Postprint: Research on Phase Detection Methods for Long-Baseline Stellar Optical Interferometry Based on Spatial Modulation

Authors: Wei Wei, Xu Teng, Hou Yonghui, Sun Yue

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Abstract

Within the atmospheric isoplanatic angle, simultaneous measurement of interference fringes from both the scientific target and the tracking target enables microarcsecond-level astrometric precision through precise determination of the optical path difference between the two fringe patterns. For high-precision astrometry with long-baseline stellar interferometry, we propose a phase measurement method based on spatial modulation that achieves synchronous phase shifting via polarization modulation, enabling phase-level optical path difference measurement, with further improvement in optical path difference detection precision attained through statistical averaging of multiple measurements. The feasibility of this phase detection method is demonstrated through numerical simulation and experimental validation, achieving a detection precision better than 1/18 wavelength and a statistical measurement precision of optical path difference better than 5 nm. Furthermore, error sources are analyzed through measurements of environmental disturbances, providing technical support for achieving the designated scientific objectives of China's under-construction hundred-meter-level long-baseline astronomical optical interferometric array.

Full Text

Research on Phase Detection Method for Long-Baseline Stellar Optical Interferometry Based on Spatial Modulation

WEI Wei^{1,2,3}, **XU Teng**^{1,2}, **HOU Yong-hui**^{1,2,3†}, **SUN Yue**^{1,2}

^{1}Nanjing Institute of Astronomical Optics & Technology, Chinese Academy of Sciences, Nanjing 210042

^{2}CAS Key Laboratory of Astronomical Optics & Technology, Nanjing Institute of Astronomical Optics & Technology, Nanjing 210042
^{3}University of Chinese Academy of Sciences, Beijing 100049

Abstract

Measuring the interference fringes of scientific and tracking targets simultaneously within the atmospheric isoplanatic angle enables micro-arcsecond-level astrometric precision through precise determination of the optical path difference between the two interference fringes. This paper proposes a phase measurement method based on spatial modulation for high-precision astrometry using long-baseline stellar optical interferometry. Synchronous phase shifting is achieved through polarization modulation, enabling phase-level optical path difference measurement, with further improvement in optical path difference detection accuracy obtained through multiple measurements and statistical averaging. Numerical simulations and experimental verification demonstrate the feasibility of this phase detection method, achieving detection accuracy better than 1/18 wavelength and statistical measurement precision of optical path difference better than 5 nm. Error sources are further analyzed through environmental disturbance measurements, providing technical support for achieving the scientific objectives of China's under-construction hundred-meter long-baseline astronomical optical interferometer array.

Keywords: instrumentation: interferometers, instrumentation: high angular resolution, techniques: interferometric, techniques: phase detection, methods: spatial modulation

1. Introduction

Long-baseline stellar optical interferometry represents a crucial pathway for achieving high-precision astrometry and imaging observations, with numerous long-baseline optical interferometer arrays emerging internationally since the 1970s [1—2]. However, China has not yet established a long-baseline optical interferometer array for astronomical observations. Drawing upon technical expertise accumulated since the 1980s [5—9], the Nanjing Institute of Astronomical Optics & Technology is constructing the first long-baseline astronomical optical interferometer array at the Xuyi Observatory Station of Purple Mountain Observatory, featuring a maximum baseline of 100 m to provide new observational methods for frontier astronomical research in China.

Phase detection technology determines the astrometric precision of long-baseline optical interferometer arrays and constitutes one of their core technologies. Atmospheric turbulence and instrumental vibrations introduce optical path difference disturbances that degrade measurement accuracy of terminal interference fringe contrast, typically requiring optical path difference disturbances to be less than 1/14 of the detection wavelength. Meanwhile, micro-arcsecond astrometric precision based on differential delay depends on the optical path separation between interference fringes from two target celestial bodies, imposing higher demands on optical path difference statistical measurement precision for long-baseline stellar interferometer arrays. The GRAVITY instrument at the European Southern Observatory's Very Large Telescope Interferometer (VLTI) can stabilize optical path difference on a 130 m baseline in the near-infrared band, achieving astrometric precision better than 10 as and optical path difference statistical measurement precision better than 5 nm [10−11].

This paper proposes a spatial modulation-based phase detection method for stellar optical interferometry for the upcoming 100-meter baseline long-baseline interferometer array at Nanjing Institute of Astronomical Optics & Technology, enabling phase tracking and high-precision optical path difference detection. This method employs polarization devices to introduce phase shifts and uses a four-step phase shifting algorithm to solve for phase information and convert it to optical path difference. Multiple measurement statistical averaging further improves optical path difference detection accuracy. The synchronous phase shifting strategy avoids phase shifting disturbances caused by displacement accuracy errors of moving components compared with traditional temporal phase shifting, increases optical path difference detection frequency, and facilitates phase tracking. This paper conducts simulation and experimental studies of the polarization modulation-based phase detection method, demonstrating a measured phase detection accuracy of 34.7 nm (approximately $\lambda/18$) in the visible band (@650 nm), with statistical averaging measurement precision better than 5 nm.

2. The 100-Meter Long-Baseline Optical Interferometer Array Under Construction

Long-baseline stellar optical interferometry technology is revealing detailed structures of celestial objects across different scales in the universe with unprecedented precision, advancing astronomical observation accuracy to the milli-arcsecond and even micro-arcsecond level. In 2020, German scientist Genzel confirmed the supermassive compact object at the center of the Milky Way using VLTI and was awarded the Nobel Prize, marking long-baseline stellar optical interferometry as an important technical means for frontier astronomical research. Supported by the National Natural Science Foundation of China's Major Research Instrumentation Project and the Ministry of Science and Technology's Key Research and Development Project, the Nanjing Institute of Astronomical Optics & Technology is constructing China's first long-baseline optical interferometer array for astronomical observations at the Xuyi Observatory Station of Purple Mountain Observatory. Comprising three 600 mm aperture telescopes with a maximum baseline of 100 m, the array will be used for high-resolution imaging at the milli-arcsecond level and high-precision astrometric research, with first light planned for the end of 2025. The three-dimensional design and current progress of this optical interferometer array are shown in [Figure 1: see original paper].

The 100-meter long-baseline optical interferometer array aims to achieve astrometric precision of 20 as and even 10 as, requiring phase tracking on three telescopes and statistical averaging processing to improve optical path difference (OPD) measurement precision to 5 nm.

3.1 Phase Detection Principle

Phase detection constitutes the most critical component in the fringe tracking system of long-baseline stellar optical interferometry, with precision requirements reaching 1/14 wavelength. Figure 2 illustrates the overall logic of phase detection, which typically requires a coarse tracking algorithm to lock the optical path difference between different telescopes within one wavelength. This paper focuses on how to identify optical path differences better than 1/14 wavelength using the spatial modulation-based phase detection method after completing coarse fringe tracking.

The synchronous phase shifting method is commonly used for optical surface measurement [12—13], simultaneously obtaining multiple phase-shifted interference patterns in the spatial domain through optical elements such as two-dimensional gratings [14] to achieve high-speed phase detection. Figure 3 [Figure 3: see original paper] demonstrates the principle of achieving phase detection in astronomical optical interferometry optical path difference detection based on spatial modulation. Two stellar beams achieve synchronous phase shifting in space through a 1/4 Fresnel prism, beam splitter, and polarizing beam splitter, obtaining four pupil-plane interference images A, B, C, and D, with intensity functions expressed as:

$$\begin{aligned} A(\lambda) &= I_s(\lambda)\{1+\nu(\lambda)\cos[\phi(\lambda)]\}; \\ B(\lambda) &= I_s(\lambda)\{1-\nu(\lambda)\sin[\phi(\lambda)]\}; \\ C(\lambda) &= I_s(\lambda)\{1-\nu(\lambda)\cos[\phi(\lambda)]\}; \\ D(\lambda) &= I_s(\lambda)\{1+\nu(\lambda)\sin[\phi(\lambda)]\}: \end{aligned} \tag{1}$$

where $I_s(\lambda)$ is the normalized spectral intensity at the detection center wavelength λ, and $\nu(\lambda)$ is the fringe contrast at wavelength λ. When the group delay optical path difference is locked, the actual optical path difference is within λ, meaning the phase difference $\phi(\lambda)$ is within 2π. According to the four-step phase shifting algorithm, the phase difference $\phi(\lambda)$ can be obtained:

$$\phi(\lambda) = \tan^{-1}\left[\frac{D(\lambda)-B(\lambda)}{A(\lambda)-C(\lambda)}\right]. \tag{2}$$

The phase difference $\phi(\lambda)$ can be converted to optical path difference according to wavelength λ. When phase detection is performed across multiple bands, the optical path difference detection results from each band can be numerically averaged to improve optical path difference OPD detection precision:

$$\mathrm{OPD} = \frac{\sum_{i=1}^{n}[\phi(\lambda_i)\frac{\lambda_i}{2\pi}]}{n}; \tag{3}$$

where n is the number of wavelengths participating in statistical averaging. Furthermore, the optical path difference obtained in equation (3) represents a single measurement result. Through multiple optical path difference measurements of scientific observation targets, detection precision can be further improved, thereby enhancing astrometric precision:

$$\mathrm{OPD} = \frac{\sum_{j=1}^{m}\mathrm{OPD}_j}{m}; \tag{4}$$

where m is the number of multiple measurements.

3.2 Numerical Simulation

Phase calculation through four-step phase shifting is an error-free measurement method under ideal conditions. In actual stellar optical interferometers, phase detection error sources mainly include phase shifting error, environmental disturbance, and image processing. Multiple phase detection bands were selected within the 600–900 nm band, and the feasibility and reliability of the phase detection method were further verified through numerical simulation according to equation (2).

The numerical simulation process follows the flow shown in [Figure 4: see original paper]. Phase shift error is added during the phase shifting process to solve for phase difference, which is converted to optical path difference according to the detection band wavelength. Optical path differences obtained from multiple detection bands are averaged as the detection result. Detection error is obtained by comparing the optical path difference detection result with the reference optical path difference, and statistical averaging measurement error is obtained through multiple measurement results.

During numerical simulation, phase detection error sources are comprehensively considered as phase shifting error. Based on laboratory test results, the system's phase shifting error is set to randomly appear within 3.6° (corresponding to a phase shifting error of 4 nm). First, according to the principle of beam superposition and reference optical path difference values, the four-step phase shifting expressions shown in equation (1) are obtained. Then phase values are solved according to equation (2), and this process is extended to multiple detection bands within 600–900 nm to obtain phase values corresponding to each detection band. Finally, phase is converted to optical path difference according to detection bands and processed through numerical averaging. [Figure 5: see original paper] shows the simulation results of optical path and phase detection using a reference optical path difference of 200 nm as an example.

The simulation results in Figure 5 show that the detection result averaged across multiple detection bands is 205.3 nm, with a deviation of 5.3 nm. The blue curve in Figure 5 indicates that 66.7% of single-band measurement errors (700–900 nm) are greater than 5.3 nm, demonstrating that multi-band averaging measurement can effectively reduce measurement error through just a single measurement.

Furthermore, [Figure 6: see original paper] presents numerical simulation results for reference optical path differences between 100–500 nm.

Numerical simulation results demonstrate that the proposed spatial modulation-based optical path difference detection method achieves root mean square (RMS) error better than 7 nm under 3.6° phase shifting error conditions, with precision better than 1/100 wavelength (@750 nm). After multiple measurement statistical averaging, optical path difference detection error is better than 0.4 nm. This method enables reliable high-precision detection of optical path differences within one wavelength (<600 nm), with statistical averaging measurement error better than 5 nm after multiple measurements, meeting the optical path difference detection precision required for micro-arcsecond-level astrometry.

4.1 Experimental Design

To further verify the feasibility of the phase detection method, an experimental optical path was constructed in the laboratory as shown in Figure 7, conducting spatial modulation-based phase detection experiments in the visible band using a narrowband laser source (@650 ± 5 nm). The spatial modulation phase detection optical path employs an amplitude-splitting method to divide collimated parallel light from a common beam splitter (Beam Splitter 1) into two beams simulating two stellar beams. A piezoelectric ceramic (PZT) and corner prism are used in one path to introduce optical path difference variations, with the corner prism serving as a retroreflector to ensure the beam does not pitch or yaw during forward and backward movement. The other beam undergoes polarization state modulation after passing through a 1/4 Fresnel prism. The two beams are split and recombined on a common beam splitter (Beam Splitter 2) after passing through a turning mirror group. The combined beams then pass through polarizing beam splitters (Polarized Beam Splitter 1 and 2) to form four phase-shifted interference combined beams, which are focused by lenses onto different regions of the camera.

The experiment verifies the precision of the phase detection method by comparing the four-step phase shifting optical path difference detection results with the input displacement of the PZT stage (which has been calibrated using a dual-frequency laser interferometer).

4.2 Experimental Results

Since visible light has a short wavelength and is susceptible to environmental disturbances, the experiment first measured laboratory environmental disturbances and system phase shifting errors as references. Under stable nighttime conditions, the system's phase shifting error RMS value was measured at 1.9°, and the disturbance caused by optical component support structure vibration and air flow was measured at 15 nm/s (RMS) using a dual-frequency laser interferometer. Under 1 kHz high-frequency optical path difference detection conditions, phase detection error caused by environmental disturbances is very small.

The experiment controlled the PZT stage to perform reciprocating motion exceeding the central wavelength of 650 nm to eliminate displacement errors during PZT stage reversal. [Figure 8: see original paper] presents the experimental results of phase detection. The normalized measurement results of four synchronous phase shifting channels at the central wavelength detection band (@650 nm) are shown in Figure 8(a). The solved phase according to equation (2) is shown in Figure 8(b). Three 2π jumps caused by PZT motion multiplied by the detection wavelength yield OPD. Comparing with the input PZT movement Ref yields the optical path difference detection error (Error) shown in Figure 8(c).

Experimental results demonstrate that the optical path difference measurement error using the proposed spatial modulation-based method achieves an RMS value of 34.7 nm, with measurement precision better than 1/18 wavelength at 650 nm central wavelength. After multiple measurements, statistical averaging measurement precision reaches 4.84 nm. These experiments verify that the spatial modulation-based phase detection method can achieve stable phase tracking under single detection conditions and high-precision optical path difference detection under multiple detection conditions, ensuring that the technical specifications of the 100-meter baseline telescope interferometer array at Xuyi Observatory Station meet design requirements.

5. Conclusion

This paper proposes a phase detection method based on spatial modulation, achieving spatial four-step phase shifting through polarization phase shifting devices, avoiding temporal phase shifting errors and increasing detection frequency. The feasibility and reliability of the method are verified through numerical simulations with random errors and indoor phase detection experiments at 650 nm wavelength. The measured optical path difference detection precision of this method is better than 1/18 wavelength, with statistical averaging measurement precision better than 4.84 nm. It is anticipated that under well-controlled environmental conditions, stable single-phase detection and multiple statistical averaging measurements of targets will enable the under-construction 100-meter baseline long-baseline optical interferometer array to achieve stable and high-precision phase tracking, with astrometric capability better than 10 as. This research establishes the technical foundation for the interferometer array to achieve its established scientific objectives.

Note: The original Chinese references have been omitted as they were not accompanied by English translations in the source material. The English title and abstract provided at the end of the original document have been incorporated into the main translation.

Note: Figure translations are in progress. See original paper for figures.

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