Determination and Correction of Optical Distortion in Cryogenic Target Characterization

Francis White

McQuaid Jesuit High School
Rochester, NY

Advisors: Dana Edgell, Mark Wittman

Laboratory for Laser Energetics
University of Rochester
Rochester, NY
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Abstract

The DT ice layer in cryogenic targets used for direct-drive inertial fusion experiments must have an rms surface roughness less than 1 μm for successful implosion. The solid fuel layer is characterized by both shadowgraphy and x-ray phase-contrast imaging in layering experiments being performed at LLE. Optical distortion present in these characterization methods must be determined and corrected for accurate measurement of the fuel layer's uniformity. It was determined that x-ray images inherently possess distortion less than 0.1 μm. To eliminate ellipticity of a circular object imaged with x rays, a precisely spherical steel ball was examined at various angles of camera tilt with respect to the x-ray beam axis, and the optimum tilt angle was determined. To calibrate the shadowgraphic imaging system, a zoom scan was performed using a regularly spaced dot array to center its optical axis on the center of the capsule and determine the imaging system's distortion. It was found that distortion varies with magnification and must be calibrated for each field of view. The imaging system's focus was registered and scanned to produce the highest contrast image of the steel ball. It was determined that the best focus varies slightly with magnification and must be corrected when changing the field of view. Finally, the known *l*-modes of a surrogate "bright-ring" target were reproduced by correcting for distortion using the information obtained from these calibration experiments.

1. Introduction

In laser-driven direct-drive inertial confinement fusion (ICF) experiments, energy is delivered to a target from multiple high-power lasers causing an implosion. The 60-beam, 30-kJ OMEGA Laser System[1] at the University of Rochester Laboratory for Energetics (LLE) conducts direct-drive ignition (DDI) experiments, in which laser energy is directly transferred to a target. In indirect-drive ignition (IDI) experiments, which are to be carried out at the National Ignition Facility (NIF),[2] laser energy is transferred to a metal container surrounding the target, and generated x rays energize the target. The design for direct drive ignition (DDI) calls for a layer of condensed hydrogen fuel adhered to the inner surface of a spherical shell ablator. The hydrogen fuel is delivered to the capsule via a fill tube. When photon energy is deposited on the target, the outer surface ablates causing an implosion that compresses the hydrogen fuel layer and gaseous fuel at the center of the target. Perturbations on the inner ice surface of the target can cause asymmetric implosion which may result in a failed ICF experiment. Specifications for DDI experiments on the NIF require the inner ice layer to have a total root-mean-square (rms) deviation of less than 1 μm. Therefore, it is imperative that the cryogenic targets be characterized with a resolution of ~0.1 μm to determine whether or not this uniformity requirement is met.

Two optical imaging systems are currently being used to characterize cryogenic targets: x-ray phase contrast imaging[3-5] and backlit optical shadowgraphy.[6] In x-ray imaging, the fuel layer is diagnosed by measuring rings due to x rays refracting at the inner ice surface. These rings appear in the image within a few microns of the actual ice surface. In optical shadowgraphy, the fuel layer is diagnosed by measuring the “bright ring" due to light reflecting off the inner ice surface. OMEGA uses optical shadowgraphy, while the NIF uses x-ray phase contrast imaging.

The purpose of this project was to determine and correct optical distortion in both of these characterization methods. The distortion was measured for each of these techniques to enable correction in the final uniformity analysis. It was found that x-ray imaging is inherently distortion free, but that the camera's angle must be adjusted to remove ellipticity in the image. The shadowgraphy imaging system was calibrated and reproduced the known modes fabricated on a surrogate target with known imposed perturbations.

2. X-ray Phase Contrast Imaging and Backlit Optical Shadowgraphy

Cryogenic fill-tube targets are characterized using x-ray and visible-light imaging systems. The cryogenic fill-tube-target test facility (CFTF) shown in Figure 2 uses both characterization methods to test cryogenic targets for imperfections. The x-ray and shadowgraphy imaging systems are oriented orthogonally to each other. A right-handed coordinate system has been imposed on this setup. By definition, the x-axis is oriented horizontally along the x-ray imaging system with the positive direction pointing towards the x-ray camera. Likewise, the y-axis is oriented vertically along the shadowgraphy imaging system with the positive direction pointing away from the shadowgraphy imaging optics. The z-axis is orthogonal to both the x and y axes with the positive direction pointing down the fill tube toward the capsule. The coordinate system is important because the two imaging techniques must both be optimized at once when the center of the capsule coincides with the origin, i.e., the intersection of the optical axes of both systems. This can be accomplished by manipulating the target's position with the xyz-positioner.

2.1 X-ray Phase Contrast Imaging

X-ray phase contrast imaging is to be the primary diagnostic of cryogenic targets used on the NIF. This technique uses refracted x rays to determine information about a cryogenic target's inner condensed deuterium-tritium (DT) layer. A tungsten anode generates x rays which pass through a target suspended in the target chamber. The x rays pass through the target and are collected by a 1340x1300 pixel, 16 bit x-ray camera. The largest refraction occurs at grazing-incidence angles, i.e., x rays that pass through the target tangential to the DT ice surface have the greatest deflection. This is illustrated in Figure 3. In general, however, the x-ray deflection is very small. Since the imaging system relies on the x-ray deflection to create an accurate intensity map of the target, the x rays must propagate for approximately 1 m after passing through the target to create sufficient deflection before being collected by the x-ray camera.

The deflection of the x rays causes a variation of x-ray intensity. Deflection of x rays off the inner ice surface creates a bright ring in the resulting phase-contrast image. Figure 4 is an example of an x-ray phase contrast image of a thick-walled plastic calibration target. The inner blue ring is the result of x rays refracting off the inner ice surface. These high intensity rings appear within a few microns of the actual ice surface.[5]

2.2 Backlit Optical Shadowgraphy

Optical backlit shadowgraphy is one of the most widely used diagnostics of cryogenic targets used in ICF experiments. Red light with a wavelength of 627 nm passes through the target and is collected by a 2048x2048 pixel, 12 bit CCD camera. Rays are both reflected and refracted at the shell wall and inner ice layer interface. Some of these rays form characteristic rings on the resulting intensity map (Figure 5). The brightest (most intense) ring is caused by rays that totally internally reflect off the inner ice surface. This is illustrated in Figure 6, in which the yellow lines indicate rays passing through the target and the red lines indicate the apparent paths of the rays viewed by the camera. Figure 6 shows that when these rays are traced back they form a caustic, which appears as the bright ring. Ray tracing programs correlate the position of the bright ring in the shadowgraph to the position of the inner surface of the ice layer allowing characterization of the nonuniformity of the inner surface.[6]

3. Experimental Correction of Optical Distortion

3.1 X-ray Phase Contrast Imaging: Optimal Camera Tilt Angle

It was discovered that x-ray images do not need to be calibrated for distortion, but that incident camera angle is important. Ellipticity in the image of a circular object is produced when the camera is tilted with respect to the axis of symmetry of the incident radiation. To find the optimum tilt angle, ellipticity (measured by Fourier mode 2 in the radius of the circular image of a precisely spherical steel ball as a function of angle) was examined as the angle of the camera relative to the y and z axes were varied. The optimum tilt angle occurs when the mode 2 is minimized. This occurred when $\theta_y = -2°$ and $\theta_z = -1°$. (see Fig. 7 and 8).

3.2 Backlit Optical Shadowgraphy

3.2.1 Determining the Best Focus

A focus scan of a precisely spherical steel ball was used to find the focus that produced the highest contrast edge. It was discovered that the best focus varies with magnification and must be calibrated for each field of view. The results of experiments involving a 1.0-mm field of view and a 3.4-mm field of view are summarized below in Figures 9 and 10. The focus was varied through rotations of a focusing ring integral to the imaging system (measured in arbitrary units). The optimal focus occurs when the contrast at the edge of the steel ball is the greatest. This is measured by the steepness of a lineout of intensity (i.e. slope) at the perimeter of the steel ball. As a precaution, in the 1-mm field of view experiment, the dial was rotated from 1.18 back to 1.02 after gathering the original data in order to check for hysteresis. Since both sets of data peak at a dial indicator position of 1.1, hysteresis was not present.

3.2.2 Measurement of Distortion

There is distortion in any optical system. In order to adequately characterize cryogenic targets with backlit shadowography, distortion needs to be corrected. There are two kinds of optical distortion: pincushion and barrel. In "pincushion distortion," image magnification increases with distance from the optical axis, while in "barrel distortion" image magnification decreases with distance from the optical axis.[7] To correct optical distortion, one has to know how far the distance between points in the image varies as a function of distance from the optical axis. Thus, a zoom scan of a dot array (Figure 11) was used to adjust the shadowgraphic imaging system's optical axis and measure its distortion (D), which varies directly with the cube of the distance (r) from the optical axis ($D \sim r^3$). It was experimentally determined that D varies with magnification and that the imaging system must be calibrated for each field of view.

3.2.3 Distortion Correction

In order to show that the distortion correction is accurate, the known modes of a surrogate "ring" target were reproduced. The outer perimeter of the ring is circular with a diameter of 900 μm, while the inner ring has a known mode structure that meets NIF specifications. Figure 12 is a shadowgraphic image of the surrogate target before the distortion correction. Figure 13 is an "unwrapping" of Figure 12 showing the radial variation in intensity near the target edge. Each vertical line in Figure 13 is a radial lineout of the intensity in the bright ring to outer edge region of Figure 12. The angle in the unwrapping has zero at the far right side of Figure 12 and increases in the counterclockwise direction. Figure 14 is a graph of the power spectra of the surrogate target's outer and inner rings. The large variation in the magnitude of mode 2 with respect to the calibration target's NIF design spec (dotted line) is indicative of the optical distortion discussed above. Following the distortion correction, the power spectrum of the outer edge became relatively constant, and the power spectrum of the inner ring more closely matched the NIF specification of 1.00 μm ms. These new power spectra are plotted in Figure 15.

4. Conclusion

Both the x-ray phase contrast imaging and backlit optical shadowgraphy characterization systems were calibrated and corrected for distortion. The distortion was measured for each of these techniques to enable correction in the final uniformity analysis. It was found that x-ray imaging is inherently distortion free, but that the angle of the camera is important in removing ellipticity from the image. For the shadowgraphic imaging system, it was found that the optimal focus depends on the field of view. Moreover, the pincushion distortion present in this imaging system was discovered to vary with magnification and must be calibrated for each field of view. Corrections to this distortion were found to be accurate by reproducing the known l-modes fabricated on a surrogate target.

5. Acknowledgements

I would like to thank Dana Edgell and Mark Wittman for their incredible support helping me complete this project. It is truly kind that they would take in a high school student (with absolutely no prior knowledge of laser fusion) and support me in this scientific endeavor. Work on this project wasn't always easy, but I've come away knowing what it means to work for the benefit of mankind. I would also like to thank Dr. Craxton for his tireless efforts in directing the LLE Summer Research Program for High School Students. He has given me and so many other high school students the opportunity to experience science as professional scientists do it. I am in his debt. Lastly, I would like to thank my fellow high school internees. Because of their support and camaraderie, I had one of the most enjoyable summers ever.

6. References

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2. W. J. Hogan et al., “The National Ignition Facility,” *Nucl. Fusion,* **41**, 567 (2001).

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5. T. Lu., “X-Ray Phase-Contrast Characterization of Cryogenic Targets,” *2009 Summer Research Program for High School Juniors at the University of Rochester’s Laboratory for Laser Energetics*

6. D. H. Edgell et al., “Three-Dimensional Characterization of Cryogenic Target Ice Layers Using Multiple Shadowgraph Views,” *Fusion Science and Technology*, **49**, 617 (2006).

7. “Distortion,” http://toothwalker.org/optics/distortion.html.

Figure 1. Photograph of a cryogenic fill-tube target with a 3 mm diameter. The fill tube enters the target with a 30 µm diameter.

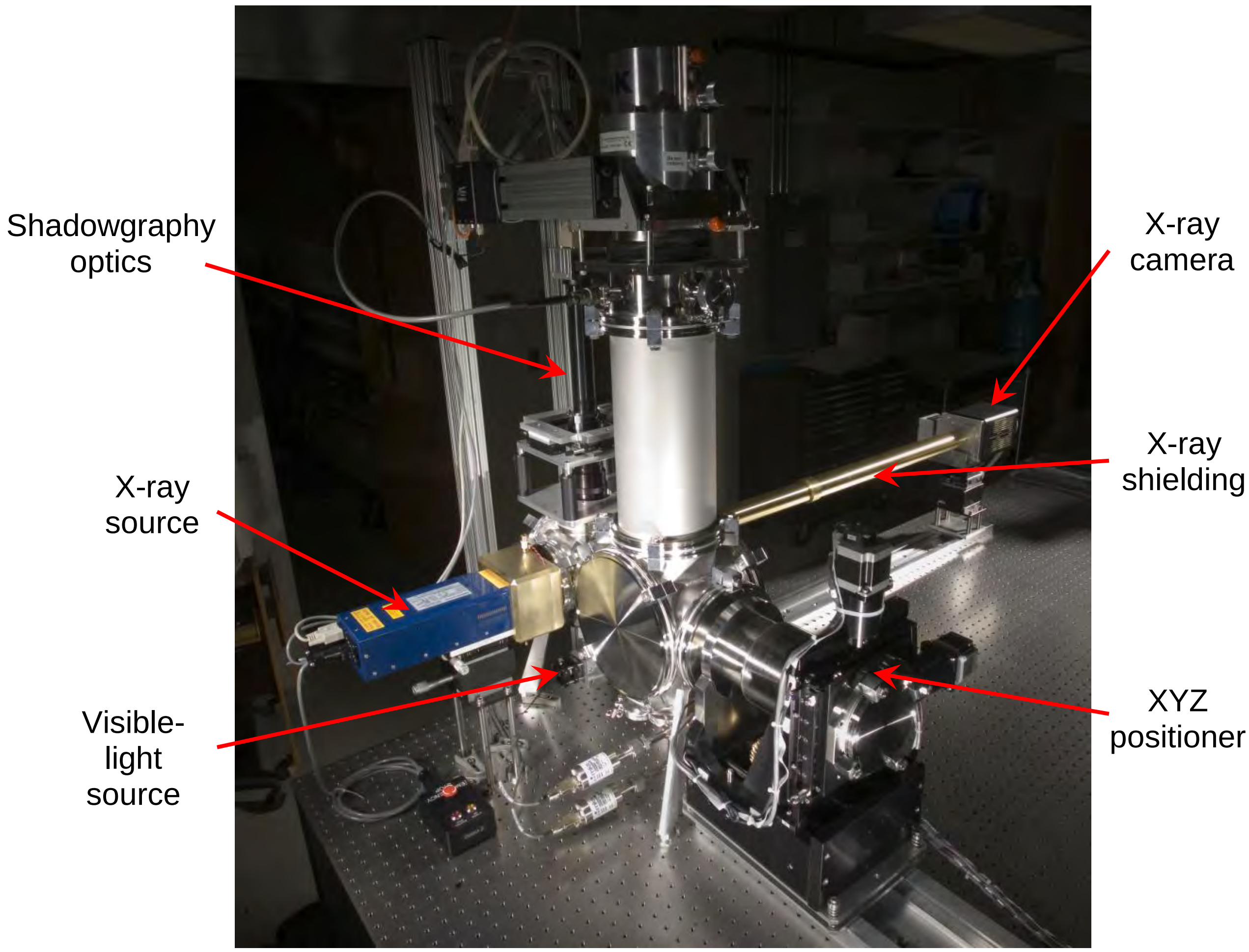
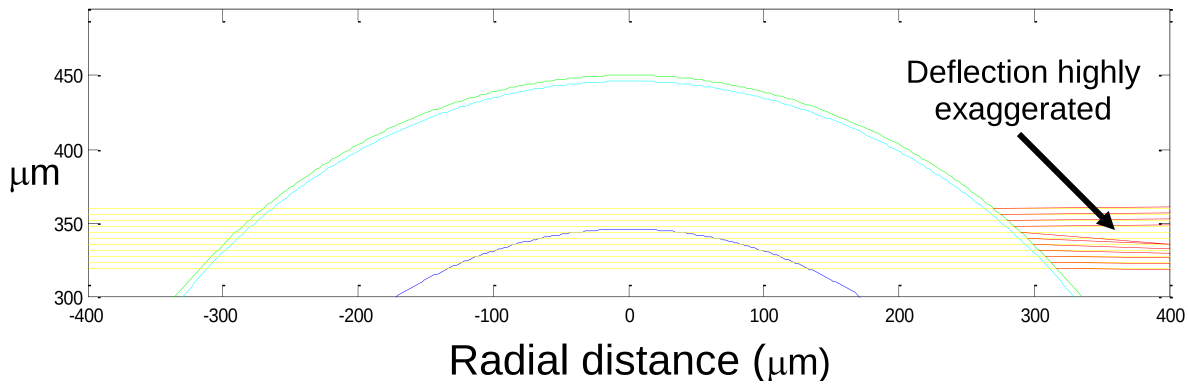


Figure 2. Photograph of the x-ray and optical characterization systems in the experimental setup.



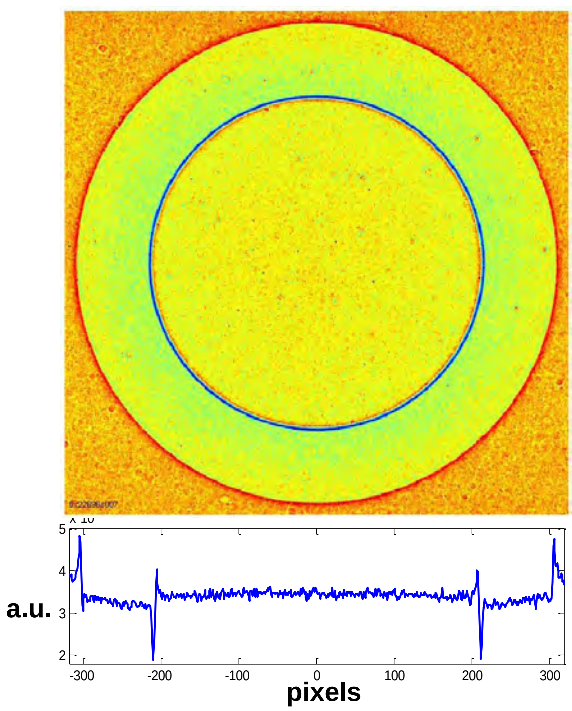


Figure 4. X-ray phase contrast image of a thick-walled plastic shell used for calibration purposes (from Ref. 5). A lineout of intensity is added. (False-color enhancement of an original black-and-white image.)

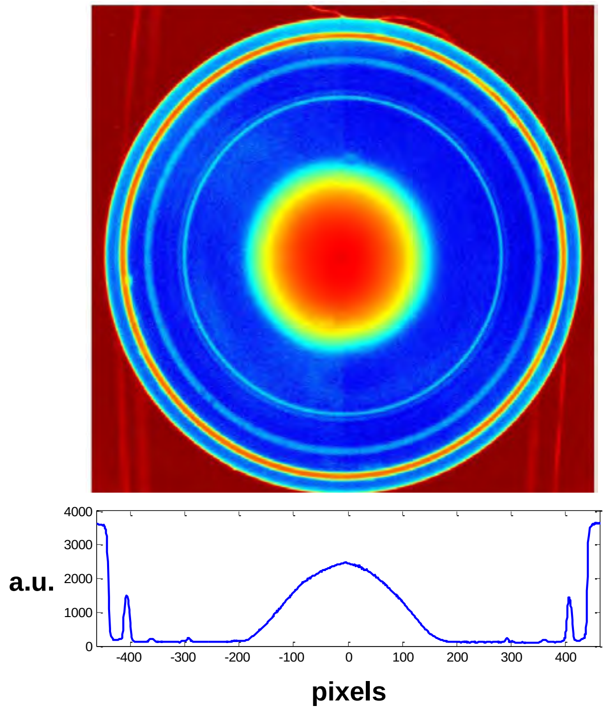
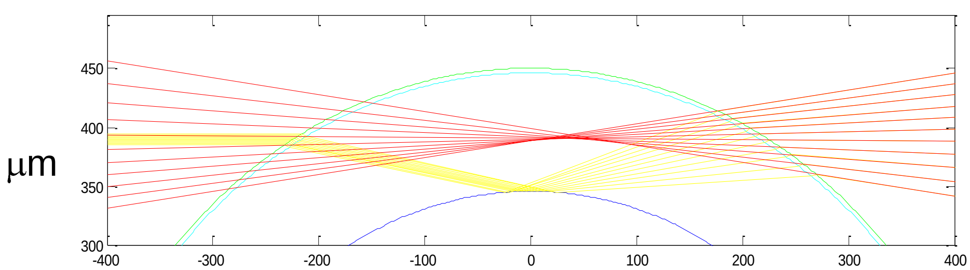


Figure 5. Shadowgraphic image of a thick-walled plastic calibration target. (False-color enhancement of an original black-and-white image)



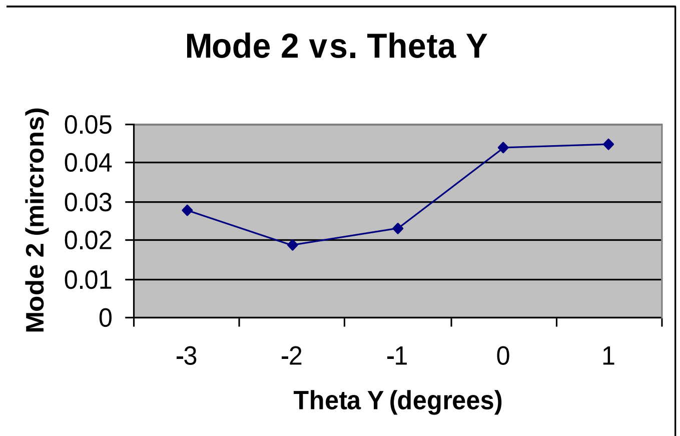


Figure 7. Plot of the mode 2 amplitude versus tilt angle about the y-axis. The minimum mode 2 occurs at

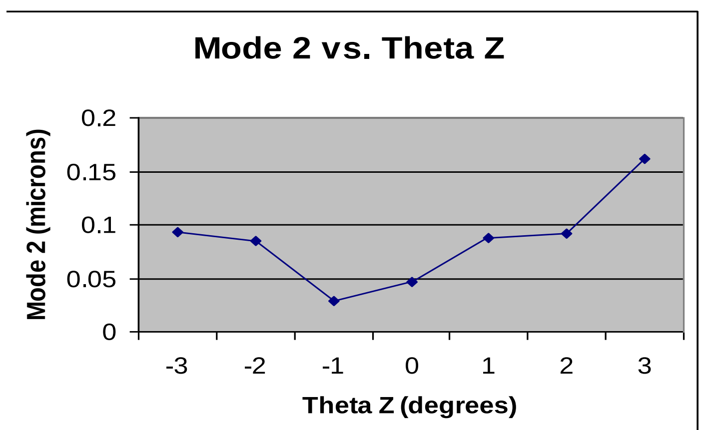


Figure 8. Plot of the mode 2 amplitude versus tilt angle about the z-axis. The minimum mode 2 occurs at

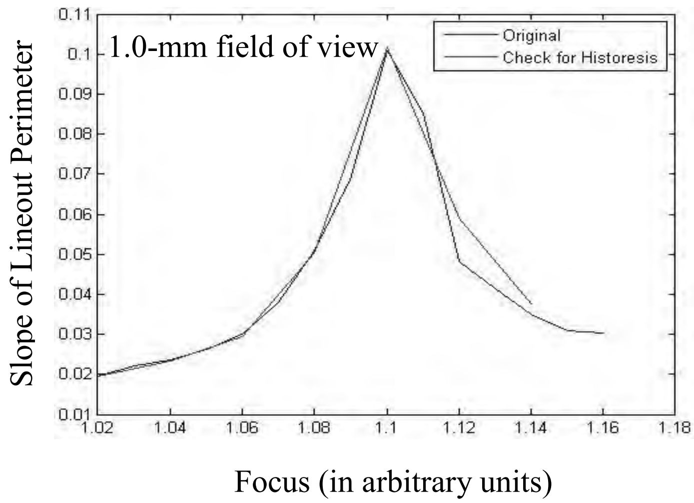


Figure 9. Plot of focus versus slope at a 1-mm field of view. Points along the blue curve were taken as the focus dial was turned to the right. Points along the green curve were taken as the focus dial was turned to the left from 1.14 in order to check for hysteresis. The optimal focus occurs at 1.1 where both lines achieve a maximum. Because both curves peak at 1.1, there was no hysteresis in the bearings.

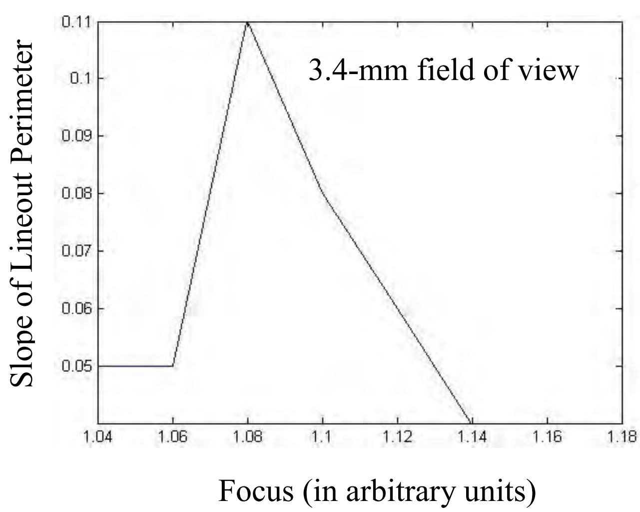


Figure 10. Plot of focus versus slope at perimeter at a 3.4-mm field of view. This curve achieves a maximum at a focus of 1.08, which indicates that best focus varies with magnification.

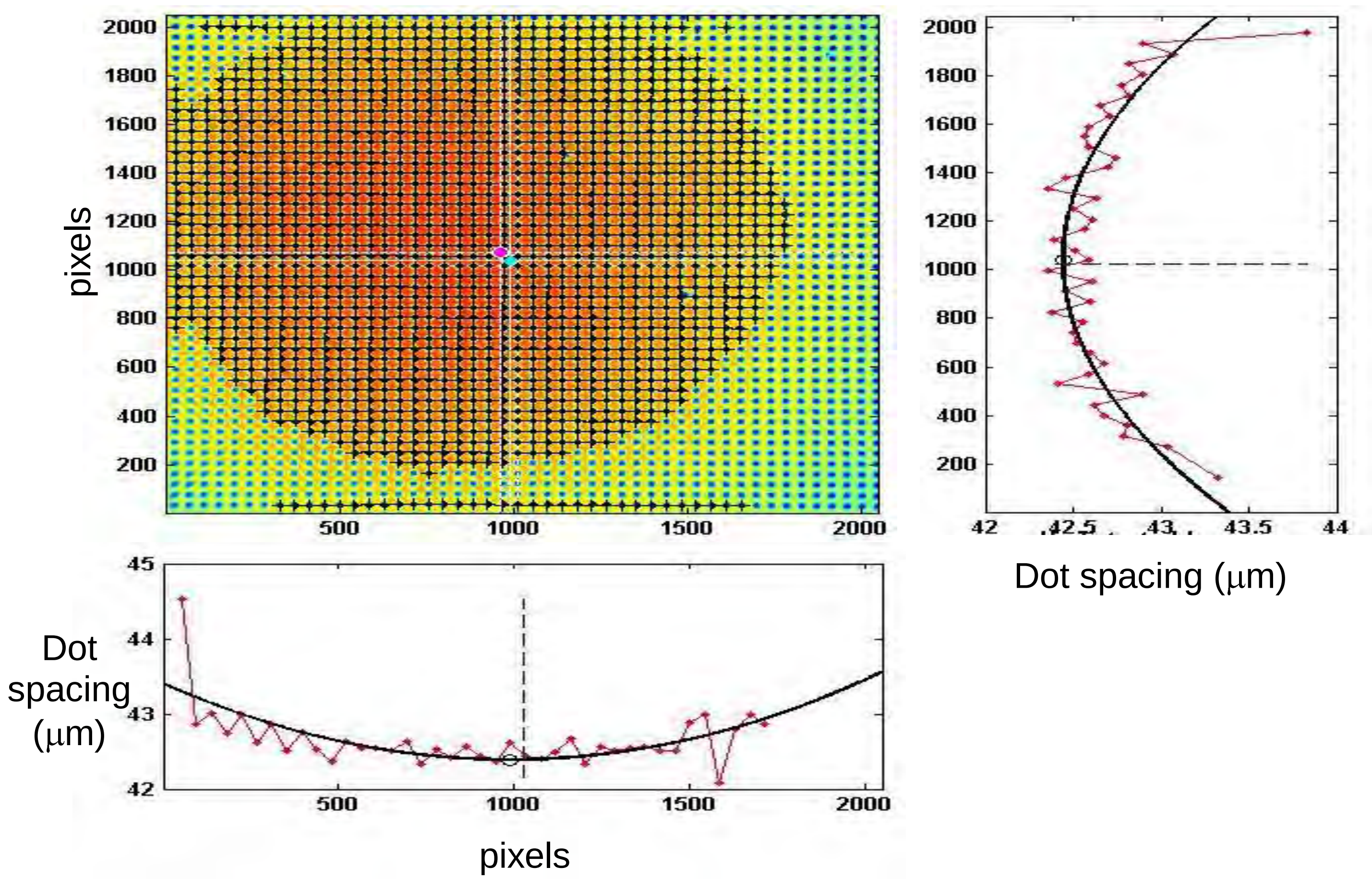


Figure 11. Shadowgraphic image of a dot array showing pincushion distortion. Distortion causes the black dots to spread out radially from the optical axis and must be corrected for. The two graphs show the distance between successive points in the image in the x and y directions.

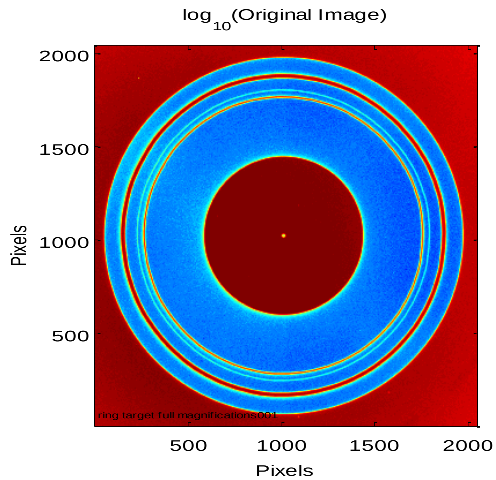


Figure 12. Shadowgraphic image of a surrogate ring target. The perimeter of the target is circular. The inner red ring has a known mode structure that meets NIF specifications

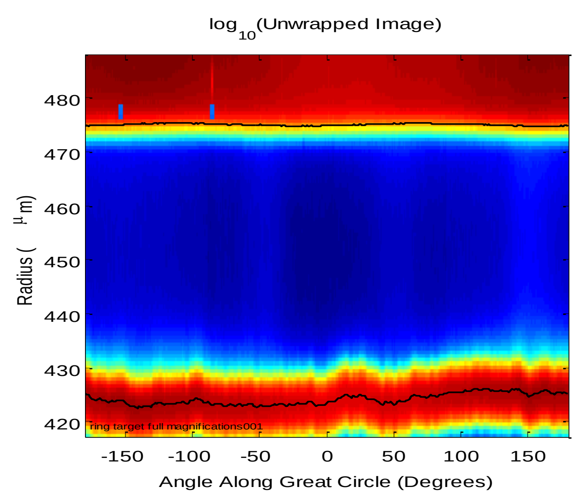


Figure 13. Line out of Figure 12 without distortion correction.

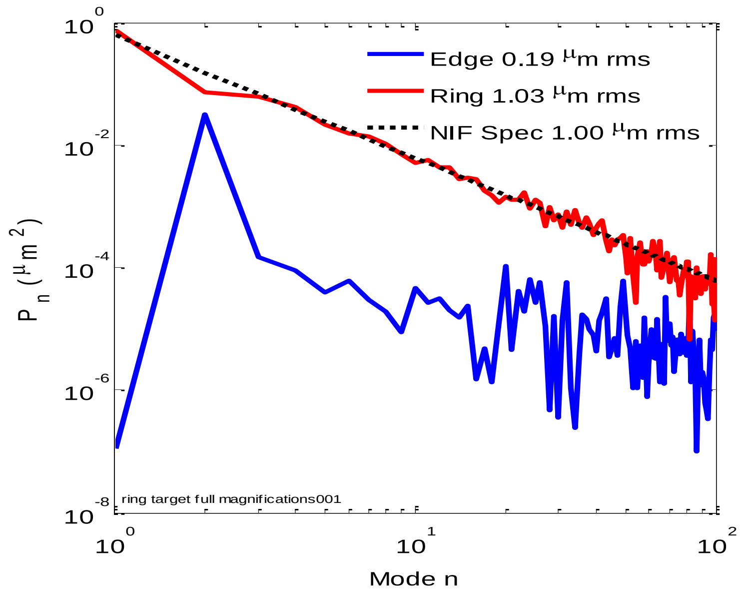


Figure 14. Power spectrum of the surrogate target's outer edge (blue) and first inner ring (red) before distortion correction.

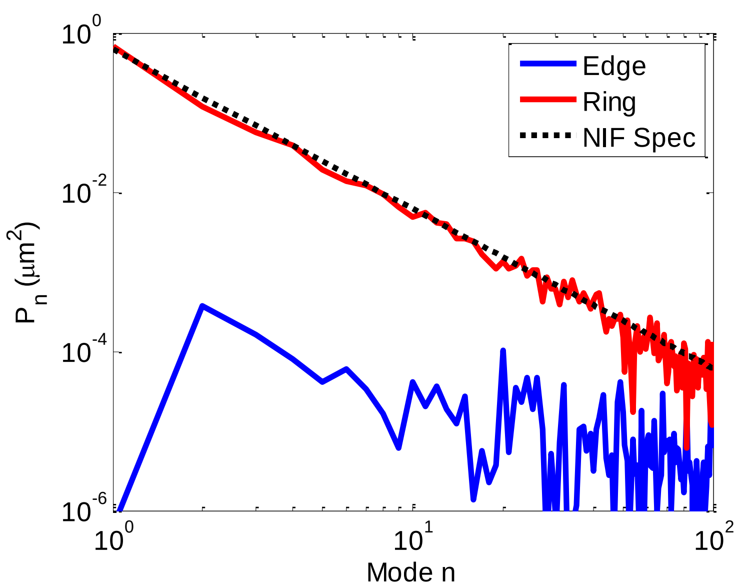


Figure 15. Power spectra of the inner ring and outer edge following the distortion correction. The outer edge (blue) is relatively constant and the inner ring (red) meets NIF specifications (dotted line).