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Abstract

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Full Text

The Edge Sensor of Segmented Mirror Based on Fringes of Equal Thickness

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Abstract

Co-phase and co-focus detection represents one of the key technologies for large-aperture segmented mirror telescopes. In this paper, we develop a novel edge sensor based on fringes of equal thickness that can detect relative piston, tilt, and tip errors of each segment directly from interferograms. Motivated by the co-focus requirements of many ground-based seeing-limited segmented mirror telescopes, we have built an edge sensor prototype based on this principle and applied it to an indoor segmented mirror experiment system in our laboratory. In accordance with the co-focus requirement of the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST), we conducted extensive simulations and experiments for co-focus error detection of the segmented mirror system. Experimental results demonstrate that the co-focus accuracy achieves better than 0.02 rms, meeting the co-focus requirements of most large or extremely large segmented mirror astronomical telescopes.

Key words: instrumentation: interferometers – astronomical instrumentation – methods and techniques – techniques: interferometric

1. Introduction

Active optics technology is crucial for large-aperture segmented mirror telescopes to achieve maximum resolution and optimal light-gathering power. Co-phase calibration and maintenance are performed frequently before and during astronomical observations. The co-phase calibration process can be divided into two steps: co-focus and co-phase. During the co-focusing step, the tip/tilt error between mirror segments is measured and adjusted using Shack-Hartmann wavefront sensors. Subsequently, during the co-phase step, the piston error is measured and adjusted to achieve perfect diffraction-limited performance of the full aperture optical system [?]. Various detection methods have been studied for measuring relative displacement (piston) and attitude (tip/tilt) between neighboring segments, including Broadband/Narrowband Phasing algorithms [?, ?], Pyramid Phase Sensing (PYPS) [?], Dispersed Fringe Sensing (DFS) [?], and Phase Retrieval (PR) [?]. The broadband/narrowband phasing algorithms have been successfully employed for the Keck telescope, the dispersed fringe sensing method has been used for coarse phasing of the James Webb Space Telescope (JWST), and phase retrieval has been applied to fine phasing of JWST. During the co-phase calibration stage, these optical detection methods are typically adopted to detect segment errors and establish the zero-point for edge sensors; during the co-phase maintenance stage, edge sensors are used to detect piston error of segments to maintain the co-phase state.

The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST, [?]) is a special quasi-meridian reflecting Schmidt telescope that has been in

operation for 12 years. Its optical system consists of a reflecting Schmidt Ma, a spherical primary mirror Mb, and a focal surface positioned between them. Mb has dimensions of 6.67 m \times 6.05 m and comprises 37 hexagonal spherical mirrors, each with a diagonal diameter of 1.1 m and thickness of 75 mm. During observations, the spherical mirror Mb remains fixed, resulting in no significant changes in gravitational force on its mirror support and co-focus system, as shown in Figure 1 [Figure 1: see original paper] [?]. Currently, LAMOST has achieved co-focus of the segmented mirror telescope in the visible band using active optics technology, including calibration with a wavefront sensor and adjustment with actuators. Edge sensors are required for Mb to maintain co-focus during operation, and this edge sensor prototype is designed specifically for the co-focus of Mb.

Many ground-based large segmented mirror telescopes similar to LAMOST operate in seeing-limited observation mode without adaptive optics, such as the Hobby–Eberly Telescope (HET) [?] and the Southern African Large Telescope (SALT) [?]. For these telescopes, employing only co-focus active optics is essential to achieve high light-gathering power and efficiency. Edge sensors play a crucial role in providing the active optics system with real-time fine co-focus error detection of the segmented mirror.

Currently, edge sensors for segmented mirrors primarily employ electrical measurement methods, including capacitive, inductive, or eddy current sensors. These sensors are utilized in various large segmented mirror telescopes worldwide. The Thirty Meter Telescope (TMT) [?], Keck telescope [?], and Gran Telescopio Canarias (GTC) use similar capacitive edge sensors [?], while the Extremely Large Telescope (ELT) will employ inductive edge sensors [?]. The parameters of each edge sensor are as follows: the capacitive sensor of the Keck telescope has a measurement accuracy of 3 nm, a range of $\pm 12 \mu\text{m}$, with a temperature drift of $2 \text{ nm}^\circ\text{C}^{-1}$ and a time drift of 3.2 nm per week [?]; the TMT telescope's edge sensor was improved from the Keck design with a measurement accuracy of 1 nm, but still exhibits temperature drift [?]; the inductive edge sensor for ELT has a measurement accuracy of 1 nm, a range of 400 m, and a temperature drift of $1.32 \text{ nm}^\circ\text{C}^{-1}$ [?]. The measurement accuracy of such electrical sensors is significantly affected by environmental factors, including temperature drift and time drift, which are challenging to eliminate, and they exhibit poor anti-electromagnetic interference capability. Due to temperature drift, the electrical edge sensors mentioned above must be calibrated periodically. For LAMOST, the impact of environmental temperature changes will be more pronounced because the temperature range at most Chinese astronomical observatories exceeds 50°C per year, at least twice that of other sites worldwide. It is therefore necessary to find an alternative edge sensor different from traditional electrical edge sensors.

Based on the edge sensor detection principle of interference fringes of equal thickness proposed by our team earlier [?], combined with the indoor segmented-

mirror active optics experiment system [?], we have developed an optical edge sensor experimental prototype for co-focus detection of tip/tilt errors and propose a new interferogram detection algorithm. The advantages of this optical edge sensor are: segment errors are measured directly, which simplifies the co-phase and co-focus process without requiring calibration; the sensing method based on fringes of equal thickness is not susceptible to temperature changes like electrical edge sensors, and the tilt/tip/piston error of the segments can be obtained and used as high-precision feedback to provide real-time correction for actuators, enabling co-phase maintenance. Simulation and experiments were performed on the integrated system, and the co-focusing performance achieved the technical requirements, with temperature drift eliminated completely.

In the following section, we describe the detection principle and optical system structure of the edge sensor. Section 3 introduces the interferogram processing algorithms based on fringes of equal thickness. Sections 4 and 5 describe the simulation and experimental tests, respectively. Discussion and conclusions are presented in Section 6.

2. The Detection Principle, Experimental System, and Mounting Analysis

2.1. The Detection Principle of the Edge Sensor Based on Fringes of Equal Thickness Fringes of equal thickness occur when both coherent beams are obtained by division of the amplitude of the original wavefront using a partially reflecting optical surface and then recombined from different paths. Each fringe represents the positions of all points where the two optical surfaces (or wavefronts) have the same path difference. The detection principles of the Newton ring interferometer and the edge sensor based on fringes of equal thickness are shown in Figure 2.

Consider the optical structure in Figure 2(a), where the spherical surface of one plano-convex lens is placed against the flat surface of another mirror. The initial beam enters the plano-convex lens and partially reflects from the second surface, from which the beam is separated into two coherent beams. The coherent beam passing through the spherical surface is reflected from the upper surface of the flat mirror and recombines with the coherent beam reflected from the spherical surface to form fringes of equal thickness. Since the radius of curvature of the spherical surface is known, the spherical surface serves as the reference surface, and the flat surface is the surface to be measured. Each fringe forms a circle, called a Newton ring. The method of testing using interference fringes is widely employed in various optical fields, such as the Fizeau interferometer, Twyman-Green interferometer, and Mach-Zehnder interferometer [?, ?].

Suppose the shape of the surface to be measured is spherical and the reference surface is flat. In that case, the fringes of equal thickness will also appear as circles after recombining the two beams. The fringe represents the position of all points with equal optical path differences between the two surfaces, with

the optical structure shown in Figure 2(b). R is the radius of curvature of the spherical mirror; r_0 is the radius of the 0-level interference fringe and also the radius of the reference surface; d_b is the thickness of the air gap at a point on the mirror surface, and r_b is the radius of the fringe there. The wavelength of the incident light is λ . From the geometrical relationship and the equation of optical path difference:

$$2nd_b = k\lambda \quad (k = 0, 1, 2, \dots)$$

Substituting the geometric relationship into Equation (1) yields:

$$r_b^2 = (2R - d_b)d_b \approx 2Rd_b \quad (k = 0, 1, 2, \dots)$$

Combining Equations (1) and (2) gives:

$$r_b^2 = \frac{kR\lambda}{n} \quad (k = 0, 1, 2, \dots)$$

where n is the refractive index and k is the fringe order. The fringe radius can be calculated using the above equations.

Based on this principle, if two segmented spherical mirrors replace the spherical mirror in Figure 2(b) and the reference flat is set up on the gap between the two segments, the circular interference fringe will be divided into two semicircles. When the two segments are in the co-focus state, the rings on both sides should be concentric; furthermore, when the two segments are in the co-phase state, both sides of the ring are perfectly aligned, the circle centers are coincident, and the radii are equal. The tilt/tip and piston errors of the two segments can be calculated by measuring the fringe circle centers and radii, and the position and posture of the segments can be adjusted using actuators to achieve co-focus and co-phase.

In traditional detection of fringes of equal thickness, the piston error may also be an integer multiple of half wavelength. From Equation (3), it can be seen that the fringe radius is related to the incident light wavelength λ . Therefore, using two or three lasers (such as 511, 532, and 632.8 nm) can obtain different radius sizes. When switching between light sources with different wavelengths, if the radius of fringes on both sides can be made consistent, the piston error of segments can be measured as zero. In that case, the uncertainty that may exist in the alignment of arbitrary circular fringes can be eliminated by switching the incident light source, and the detection range of piston error can be expanded.

ZEMAX software is used for optical design, primarily to evaluate beam quality, fringe contrast, light intensity distribution, stray light, noise, and system optimization. The design includes light wavelength, optical component size, coating,

detector size, and other parameters. The optical system parameters are shown in Table 1 .

For this optical system, the theoretical sensitivity of the sensor is 3.868 pixel^{-1} , and the allowable error of sensitivity is $\pm 0.232 \text{ pixel}^{-1}$. To achieve co-focus of all segments, the edge sensor must detect interference fringe changes when each segment is tilted/tipped (with tilt/tip angle accuracy of 0.02 rms). The design targets of the edge sensor are: measurement accuracy of 0.02 rms and measurement range of ± 60 .

2.3. Mounting Analysis for Application in LAMOST An experimental prototype of the edge sensor based on fringes of equal thickness was designed to test the performance and accuracy of the sensor, as shown in Figure 3 [Figure 3: see original paper]. The optical system features a simple structure that facilitates analysis of each surface error in the experiment; the measurement path is separated from the reference path, which can effectively reduce noise from parasitic reflected light.

The experimental system in the laboratory is shown in Figure 4 [Figure 4: see original paper], consisting of a segmented primary mirror with two spherical hexagonal segments—one fixed mirror and one movable mirror. Three high-accuracy actuators are placed under the movable mirror, allowing free adjustment of the mirror position and posture. The edge sensor is positioned on the gap between the two mirror segments to detect co-focus errors.

Since the sensor system has a simple structure with few components, it is easy to integrate and mount. The preliminary design is shown in Figure 5 [Figure 5: see original paper]: the sensor bracket is divided into two parts, the upper bracket is fixed to the outer part of the sensor by clamps and connected to the lower bracket through the mirror gap, while the lower bracket is fixed to the mirror chamber structure. To minimize measurement noise and avoid damage to the mirror surface, the sensor body is pressed against the mirror surface with a soft gasket. As the mirror surface is tipped or tilted, the expansion and contraction of the soft gasket can reduce the influence of stray light and dust.

As the edge sensor is mounted in front of the mirror surface, it will block part of the beam. The sensor's size can be minimized by using smaller components. The diameter of the optical components in the experiment is 25.4 mm, and the detector size is 90×97 mm. Therefore, the area blocked by a single sensor is 0.00873 m^2 . Figure 6 [Figure 6: see original paper] shows the mounting of the sensors on LAMOST, which requires 90 sensors. The total beam blocking area is 0.7857 m^2 , and the blocking ratio is only 2.7%, which is within the permissible range for observation with minimal impact.

3. Image Processing Algorithms for Interferograms

The image processing algorithm focuses on detecting the circle center coordinates of the interference fringes, from which the relative tip/tilt error between

neighboring segments can be calculated. The image processing is divided into two steps: image preprocessing and extraction of the circle center coordinates of interference fringes using concentric fringe detection algorithms.

3.1. Image Preprocessing Image preprocessing aims to extract regions of interest (ROI), remove noise, and enhance useful information to facilitate deeper image processing. Therefore, image preprocessing is also divided into two steps: ROI extraction and image enhancement.

The interference fringes of equal thickness in this edge sensor are generated by recombining two coherent beams—one reflected from a spherical mirror and the other reflected by a flat mirror. The beam diameters of the two beams after reflection differ in size, as the convergence effect of the spherical mirror makes the reflected beam diameter smaller than the other. Interference fringes appear only within the range of the smaller beam. Thus, by analyzing the light intensity changes in the image, the position of the smaller beam can be located, enabling ROI extraction.

Image enhancement can be divided into two methods: frequency domain method and spatial domain method [?]. In this process, combining both methods yields better results. A high-pass filter in Fourier space is used to remove low-frequency noise, followed by various spatial domain methods (nonlinear filtering, contrast limited histogram equalization [?], adaptive binarization [?], etc.) to address other noise. Through this process, feature regions are highlighted, other regions are suppressed, and the clarity of valid information in the image is enhanced to meet subsequent processing needs.

The ideal and noise-containing interferograms are shown in Figures 7(a) and (b). Figures 7(c) and (d) show the original interferogram obtained in the experiment and the interferogram after preprocessing.

3.2. Concentric Fringes Detection Algorithms for Interferograms

Since the fringes are concentric interference fringes composed of many bright and dark circles, circle detection is essential to the concentric fringe detection algorithm. Circle detection methods widely used can be divided into two categories: pixel-based methods and contour-based methods [?, ?]. The pixel-based method primarily detects circles using Hough transform (HT) or its variants, classifying and extracting image pixels, which is robust for various image detection tasks [?]. However, this method's detection speed is slow due to the large amount of storage space required. Contour-based methods, also known as edge-tracking algorithms, detect geometric structures by tracking connectivity between pixels. Using contours rather than individual pixels can significantly improve computational speed. The structure of the concentric fringe detection algorithm based on interference fringe contours is shown in Figure 8 [Figure 8: see original paper].

After image preprocessing, a contour data set consisting of interference fringe

contours can be obtained using a contour tracking algorithm. The circle center coordinates of each contour are fitted using the least squares method to form a set of circle center points. The standard deviation of the circle center point set $O\sigma$ is calculated. The clustering degree of the circle center set is determined by comparing the magnitude of the empirical threshold P with $O\sigma$: if $P < O\sigma$, there are outliers with significant deviation, then an empirical threshold Q is used to identify the outliers. After the outliers are removed, a concentric circle candidate set can be obtained, and its clustering degree is determined again until it meets the requirement. Finally, the circle center set with reasonable clustering degree is regarded as the concentric circle set, and its median is taken as the detection result.

Comparing the size and clustering degree of the circle center set and the execution time, the above two types of algorithms can be evaluated, as shown in Figure 9 [Figure 9: see original paper]. It can be seen that the pixel-based algorithm obtains a larger amount of data on the circle centers and gets more data points than the contour-based algorithm, resulting in poorer clustering and more outliers that require repeated filtering. Compared with the pixel-based algorithm, the contour-based algorithm has higher detection accuracy and shorter execution time.

4. Simulation Tests

Co-focus simulations are carried out by processing interferograms generated by simulation software to evaluate the performance of the edge sensor, including accuracy, sensitivity, linearity, and measurement range. ZEMAX software is used to generate ideal interferograms for the system. Noise-containing interferograms can be obtained by adding random noise to the ideal interferograms. The robustness of the image processing algorithm can be evaluated under different noise conditions by examining both ideal and noise-containing interferograms.

4.1. Simulation Tests of Ideal Interferograms In the first step, the accuracy and sensitivity of the edge sensor are tested. The segmented mirror system has two segments: one fixed and one movable. The tilt angle of the movable segment is changed gradually from 0 to 0.4 in steps of 0.01, generating 40 interferograms. Similarly, gradually changing the movable segment tip angle yields another 40 interferograms. The accuracy and sensitivity of the edge sensor can be determined by analyzing the variation pattern of the concentric coordinates.

The relationship between the tilt angle and the y-axis coordinates of fringe centers is shown in Figure 10 [Figure 10: see original paper]. When the mirror's tilt angle changes, the fringe center shifts accordingly, and the y-axis coordinate of the fringe center is linearly related to the tilt angle. The maximum error in the y-direction is 0.00279 pixel (0.00072). A linear fit to the y-axis coordinate data of the circle centers is performed, and the fitted equation slope represents

the sensitivity of the edge sensor in the tilt direction. The sensitivity in the tilt direction is $3.85209 \pm 0.00166 \text{ pixel}^{-1}$.

Similar simulation results in the tip direction are shown in Figure 11 [Figure 11: see original paper]. When the movable mirror's tip angle changes, the fringe center's x-axis coordinate changes linearly. The maximum error in the x-direction is 0.0043 pixel (0.0011), and the sensitivity in the tip direction is $3.89306 \pm 0.00527 \text{ pixel}^{-1}$.

In the next step, the linear measurement range of the sensor is evaluated. The tilt/tip angle of the movable segment is changed gradually from 0 to 100 in steps of 10 , generating two sets of interferograms. Increasing the tilt/tip angle allows measurement of its linear operating interval, and analyzing the deviation between measured and theoretical values can evaluate the sensor's linearity within the measurement range. When the mirror is gradually tilted/tipped in steps of 10 , the changes in fringe center coordinates in the tilt/tip direction are shown in Figure 12(a)/Figure 12(b), and the errors are shown in Figure 12(c).

Figures 12(a) and (b) show that the slope values of both lines obtained by linear fitting are compatible with the sensitivity requirements, and the fitted straight lines overlap very well with the theoretical ones. It should be noted that the absolute error shown in Figure 12(c) is caused by image detection algorithm limitations. The absolute errors in the tilt direction are significantly smaller than those in the tip direction, which is due to the nature of the interferograms. Since the sensor is located in the gap between two mirror segments, the interferogram is split into two semicircles along the y-axis. When detecting the x-axis coordinate, the semicircle is located on the side of the circle center, so the result slightly deviates. In contrast, when detecting the y-axis coordinate, the semicircle is symmetrical, so the detection result is closer to the theoretical value. However, the error values of the detection results on both sides are within the allowed range. Figure 12(c) shows that when the tilt/tip angle is 100 , the maximum error in the tilt direction is 0.00886 pixel, and the maximum error in the tip direction is 0.07277 pixel. Both are well within the accuracy requirement of 0.02 rms (Root Mean Square, 0.077 pixel) or 0.12 PV (Peak to Valley, 0.464 pixel). Linearity error represents the deviation of the sensor output curve from a specified theoretical straight line over the desired range. The equation for linearity error is given below:

$$\text{Linearity} = \pm \frac{Y_{\max}}{Y_F} \times 100\%$$

where Y_{\max} is the maximum deviation (pixel) of the measured data from the theoretical straight line (the maximum absolute error), and Y_F is the measured value (pixel) of the sensor at full range. From this, the linearity of the sensor can be calculated separately in the interval of tilt/tip angle ≤ 100 : 0.00229% in tilt direction and 0.01881% in tip direction.

In actual application, the range of the edge sensor is not only related to its detection capability but also limited by the actuator movement range. Moreover, the tilt/tip angle error is usually on the order of tens of arcseconds for the segments, so this measurement range can fully meet co-focus requirements.

4.2. Simulation Tests of Noise-containing Interferograms In this section, the two sets of interferograms from Section 4.1 are processed with several random noise algorithms, such as salt-and-pepper noise, Gaussian noise, and others. After adding noise, two sets of noise-containing interferograms are obtained. The SNR of the processed noise images is approximately 20 dB. Since the random effect of the noise-adding algorithm influences measurement accuracy, we employ a signal-averaging method to mitigate it: an interferogram is processed 25 times by the random noise-adding algorithm to obtain a set of noise-containing interferograms, and the final result is obtained by averaging the results of all detections. The relationship between the fringe center coordinates of noise-containing interferograms and the tilt/tip angle changes can be obtained, as shown in Figures 13(a) and 14(a). The accuracy is represented by the rms, shown in Figures 13(b) and 14(b).

The results show that for noise-containing interferograms (SNR = 20 dB), the detection sensitivity in the tilt direction is $3.85684 \pm 0.00158 \text{ pixel}^{-1}$, and the rms of all detected results is less than 0.002. The sensitivity in the tip direction is $3.86342 \pm 0.0051 \text{ pixel}^{-1}$, and the rms of all detected results is less than 0.006. Therefore, when the SNR of interferograms is greater than 20 dB, the edge sensor can still meet the requirements for segmented mirror co-focus detection, and the detection accuracy is much better than 0.02 rms.

5. Experimental Test

The repeatability, sensitivity, linearity, and accuracy of this edge sensor were tested experimentally. The laboratory system consisted of a fixed mirror and a movable mirror, with three high-precision actuators installed under the movable mirror. The actuators A1, A2, and A3 are shown in Figure 15 [Figure 15: see original paper]. Based on the geometric relationship, when actuator A2 moves, the movable mirror rotates around the line A1A3, changing the tip angle of the mirror; if actuator A2 moves by 1 mm, the relative tip angle of the movable mirror changes by 1.62°.

In practical applications, sensor repeatability is an important parameter. The rms of measurement results can quantitatively represent repeatability. Additionally, higher measurement accuracy can be achieved if the average of all measurements is used as the final result. Accordingly, we designed experiments to test the edge sensor's repeatability and determine the optimal number of repeated measurements to meet design targets.

First, 100 interferograms are captured and detected with actuator A2 moving in steps of 20 nm (0.0324°). Second, interferograms are taken as a group, and

the average value of ten images is taken as the measurement result for that group. Finally, the rms of the ten groups is calculated. Using this method, the number of repeated measurements per group is set to 10, 15, 20, 25, 30, and 35. Figure 16 [Figure 16: see original paper] shows the distribution of measurement results for the six sets. It can be seen that as the number of measurements increases, the rms results first decrease and then increase. This indicates that an appropriate increase in the number of repeated measurements does help improve measurement accuracy, but as measurement time increases, other errors may be introduced that lead to decreased measurement accuracy. Figure 16 shows that the minimum rms occurs when the number of repeated measurements is 25.

In the next experiment, the step size for tip angle changes is set to a fixed value to detect sensitivity in the fine-tuning measurement range. The movement of actuator A2 is 100 nm per step, corresponding to a tip angle of 0.162°, and 25 interferograms are captured for each movement. The detection results are shown in Figure 17 [Figure 17: see original paper], and the rms of each measurement is shown in Figure 18 [Figure 18: see original paper].

The experimental results show that the sensitivity is $3.8946 \pm 0.0277 \text{ pixel}^{-1}$, with a maximum absolute error of 0.17038 pixel. Based on the maximum absolute error, linearity is approximately 1.48%. Both rms values are less than 0.02. Therefore, this edge sensor can detect the tilt/tip error of the segmented mirror, and all relevant performance parameters meet the design targets.

6. Conclusion

Co-focus and co-phase detection is one of the key technologies for large-aperture segmented mirror telescopes. Based on fringes of equal thickness and the two-segmented mirror active optics experiment system, we have successfully developed a new type of edge sensor prototype, together with two kinds of concentric fringe detection algorithms. Simulations and experiments have shown that the edge sensor can achieve accuracy better than 0.02 rms and linearity less than 1.48%. These results meet the co-focus detection requirements of most large or extremely large segmented mirror astronomical telescopes.

According to different segmented mirror requirements, we need only adjust and optimize sensor parameters, such as the surface shape of the segmented mirror, light wavelength, beam diameter, diaphragm aperture, and detector pixel size and resolution, to achieve optimal system performance and lower manufacturing cost. Because of these advantages and the avoidance of environmental factor influences and on-sky calibration demands associated with most electrical edge sensors, it is feasible and low-cost to build this optical edge sensor based on fringes of equal thickness for most segmented mirror telescopes.

In the future, this sensor will be used on LAMOST for co-focus testing, and further engineering research will be conducted for practical applications. In addition, to achieve co-phase of the segmented mirrors, the piston error of the

segments must be detected. It is feasible to detect the radius when the center position of the fringes of equal thickness is known. Based on the concentric fringe detection algorithm mentioned in this paper, we will develop another algorithm to detect the radius of those concentric fringes. Piston error detection using this edge sensor is planned to be tested and studied so that this type of edge sensor can be adapted to the co-phasing process of segmented telescopes. Therefore, the edge sensor could be used for future large telescopes, such as the 12 m Large Aperture Optical/infrared Telescope (LOT) in China.

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