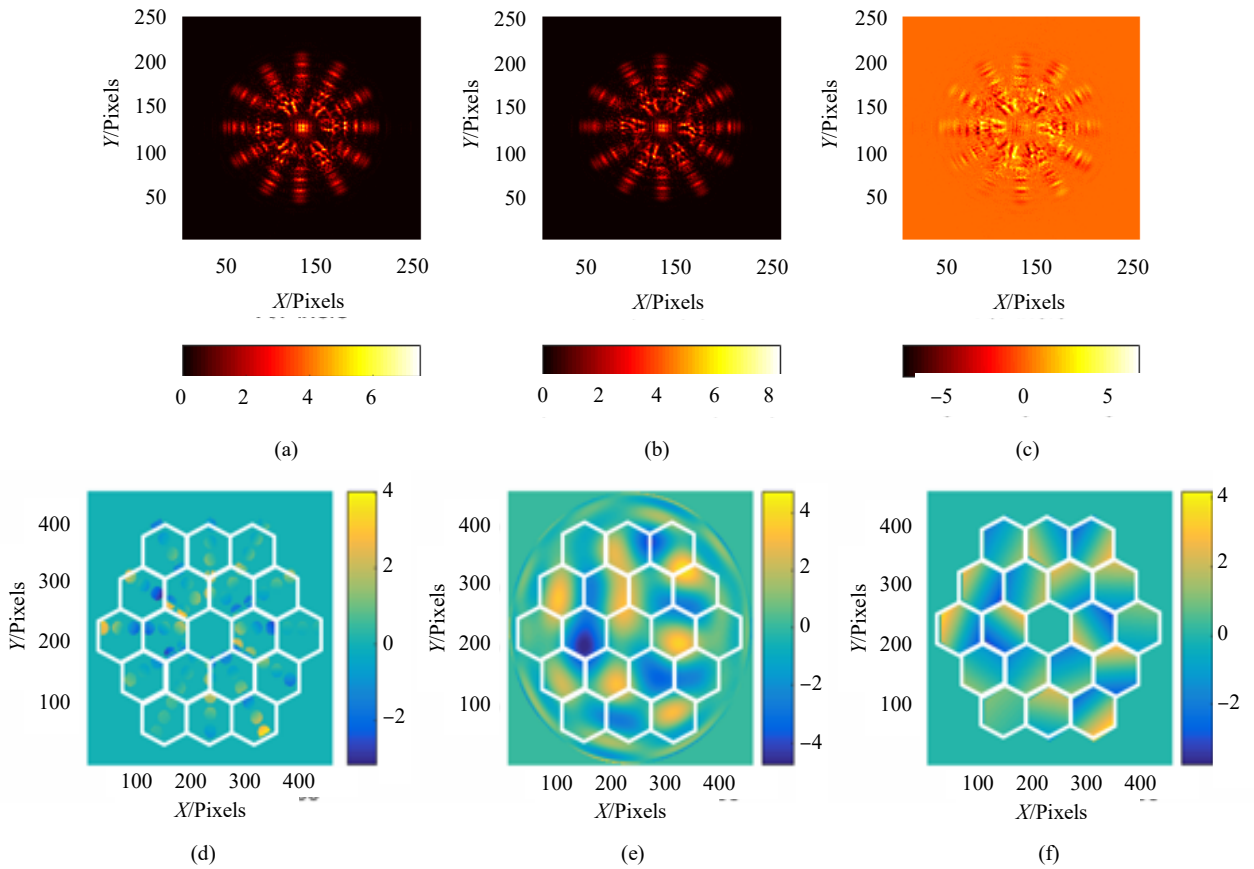
Traditional adjustment component systems have high stiffness and small adjustment dimensions, resulting in high execution accuracy. However, as the system span and adjustment dimensions increase, the system stiffness decreases. To compensate for these changes, the perception and control capabilities of the adjustment mechanism must be increased. Staggered detectors have been used for distance lock-in measurements with a single exposure. The larger the defocus amount in the curvature sensing process, the stronger the ability to perceive high-order aberrations. However, this configuration requires that there would be no overlapping areas between the defocused star images, as an increase in defocus causes the overlapping of bright stars and renders them unusable for wavefront sensing, this reduces the spatial frequency and signal-to-noise ratio of wavefront sensing (as long integration of faint stars introduces dark current and shot noise). Therefore, a partitioned curvature-sensing method was proposed to resolve the contradiction between the high-sensitivity, large-defocus curvature-sensing architecture required for fine temporal observations and the loss of usable guide stars resulting from the overlap of defocused star images. In this method, guide stars with overlaps were segmented and joined after segmentation, and wavefront

curvature sensing was performed. The final solution accuracy can be obtained by analyzing the precision of the algorithm, effect of the camera-seeing parameters, system errors of the defocus lock-in architecture, and tilt, distortion, and concentric expansion of the detector.

By using lookup tables, a rough alignment can be achieved through a wide-range adjustment, with the wavefront reaching the micrometer level. After ensuring that the light entered the system, fine alignment was performed based on an internal measurement system. The calibration of mirror group and secondary mirror was adjusted by changing the wavefront to the submicrometer level. Further adjustments were made by using an external measurement system (wavefront sensing). A displaced curvature sensor was built into the camera terminal by using two detectors located in front of and behind the focal plane to acquire defocused

images simultaneously. The illumination intensity of the light source was assumed to be unsaturated. Curvature sensing can be used to perceive the low-order and large-dynamic-range wavefront of the segment mirror, and the correlation coefficient with the original wavefront was found to be >0.8 , as shown in Fig. 5.

To achieve an overall accurate balance and alignment, each module must employ closed-loop control as the final calibration method. After the initial calibration using three-dimensional coordinates, further fine calibration was conducted using wavefront sensing. The initial calibration covered the entire working space, which was characterized by a large amplitude and numerous parameters. Wavefront-sensing-based fine calibration is known for its high precision and limited range, primarily focusing on the agile space, which is the active optical adjustment range. The final



(a) Subaperture sampling pre-focus energy distribution, (b) Subaperture sampling post-focus energy distribution, (c) Subaperture sampling energy difference, (d) Subaperture pre-sowing sampling position, (e) Reconstructed wavefront, (f) Ideal wavefront.

Fig. 5 Wavefront restoration based on step differences in the system

wide-range calibration process achieved an accuracy of $<30\text{ }\mu\text{m}$ and an angular precision of $<10\text{ arcsec}$. The precision achieved through wavefront-sensing-based calibration was $<10\text{ }\mu\text{m}$.

5 Summary

Stability directly affects the ultimate detection capability of an optical system and the achievement of scientific objectives. By employing multilevel motion control and calibration of macro-pointing and wavefront errors, wavefront stability and optical axis stability at the nanometer level was achieved. A model for perceiving and controlling the tilt of the segmented mirror and boundary stability based on the wavefront curvature (spatial second-order derivative) was constructed to achieve global wavefront compensation.

Curvature sensing offers advantages such as a large field of view, no interference, noniterative operation, and a large measuring range. Compared to traditional Hartmann sensors, it enables the detection of large-dynamic-range non-common-path wavefront aberrations in multiple fields of view, flexible subaperture configurations, and adaptable sensitivity to different observation targets. Compared to phase-retrieval methods, curvature sensing does not suffer from 2π ambiguity and does not require high spatial frequency sampling. The number of edge interferometric measurement channels (in each block) was reduced from 6 to 2, and the throughput was increased by a factor of 3. To ensure the final fringe resolution of future ultra-large-aperture splicing telescopes, the target size, volume, and weight of the system detector can be effectively reduced. Furthermore, for large-aperture segmented mirror systems with a high degree of freedom, the iterative phase-retrieval algorithm requires multiple iterations for each submirror's pose parameters, resulting in exponentially increasing time costs, making it unsuitable for high-frequency stability detection. Moreover, curvature sensing is highly sensitive to

boundary variations, making it suitable for maintaining the stability of optical systems during assembly.

Acknowledgments

We thank Dr. Hu and Dr. Wang for their help with testing.

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基于天文光子学的拼接主镜望远镜位相传感与对准

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摘要: 系统孔径的增加可以有效提高测量观察的灵敏度和分辨率, 从而得到高质量的深场测量数据. 然而孔径的增加不仅给系统尤其是具有拼接主镜的巡天望远镜系统引入了新的影响因素, 从而使其变得更复杂, 而且改变了现有组件的操作模式和效果. 在这项研究中, 我们将子孔径镜检测与曲率传感相结合, 该策略可以利用焦平面前后的强度差异测量系统中的对齐倾斜和相位差, 从而实现对齐调整和波前稳定性的维护. 在子孔径之间使用波前信息来保持连续性, 而在系统接口处使用条纹模式来调整对齐倾斜方向. 最终实现了原始波前的相关系数大于 0.8, 子镜边缘区域的 PV 值减少了超过 40%, 并且实现了 2" 的共焦分辨率, 以及在 5 μm 范围内的 0.08 μm 的共相位分辨率. 此外, 每个子镜的边缘干涉测量通道数量从 6 个减少到 2 个, 吞吐量增加了 3 倍. 为确保未来超大口径拼接望远镜的最终条纹分辨率, 必须有效地减小系统探测器的目标尺寸、体积和质量. 而这种基于天文光子学器件的方法能够有效地增加系统的集成度, 减少环境对地基系统的影响, 降低天基系统的发射成本与风险.

关键词: 大型望远镜; 主动光学; 单次曲率传感; 天文光子学

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