

## Co-phasing Detection and Control Method for Fizeau-type Optical Interferometric Telescopes Based on Broadband Fringe Contrast (Postprint)

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### Abstract

For Fizeau-type optical interferometric telescopes, the key to achieving high-resolution imaging is the elimination of phase piston errors between sub-mirrors. The broadband spectral fringe contrast detection method constitutes an effective approach for detecting such piston errors. Based on fundamental principles of physical optics, this study demonstrates the relationship between piston errors and the system point spread function, simulates cophased far-field fringe images, analyzes methods for the cophasing detection and control process and data pre-processing, proposes a weighted contrast algorithm and a cophase maintenance method, and finally obtains cophased far-field images for comparison with simulation results. The results indicate that both the energy distribution patterns and numerical values of the experimental and simulated cophased far-field images are in close agreement, demonstrating that this method can successfully detect and control phase piston errors between sub-mirrors.

### Full Text

## Co-phasing Detection and Control Method Based on Broadband Spectrum Fringe Contrast for Fizeau Optical Interferometric Telescope

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## Abstract

For Fizeau optical interferometric telescopes, eliminating relative phasing piston errors between sub-mirrors is essential for achieving high-resolution imaging. The broadband spectrum fringe contrast detection method provides an effective means for detecting these piston errors. Based on fundamental physical optics principles, this paper analyzes the relationship between piston errors and the system's point spread function, and simulates far-field fringe patterns under co-phased conditions. We describe the experimental process for co-phasing detection and control, along with data preprocessing methods. Additionally, we propose a weighted contrast algorithm and a method for maintaining co-phasing. Experimental co-phased far-field images were obtained and compared with simulation results, demonstrating close agreement in energy distribution morphology. The results indicate that this method can successfully detect and control phasing piston errors.

**Keywords:** Co-phasing detection; Segmented sub-mirrors; Phasing piston errors; Fringe contrast

**Classification:** TH744, TH751

## Introduction

Spatial resolution is a critical technical indicator for evaluating astronomical telescope observation capabilities. Higher spatial resolution enables telescopes to resolve finer details of targets and acquire more information [1]. For a given wavelength, telescope resolution increases with primary mirror aperture. However, current technological limitations in mirror material preparation, fabrication and testing, support structures, and cost constrain the maximum feasible aperture size [2]. The largest single-piece optical telescope primary mirrors currently achieve diameters of approximately 8.4 meters. To construct larger-aperture optical telescopes, astronomical optical interferometry technology can be employed [3].

Astronomical optical interferometry arranges multiple small optical apertures (sub-mirrors or independent telescopes) in specific spatial configurations to form multi-baseline arrays, obtaining celestial information through wave interference. This approach achieves resolution equivalent to that of a single-aperture telescope with a diameter equal to the baseline length. Depending on baseline configuration, astronomical optical interferometry can be categorized as long-baseline interferometry or optical synthetic aperture. In long-baseline systems, baseline lengths far exceed sub-aperture diameters, and the intensity distribution of the observed source is reconstructed through inverse Fourier transform of complex visibilities measured from interference between any two small apertures. In optical synthetic aperture systems, baseline lengths are comparable to sub-aperture diameters, enabling direct high-resolution imaging under sufficient spatial frequency coverage.

Segmented sub-mirrors represent a structural configuration for optical synthetic

aperture telescopes, offering advantages such as minimal central obstruction and the ability to install imaging terminals on independent optical platforms. However, this approach presents technical challenges in detecting and maintaining co-phasing between sub-mirrors. The image fields generated by each sub-mirror must share identical phase to constructively interfere at the center of the Airy pattern and obtain high-resolution images [4]. In optical synthetic aperture telescope systems, co-phasing errors significantly impact imaging quality, requiring co-phasing precision of at least  $\lambda/10$  in practical applications.

In recent years, high-precision co-phasing detection for interferometric telescopes has become a research focus. Researchers worldwide have conducted extensive studies and proposed numerous effective detection methods, including pyramid wavefront sensing, dispersed fringe sensing, dispersed Hartmann sensing, Zernike phase contrast methods, and differential capacitive displacement sensor approaches [5]. Fringe detection methods provide particularly effective means for detecting relative optical path differences between sub-mirrors [6].

This paper investigates a broadband spectrum fringe contrast method for co-phasing detection and control of piston errors between separated sub-mirrors in a Fizeau optical interferometric telescope. Using a 500 mm diameter segmented prototype system with seven sub-mirrors based on Fizeau interferometric technology as the experimental platform, we implement closed-loop control mechanisms and phase correction techniques to achieve co-phasing detection. This method achieves detection precision better than  $\lambda/10$ , providing valuable reference for further research in co-phasing error detection and control.

## 1. Theory and Simulation

Piston errors originate from optical field differences between sub-beams along the z-axis of the exit pupil plane. When considering only piston errors, if the phase of one sub-beam is delayed by a constant  $\phi$ , the pupil function can be expressed as [MATHEMATICAL EXPRESSION]. Under monochromatic illumination, if piston errors exist between sub-mirrors, the far-field intensity of the system is [MATHEMATICAL EXPRESSION]. For broadband illumination, the far-field intensity distribution represents the superposition of far-field intensities from each monochromatic component [MATHEMATICAL EXPRESSION], where  $\lambda_0$  represents the central wavelength of the broadband source,  $\Delta\lambda$  denotes the source bandwidth,  $f$  is the focal length of the combined mirror, and  $a$  is the sub-mirror radius. Specific simulation parameters include:  $\lambda_0 = [\text{VALUE}]$ ,  $\Delta\lambda = [\text{VALUE}]$ ,  $f = 1000$  mm, and pixel size = 3.45  $\mu\text{m}$ . Figure 1 [Figure 1: see original paper] shows the simulated far-field fringes when the piston error between two sub-mirrors equals zero.

Interference phenomena manifest as stable distributions of bright and dark fringes in the interference field. Fringe contrast quantifies the clarity of these interference patterns, expressed as  $C = (I_{\text{max}} - I_{\text{min}})/(I_{\text{max}} + I_{\text{min}})$ , where  $I_{\text{max}}$  and  $I_{\text{min}}$  represent the peak intensity of the central bright fringe

and the valley intensity of adjacent dark regions, respectively. The relationship between contrast and optical path difference (OPD) can be approximated as [MATHEMATICAL EXPRESSION], where  $\Delta$  is the optical path difference,  $k = 2/\lambda$  is the wavenumber, and [PARAMETER] = [VALUE]. This demonstrates that both source spectral width and optical path difference directly influence interference fringe contrast.

For a broadband source with spectral width  $\Delta$ , each wavelength component within the interference range generates its own interference fringe pattern. Except for the zero interference order, these patterns exhibit mutual displacement, with relative displacement increasing as the optical path difference between interfering beams grows. Consequently, fringe contrast decreases with increasing optical path difference, eventually reaching zero. Therefore, source spectral width limits interference fringe contrast. While monochromatic sources maintain coherence regardless of path difference, broadband sources achieve unit contrast only when phase difference equals zero; any non-zero phase difference reduces visibility. This necessitates using broadband sources for co-phasing detection. When selecting source spectral width, both coherence length ( $L_c = \lambda^2/\Delta$ ) and sensitivity of contrast variation relative to optical path difference must be considered. Figure 2 [Figure 2: see original paper] illustrates the relationship between contrast and optical path difference for spectral widths of 100 nm and 80 nm, with coherence lengths  $L_1$  and  $L_2$  respectively. Within the coherence length range, contrast varies approximately quadratically with optical path difference. As bandwidth decreases, coherence length increases (expanding measurement range), but the slope of the contrast-OPD curve decreases (reducing sensitivity). Conversely, increased bandwidth improves sensitivity but reduces measurement range. Therefore, appropriate bandwidth must be selected based on experimental requirements.

## Experimental System

The experimental prototype employs a parabolic primary mirror consisting of one central annular sub-mirror (reference) and six uniformly distributed off-axis sub-mirrors. All mirror surfaces achieve RMS figure accuracy better than  $\lambda/40$ , fabricated from Zerodur glass ceramic. Each sub-mirror measures 150 mm in diameter, with the annular sub-mirror having a 60 mm inner diameter. Sub-mirror spacing is 15 mm, yielding a primary mirror fill factor of 0.68. Each sub-mirror assembly provides six degrees of freedom adjustment capability: translation along X, Y, Z axes and rotation about X, Y, Z axes. Three linear micro-displacement actuators mounted on each sub-mirror backplane drive wire mechanisms to adjust normal displacement and two-dimensional tilt, enabling correction of both piston and tilt errors. The seven separated sub-mirrors and their adjustment mechanisms are installed on a primary mirror frame (Figure 3 [Figure 3: see original paper]). The experiment utilizes a broadband source with center wavelength 600 nm, bandwidth 100 nm, and coherence length of 36  $\mu$ m.

## 2.2 Experimental Procedure

Phase 1 of the experiment involves coarse co-phasing of sub-mirrors. Using interferometric wavefront detection combined with mechanical adjustment, all six off-axis sub-mirrors are optimized to minimize wavefront error, reducing piston errors between sub-mirrors to tens of micrometers. Subsequent fine co-phasing correction addresses both piston and tilt errors for each sub-mirror pair. Tilt errors are corrected through closed-loop detection of geometric offsets in defocused image spots [4]. For piston error correction, when errors are large, the grating dispersed fringe method first determines the error direction, enabling manual adjustment to gradually reduce the error until fringes become sufficiently sparse that dispersion direction becomes visually indistinguishable, at which point piston error range has been reduced to within 5  $\mu\text{m}$  [8]. Due to significant experimental platform vibration and environmental effects on precise grating dispersed fringe detection, the broadband spectrum fringe contrast method is employed for fine co-phasing adjustment. By varying sub-mirror axial displacement in 20 nm steps and acquiring multiple far-field fringe datasets, contrast serves as the evaluation metric. Fitting the contrast measurement data yields a correlation curve between contrast and sub-mirror axial position, with the peak position providing the optimal co-phasing estimate for each sub-mirror pair, thereby achieving full system co-phasing.

## 2.3 Data Preprocessing

Following acquisition of far-field fringe images from sub-mirror pairs, mean filtering is first applied to mitigate CCD camera noise and eliminate sharp artifacts. Due to the directional nature of interference fringes arising from sub-mirror spatial arrangement, the fringe tilt angle must be precisely calculated using Fourier transform combined with binary image threshold traversal methods before sampling along the fringe normal direction to obtain accurate contrast values [9]. Sampling is then performed along the fringe normal direction centered on the brightest image point to obtain fringe data, as shown in Figure 4 [Figure 4: see original paper]. The primary peak in the curve represents the bright fringe maximum, while the minimum between the primary and adjacent secondary peaks defines the dark fringe valley. Contrast is subsequently calculated using the contrast formula.

Through step-scanning methods, contrast data at various sub-mirror axial positions is acquired. Based on the approximately quadratic relationship between contrast and optical path difference, Gaussian fitting is applied to process the discrete data, generating a continuous curve relating contrast to sub-mirror axial position. Cubic spline interpolation of this curve then yields the optimal co-phasing position estimate.

## 2.4 Weighted Contrast Algorithm

When employing the classical contrast algorithm, using only the valley value from one side of the peak consistently produces stratified, discontinuous contrast data (Figure 5 Figure 5: see original paper). This paper proposes a novel weighted contrast algorithm that calculates left and right contrast values  $C_L$  and  $C_R$  using valley values from both sides of the peak, then establishes a weighted average contrast metric  $C = (C_L / C_R) \times (C_L + C_R) / 2$ . This yields continuous contrast versus co-phasing position data (Figure 5(b)). Comparison of the two datasets demonstrates that the weighted contrast algorithm produces relatively continuous data. Gaussian fitting of both discrete datasets reveals that the weighted contrast algorithm achieves an RMS error of 0.037417, compared to 0.049089 for the classical method, confirming that the new algorithm offers superior accuracy and stability.

## 2.5 Co-phasing Maintenance

The large collimator used in experiments is independently mounted on a separate optical platform, and platform vibration affects co-phasing position stability. Combined with environmental influences, the Poisson spot position drifts over time, necessitating timely adjustment. The fitted data from step-scanning serves as a lookup table. When fringe contrast falls below 0.75, the corresponding Poisson spot variation is located in the table for real-time adjustment until contrast requirements are met. Figures 6 Figure 6: see original paper and 6(b) show real-time contrast variation over 25 minutes at the established co-phasing position (sampling frequency 8 Hz) without and with co-phasing maintenance correction, respectively. Figure 6(a) demonstrates significant contrast reduction over time, indicating co-phasing position drift. Figure 6(b) shows that with correction enabled, although contrast data exhibits fluctuations, timely corrections maintain the average value above 0.8 throughout the 25-minute period.

## 3. Results Analysis

Following coarse and fine co-phasing adjustment, the far-field image obtained from the experimental prototype optical system is shown in Figure 7 Figure 7: see original paper. Figure 7(a) displays the non-co-phased far-field image, while Figure 7(c) shows the simulated image. Comparison of Figures 7(b) and 7(c) reveals similar energy distribution morphology, whereas the non-co-phased image differs substantially from both experimental and simulated co-phased results. Using full width at half maximum (FWHM) as the image quality criterion for single-aperture telescopes, the simulated far-field image yields a FWHM of approximately 26.26 arcseconds, the experimental far-field image measures approximately 27.73 arcseconds, and the non-co-phased image shows a FWHM of approximately 124.15 arcseconds. The experimental co-phasing result thus differs significantly from the non-co-phased case and closely matches the simulation.

This study investigates co-phasing detection and control methods for piston errors between separated sub-mirrors in a Fizeau optical interferometric telescope. Through combined coarse and fine co-phasing approaches, all six off-axis sub-mirrors were successfully co-phased, refining the broadband spectrum fringe contrast co-phasing detection method. Results demonstrate that this method enables direct detection and correction of phasing piston errors between sub-mirrors.

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