Postprint: Research on Optical Path Detection Methods for Optical Synthetic Aperture Telescopes

Authors: Liu Qing, Jiang Aimin

Date: 2017-09-26T00:00:00+00:00

Abstract

Optical interference technology necessitates precise compensation and control of optical path difference, rendering the accurate detection of optical path difference particularly critical. This discussion primarily focuses on the application of the dispersive fringe method in optical path difference detection. Through theoretical analysis, simulation calculations, and experimental validation, a linear relationship between the optical path difference within a wavelength range and the longitudinal shift of the light intensity peak of dispersive interference fringes is verified. Analysis of white-light dispersive interference fringe data obtained from experiments reveals certain deviations from theoretically predicted values. By analyzing the primary error sources within the experimental system, it is determined that pitch fluctuations introduced by the beam splitter prism during motion constitute the main cause of experimental errors.

Full Text

Research on Optical Path Detection Methods for Optical Synthetic Aperture Telescopes

Liu Qing[1,2,3], **Jiang Aimin**[1]
[1]National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
[2]Key Laboratory of Space Astronomy and Technology, Chinese Academy of Sciences, Beijing 100012, China
[3]University of Chinese Academy of Sciences, Beijing 100049, China
Email: liuqing@bao.ac.cn

Abstract

Optical interference technology requires precise compensation and control of optical path difference (OPD), making accurate OPD detection particularly crucial. This paper focuses on the application of dispersed fringe sensing (DFS) for OPD detection. Through theoretical analysis, simulation calculations, and experiments, we verify that a linear relationship exists between OPD within one wavelength range and the longitudinal intensity peak offset of dispersed interference fringes. Analysis of experimentally obtained white-light dispersed interference fringe data reveals certain deviations from theoretical predictions. By examining the major error sources in the experimental system, we find that pitch fluctuations introduced during the movement of the beam splitter prism constitute the primary cause of experimental errors.

Keywords: Optical interference; Dispersed fringe sensing; Optical path difference; Co-phasing

---

1. Introduction

Optical synthetic aperture technology, also known as optical interferometric imaging, combines multiple smaller optical elements or systems with precise alignment to achieve coherent superposition at the focal plane under specific phase-matching conditions. After image restoration processing, this technology attains diffraction-limited resolution equivalent to that of a single large-aperture system. The concept originated with Fizeau' s stellar interferometry proposed in 1868 for measuring stellar angular diameters. The first successful stellar interference fringe observation was achieved using a mask method in front of a telescope.

Several optical synthetic aperture experimental systems with segmented sub-telescopes have been established worldwide. In 2002, MIT demonstrated a space-based optical synthetic aperture ground prototype with a field of view of approximately $0.55''$. The ARGOS system, developed by Lockheed Martin, consists of 9 sub-apertures arranged in a Golay-3 configuration with an equivalent aperture of 0.62 m and a field of view of 1 μrad, achieving an angular resolution of $0.35''$ after co-phased interference–superior to that of individual sub-apertures. In China, Beijing Institute of Technology successfully developed a co-phasing detection and control platform in 2010, achieving closed-loop control of a segmented mirror imaging system to form interference fringes. The LAMOST telescope, with its 4-meter segmented primary mirror and 5.7-meter segmented Schmidt corrector plate, employs active optics technology but has only achieved co-focal imaging, with resolution still limited by individual segment aperture size. The National Astronomical Observatories conducted theoretical analysis and principle verification experiments for synthetic aperture imaging using two telescopes in 2010, while Shanghai Astronomical Observatory also performed synthetic aperture experiments using pyramid wavefront sensing, though without achieving co-phased imaging. Compared with international developments, China’ s astronomical interferometry technology requires further advancement.

Interference in optical synthetic aperture telescopes only occurs when all sub-apertures achieve co-phasing, enabling complex amplitude superposition rather than simple intensity addition. Precise detection of OPD between beams is therefore essential for realizing optical interference. Various OPD detection methods have been developed internationally, including: (1) curvature sensing, which reconstructs OPD errors by measuring phase discontinuities at segment edges; (2) phase retrieval methods that solve pupil phase distribution from focal and defocused intensity data; (3) broadband and narrowband Hartmann-Shack methods proposed by Gary Chanan; (4) out-of-pupil detection that calculates OPD errors through correlation coefficients between sampled aperture diffraction patterns and template patterns; and (5) dispersed fringe sensing (DFS) used in the James Webb Space Telescope, which determines OPD errors by processing dispersed interference fringes between adjacent sub-apertures.

The National Astronomical Observatories undertook the task of developing a prototype sparse aperture imaging system and comprehensive data processing technology under the National High-Tech Research and Development Program. This study investigates OPD detection methods theoretically and experimentally, focusing on dispersed fringe sensing for detecting OPD within one wavelength range.

2. Theoretical Analysis and Simulation

2.1 Dispersed Fringe Sensing Principle

The intensity distribution of interference patterns formed by two circular apertures at the telescope focal plane after dispersion along the x-direction by an Amici prism is given by:

$$I(x(\lambda), y) = 2I_0 \left[1 + \cos\left(\frac{2\pi d}{\lambda f} y + \phi\right)\right] \cdot \left[\frac{2J_1\left(\frac{\pi a r}{\lambda f}\right)}{\frac{\pi a r}{\lambda f}}\right]^2$$

where I_0 represents the signal light intensity, x and y are horizontal and vertical coordinates respectively, a is the circular aperture radius, f is the telescope focal length, d is the baseline length, $x(\lambda)$ is the wavelength dispersed along the x-direction, and ϕ is the OPD between the two circular apertures.

[Figure 1: see original paper] shows a schematic diagram of the two circular apertures in the OPD detection section of a Fizeau-type interferometric system, with parameters: aperture radius $a = 10$ mm, baseline length $d = 40$ mm, and focal length $f = 1680$ mm.

2.2 Single-Wavelength Interference Analysis

First considering single-wavelength interference, the longitudinal intensity distribution is:

$$I_f(y) = 2I_0\left[1 + \cos\left(\frac{2\pi d}{\lambda f}y + \phi\right)\right]$$

The relationship between the independent variable OPD (ϕ) and the dependent variable peak offset (y) is:

$$y = \frac{\lambda f}{2\pi d}\arccos\left(\frac{I_f(y)}{I_{\text{peak}}} - 1\right) - \frac{\lambda f}{2\pi d}\phi$$

Numerical simulations were performed for three single-wavelength interference fringes at $\lambda = 500$ nm, 600 nm, and 700 nm, with OPD ϕ varying within one wavelength range. The sampling interval for OPD was 10 nm. The linear correlation coefficient r is defined as:

$$r_{xy} = \frac{l_{xy}}{\sqrt{l_{xx}l_{yy}}}$$

where $l_{xx} = \sum_{i=1}^{n}(x_i - \bar{x})^2$, $l_{xy} = \sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})$, and $l_{yy} = \sum_{i=1}^{n}(y_i - \bar{y})^2$.

Under all three single-wavelength conditions, the calculated slope $K \approx -39.51$ and the linear correlation coefficient r exceeds 99.99%, confirming that for monochromatic light interference, OPD within one wavelength range satisfies a linear relationship with y.

2.3 Multi-Wavelength Dispersed Fringe Analysis

For multi-wavelength dispersed interference fringes, assuming a linear dispersion relationship $x(\lambda) = 2 \times 10^{-6} \cdot (\lambda - 650 \times 10^{-9})$ m, simulations were conducted with OPD varying from -250 nm to $+250$ nm and wavelength range of 600–700 nm. Linear fitting yielded a slope $K \approx -39.37$ (/piston) with linear correlation coefficient $r \approx 99.9999\%$. The slope is essentially consistent with the single-wavelength case, demonstrating that multi-wavelength dispersed interference fringes also exhibit a linear relationship between longitudinal intensity peak position y and OPD.

[Figure 2: see original paper] shows the relationship between peak offset and OPD for single-wavelength interference, while [Figure 3: see original paper] displays the corresponding relationship for multi-wavelength interference.

3. Experimental Setup and Data Processing

3.1 Experimental System

The experimental system comprises a light source telescope and a combining imaging telescope. The light source is an NKT supercontinuum laser with 100 nm spectral width. Beam splitter prism S_1 remains fixed while S_2 is mounted on a linear motion stage (LPS-45) to vary OPD. An Amici prism provides dispersion, and a CMOS camera (2048 × 1088 pixels) captures the interference patterns under computer control.

[Figure 4: see original paper] shows a photograph of the laboratory system, and [Figure 5: see original paper] illustrates the optical path diagram. [Figure 6: see original paper] displays the zero-OPD interference fringe pattern acquired experimentally.

3.2 Data Processing Method

Based on the simulation results showing linear correlation between y and OPD, dispersed interference fringes were acquired at different OPD values ranging from -250 nm to $+250$ nm in 10 nm increments. To reduce errors, n groups of longitudinal intensity profiles perpendicular to the dispersion direction were extracted from each interference fringe and fitted to determine the peak position offset y_i. The mean value $\bar{y}$ was then calculated.

[Figure 7: see original paper] presents experimental fitting results for one set of interference fringes, showing the relationship between longitudinal intensity peak offset $\bar{y}$ and OPD. Linear fitting yields a slope $K = -50.74$ and linear correlation coefficient $r = 99.81\%$.

4. Error Analysis

4.1 Comparison with Simulation Results

The experimental slope shows significant deviation from the simulated value. A systematic analysis of major error sources was conducted.

4.2 Influence of System Parameters

A multi-wavelength dispersed interference model was established in MATLAB to analyze how variations in key design parameters affect the fitted slope K. With wavelength range 600–700 nm:

- Circular aperture radius a variation of $±$1 mm causes slope change of approximately $±$0.5
- Imaging telescope focal length f variation of $±$100 mm causes slope change of approximately $±$1
- Baseline length d variation of $±$1 mm causes slope change of approximately $±$2

These results indicate that variations in these system parameters have relatively minor influence on the slope and are not the primary cause of experimental deviation.

and detail the specific influence of parameter combinations on K.

4.3 Influence of Source Spectral Curve

White light source spectral curves show intensity variations across wavelengths. Two spectral distributions were simulated: (1) uniform random allocation of intensity across wavelengths, and (2) wavelength-dependent intensity distribution. Simulation results in [Figure 8: see original paper] demonstrate that both cases yield identical slope values ($K = -39.37$) and linear correlation coefficients ($r = 99.9999\%$) as the uniform intensity case, confirming that spectral curve shape is not responsible for slope variation.

4.4 Influence of Angular Disturbances During Prism Motion

The piezoelectric linear stage (LPS-45) moving beam splitter prism S_2 has maximum travel of 13 mm ($±$6.5 mm), bidirectional repeatability of $±$18 nm, minimum incremental motion of 6 nm, and pitch/yaw specifications of $±$50 μrad. Pitch disturbances cause vertical fringe shifts, while yaw disturbances cause horizontal shifts.

Simulations of beam misalignment show: - Horizontal misalignment (X_{shift}) of $±$4 μm causes maximum peak offset difference of only ~0.1 nm, indicating minimal impact - Vertical misalignment (Y_{shift}) of $±$4 μm causes maximum peak offset difference of ~126 nm, indicating significant impact

When both beams are vertically misaligned by Y_{shift} ranging from -4 μm to $+4$ μm, the slope K varies dramatically from -27.20 to -51.45. This pitch-induced vertical fringe misalignment is identified as the primary cause of deviation between experimental and simulation results.

summarizes the slope K values under various vertical misalignment conditions.

5. Conclusion

This paper presents the method and experimental results of using dispersed fringe sensing for optical path difference detection. Numerical calculations demonstrate an excellent linear relationship between OPD within one wavelength range and the longitudinal intensity peak offset of dispersed interference fringes. An experimental optical system was constructed to verify this relationship by controlling beam splitter prism motion to vary OPD between two beams. Data processing of the acquired interference fringes yielded slope values showing significant deviation from simulation results.

Comprehensive error analysis was performed on major system parameters, source spectral curves, and angular disturbances introduced during prism motion. The results indicate that pitch angle errors during prism movement, causing vertical fringe offsets, are the primary reason for the substantial deviation between experimental and simulated slope values. Future work will address this issue through system calibration using a dual-frequency laser displacement interferometer to precisely measure prism position, enabling calibration of the slope K for accurate OPD determination via $piston = y/K$.

References

[?] Chung S J, Miller D W, Weck O L D. ARGOS testbed: a study of multidisciplinary challenges of future spaceborne interferometric arrays. *Optical Engineering*, 2002, 2156-2167.

[?] Kendrick R L, Aubrun J N, Bell R, et al. Wide-field Fizeau imaging telescope: experimental results. *Applied Optics*, 2002, 4235-4240.

[?] Research on error detection method based on dispersed Rayleigh interference principle. Beijing: Beijing Institute of Technology, 2010.

[?] Chanan G A, Troy M. Phasing the Keck Telescope using out-of-focus images in the infrared. *Proceedings of SPIE*, 1998, 632-642.

[?] Redding D C, Basinger S A, Cohen D, et al. Wavefront control for a segmented deployable space telescope. *Proceedings of SPIE*, 2000, 546-558.

[?] Esposito S, Devaney N. Segmented telescopes co-phasing using Pyramid Sensor: a comparison of different techniques. *ESO Conference and Workshop Proceedings*. Germany: European Southern Observatory, 2002.

[?] Fang S, King B M, Sigrist N, et al. Phasing the primary mirror segments of the Keck telescopes. *Proceedings of SPIE*, 2002, 188-202.

[?] Matthaeus W M, et al. NIRCam long wavelength channel grisms as the dispersed fringe sensor for JWST segment mirror coarse phasing. *Space Telescopes and Instrumentation 2008: Optical, Infrared, and Millimeter. Proceedings of SPIE*, 2008.

[?] Mathematics Handbook Editorial Group. *Mathematics Handbook*. Beijing: Higher Education Press, 836-840.

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