Analysis of inner ice surface perturbations using bright ring characterization

Rosie Wu

Brighton High School
Rochester, NY

Advisor: Dr. Dana Edgell

Laboratory for Laser Energetics
University of Rochester
Rochester, NY

Abstract

The uniform implosion of cryogenic targets is imperative to a successful fusion reaction. It is necessary to analyze the inner ice surface to an extremely precise degree as tiny imperfections on the surface of the target grow during the course of an implosion. When a shadowgraphic target is viewed with a CCD camera, it exhibits a bright ring, which can be used to estimate the radius of the inner ice surface. However, when comparing the actual surface radius with the experimental radius (determined according to the bright ring using only one view of the bright ring), discrepancies of up to 1 micron are observed. A program was devised that averaged two opposite views of the bright ring, resulting in a difference of less than 0.2 microns. Unfortunately, as the two cameras on the actual OMEGA system are situated at 12.6 and 22.6 degrees above the horizontal, it is physically impossible to observe two exact opposite views. Therefore, modifications were made to the program in order to incorporate the OMEGA system's actual design. It was found that the averaging of opposite views using a tilted camera yielded good results for modes up to n=5 (in other words, if the nonuniformities are broad and gradual).

Introduction

The purpose of the Laboratory for Laser Energetics is to perform high energy laser fusion. A small target is shot with the 60 powerful laser beams of the OMEGA laser system. As it implodes, the target generates an enormous amount of heat, which triggers a fusion reaction. A cryogenic target consists of an outer shell made of hydrocarbon plastic (~3 µm thick), a thick layer of deuterium (D2) or occasionally deuterium tritium (DT) ice (~80 µm thick, with a temperature of about 18 K) and a center of deuterium gas. The entire target has a diameter of about 900 µm.

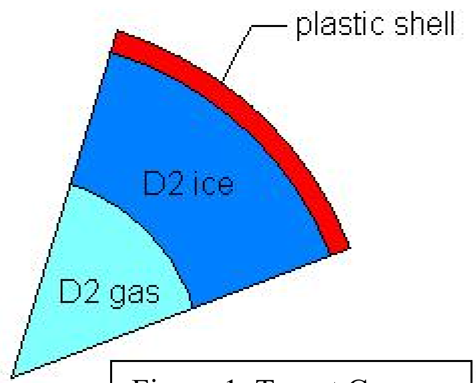

Figure 1. Target Cross-section

However, for the fusion reaction to be successful, the irradiation and the inner surface of the deuterium ice layer must be uniform. To achieve uniform irradiation, the target is suspended by spider silk and the 60 laser beams impact the target from all directions. A uniform inner ice surface (the gas-ice interface) is difficult to achieve, and irregularities on the surface are problematic. Thinner sections of the ice will implode faster than thicker sections, causing an uneven implosion that will fail to generate enough heat for a fusion reaction.

Shadowgraphy

A method by which the surface of a target can be determined uses a technique called shadowgraphy. A target is backlit with a collimated light source, and the image is taken by a CCD camera.

There are three major kinds of light rays recorded by the shadowgraphs. “A” rays pass through the deuterium gas area of the target. “C” rays miss the target entirely. “B” rays, however, enter the target and reflect off the inner ice surface, exiting as a diverging group of rays that all appear to come from a single radius in the plane through the center of the target. These B rays are viewed in the shadowgraph as a bright ring (see Fig. 3). The position of this bright ring can be used to calculate the inner ice radius by using a simple theory for spherical surfaces. Therefore, nonuniformities on the bright ring can be used to calculate nonuniformities on the ice surface. If shadowgraphs of the target are taken from many different views, they can be used to create a 3-D model of the target.

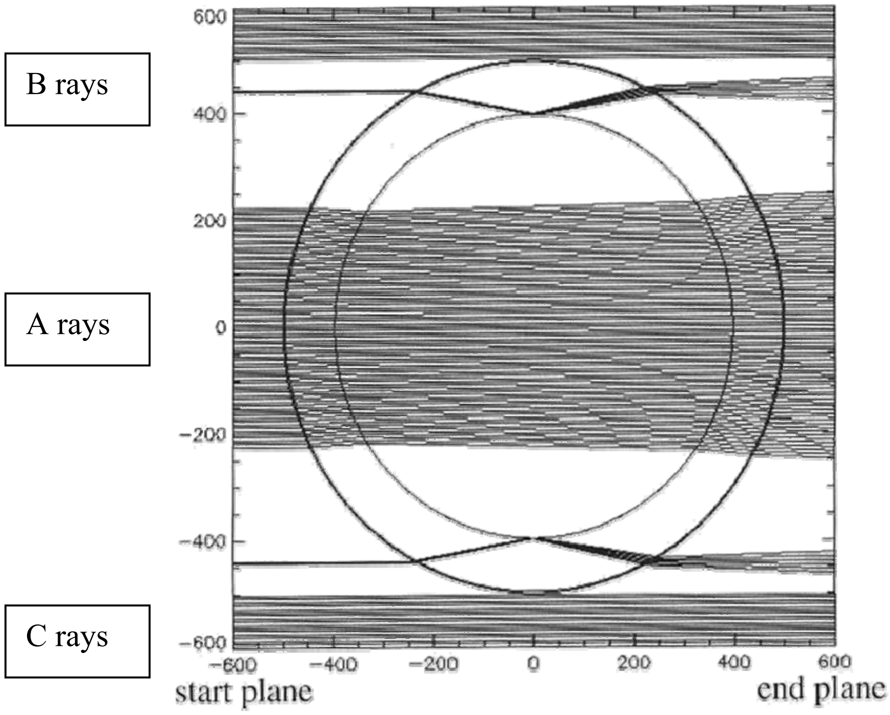

Fig. 2: A, B, and C ray paths through a cryogenic target from left to right (from Ref. 1).

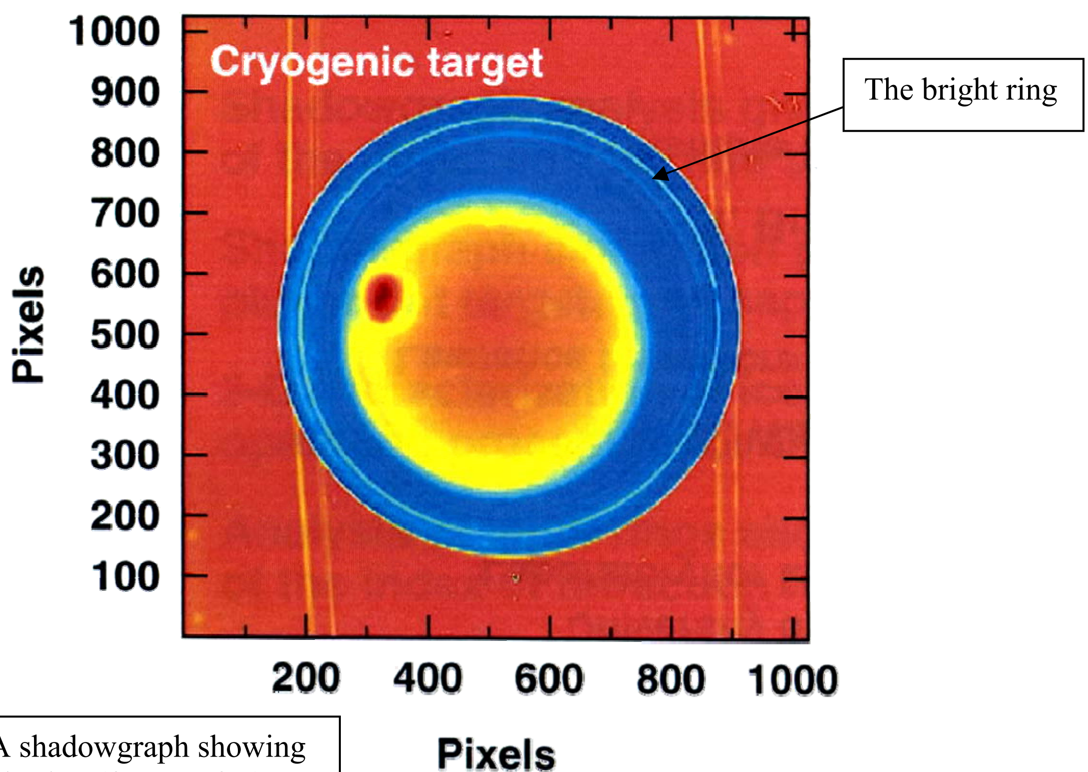

Fig.3: A shadowgraph showing the bright ring (from Ref. 2).

Noting from Fig. 2 that the emerging B rays appear to come from a single point, the radius of the bright ring is equal to the radius of the B ray that emerges exactly parallel to the horizontal axis. Thus, the shadowgraphs taken from opposite views should be the same. However, if there are nonuniformities on the surface, the B rays will exit at a different level as shown in Fig. 4. Thus, a shadowgraph taken from one position will show a bright ring of a different radius than a shadowgraph taken from the opposite position. [2]

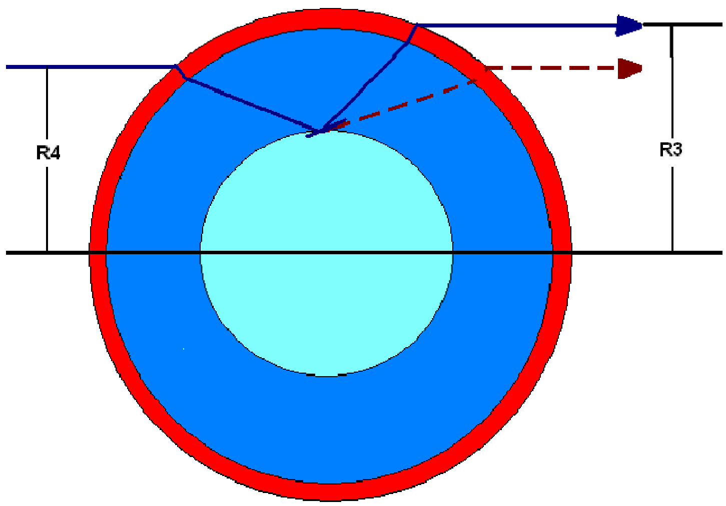

Fig.4: Paths of rays forming the bright ring for a uniform ice surface (dashed) and for an irregular surface (solid).

Therefore, any single view of the bright ring does not uniquely define an aspherical ice surface, and calculating the radius of the target using only a single view will yield errors of up to 1-2 microns, as can be seen in Figure 5.

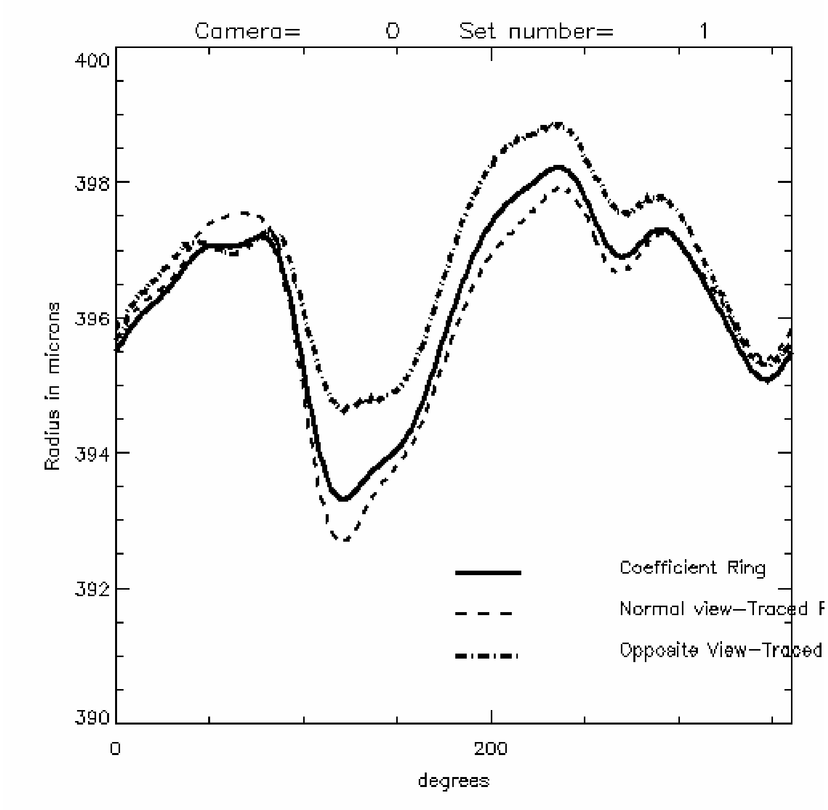

Fig. 5: The solid line represents the actual ice surface represented as a sum of spherical harmonics; the dotted lines are the calculations using only one view of the bright ring (from Ref. 2).

The Program

A program was written by Gregory Balonek [2] that traced rays through the target and found the radius of the surface.

To find the correct rays to make up the bright ring, it shoots rays through one side of the target. The first ray leaves the target on the other side with a positive angle to the direction it came in, and the program continues to launch rays at higher successively higher levels until the ray leaves the target with a negative angle. Then, the program ceases to launch rays, and interpolates to find the level at which the outgoing ray is parallel to the direction it came in. The program does this for 360 degrees around each view, by one degree increments, and for fifty views of the target.

The program sets up a cube, on each side of which is a grid. The intersection of a line passing through the origin, in a given direction expressed through phi and theta, with any face of the cube can be determined. The radius of the surface can be calculated with a formula

$$R(\theta,\varphi) = \sum_{L=0}^{Lmax} \sum_{M=0}^{L} [Ac(l,m)Clm(\theta,\varphi)+As(l,m)Slm(\theta,\varphi)]$$

in which Clm's and Slm's are standard spherical harmonic functions, Ac's and As's are predetermined coefficients, and Lmax is typically 11. [1] As the radius is expressed in terms of phi and theta, it is possible to determine the radius of the surface at each point of the grid, and thus trace rays through perturbed surfaces. At each point of the grid, three radii are stored: R1 is the outer radius of the plastic shell, R2 is the radius of the plastic-ice interface, and R3 is the radius of the gas-ice interface.

The program then averages the values of R3 for views 180 degrees apart, and graphs it in comparison to the actual surface (determined through the spherical harmonic sum). The averages were found to correspond well to the true surface, with an error of about 0.2 microns.

The original program was modified to change the angle of the cameras. One camera was kept at 0 degrees, for purposes of comparison. The other camera was elevated to 12.6 degrees corresponding to an actual shadowgraphy view used on Omega. The cameras would take data at 25 positions. The slanted camera was unable to obtain opposite views, so it averaged views in a slightly different way. For example, in Figure 6, the red and blue circles are opposite views as seen by the slanted camera. (The tilt is exaggerated.) The bright ring radii at point A and point B would be averaged in order to determine the bright ring radius at point C.

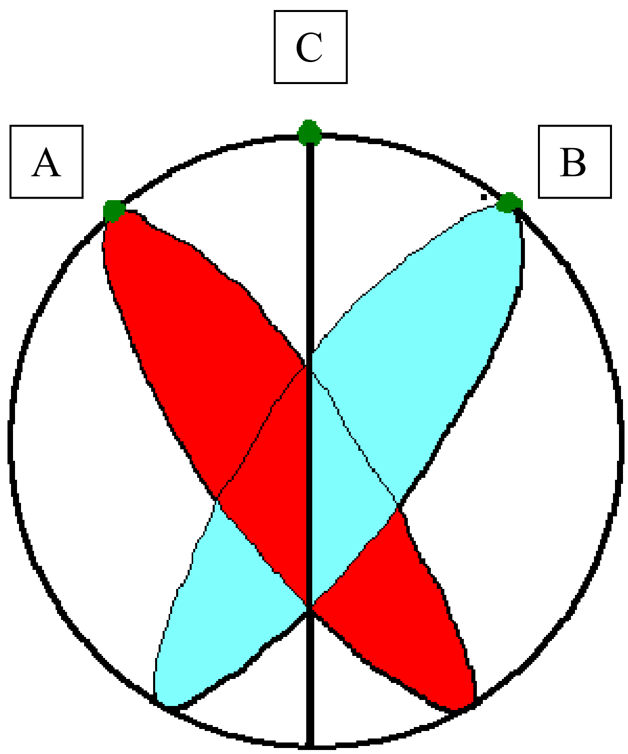

Fig. 6: The blue and red circles are the exaggerated views of the target taken 180 degrees apart seen by a slanted camera.

Results

The averaging of two slanted views yielded the graph in Figure 7. This method is relatively accurate for gradual changes in the ice surface. Thus, the overall shape is fairly accurate. However, for sudden changes in the surface radius, such as occurs between 225-275 degrees, the average values are unable to accurately predict the surface. This could be because, were the nonuniformity to occur between points C and B of Figure 6, the camera using the blue view would be able to detect the nonuniformity, but the camera using the red view would not. However, if the camera was equatorial, this problem would not occur.

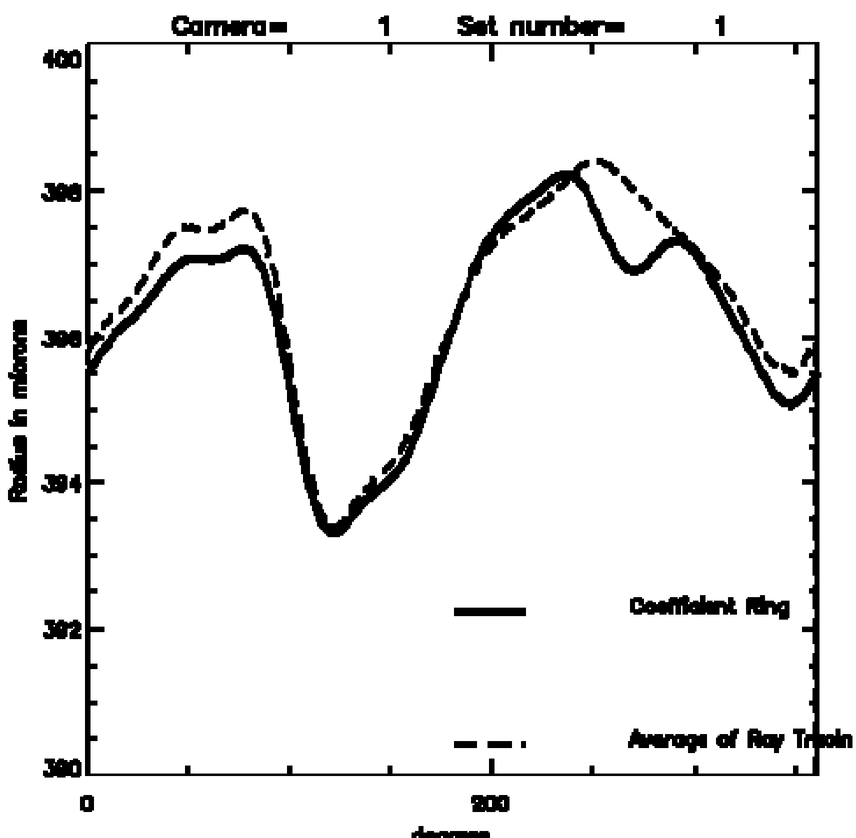

Fig.7: The actual surface (solid graph) vs. average of two slanted views (dotted graph).

Conclusion

The average of opposite views using the camera at 0 degrees yielded excellent results, with an error of about 0.2 microns. The averaging of opposite views using the slanted camera works relatively well for gradual non-uniformities (modes up to $n = 5$). Thus, the program is able to predict changes in the thickness of the ice layer that occur slowly over a large area. However, if there are irregularities localized to a small area, the camera may be situated so that the defect can only be seen in one view. Thus, slanted cameras view different surface perturbations than equatorial ones. Improved characterization is possible with two slanted views, but only for long-wavelength nonuniformities.

Acknowledgements

I would like to thank Dr. Craxton for allowing me to work at the Laboratory for Laser Energetics as part of the High School Summer Research Program. I would also like to thank Dr. Edgell for all the help he has given me as my advisor. I would also like to thank the other students in the program and Bruce Brewington for their support and friendship.

References

[1] Jin, Sharon "A Ray-Tracing Model for Cryogenic Target Uniformity Characterization" 2002 Summer High School Research Program at the University of Rochester Laboratory for Laser Energetics.

[2] Balonek, Gregory J. "How Good is the Bright Ring Characterization for Uniformity of Deuterium Ice Layers within Cryogenic Nuclear Fusion Targets?" 2004 Summer High School Research Program at the University of Rochester Laboratory for Laser Energetics.