Suppressing Laser Triangulation's Optical Aberrations by Replacing the Lens with a Slit

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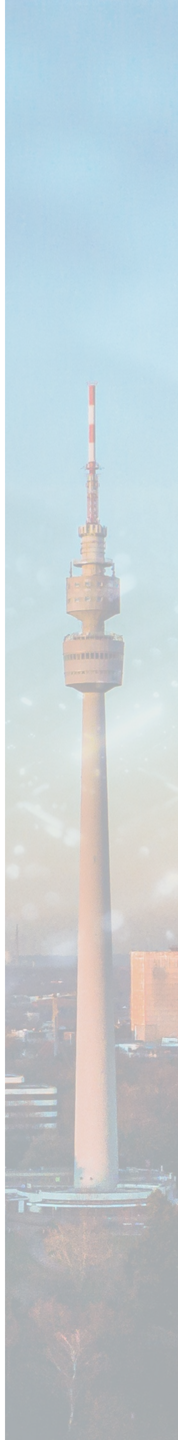
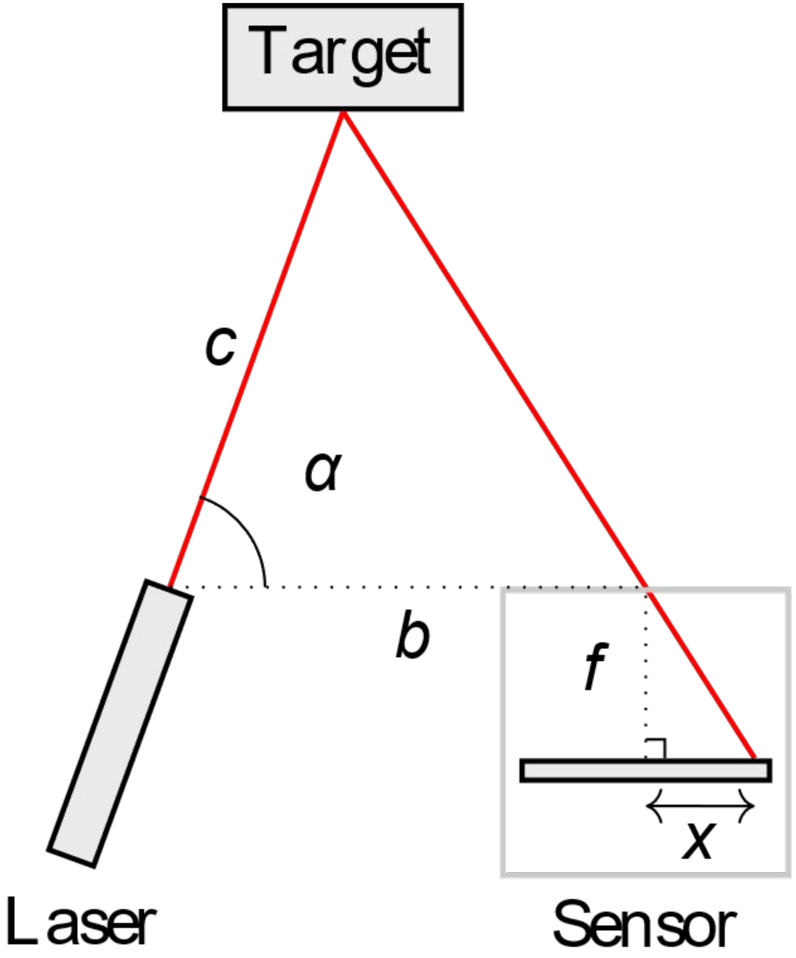


Introduction

- Need for a way to measure distances without contact
- Centimeter-scale distances ➡ laser triangulation sensors
    - Accuracy in the order of micrometers

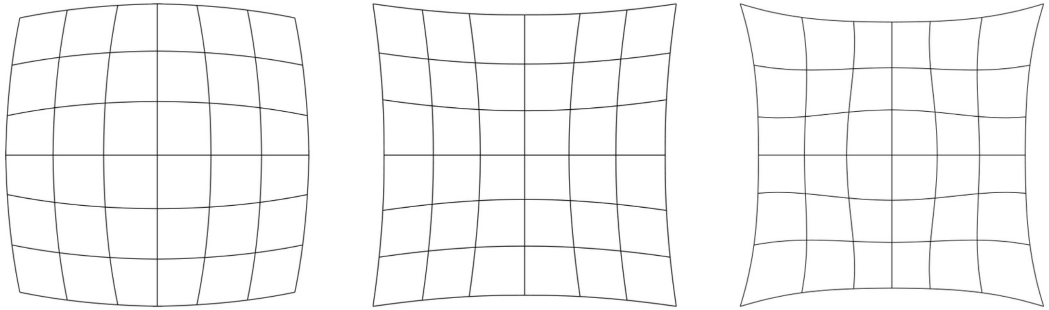
Laser Triangulation Geometry

- A laser beam and a photosensitive sensor placed at an angle to each other
- The laser beam is reflected by a target to the photosensitive sensor
- The projection of the laser spot on the sensor only moves horizontally
- Given the geometry of the system we find the following relation:



Lens Monochromatic Optical Aberrations

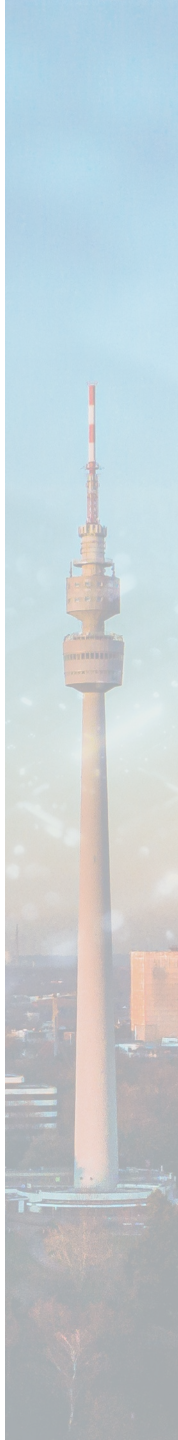
- Defocus
- Spherical
- Coma
- Astigmatism
- Field curvature
- Image distortion



- Also susceptible to lens flare

Pinhole Photography advantages

- Offers a theoretically infinite depth of field
- Does not create spherical optical aberration
- Does not create coma
- Does not create field curvature
- Does not create distortion
- Decreases lens flare
- Easily offers a viewing angle of up to 180°

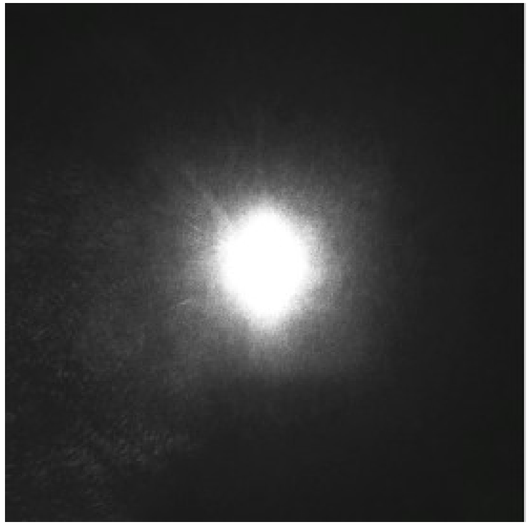


Pinhole Photography disadvantages

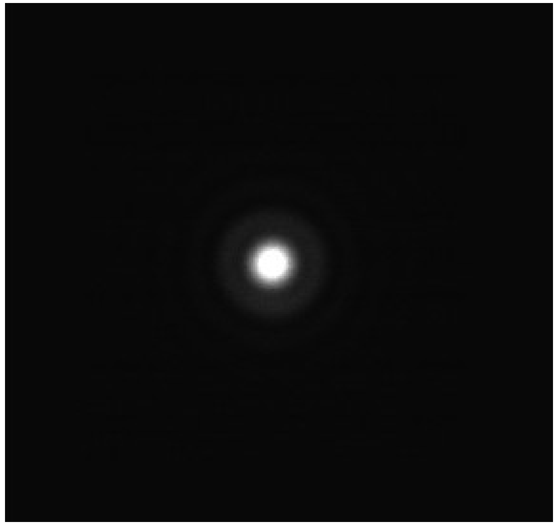
- Longer exposure time
- Symmetrical astigmatism on the horizontal axis
- Chromatic aberrations (can be neglected for this use case)

Circular Aperture Diffraction Pattern

- A laser observed through a pinhole creates an Airy disk diffraction pattern
- It is sharper and symmetrical



Lens laser spot on sensor

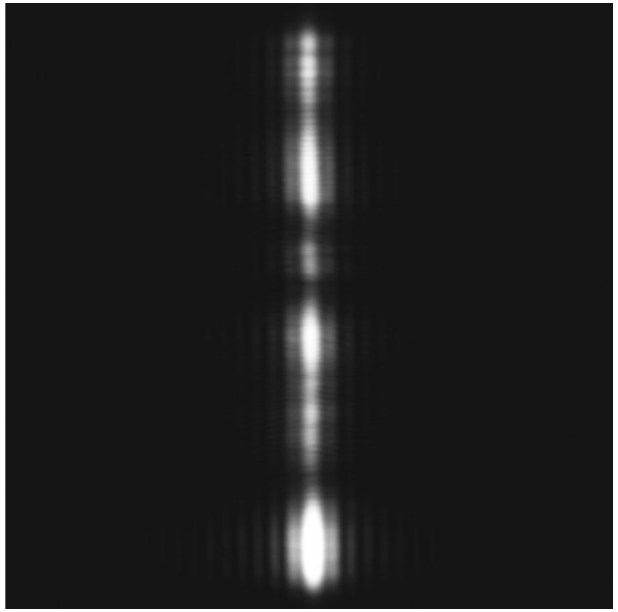


Airy disk on sensor

Slit Diffraction Pattern

- Diffraction is sensitive to speckle noise
- Replace circular aperture with vertical slit
- line-by-line analysis, averaging the errors in each pixel lines

Airy disk deformed by speckle noise



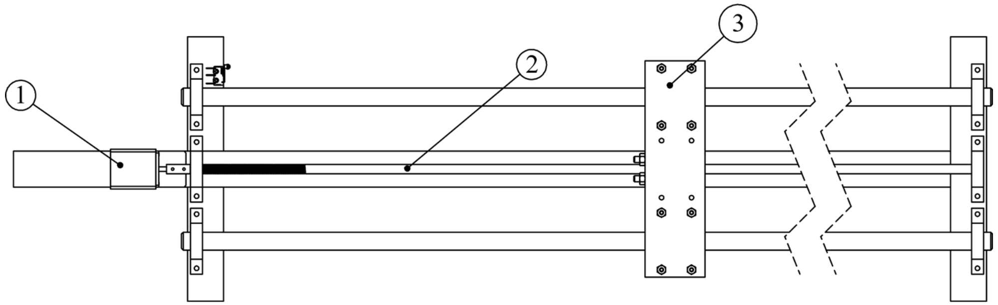
Slit diffraction pattern

Hypothesis

- Replacing the lens with a slit:
  - Improves accuracy and range by bypassing most of the optical aberrations of lenses
  - Decreases internal reflection
  - Offers better range
  - Exploits diffraction patterns for better image analysis

Prototype

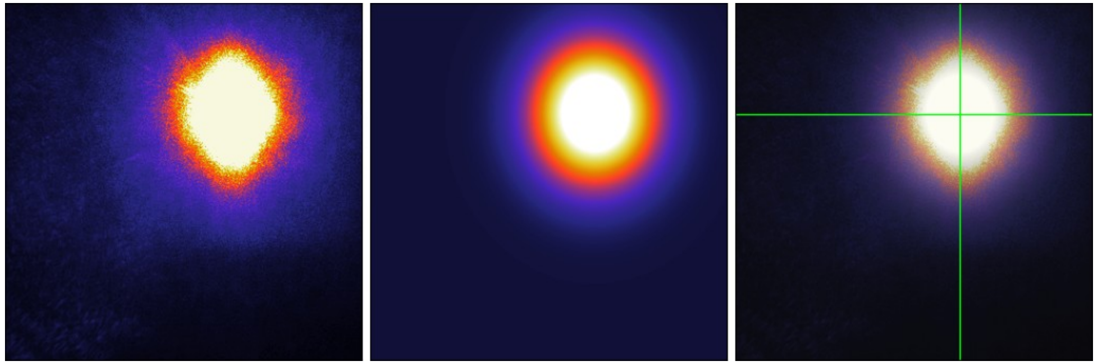
- Carriage that can support different targets, placed on a worm screw
- Capture at 25 μm intervals, 60 cm to 102 cm from to sensor
- Capture done on different materials
    - Brushed metal
    - Unevenly rusted metal
    - Light wood plank
    - Printer paper
    - Black electrical tape
    - Microfiber cloth

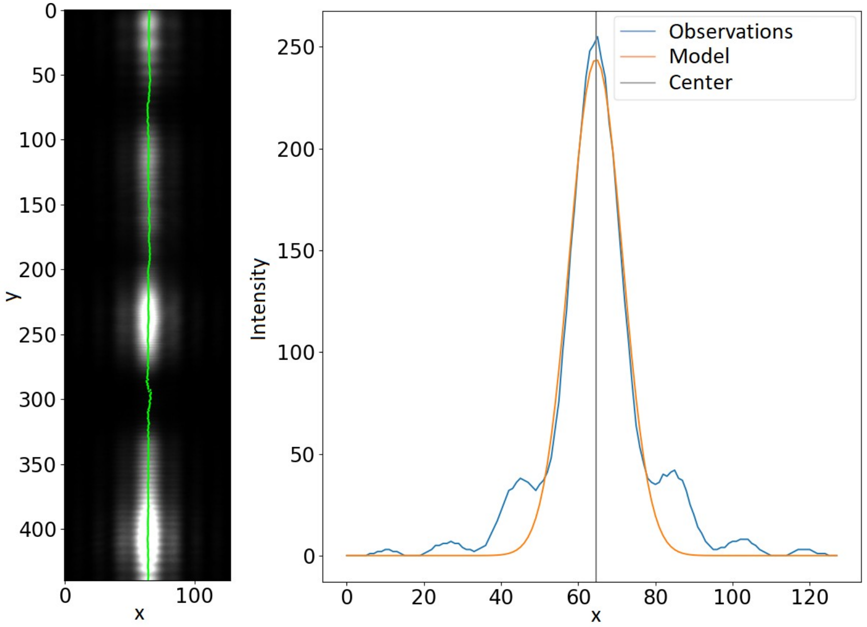


Motorized linear displacement table

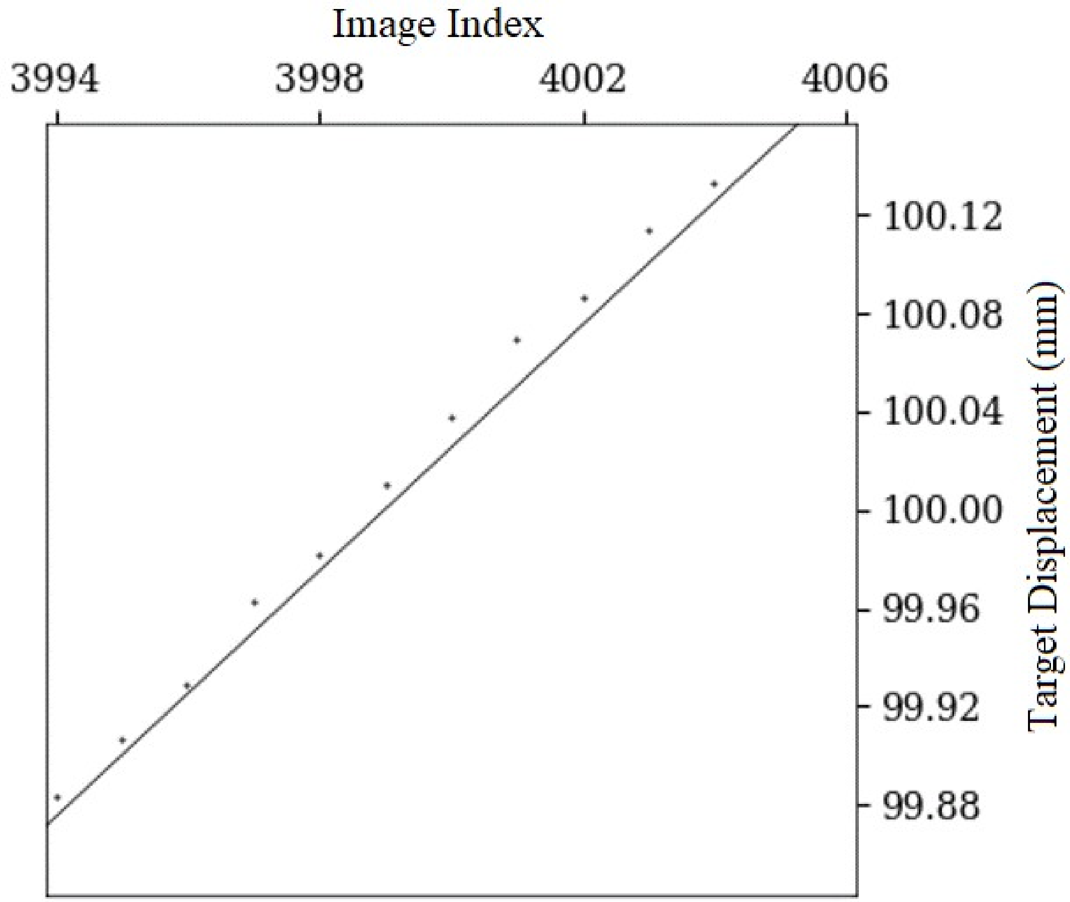
Algorithms

- Least squares regression of Gaussian Function
  - Lens: 2D
  - Slit: line-by-line



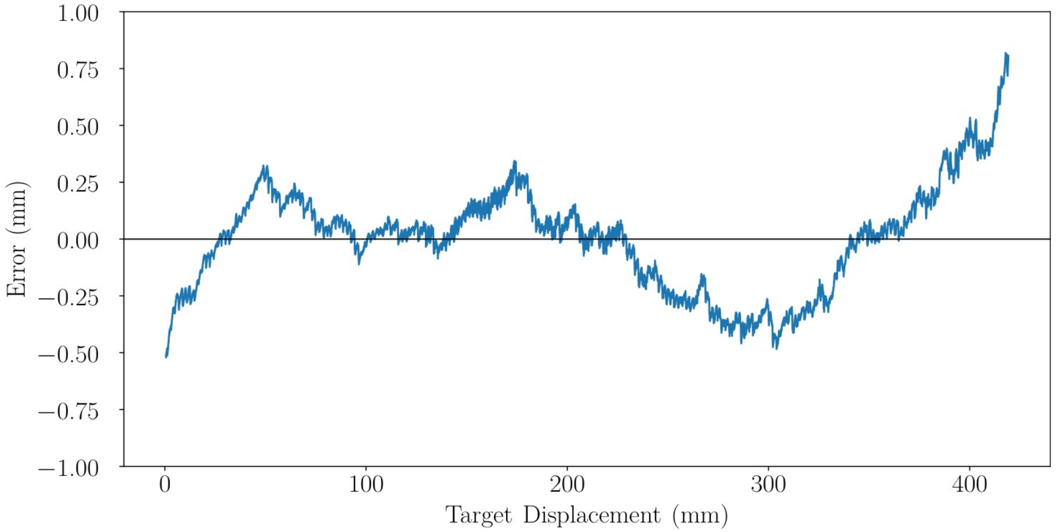


Distance Model Predictions

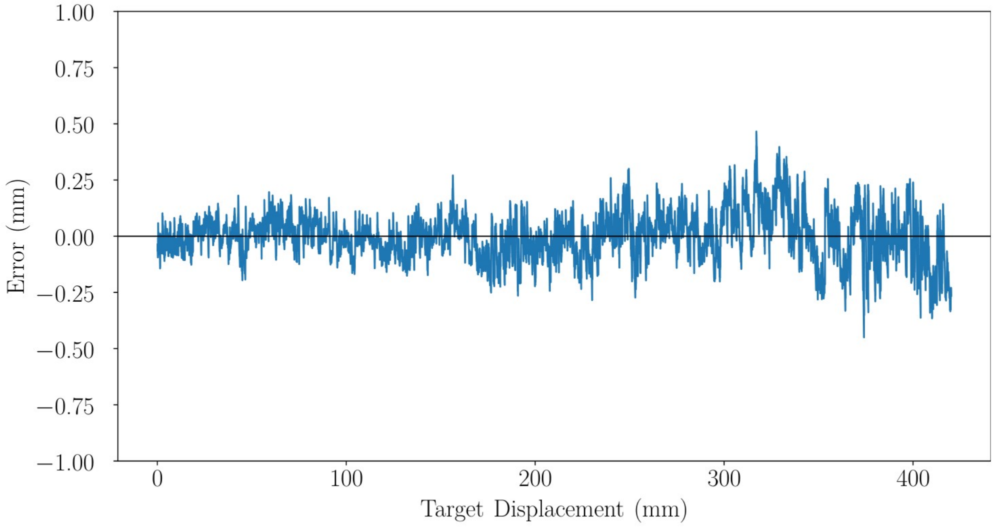


Model Prediction Errors Examples

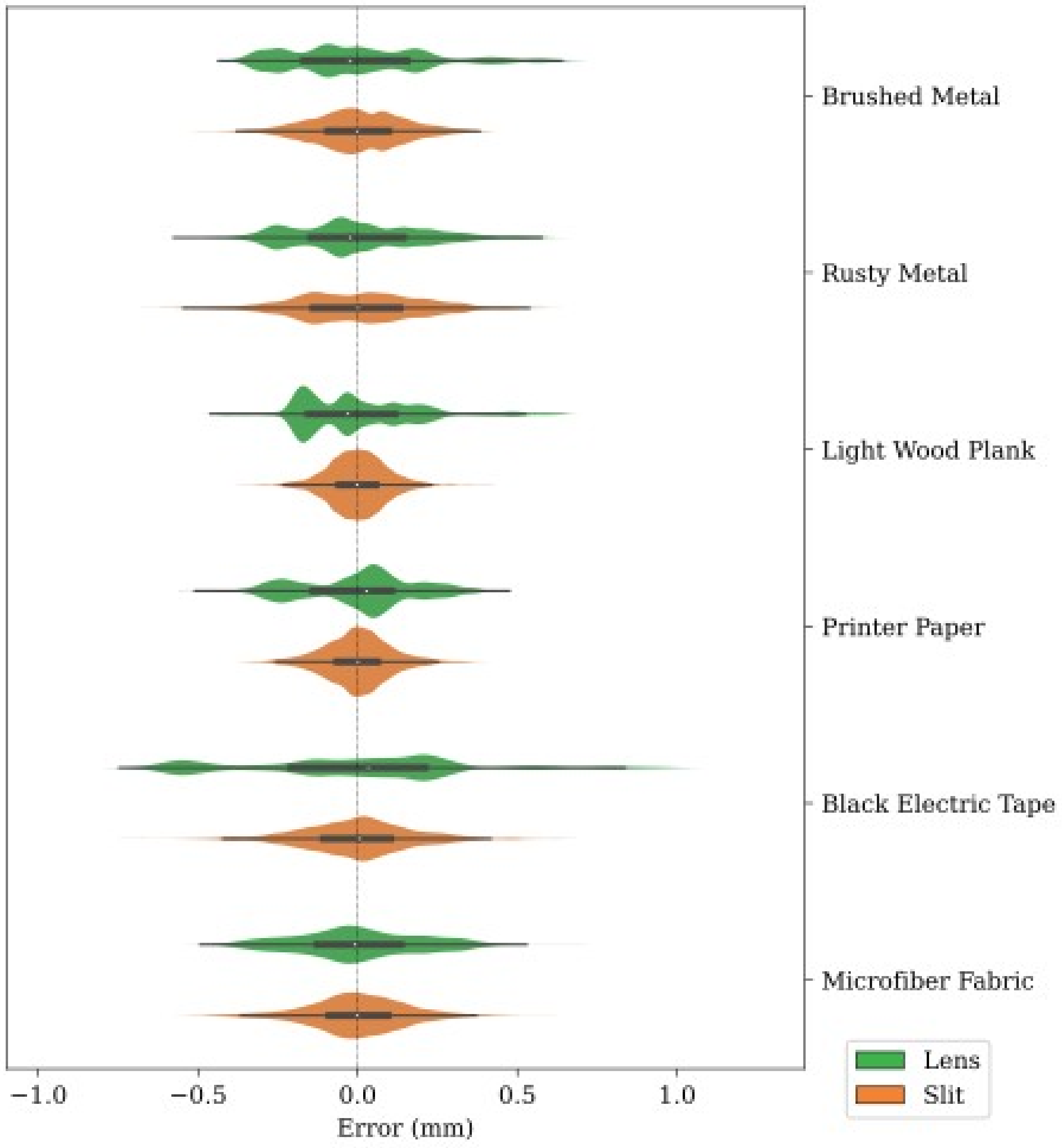
Lens



Slit



Violin Plot of Errors



Conclusion

- Hypothesis verified:
  - Slit bypassing most of the optical aberrations of lenses
  - Slit decreases internal reflection
  - Slit offers better range
  - Slit diffraction pattern symmetry helps with image analysis
- Slit is less precise, but overall, more accurate in average
  - Image darkened and affected by speckle noise

Potential Improvements

- Shorter wavelength laser
- Other speckle noise mitigations
- Usage of the Fraunhofer or the Fresnel approximations

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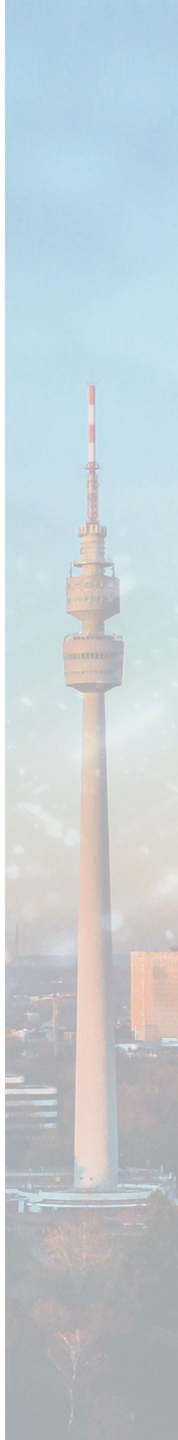

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Thank you for your attention

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