Modeling Damage Propagation on the OMEGA EP Laser

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1. Abstract

A set of tools was created to simulate the propagation of the OMEGA EP laser after being reflected off a damaged optic. The simulations can be used to assess laser damage threats to subsequent optics due to modulations in the propagated beam. Microscope images of damage on a final OMEGA EP UV target mirror were processed and used as inputs to the simulations. The simulations were validated by comparison with actual propagation images of the same damage regions. The acquired actual propagation images had significant background artifacts due to the camera and laser illumination source that were removed before comparison with the simulations. After the simulation tools were tested, they were used to determine the size of damage on the UV target mirror that would pose the greatest threat to the UV focus lens in the OMEGA EP laser. These tools will be used in the future to evaluate the damage threat to additional critical OMEGA EP final UV optics, such as the distributed phase plate and the vacuum window, in an ongoing attempt to increase UV performance on OMEGA EP shots by better understanding UV optics damage.

2. Introduction

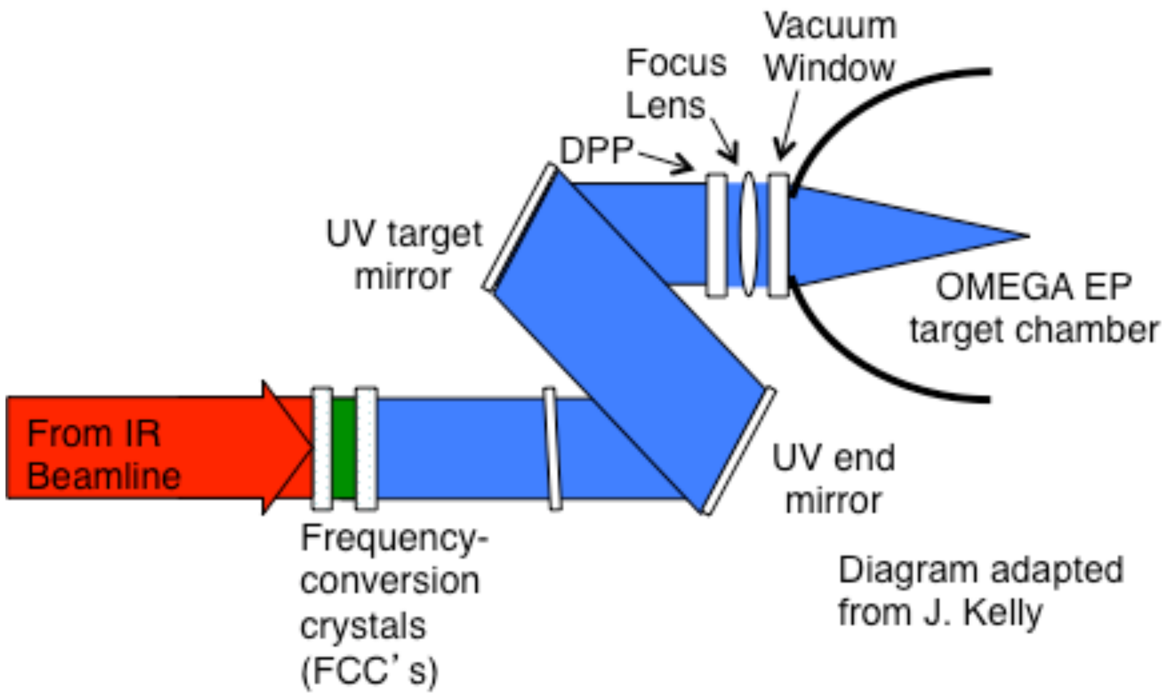

Figure 1: The final UV optics on the OMEGA EP laser. The DPP, focus lens, vacuum window, and UV target mirror are shown.

Damage issues related to the final UV optics limit the energy available from the OMEGA EP laser. These optics, shown in Figure 1, start at the frequency conversion crystals where the IR beam is converted to the UV and include two mirrors, a distributed phase plate (DPP) used to smooth the beam, a focus lens, and a vacuum window. The issue of damage on the final UV optics of OMEGA EP was discovered in August 2014 and has led to reduced UV energy limits for most shots. In this situation, a part of the beam was reflected back (a ghost beam), was highly modulated by the DPP, and came into focus near the UV target mirror, resulting in heavy damage in a central square region on the target mirror. This problem has since been resolved by moving the target mirror so that the beam would focus farther from the UV target mirror. Despite eliminating this damage mechanism, there still is some minor damage occurring on the target mirror. The cause of this damage is unknown, but damage appears to occur randomly over the whole mirror. For the purposes of this work, damage is defined as areas that scatter or diffract light, as opposed to reflect (for a mirror) or transmit (for a lens or other transmissive optic). The damage causes intensity modulations in the main EP beam, which then threaten to damage the downstream final optics including the DDP, the focus lens, and the vacuum window.

While damage does occur to other UV optics, most of the damage that propagates to the final optics is from the UV target mirror, because the target mirror is the closest to these final optics. Therefore, the project focused solely on studying damage propagating from the UV target mirror. These optics are costly and difficult to replace, and as a result, reduced energy limits are set to prevent damage to the final UV optics, meaning the laser is not being used at full capacity. A simulation of damage propagation will be helpful because it allows users to predict how the damage will propagate before the laser is actually shot, therefore hopefully preventing damage on the final UV optics.

3. Experimental Setup

3a. Acquisition and processing of microscope damage images

First, the simulation of damage propagation was verified by comparing it to measured images of actual propagation from damaged regions. In addition, microscope images of damaged regions were obtained, both for studying damage morphology and for use as input to the damage propagation simulations. Using a damaged optic that had been taken off OMEGA EP, the technique for visible-light microscope imaging was developed in an off-line lab. After taking images of damaged regions with both an off-axis plasma light source and an on-axis ring light that was attached directly to the microscope, it was clear that the ring light provided clearer images, as shown in Figure 2. After the technique was tested in the lab, it was used with optics still installed on the OMEGA EP laser. Images were taken of multiple damaged regions on the UV target mirror. Only a small portion of the mirror that showed significant damage was imaged. Figure 2 shows a zoomed-in portion of one of these images to more clearly show the detail in one of the damage regions. The size of the imaged region was essentially limited by the microscope that was used and the distance away from the mirror in which it was possible to image the region clearly. So, the imaged region was always much smaller than the 35 cm beam diameter.

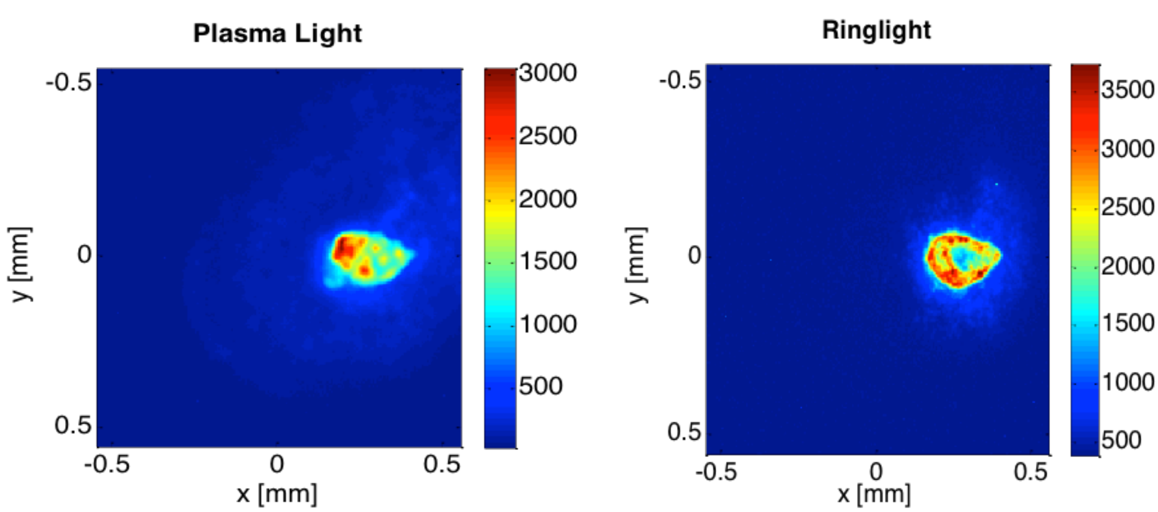

Figure 2: Damage spot imaged with plasma light source and damage spot imaged with ring light. The ring light was selected since that image shows more detail in the damaged region.

Because the OMEGA EP laser operates in the UV, but all microscope images are in visible light, the microscope images had to be interpreted to be applicable to what would actually propagate through the final UV optics. When the microscope images were taken, the visible light that is scattered shows up as bright regions on the image. The rest of the visible light passes through the mirror since the mirrors are specifically designed to reflect UV light, not visible light, and will show up as dark regions in the image. Therefore, it is assumed that dark areas are undamaged and will reflect the light well in the UV spectrum. In addition, it is assumed that areas that scatter visible light will also scatter UV light, and therefore these areas are considered damage. To apply these interpretations, the microscope images of damaged regions needed to be inverted, so that damage areas become low pixel values and areas that are assumed to reflect UV light become high pixel values.

In order to invert these images, first all the values were normalized by dividing by the maximum value. This ensures that all of the pixel values in the image are between 0 and 1, and all the values can simply be subtracted from 1 to get the inverted image. Following these steps, all the pixels values are divided by the median value. Since the background is relatively flat and large in comparison to the damage, it is reasonable that the median of the image will essentially be the background value, or region of high UV reflectance, therefore making the values of most background pixels roughly 1. The normalization is important because it allows different images, which may have different pixel values at first, to be compared side by side.

Next, the modified image is thresholded to create a transmission mask. This allows the image to be interpreted so that all values below a certain cutoff limit are considered damage, and all of the light that passes through these areas will be scattered. In practice, image values from the microscope image of damage that are below the cutoff limit are set to 0, indicating that no light is reflected in these regions. This cutoff limit may have to be varied from image to image, but generally it was found to be around 0.8.

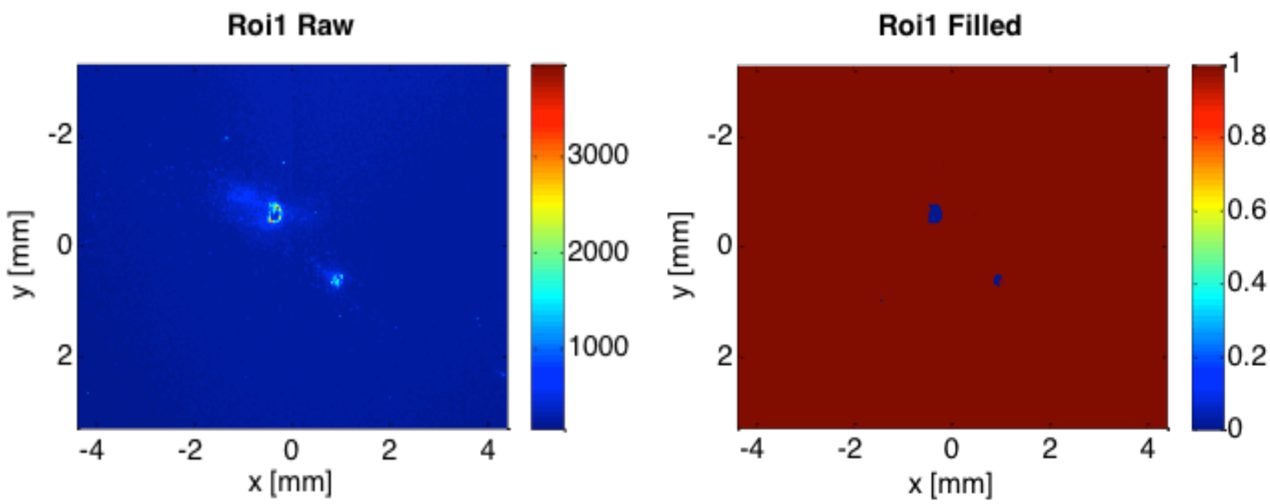

Figure 3: Original damage image and the corresponding transmission mask. The left shows the original damage image that was taken via a long-working-distance microscope. The right shows the transmission mask, which is the modified image after it is inverted, normalized, and has the damage spots filled in.

In microscope images of damaged regions, the center of damage often appears dark, as shown in figures 2(b) and 3(a). But it is assumed that the center is still damaged even though the area no longer scatters light. Therefore, the “holes” that appear on the image after thresholding are treated as damage, and filled in and set to 0. An example of the final transmission mask created after all these steps is shown in figure 3(b), which may be compared with a microscope image of that damaged region shown in figure 3(a). The original image is then multiplied by the transmission mask in order to make the image more realistic by including some of the minor background noise, which may potentially be smaller damage sites. This multiplication preserves the damage regions because they have been set to zero already by the thresholding. Next, a super-gaussian border must be added to the modified microscope damage image. A super-gaussian border can be thought of a mathematically determined edge to the image, so that the color gradually slopes downward from pixel values of roughly 1 to pixel values of 0. The purpose of the super-gaussian border is to limit artificial diffraction around the edges of the image during the simulation, which would otherwise occur due to the steep drop-off from the background of the image, which has pixel values of around 1, to the edge of the image. This artificial diffraction occurs because the image ends abruptly due to the fact that the image is not actually the entire beam. The super-gaussian border reduces this diffraction because it gradually transitions from ones to zeroes at the edges of the image. In order to add this transition at the edges, the modified microscope image of the damaged region is extended in all directions to ensure that when the Gaussian border is added, none of the microscope image of the damage region is disturbed.

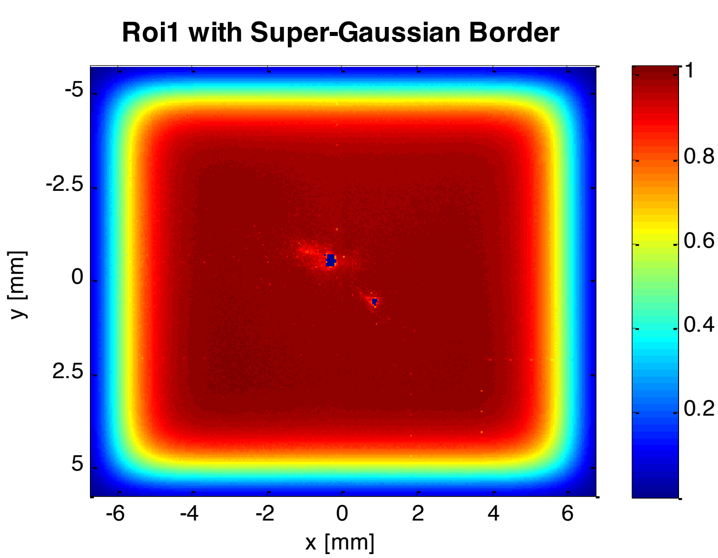

Figure 4: A damage region just before it is inputted into the simulation, modified by the addition of a super-gaussian border around the edges. The image is artificially enlarged so that no information about the damage region is lost.

Finally, before inputting the image into the simulation, the images were converted from intensity to electric (E)-field magnitude. The microscope images directly measure intensity, but the input to the Fresnel Propagation program (described below) must be E-field magnitude. The images are converted according to:

$$|E| \propto \sqrt{I}$$

3b. Simulated propagation of damage images

After these steps, the microscope damage images were processed by a Fresnel Propagation code to study how the damage regions modulate an input beam at various propagation distances. The code, developed by LLE scientist, Brian Kruschwitz, is based on an algorithm in Ref. 1. The code simulates the propagation of light at a specific wavelength to a certain distance, which can be inputted into the code. A set of output propagation images is shown on the left of Figure 6 below. Care is also required to properly set the spatial sampling size for the simulation, in order to produce output images that can be subsequently compared to measured images of a modulated beam. After propagation, the code returns the E-field magnitude at each pixel location, which is then converted back to intensity.

A few additional manipulations were performed on the simulated damage images in order to process them in the same way that the measured propagated damage images were processed, as described below. In particular, the images were median filtered in an 110 µm, or 20x20 pixel, box for the images that were used. Median filtering is the process of setting every pixel equal to the median pixel value of a box of a specified size around it. This smoothens the image and makes it more realistic in this case. The last step before comparison is removing the super-gaussian borders by simply displaying the region inside of the borders, since these were artificially added.

3c. Acquisition of actual propagation images

In order to verify the simulation, the simulated propagation images were compared with actual propagated images. To do this, propagation images were taken on the OMEGA EP laser using a UV alignment laser beam; an example image is shown in figure 5. Images were taken at varying propagation distances from the OMEGA EP optic of interest (the UV target mirror) from 41 cm to 81 cm at increments of 10 cm. Before comparison with the simulation, artifacts in the measured propagation images had to be eliminated. Artifacts in the propagation images were due to the UV alignment beam, which is not perfectly flat. As a result, there were areas of high and low pixel values in the background that would affect the image statistics if they were not removed. To do this, the image was first median filtered with a 200x200 pixel box. The 200 pixel box is quite large, so it

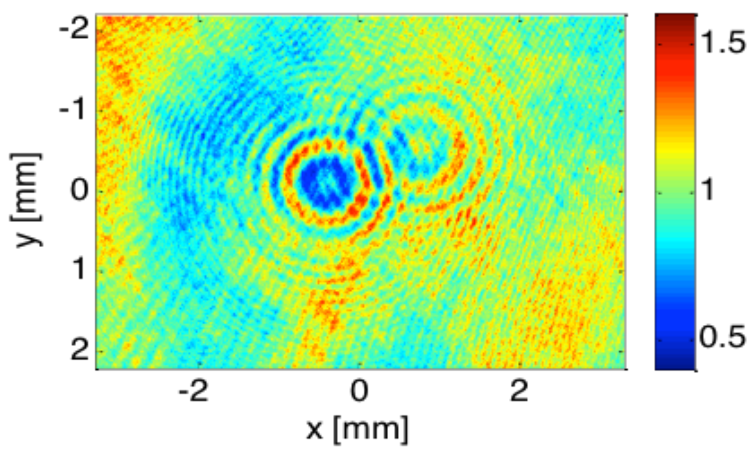

Figure 5: A raw damage propagation image from the OMEGA EP laser. There are image artifacts that need to be eliminated prior to comparison with simulated images.

effectively removes the damage spots, which are small relative to the size of the background. However, it mostly leaves the large-scale features of the UV alignment beam. As a result, the median filtered image can be subtracted from the original image to leave the damage spots with a relatively flat background. The resulting image is then median filtered again, this time using a 20x20 pixel box. This removes fringing in the image due to interference in camera optical elements. In order for the images to match up visually, the actual propagation images were also rotated to match the orientation of the initial damage site microscope images.

4. Analyzing the images

The actual and simulated propagation images were compared qualitatively and quantitatively to validate the simulation results. Figure 6 shows that the images display many qualitative similarities, particularly with the size and amplitude of the diffraction pattern peaks and valleys, throughout all distances, from 41 cm to 81 cm. Figure 6 includes the actual and simulated images from the damage image in Figure 5. Quantitative analysis was performed on the pixel values from the images to measure the modulation of the beam as a result of the damage on the target mirror. One important measure of the modulation enhancement is the peak-to-mean ratio for a damage propagation image. The peak is the brightest pixel in the image and, in this case, the mean was essentially 1 because the background was normalized to 1 for both the measured and simulated images. The peak-to-mean value is significant so that these images can be more generally compared with other images that are not normalized, such as beam profiles of the OMEGA EP UV beam itself. It can also be seen that the diffraction pattern size is the same in both the simulated and actual propagation at the varying distances.

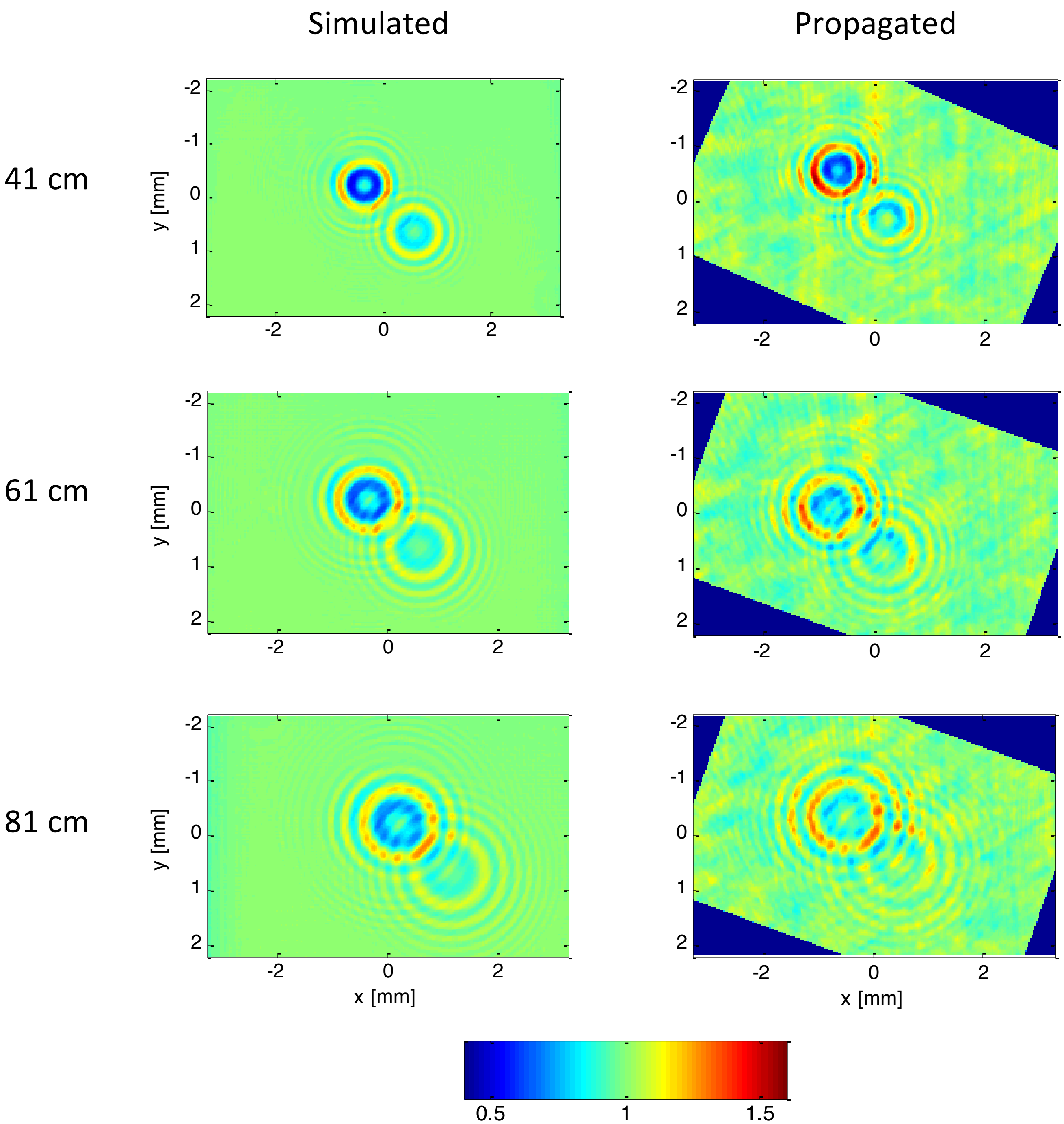

Figure 6: A side by side comparsion of the simulated and actual propagation images at varying distances. Simulated images are shown on the left; measured propagation images are shown on the right. In all of the images, there is good agreement between the size and amplitude of the propagating diffraction pattern resulting from damage on the UV mirror being studied.

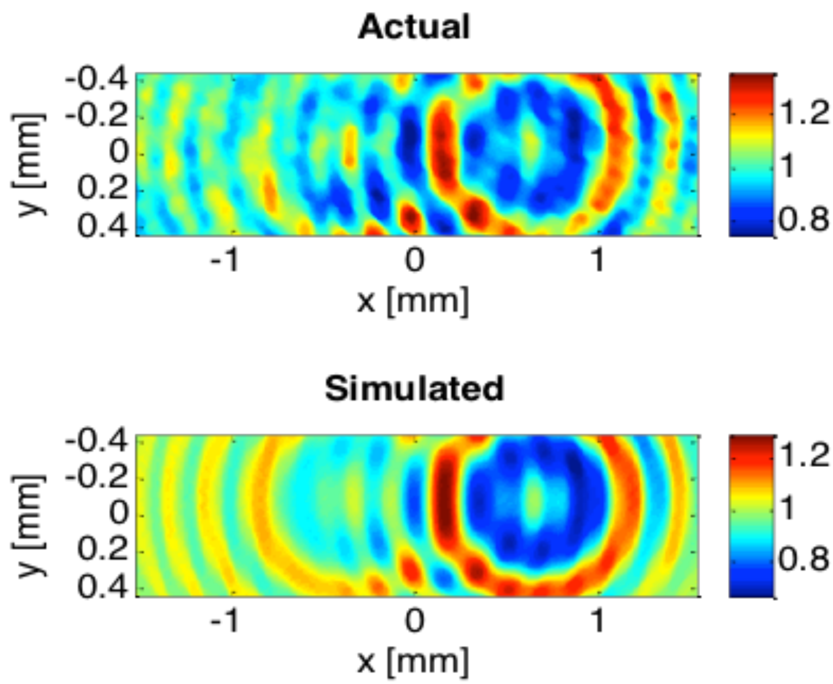

Figure 7: A close up comparison of the damage regions in both the simulated and actual propagation images. These regions were used to generate the graph shown in figure 9.

In addition, line plots were made to compare pixel values in corresponding regions of the simulated and measured damage propagation images. A program was written to create such a line plot over a specified box size, and at an arbitrary angle, in both measured and simulated images. Figure 7 shows close-up intensity contour plots of the damage regions shown in Figure 6 at 81 cm. This gives a visual comparison of the structures in the two images. Figure 8 gives line plots corresponding to Figure 7, found by averaging over the whole vertical region shown in Figure 7. Figure 8 shows close similarity between the propagated and simulated regions with the shapes of the diffraction patterns in good quantitative agreement.

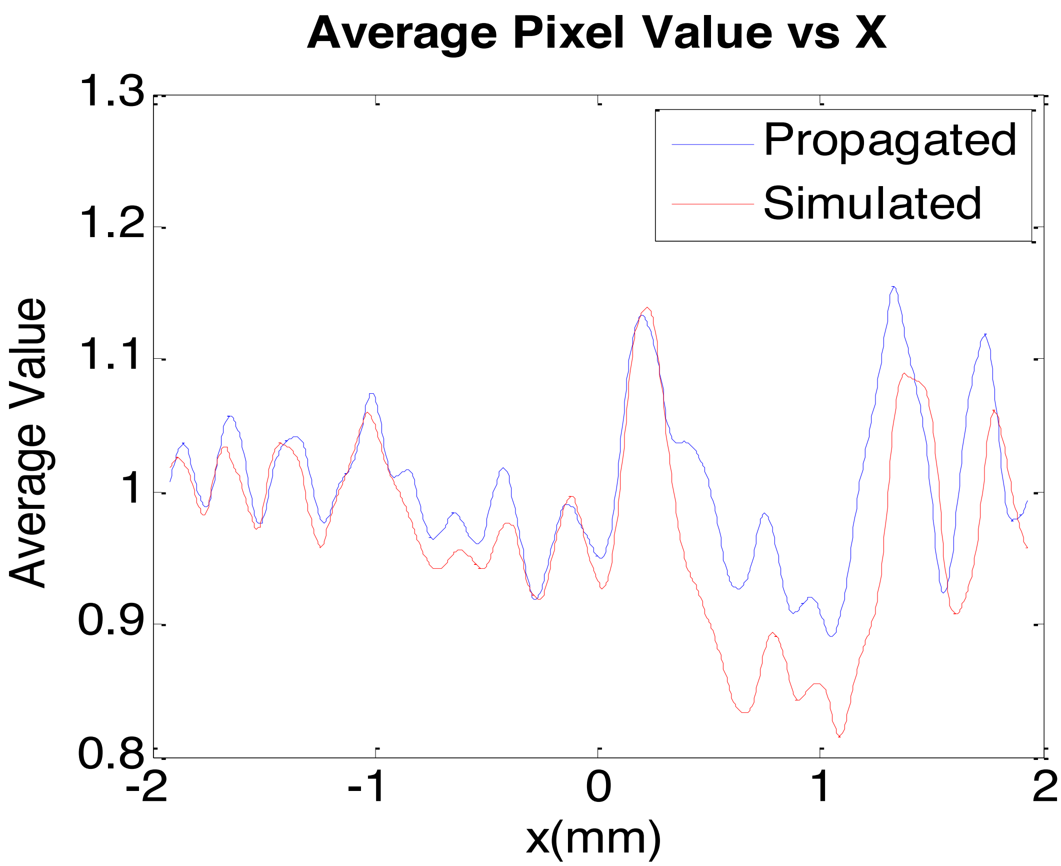

Figure 8: Plots of the average pixel values (found by averaging vertically in the entire damage region against horizontal distance). The propagated and simulated match closely, in both shape and intensity.

5. Applications and Future Possibilities

This simulation program can be used in the future to predict how damage will affect the laser before a shot is actually taken. Most importantly, the simulations can be run with actual optic damage taken from the laser, to predict whether that damage is harmful to the final UV optics on the laser. Additionally, these simulations provide insight into how real damage propagates. Applications of these simulations also include using them to find the size of damage that will result in the greatest effect on downstream optics at a fixed distance, or the distance at which a fixed size of damage will result in the greatest damage to downstream optics.

6. Conclusion

In this project, a set of tools was created and verified to simulate downstream propagation of damage from the UV target mirror on OMEGA EP. The tools were shown to result in simulated propagation images that have reasonable agreement, both quantitatively and qualitatively, with actual propagation images taken on the laser. Downstream propagation is a concern because it threatens to damage expensive final UV optics in the OMEGA EP laser, including the distributed phase plate, the focus lens, and the vacuum window. Energy limits are currently imposed in order to preserve these optics, but as a result of these simulation tools, there is the opportunity to better understand which shots and which pieces of damage will have the greatest effect on the downstream optics. This work is part of an ongoing effort to increase the overall UV performance on shots with the OMEGA EP laser.

7. Acknowledgments

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References

[1]Fienup, J. R. "*Phase-retrieval algorithms for a complicated optical system.*" Applied Optics 32, p1737-1746 (1993).