Postprint: Simulation of Absolute Flatness Testing Based on the Two-Flat Mutual Inspection Method

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Abstract

The utilization of large-aperture planar optical elements is becoming increasingly widespread; however, their measurement precision is constrained by the surface figure error of the reference surface in large-aperture interferometers. To resolve this issue, a dual-plate mutual calibration method is adopted to calibrate the absolute surface figure error of the interferometer reference surface, thereby eliminating the influence of reference surface figure error during measurement. The dual-plate mutual calibration method offers the advantage of requiring only two plates, and during the measurement process, there is no need to repeatedly interchange the interferometer reference surface, rendering it more suitable for absolute testing of large-aperture optical flats. Simulations are performed on the mathematical model of the dual-plate mutual calibration method for optical flat testing to validate the method' s correctness, and error analysis of the experimental process is conducted through simulation. This research addresses the current bottleneck where interferometric measurement accuracy is limited by reference flat precision, while simultaneously providing technical support for the calibration of reference flat errors in future ultra-large-aperture (aperture greater than lm) planar interferometers.

Full Text

Preamble

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Simulation of Absolute Flatness Measurement Based on the Two Flats Test

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Abstract

Large-aperture optical flats are increasingly used in major optical systems, but their measurement accuracy is fundamentally limited by the surface figure error of the interferometer' s reference flat. To overcome this limitation, the Two Flats Test method calibrates the absolute surface figure error of the interferometer reference flat, thereby eliminating its influence during subsequent measurements. The primary advantage of this method lies in its requirement of only two optical flats and the elimination of repeated reference flat exchanges during measurement, making it particularly suitable for absolute testing of large-aperture optical surfaces. This paper presents a mathematical simulation of the Two Flats Test to validate its correctness and analyzes potential experimental errors through modeling. This research addresses the current bottleneck where interferometric testing precision is constrained by reference flat accuracy, while providing technical support for future calibration of reference flats in ultra-large aperture (aperture >) interferometers.

Keywords: optical measurement; absolute test; two flats test; mathematical simulation

Introduction

Large-aperture optical flats serve as core components in major optical systems such as the National Ignition Facility (NIF), the Large Sky Area Multi-Object Fiber Spectroscopy Telescope (LAMOST, also known as the Guo Shoujing Telescope), and laser Inertial Confinement Fusion (ICF) systems. For instance, LAMOST' s Schmidt corrector mirror consists of 24 hexagonal segmented mirrors, while NIF' s high-power laser system employs numerous large-aperture planar optical elements. The surface figure quality of these components directly determines the imaging performance of their respective optical systems, creating a critical need for high-precision measurement techniques for large-aperture planar surfaces.

Interferometric testing represents the most precise method for optical surface characterization, with the Fizeau interferometer being the standard instrument for such measurements. However, high-precision planar surface measurement is fundamentally limited by the accuracy of the interferometer' s reference flat. Traditional approaches require an even higher-precision reference surface, creating a recursive challenge. To achieve high-precision measurement of optical flats, the reference surface error must be eliminated from measurement results, necessitating absolute calibration of the interferometer' s reference flat.

Various absolute testing methods have been developed internationally, each with limitations for large-aperture applications. The liquid surface method, proposed by Rayleigh, is susceptible to environmental disturbances such as vibration and temperature fluctuations. The three-flat test method, introduced by Schulz and Schwider, requires testing along diameter lines and demands repeated reference flat exchanges. Zernike polynomial fitting approaches work well for large flats dominated by low-frequency errors but involve complex rotational operations. Rotational shear methods, building upon the even-odd function technique, also require multiple flat rotations and exchanges, increasing measurement risk and complexity for large components.

The Two Flats Test method offers significant advantages: it requires only two optical flats, eliminates repeated reference flat exchanges, reduces measurement risk, saves time, and demonstrates strong operability. This paper provides mathematical validation of the Two Flats Test through simulation and conducts comprehensive error analysis to establish a theoretical foundation for high-precision measurement of large-aperture optical flats.

Principle of the Two Flats Test

The Two Flats Test involves four measurement configurations. Flat A is positioned as the interferometer' s reference surface, while Flats B and C serve as test surfaces. The measurement sequence proceeds as follows:

1. **Configuration 1:** Flat A' s rear surface interferes with Flat B' s front surface
2. **Configuration 2:** Flat A' s rear surface interferes with Flat C' s front surface
3. **Configuration 3:** Flat C is flipped about the x-axis and rotated counterclockwise by angle about the z-axis, then interferes with Flat A
4. **Configuration 4:** Flat C (in the same flipped and rotated orientation) interferes with Flat B

Any two-dimensional function can be decomposed into rotationally invariant and rotationally dependent components. By leveraging the rotational invariance properties of specific Zernike polynomial terms, the absolute surface figure of Flat A can be determined while eliminating alignment errors. [Figure 1: see original paper] illustrates these four measurement configurations.

Simulation of the Two Flats Test

Simulation Methodology

This simulation validates the Two Flats Test principle and analyzes experimental errors, including rotation alignment error and translation alignment error. The analysis quantifies their impact on results and establishes tolerance limits for achieving required measurement precision.

The simulation follows a closed-loop approach:
1. Generate random surface figure matrices for Flats A, B, and C with errors within typical interferometer detection ranges
2. Simulate the four interference measurements M_1, M_2, M_3, M_4 using the Two Flats Test equations
3. Apply the Two Flats Test algorithm to reconstruct the surface figures
4. Compare reconstructed surfaces with original inputs to validate accuracy

The simulation uses actual surface data from a Zygo Fizeau interferometer measurement as the basis for Flats A, B, and C. [Figure 2: see original paper] shows the surface figures of the three given flats. Matrix operations simulate Flat C’ s flipping and rotation, with refractive index $n = 1.5$ and rotation angle $= 54°$. Non-uniformity errors are assumed ideal ($\delta = 0$). [Figure 3: see original paper] displays Flat C’ s surface after flipping and rotation.

Using these parameters, the four interference measurement matrices M_1 through M_4 are calculated. [Figure 4: see original paper] presents the resulting interference patterns.

Reconstruction Process

The reconstruction involves two main steps:
1. Decompose the known measurement matrices M_1-M_4 into Zernike coefficients, separating rotationally invariant terms (Zernike terms 1, 4, 9, 16, 25, 36) from rotationally dependent terms
2. Apply the Two Flats Test algorithm to calculate the surface figures of Flats A, B, and C

[Figure 5: see original paper] shows the reconstructed surface figures of Flats A, B, and C computed using the Two Flats Test method.

Results Analysis

Subtracting the reconstructed surfaces from the original surfaces reveals the fitting accuracy. The difference images show minimal color variation, indicating excellent agreement between reconstructed and original surface figures at every point. [Figure 6: see original paper] presents these subtraction images.

Quantitative analysis uses the RMS values of the subtraction matrices. lists the RMS values for Flats A, B, and C:

Table 1 RMS Values of Subtraction Matrices for Surfaces A, B, and C (RMS)

Surface	RMS Value
A	2.0418e-34
B	4.6895e-34
C	1.0995e-33

These theoretical values are extremely small, demonstrating that the fitting error is negligible for engineering applications. The error magnitude (10^{-33}) arises from MATLAB’ s computational precision—trigonometric functions used in Flat C’ s rotation are calculated with limited decimal precision (default 16 digits), not from fundamental principle errors. This confirms the correctness of the Two Flats Test method.

Impact of Zernike Polynomial Terms

Most interferometers use the first 36 Zernike polynomial terms for fitting. The optimal number of terms depends on the detector’ s sampling points. With a 1024$×$1024 matrix, too few terms lose high-frequency information, while too many terms increase computation time without improving fit quality.

The simulation analyzes RMS and Peak-to-Valley (PV) values as functions of Zernike term count. [Figure 7: see original paper] shows RMS variation, and [Figure 8: see original paper] shows PV20 variation. Both stabilize when using more than 34-36 terms. provides detailed RMS and PV values for different term counts.

Table 2 RMS (λ) and PV (λ) of Simulated Surfaces A, B, C Relative to Original Surfaces Using Different Zernike Term Counts

Terms	RMS (λ)	PV (λ)
6	0.0037	0.5187
12	0.0040	0.5062
18	0.0158	0.3767
24	0.4799	0.8092
30	0.1881	0.3529
34	0.1254	0.2412
36	0.0000	0.6862

The data show that RMS decreases and PV increases with more terms, indicating better representation of high-frequency information. For experimental simulation, using the first 36 Zernike terms provides optimal results.

Error Analysis

The Two Flats Test' s advantage lies in manipulating only one flat (Flat C), making error control easier than traditional three-flat methods. This section analyzes primary error sources using controlled variable methods.

Rotation Alignment Error

Ideal conditions require perfect rotational alignment about the center for each test. In practice, rotation angle errors are inevitable. Since Flat C' s surface figure error propagates directly to Flat A's calculation, rotation errors significantly impact results.

Simulations analyze rotation angle deviations from -2° to +2° in 0.5° increments, with nominal rotation at 54°. [Figure 9: see original paper] shows theoretical Flat A, error-containing Flat A, and their difference. [Figure 10: see original paper] plots RMS versus rotation error.

Key findings:
- Larger absolute rotation errors produce greater surface figure errors
- Error sign determines whether the error appears convex or concave relative to the original
- At $±0.5°*deviation*, *RMSdifferenceislessthan*10^{-6}$ λ
- At $±$2° deviation, RMS reaches 0.0197 λ compared to original 0.0193 λ—a difference of 10^{-4} λ

For high-precision measurements, even small RMS differences are significant. The method requires rotation control better than $±$0.5°.

Translation Alignment Error

The experimental configuration keeps the interferometer's reference flat (Flat A) stationary while moving Flat C. Translation misalignment between flats introduces measurement errors. Since the flats are rotationally symmetric, analysis focuses on y-axis translation errors.

Simulations examine y-axis offsets of 1 mm, 2 mm, 3 mm, 4 mm, and 5 mm for a 900 mm diameter flat (corresponding to 2 mm, 4 mm, 6 mm, 8 mm, and 10 mm offsets). [Figure 11: see original paper] shows surface errors for various rotation angles with translation error. [Figure 12: see original paper] displays surface figures at 4 mm translation error. quantifies RMS errors for different translation values.

Table 3 RMS of Surface Figure Errors for Flats A, B, and C at Different Translation Errors

y-axis Translation Error (mm)	Flat A RMS (λ)	Flat B RMS (λ)	Flat C RMS (λ)
1	0.0024	0.0113	0.4408
2	0.0016	0.0069	0.0824
3	0.0010	0.0039	0.0210
4	0.0006	0.0020	0.0052
5	0.0003	0.0009	0.0011

Key findings:
- Translation error impact increases with misalignment magnitude
- Flat C is most sensitive, followed by Flat B; Flat A is least affected
- At 4 mm translation error (0.4% of aperture), Flat A' s RMS remains below 10^{-3} λ

This characteristic is beneficial for calibrating the interferometer' s reference flat (Flat A), as it remains robust against translation misalignment.

Conclusion

This study validates the Two Flats Test method for absolute flatness measurement through mathematical simulation, demonstrating complete consistency between reconstructed and original surface data. The analysis of Zernike polynomial term count, rotation alignment error, and translation alignment error establishes practical tolerance limits for experimental implementation.

The research provides a theoretical foundation for high-precision measurement of large-aperture optical flats and technical support for developing ultra-large aperture interferometers and their reference flat calibration systems.

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