3D Surface Reconstruction from Optical Flat Measurements

Ahmad Shakleya

Bachelor's thesis
Bachelor of Science in de industriële wetenschappen: elektronica-ICT

Supervisor
prof. dr. ing. J. Steckel, Cosys, UAntwerpen

Cosupervisor
ing. A. Aerts, Service Group Materials, UAntwerpen

University of Antwerp
Faculty of Applied Engineering

Contents

1. Preamble

blabla

2. Abstract

This bachelor thesis examines the 3D surface reconstruction from optical flat measurements. The goal of this research is to make a program that takes as input a photo with an optical flat measurement on it and then approximates the 3D surface using the interference fringes displayed on the photo.

3. Introduction

Optical flats are precision devices used in the field of material science to measure the flatness of surfaces or to create precisely flat surfaces. An optical flat is typically a high-quality, polished, flat glass or quartz disc used in conjunction with monochromatic light to form interference fringes that can be observed and measured to assess surface flatness or quality.[1] [1, 2, 3, 4]

.

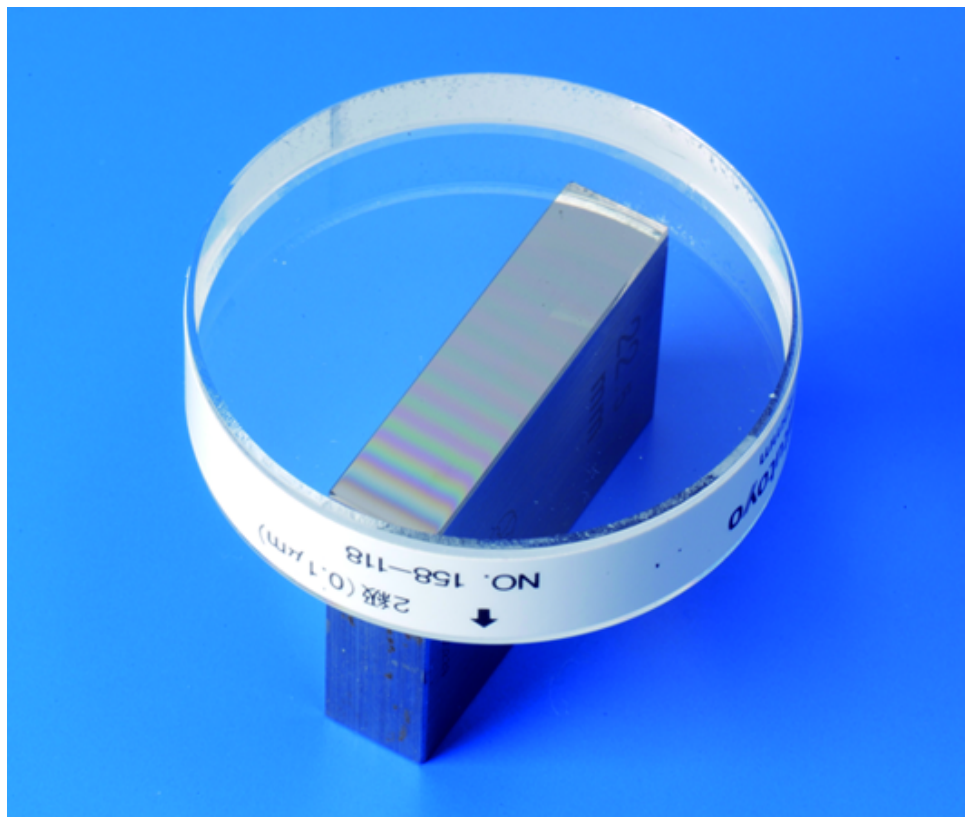Figure 3.1.: Example of an optical flat [5]

3.1. Physical Characteristics

3.1.1. Material Composition

Optical flats are predominantly made from two types of materials: fused silica and ultra-low expansion (ULE) glass. Fused silica, known for its exceptional optical clarity and thermal stability, is ideal for

---

[1]Optical flats should be handled with great precaution as they are very fragile.

precision measurement tools. It has a very low coefficient of thermal expansion, which means it remains stable under varying temperatures, thereby minimizing measurement errors due to thermal variations.[6]
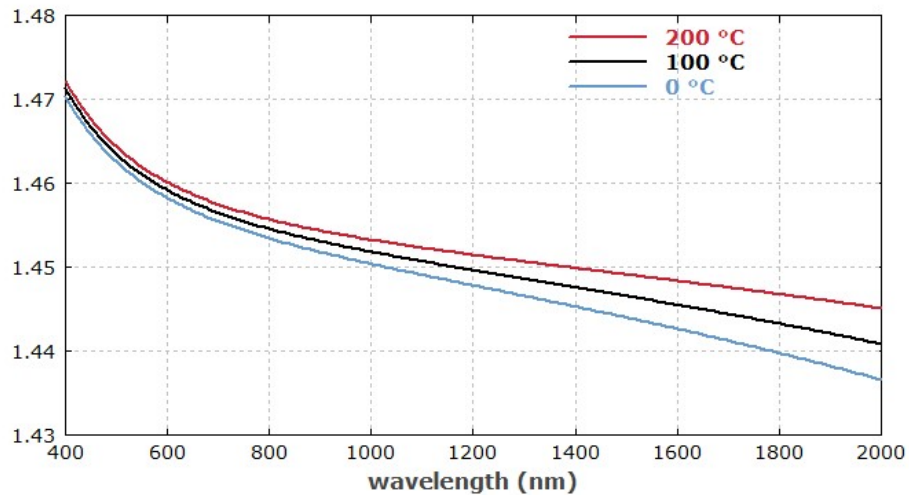

Figure 3.2.: The refractive index of fused silica versus wavelength at three different temperatures.[6]

Ultra-low expansion glass, such as Corning's ULE glass, is another favored material. This glass type is engineered to have extremely low thermal expansion rates, which are crucial in maintaining the accuracy of measurements in environments with fluctuating temperatures. ULE glass's robustness and resistance to thermal stress make it particularly suitable for high-precision optical applications, including astronomy and semiconductor manufacturing.[7]

Both materials are chosen not only for their minimal thermal properties but also for their ability to be polished to high optical qualities, ensuring that the optical flat does not introduce aberrations or distortions in the interference patterns used for surface measurements.[7, 6, 8]

3.1.2. Surface Quality

The surface of an optical flat is meticulously polished to achieve a high degree of flatness, typically within fractions of a wavelength of light ($\lambda/20$ or better). This extreme flatness is crucial for the accuracy of optical measurements. Any imperfections on the surface can distort the interference fringes, leading directly to measurement errors.[9]

After the initial polishing phases, optical flats may undergo additional processing steps such as the application of dielectric coatings. These enhancements are critical when the optical flats are used as reference mirrors in precision instruments like the Twyman–Green interferometer, where the utmost flatness is crucial.[4]

The final quality of optical flats is often verified in an interferometric setup, where they are compared against a reference surface that is of even higher precision. Occasionally, these reference surfaces may utilize fluids like mercury to achieve near-perfect flatness levels, although such materials are challenging to handle and maintain.[4]

3.2. Working Principle

The principle behind optical flats relies on the optical phenomenon of interference. This section delves into how interference fringes are formed, their types, and their importance in measuring surface characteristics.

3.2.1. Interference Fringes

Interference fringes are the result of the wave nature of light. When monochromatic light—light of a single wavelength—is used to illuminate the interface between an optical flat and another surface, variations in the gap created by surface irregularities cause the waves of light to overlap and interfere with each other. This interference can constructively or destructively affect the light waves, resulting in a pattern of dark and light bands known as interference fringes, which can be observed and analyzed.

3.2.1.1. Formation of Fringes
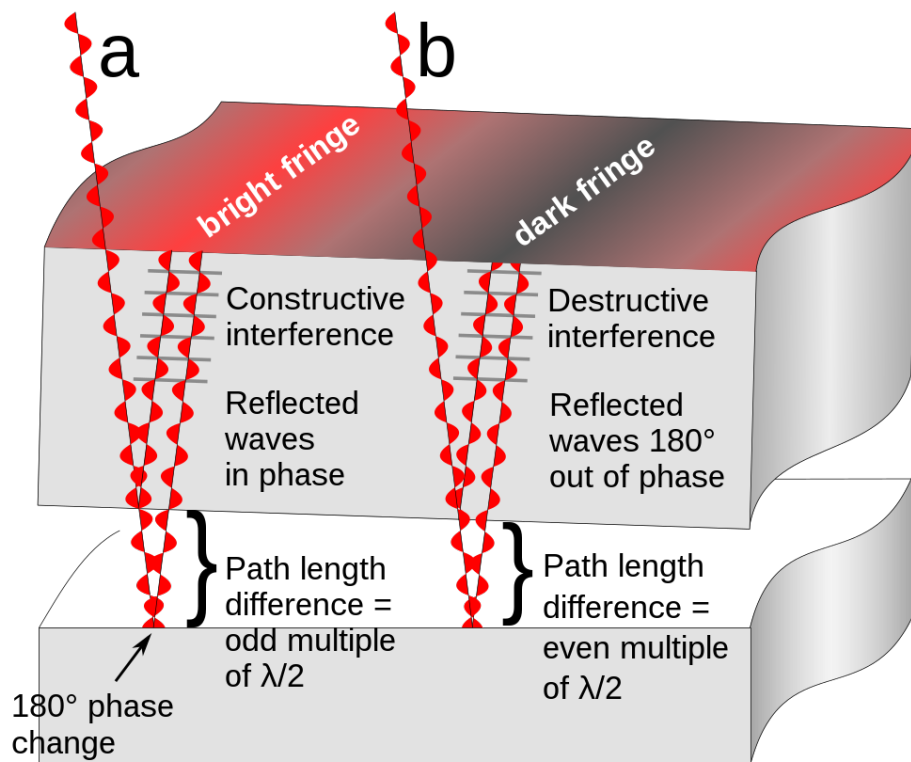
Figure 3.3.: Formation of interference fringes due to the superposition of light waves.[9]

Consider a setup where an optical flat is placed upon a surface to be tested under a monochromatic light source (figure 3.3). The light waves reflect off both the bottom surface of the optical flat and the top surface of the test object. Due to differences in the path traveled by the light waves—owing to variations in the gap between the two surfaces—these waves will interfere when they recombine. The condition for constructive and destructive interference is given by the equations:

$$2d\cos(\theta) = m\lambda, \quad \text{(constructive interference)} \tag{3.1}$$

$$2d\cos(\theta) = (m + \frac{1}{2})\lambda, \quad \text{(destructive interference)} \tag{3.2}$$

where:

- d is the gap distance between the optical flat and the test surface,

- θ is the angle of incidence of the light,

- m is an integer representing the order of the fringe,

- λ is the wavelength of the light used.

When we dive in deeper on the waves we can see the following: constructive interference occurs when the path difference between the two waves is an integer multiple of the wavelength. Superposition of the waves result in bright fringes.[9]

.

Constructive Interference Waves

Resultant Wave (Bright fringe)
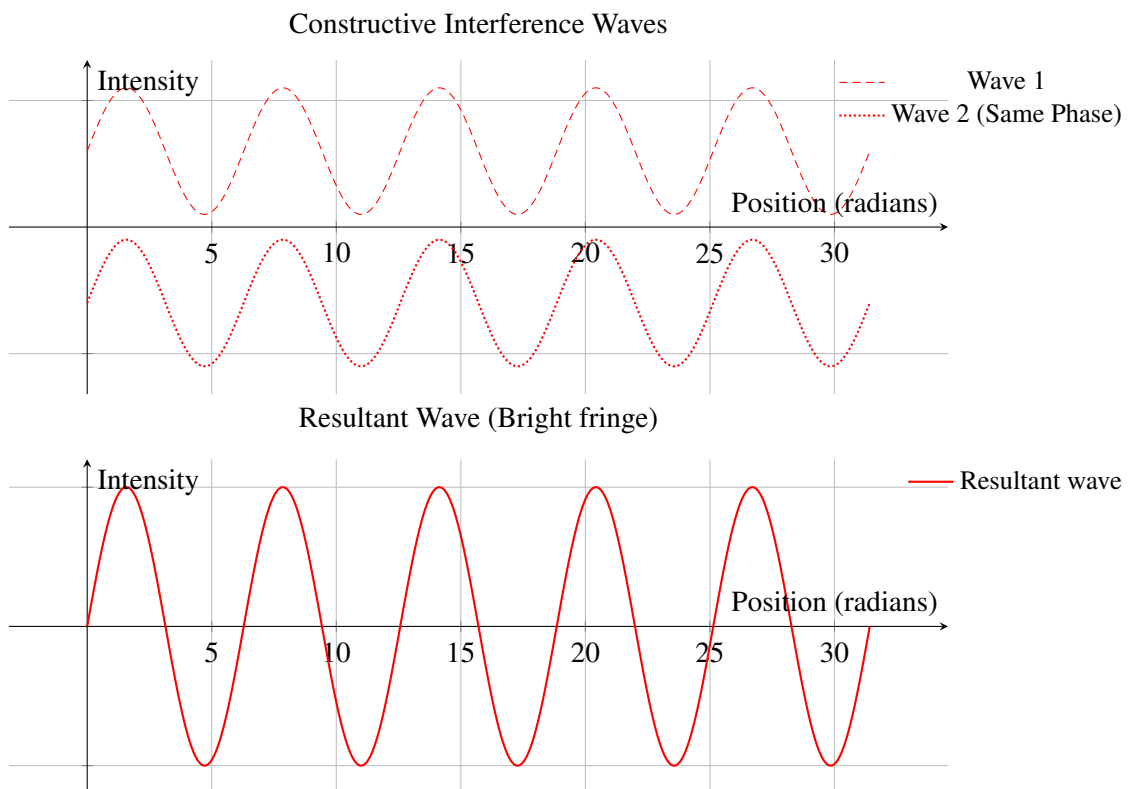
Destructive interference, on the other hand, occurs when the path difference is a half-integer multiple of the wavelength, resulting in dark fringes.[9]

.

Destructive Interference Waves

Resultant Wave (Black fringe)
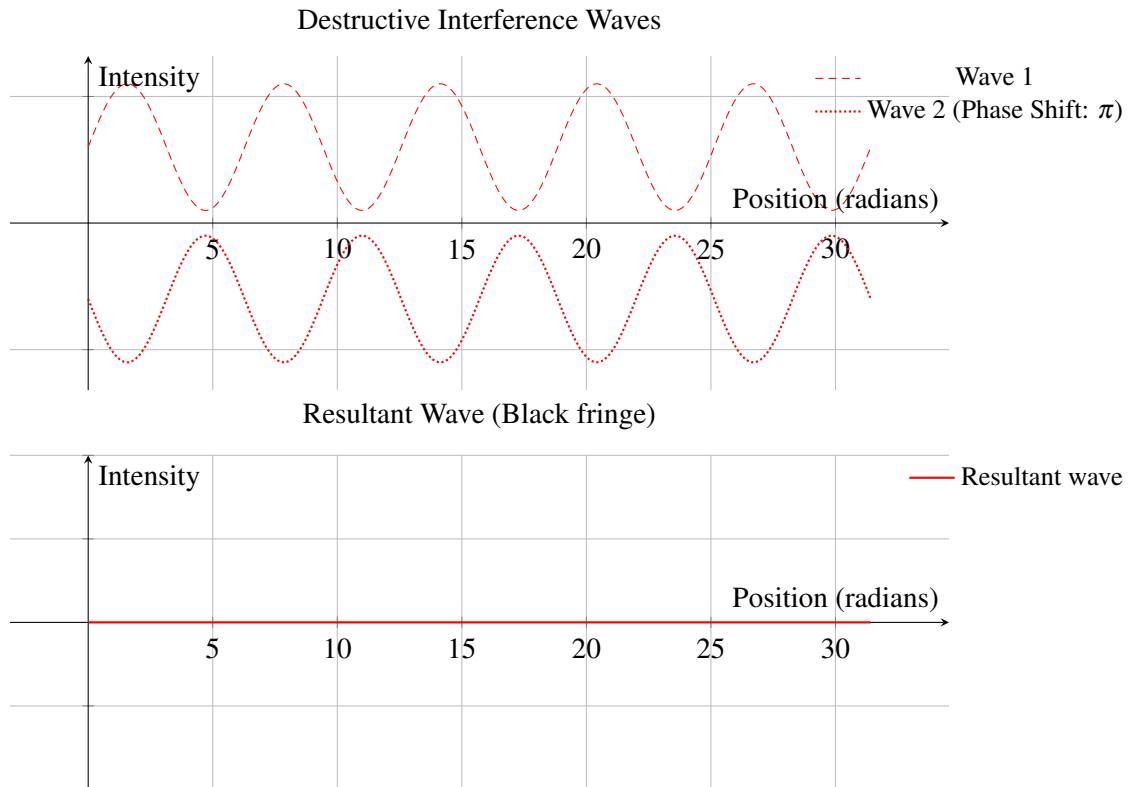
3.2.1.2. Analysis of Fringe Patterns

The pattern of the fringes provides information about the surface's properties:

- **Straight Fringes** indicate that the test surface is precisely flat. In this scenario, the gap d is constant, leading to uniformly spaced fringes.

- **Curved Fringes** suggest that the surface is spherical or cylindrical. The curvature of the fringes gives clues about the curvature of the surface itself.

- **Irregular Fringes** are indicative of surface defects, bumps, or dips. The irregularity in spacing or the fringe shape can be analyzed to quantify the nature of the surface flaws.
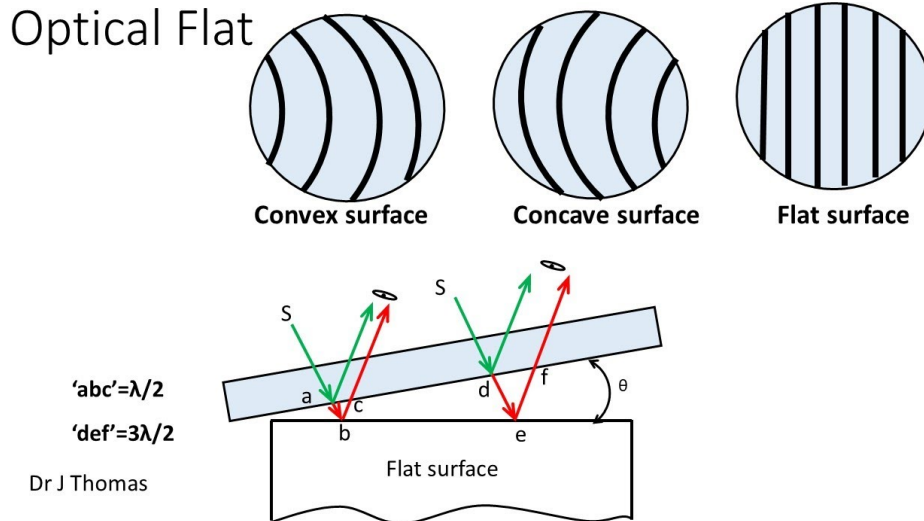
.

Figure 3.4.: Different types of interference fringe patterns and what they indicate about surface characteristics.[10]

3.3. Innovations in Optical Flat Technology

Recent advancements have expanded the traditional concept of optical flats to include plasmonic optical flats, which utilize nanostructured plasmonic surfaces. This innovation stems from the field of plasmonics, where the manipulation of light at the nanoscale allows for extreme localization and sensitivity to environmental changes. Plasmonic optical flats, comprised of nanostructured metal arrays, significantly enhance the sensitivity and resolution of surface inspections beyond the diffraction limit of light. These new optical flats are particularly effective in detecting sub-wavelength surface anomalies and offer the potential for rapid and precise surface inspection using simple, low-cost equipment.

3.3.1. Advancements in Metrology: Phase Measuring Deflectometry

A novel approach in the measurement of optical flats involves Phase Measuring Deflectometry (PMD), which offers a flexible and cost-effective alternative to interferometry. PMD uses a triangulation method involving a pinhole camera and LCD display to generate sinusoidal fringes, which are reflected by the flat surface. Distortions in these fringes are then captured and analyzed to determine the surface's figure. This technique is particularly advantageous for measuring surfaces where high slopes at edges or environmental sensitivities present challenges to traditional methods. The integration of PMD into optical flat metrology represents a significant shift towards more dynamic and accessible measurement technologies.

3.4. Applications

Optical flats are used in a variety of settings, including:

- Calibration of optical components

- Inspection of machined parts for flatness

- High-precision alignment of optical systems

- Establishing the flatness in critical engineering applications

- Enhancing the capabilities of traditional optical flats with plasmonic technology for ultra-high precision measurements.

3.5. Conclusion

Optical flats remain indispensable tools in optical research and high-precision manufacturing. Their ability to provide highly accurate measurements of flatness and surface quality ensures the reliability and effectiveness of optical components across various applications. The integration of plasmonic enhancements and advanced metrology techniques like Phase Measuring Deflectometry opens new avenues for advancements in optical measurement technologies, pushing the boundaries of what can be achieved in terms of resolution and accuracy.

4. Research Questions

4.1. Overview of Research Questions

This chapter outlines several key research questions that guide the investigation into the properties, simulation, and applications of optical flats. These questions are designed to explore both fundamental aspects and practical implementations.

4.2. What is an Optical Flat?

Understanding the fundamental nature and characteristics of optical flats is crucial. This involves examining their material composition, surface quality, and the precision standards they meet in optical testing and engineering applications.

4.3. How Can We Simulate an Optical Flat?

Simulation of optical flats involves creating virtual models that can predict and visualize the behavior of light when interacting with flat or nearly flat surfaces. This question explores the methods and technologies, such as computational modeling and software tools, used to simulate the optical phenomena associated with optical flats.

4.4. How Can We Extract 3D Information from the Measurements?

Extracting three-dimensional (3D) information from the interference patterns generated by optical flats is vital for assessing the topography of surfaces under examination. This includes methodologies for interpreting fringe patterns and converting them into quantifiable 3D surface data.

4.5. Is it Representative Enough?

This question addresses the representativeness of optical flats in various applications. It involves evaluating whether optical flats provide sufficient accuracy and resolution for the applications they are used in, from fundamental research to industrial quality control.

4.6. Simulation

Further detailing the simulation aspect, this section should delve into specific algorithms, computational techniques, and the challenges faced in accurately simulating the interaction of light with various surface types using optical flats.

4.7. Reconstruction

Reconstruction focuses on the process of translating fringe patterns observed with optical flats into detailed surface maps. This includes discussing the tools and algorithms used for digital image processing and data interpretation to reconstruct accurate surface models from measurement data.

5. Methods and Materials

5.1. Initial Approach Using Ray Tracing in C++

Initially, the simulation of optical flat measurements was attempted using a ray tracing technique in C++. Ray tracing is a powerful computational method for simulating the path of light through media. It models the propagation of light rays and their interactions with surfaces, which is particularly useful in optical studies where the understanding of light behavior in precise environments is necessary. However, this approach did not yield successful results due to complexities in accurately modeling the intricate interference patterns that are critical in optical flat evaluations.

5.2. Successful Simulation Using Python

After the initial setbacks, a more successful simulation was developed using Python. This method utilized the concept of intersecting planes with the test surface. Each plane was separated by half the wavelength of the light transmitted through the optical flat, allowing for the simulation of interference patterns by modeling how these planes interact with the surface irregularities.

5.2.1. Python Scripts and GUI Development

To implement this method, several Python scripts were created:

- **Intersection.py** - Handles the mathematical computation of plane and surface intersections.

- **Gui.py** - A graphical user interface was developed to facilitate the interaction with the simulation, allowing users to adjust parameters and visualize results in real-time.

- **Creating_image.py, Disk.py, Cylinder.py, Flat_surface.py, Shape3D.py, STLFigure.py** - These scripts contribute to generating and handling various geometrical shapes and rendering the final 3D images which represent the simulation results.

5.3. Discussion

This method of using planes separated by specific intervals corresponding to the light wavelength proved effective in simulating the necessary conditions to study optical flats. The Python environment, complemented by a user-friendly GUI, enhanced the flexibility and accessibility of the simulation, making it a robust tool for both educational and research applications in optical measurements.

6. Results

blabla

7. Discussion

blabla

8. Conclusion

blabla

Bibliography

[1] Edmund Optics, "Optical flats," 2024, accessed: 2024-05-11. [Online]. Available: https://www.edmundoptics.com/knowledge-center/application-notes/optics/optical-flats/ 3

[2] Kemet, "Optical flats," 2024, accessed: 2024-05-11. [Online]. Available: https://www.kemet.co.uk/products/flatlapping/optical-flats 3

[3] Lapmaster Wolters, "Optical flats," 2024, accessed: 2024-05-11. [Online]. Available: https://www.lapmaster-wolters.com/optical-flats.html 3

[4] R. Paschotta, "Optical flats," RP Photonics Encyclopedia, available online at https://www.rp-photonics.com/optical_flats.html. [Online]. Available: https://www.rp-photonics.com/optical_flats.html 3, 4

[5] Mitutoyo UK, "Optical flat – mitutoyo," 2023, accessed: 2024-05-11. [Online]. Available: https://shop.mitutoyo.co.uk/web/mitutoyo/en_GB/mitutoyo/$catalogue/mitutoyoData/PR/158-118/datasheet.xhtml 3

[6] R. Paschotta, "Fused silica," RP Photonics Encyclopedia, Available online at https://www.rp-photonics.com/fused_silica.html. [Online]. Available: https://www.rp-photonics.com/fused_silica.html 4

[7] "Corning® ule® glass," Jul 2022. [Online]. Available: https://www.corning.com/worldwide/en/products/advanced-optics/product-materials/semiconductor-laser-optic-components/ultra-low-expansion-glass.html 4

[8] M. V. Mantravadi and D. Malacara, *Newton, Fizeau, and Haidinger Interferometers*. John Wiley & Sons, Ltd, 2007, ch. 1, pp. 1–45. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/9780470135976.ch1 4

[9] W. contributors, "Optical flat — wikipedia, the free encyclopedia," https://en.wikipedia.org/w/index.php?title=Optical_flat&oldid=1212101911, 2024, accessed: 2024-05-11. 4, 5, 6

[10] T. Joji, "Optical flat," Jun 2023, accessed: 2024-05-11. [Online]. Available: https://youtu.be/tmFurBsknPc?si=iAR_TBQgxoM2s4Gn 8

A. References

blabla