Laser Beam Propagation in Fog

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Introduction

As a preview to our term project, we used this lab to introduce many ideas that we will explore later. The ideas in this lab we explored were how the laser beam propagates in a medium that has a partially opaque quality in order to observe beam scattering and how to properly observe the beam. By taking videos of the beam from an orthogonal angle as well as a direct view, we can observe the beam and measure qualities of the beam; specifically the scintillation index and relative intensity as the beam propagates through fog. Using both expanded and unexpanded beams, we drew conclusions as to which type of beam propagates better in terms of scintillation index and relative intensity. This comparison will be helpful for later experiments.

Setup

Five main components existed for this experiment. The laser source has a 632.8 nm wavelength and 2 mW power with expander implemented or not; one camera oriented orthogonal to beam projection with a 75mm lens, connected to a computer with image processing software; one camera placed 2.25 m downrange of the source with 1.5 power neutral density filters and a red light filter connected to its own computer with with image processing software; a clear, rectangular prism plexiglass container to hold the fog; and a water-based fog machine composed the experiment. The setup is shown in Figure 1. All experimentation was done in a dark classroom. The temperature in the fog container varied between *69.3* °F and *69.6* °F while the humidity remained a constant 49%, even with fog.

By far, the trickiest portion of the experiment was the fog density in the container. With too much fog, the direct view camera would not be able to sense the beam, and with too little fog, the beam would saturate the camera's sensor. Even during the period of the videos taken, both side view and direct view lasting approximately 30 seconds, the fog level changed noticeably enough to affect the images of both cameras at a certain setting. To compensate for this required "active trimming" of the fog machine. That is to say that the fog machine was turned on until the density was slightly more than needed for the camera settings and turned off, the cameras were triggered to record, and towards the end of the recordings the fog machine was turned back on to recover declining fog density. Although this method is imprecise from a scientific point of view, it is applied to every capture such that there is consistency among experiments and therefore results.

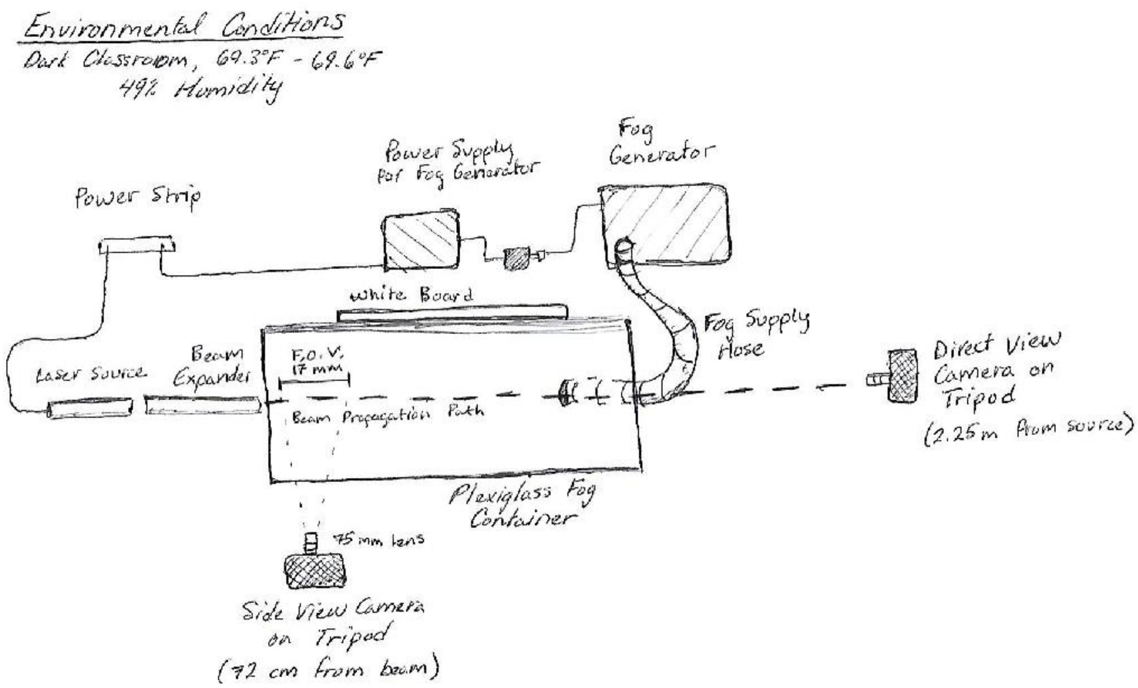

Figure 1 Sketch of laboratory setup

A less challenging area of the experiment was the camera settings themselves. Both cameras had different settings in order to best view their respective portions of the beam. We set a goal of a clear beam for the side view, requiring us to focus the lens prior to experimentation to the distance that the beam would propagate in the box. Ultimately, the side view camera had a field of view at 17 mm at the location of the beam propagation path. For the level of density of fog used in the experiment, this was sufficient to observe beam intensity loss. Further settings include exposure time to 40 ms and an intensity range of 0 to 5000 in the camera's software settings. These were applied to both expanded and unexpanded beam experiments. The direct view camera was set to 17.5 ms exposure with 1.5 power neutral density filters and a red filter applied to the sensor. This camera's image was the determining factor for fog density levels and flow rate as it was the most sensitive indicator to change.

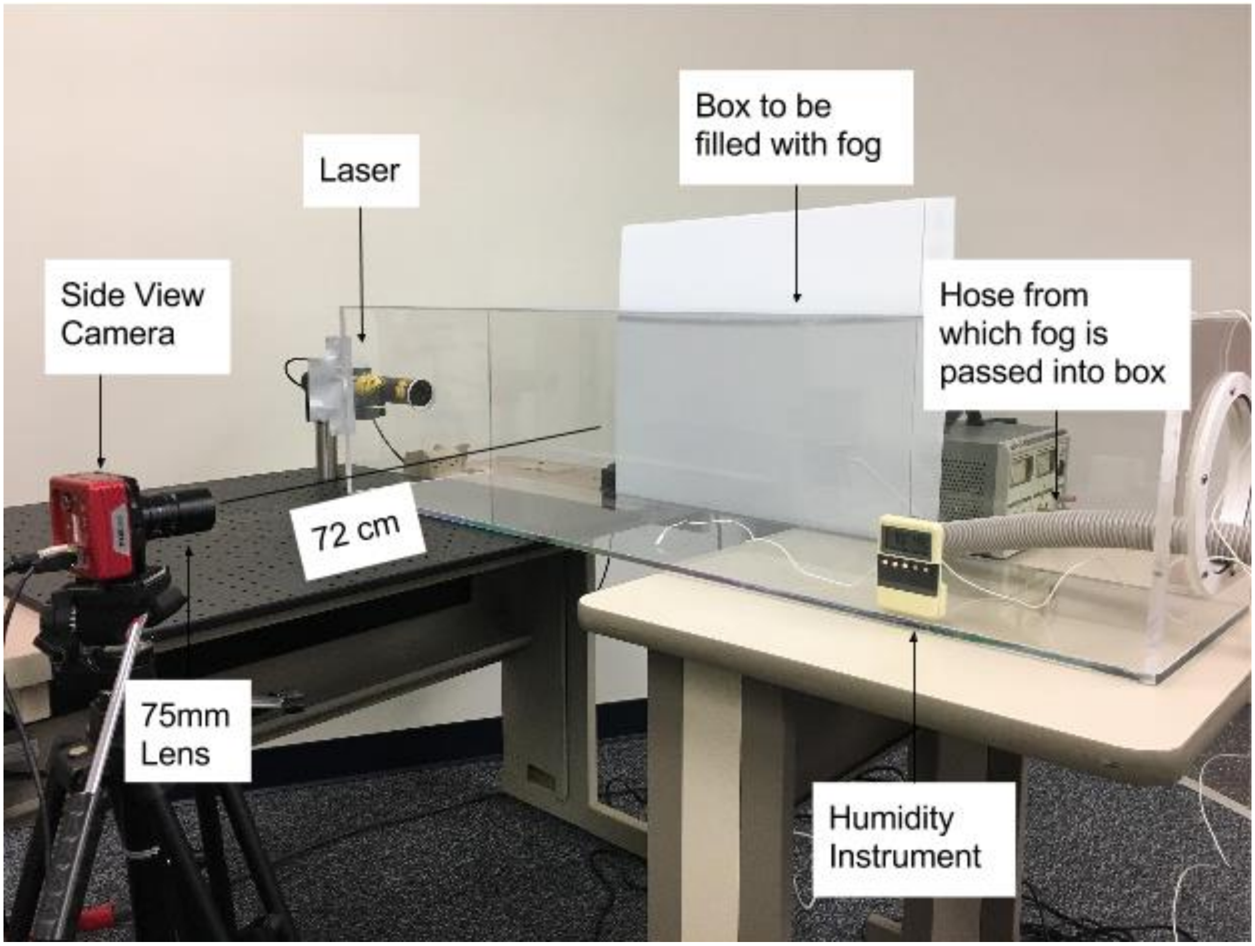

Figure 2 Laboratory Setup

Results and Analysis

We processed the video data for mean, variance, and scintillation index for both the expanded and unexpanded beams. Once this task was complete, we were able to view the results as depicted and further discussed below; starting with the view of the beam shot directly into the camera and finishing with the side view of the beams.

For the direct view videos, the mean, variance, and scintillation index was calculated for each pixel. These values for both the expanded and unexpanded beams are compared directly by graphing them in together in the same figures. The direct view functions primarily to determine how much of the beam makes it through the 1.22 m of fog that the container provides. The most conclusive result that came from the direct view measurements is the value of the mean relative intensity for each beam, shown in Figure 5. Integrating under the curves, we can determine that the expanded beam passes more energy through the fog, though the unexpanded beam passes a higher peak intensity. This leads us to the conclusion that in a maritime environment with fog, an expanded beam will have less intensity loss than an unexpanded beam. It would be worth noting, however, that we experimented on the order of a meter; whereas an actual application might require the order of a kilometer. Another notable conclusion is that the value of the scintillation index for the expanded beam is lower than that of the unexpanded beam; an average of 0.75 to an average of 7. Again, this leads us to the conclusion that the expanded beam propagates more consistently and smoothly through the opaque medium.

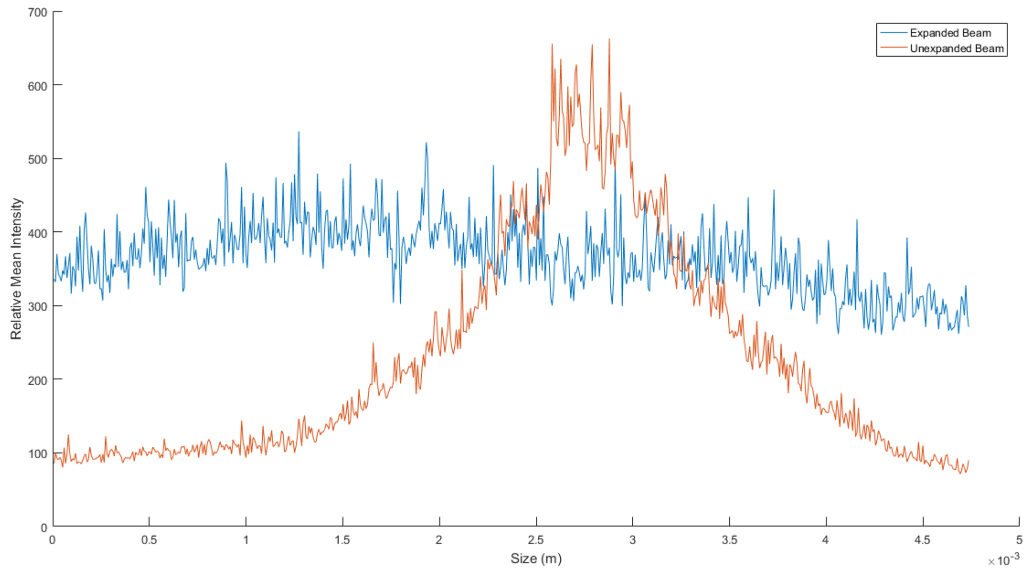

Figure 3 Mean intensity of the unexpanded and expanded beams shot directly into the camera.

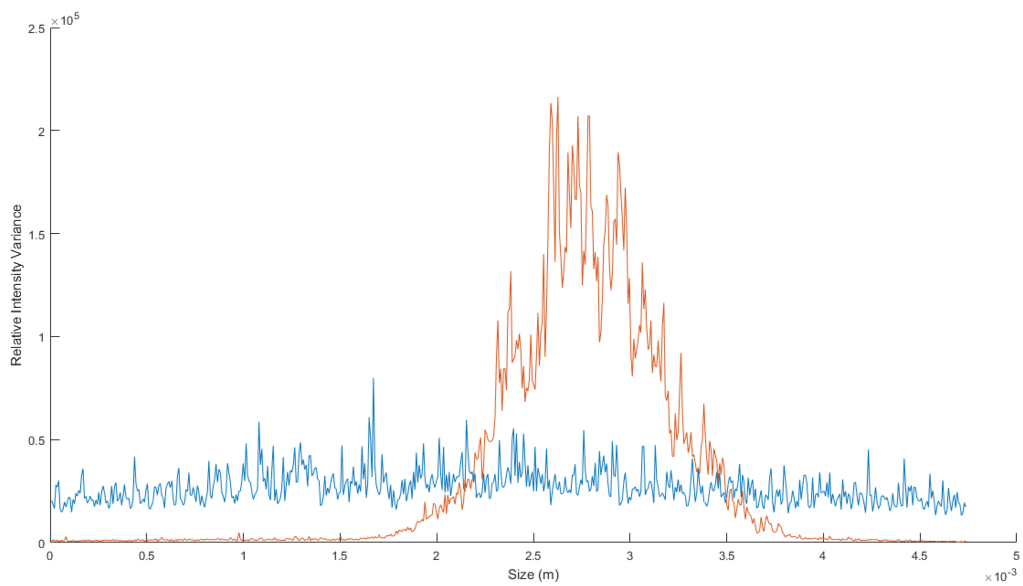

Figure 4 Variance of the unexpanded and expanded beams shot directly into the camera.

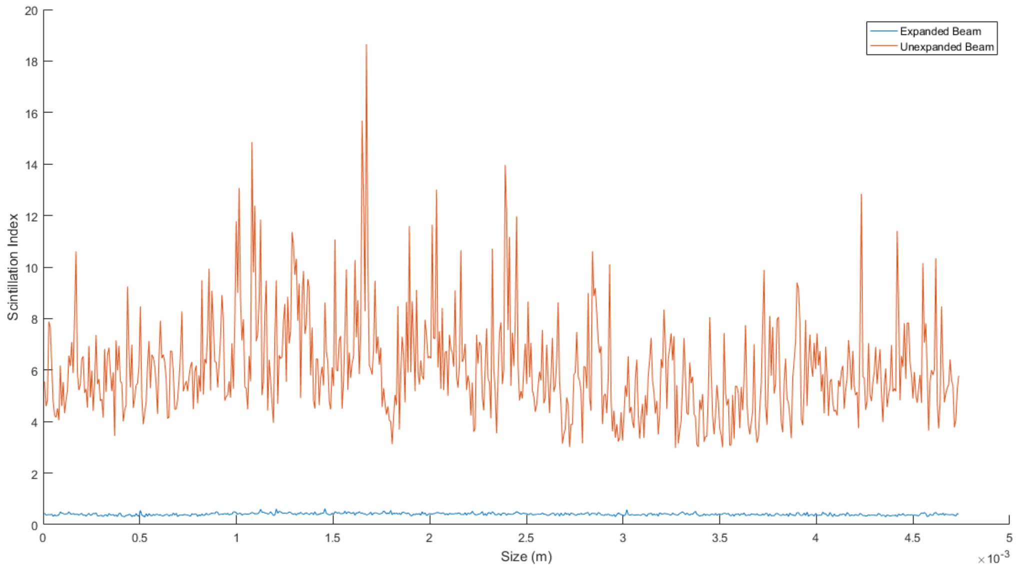

Figure 5 Scintillation index of the unexpanded and expanded beams shot directly into the camera.

As with the direct view images, the mean, variance, and scintillation index for each pixel of the side view images. The side view offers a more comprehensive observation of the scattering of the beam in the fog. FIgure 6 shows the spreading of both beams on the same color scale for easy comparison.

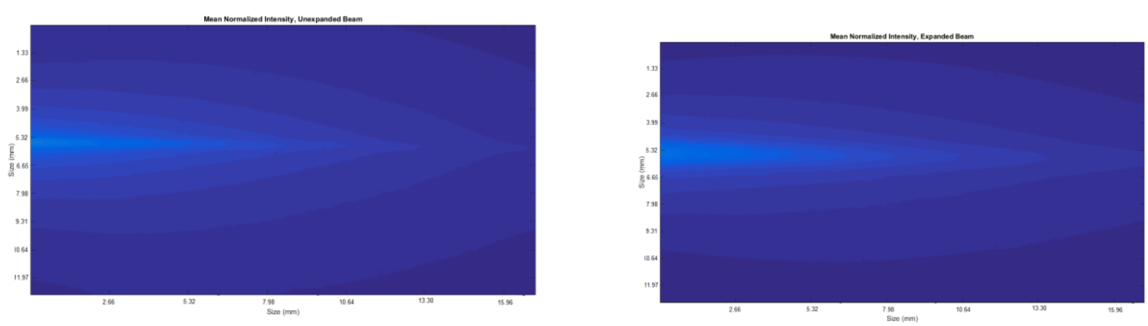

FIgure 6 Comparison of mean relative intensity of unexpanded and expanded beams. Scattering of the beam is evident by the decrease of relative intensity in these images over the field of view, which is 17 mm at the beam propagation path.

As shown in this figure, the expanded beam penetrates more deeply into the fog with less overall scattering when compared to the unexpanded beam. The fog has the property of distributing the relative intensity of each beam in a smooth and shell-like manner, such that both beams have an even spreading pattern. This image reminds one of the old driving adage that says to “turn on low beams in the fog, not high beams.” The higher peak intensity of the unexpanded beam causes more initial scattering than the lower intensity expanded beam. Affecting the mean calculations for the beams was not only the scattering but the swirling of the fog as well. This is apparent in the videos taken, and is taken into account more with the calculation of the scintillation indices. One final observation from these figures is the difference in size of the initial beam widths.

Values for the scintillation index of each beam are shown in Figures 7-10. Observations that encompass the expanded and unexpanded beam include increased scintillation at the beam entry points and decreased scintillation on the beam propagation path. The actual spreading of the beam is well represented in the following figures as areas of low scintillation. One note on the spreading between beams is that although the unexpanded beam enters the foggy medium at a tenth of the beam width of the expanded beam, both beams exit the field of view at approximately the same beam width. This suggests that the unexpanded beam has a higher rate of spreading, a fact that supported by previous experiments in non-opaque mediums and mathematical prediction.

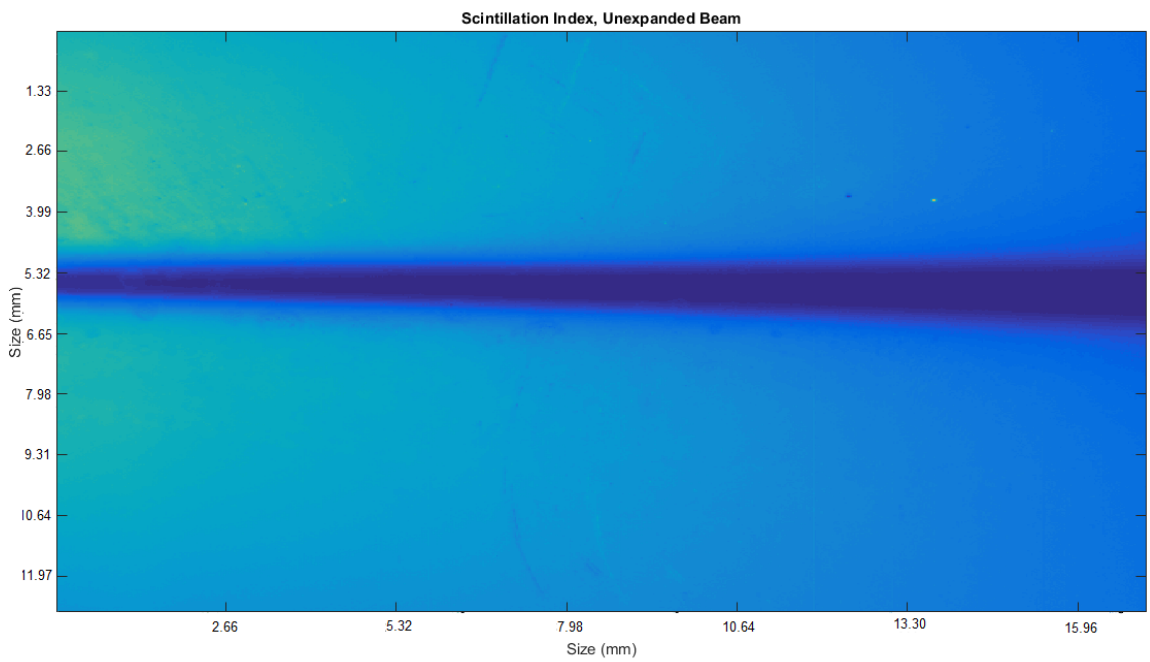

Figure 7 Scintillation index of the unexpanded beam through a foggy medium. The darker colors signify less while the lighter colors signify more scintillation.

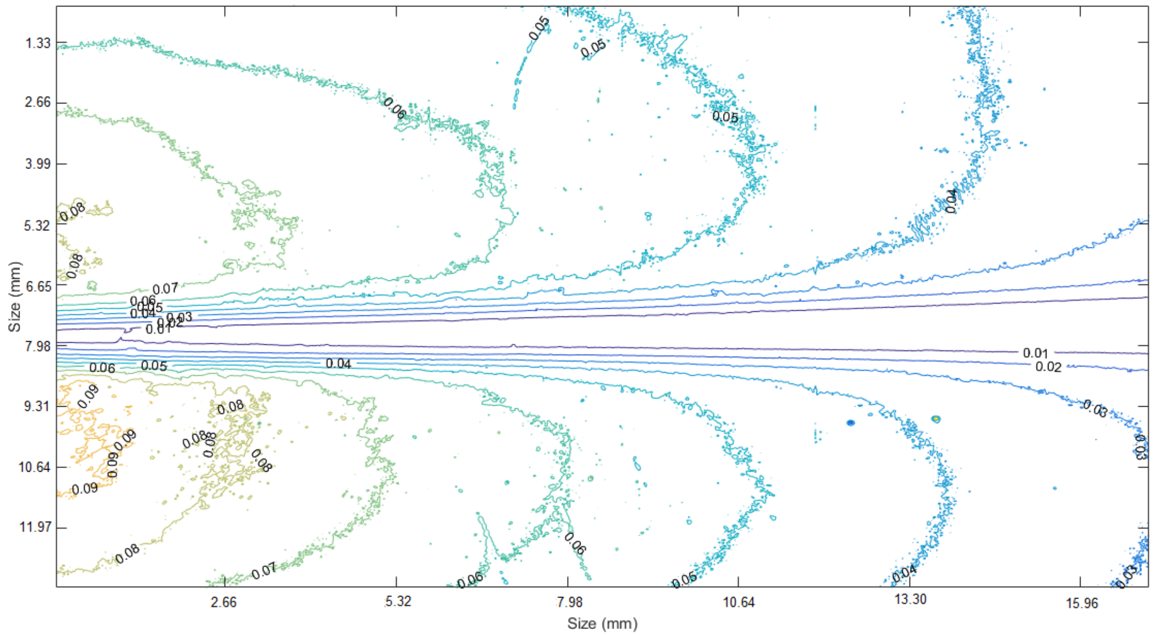

Figure 8 Contour map of the scintillation index of the unexpanded beam. The contours are labeled with the value levels they represent.

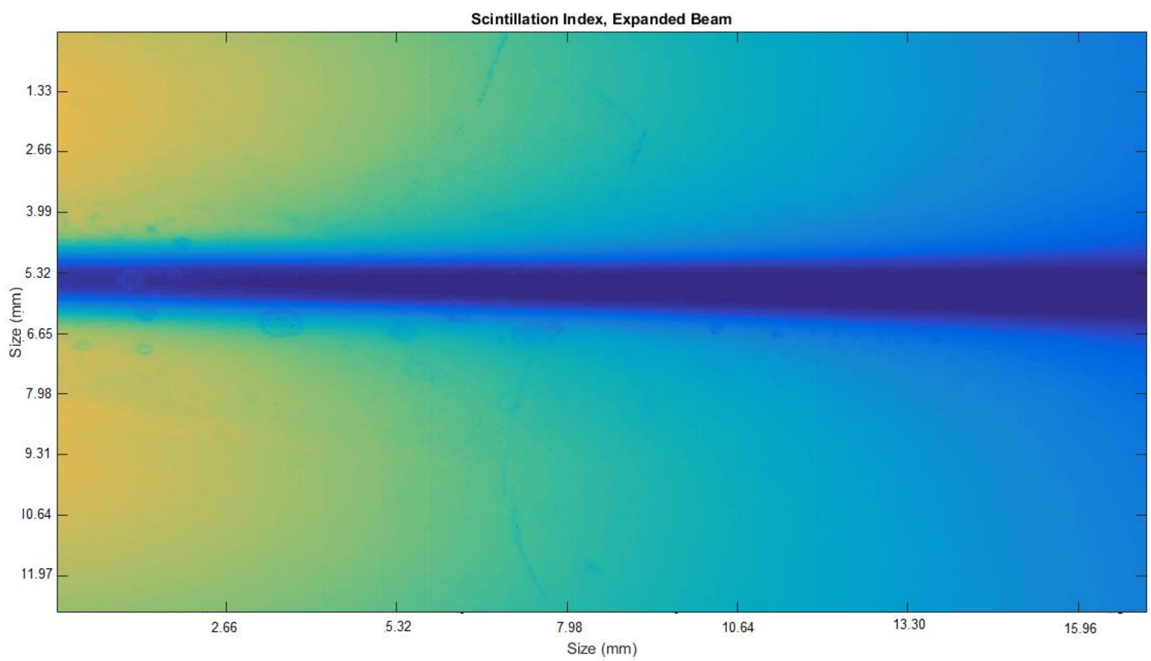

Figure 9 Scintillation index of the expanded beam through a foggy medium. The darker colors represent lower values of scintillation while the lighter colors represent higher values.

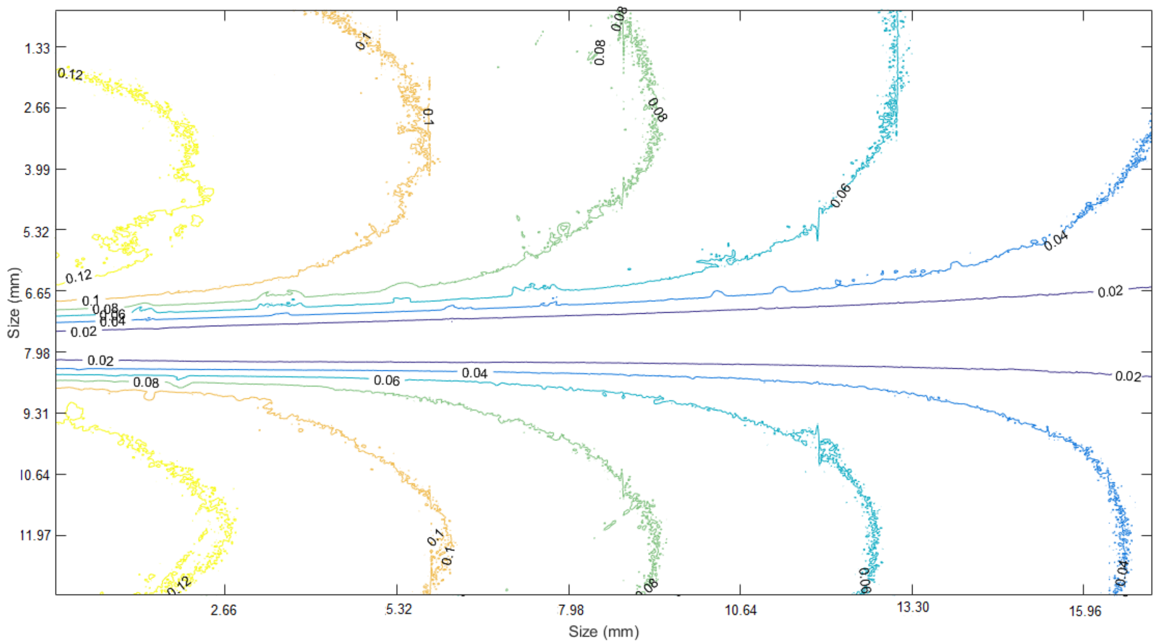

Figure 10 Contour map of the scintillation index of the expanded beam. The contours are labeled with the values of scintillation they represent.

A final observation on scintillation index: the expanded beam has higher values of scintillation index over the range of the field of view. This could owe to differences in the amount of fog in the container between experiments or higher excitation of the fog. A comparison of these values can be seen in Figures 11 and 12, where cross sections of the scintillation index are taken along the height of the container periodically along the length of the field of view.

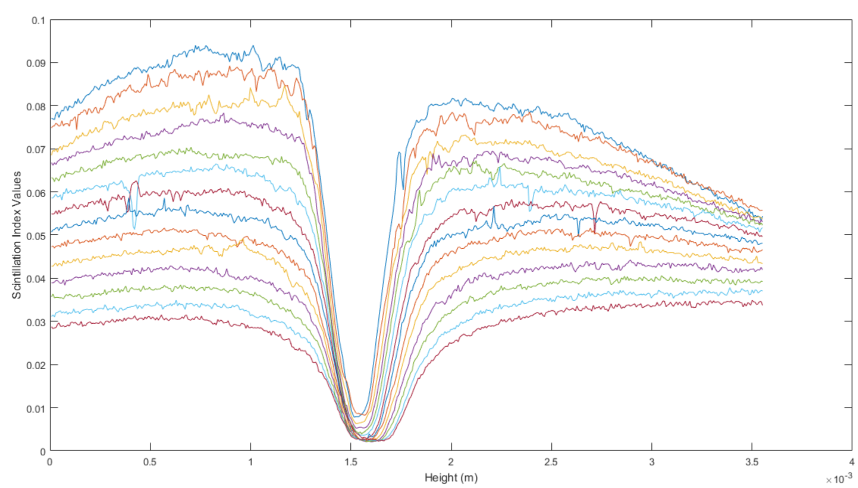

Figure 11 Cross section of scintillation values for the unexpanded beam at regular intervals along the field of view.

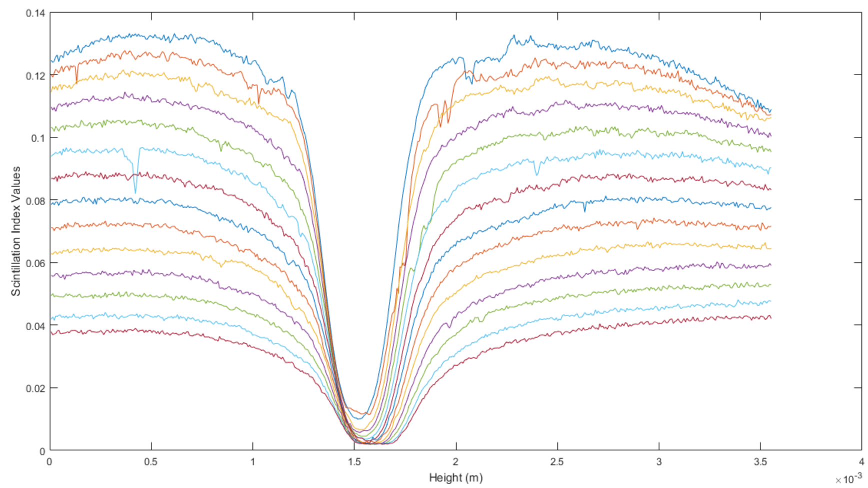

Figure 12 Cross section of scintillation values for the expanded beam at regular intervals along the field of view. Notice these values are higher than those of the unexpanded beam.

Conclusion

As can be seen from our results, the expanded beam overall is more uniform than the unexpanded beam. This is especially made apparent through the Figure 5, when comparing the scintillation of the two beams. A conclusion that could reasonably be drawn from Figure 5 in particular is that even though complications arise when shooting a beam through some form of turbulent medium, there are always steps that can be taken to mitigate the disturbances in the beam. In this case, that measure was to expand the beam.

The biggest takeaways from this lab are actually the experiences gained in shooting through a complex medium. We can translate many of these lessons learned in order to help us shoot through water for the term project. One of the biggest of these lessons is that when shooting through an opaque medium that causes lots of scattering, the best picture is made possible through an extended exposure time. Other considerations to take into account are the distance from the lens to the path that the beam is actually propagating through in order to achieve the highest level of focus attainable, as well as selecting worthwhile scaling in order to highlight differences and similarities between different runs. All of these lessons learned will pay dividends when we begin our term project.