An Analysis of Laser Light Propagation with Regards to Mean and Variance of Intensity

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Abstract

This project will focus mainly on the behavior of a laser beam propagating in a weak turbulence environment. This propagation will be analyzed through the use of statistics, primarily the mean light intensity and variance of intensity during the propagation. The light source to be used will be a 630 nm, He-Ne Laser, with a power of approximately 2 mW. The project will utilize a spatial Light modulator (SLM) to spatially change the phase of the light at the source in order to make the laser light intensity partially coherent with constant amplitude. The SLM will be used to create Gaussian and Bessel beams. The results of these two different types of beams will be compared over the propagation distance. These changes will aim to reduce the variance of intensity during the propagation, while at the same time, maintaining a high mean intensity of the light at the target. The target, for the purposes of this project, will be a light intensity sensor, a CCD camera. Using the SLM is a novel method attempted in field experiments to create partially coherent laser beams.

I. Introduction

The purpose of this research project is to investigate behavior of red laser light (approximately 630 nm) propagation in a maritime environment. The project will consist of observing laser light propagation in an indoor, weak turbulence environment. The focus will be on observing the variance of light intensity and the average intensity on the target. Data will be analyzed by using the mean and variance to estimate the level of light intensity. The project will focus on altering the phase of the laser light spatially at the transmission point, in an attempt to reduce scintillation and spreading over the propagation distance. This goal will be accomplished with two different approaches, Gaussian beams and Bessel beams. After the completion of data gathering, the results will be analyzed to determine which approach was more successful. The final objective of this project is to learn patterns in the behavior of the laser light and then creating a model to represent the laser light propagation.

The problem that this project addresses is laser light intensity fluctuations that exist during propagation. Light has inherent variations; this project will focus primarily on reducing the variance of intensity on the target. The primary performance metric by which the success will be measured will be based off of the mean, μ, and variance, σ^2, of the intensity. A higher μ will mean that more light, on average, is impacting the target during the laser shot. This is important because the average light intensity is directly proportional to the ability of a laser weapon to heat and destroy a target. A smaller variance will mean that on average, the intensity of light impacting the target deviates less from the average intensity. Success will be measured by the amount of reduction in variance and increase in mean intensity. Light intensity will be recorded using a CCD camera and the mean intensity and variance will be calculated for each trial conducted. After accounting for the environmental effects (humidity, temperature, cloud cover, etc), spatial phase changes will be applied using the SLM and the light will be propagated in the field while light intensity parameters are measured. The variance and intensity will be calculated again. The goal is to reduce variance by 10% while keeping mean intensity constant. Ideally, variance will decrease and the mean intensity will increase, once the trend of decreasing variance is observed, the trial will be reevaluated and explored in detail.

The laser will be propagated in a maritime environment and the lab table inside academic buildings at the US Naval Academy during the initial phase of the project. The maritime environment will be over water, approximately 500 meters in length at College Creek. MIDN Lipp and Dinkel will be primarily responsible for the laser shots over College Creek.

The SLM (spatial light modulator), mentioned above, will be an integral part of the second phase of the research. The SLM will change the phase of light, mainly over the area of its screen and coherence of the laser light. This in turn changes the monochromatic, collimated, and coherent properties of laser light. Monochromatic means that all the laser light is the same frequency and wavelength. Collimated means that all the light particles, photons, are in phase with each other, creating a single, very directional, beam of light [1], with minimal spreading. Coherence means that the light is all the same phase. The final factor to take into account will be scintillation of the laser light. Scintillation is caused by impacts with particles in the atmosphere, which is called turbulence. These impacts cause the photons to get out of phase with one another, making the light incoherent [8], this is due to the different refractive indices of materials in the air. Consequently, constructive and destructive interference occurs which creates light and dark spots on the target. The amount of scintillation depends upon various factors including humidity, temperature, wind, scattering of particles, and the initial phase of the light. As the light particles get more and more out of phase with each other, they begin to interfere with the propagation of other particles in the light beam. This interference will be both constructive and destructive – resulting in light (constructive) and dark (destructive) spots on the target.

Maintaining a constant intensity on the target is important for the naval applications of this project, primarily weapons (railguns or lasers) or communications systems [2]. Due to the fact that constant intensity on target is desirable, a statistical analysis of the laser light is required to analyze the mean and variance. Statistics analyze random interactions between the atmosphere and the laser light. The end goal of the project is to develop tools for analysis of laser beam propagation in a maritime atmosphere.

II. Background information on Lasers

Some basic properties of light and lasers will be explained below. Light, unlike anything else, behaves as both a particle and a wave, having wavelengths and energy associated with individual particles. These particles are called photons, streams of photons compose light. The photon is the basic element of light, according to Quantum theory, light is quantized and the photon is the elementary amount, or quantum. The energy of a particle of light is dictated by another simple equation, $E = h \cdot f$, this is known as Planck's equation. Where *f* is still the frequency of the EM wave and *h* is Planck's constant, $h = 6.63\text{x}\ 10^{-34} J \cdot s$. Due to the fact that the frequency of the laser light does not change and neither do constants, the energy of the laser light will be constant as well. Along the same lines as energy, photons also carry momentum, according to Einstein's theory of relativity. While momentum will not play a part in the laser experiments, it is important to note in research about lasers. The momentum of a single photon of can be described with the following equation $p = \frac{h}{\lambda}$.

Laser light is a special kind of EM radiation. EM waves are composed of electric and magnetic fields, traveling in space perpendicular to each other. These waves span many different wavelengths, each different wavelength being a different kind of light, the laser in this project will be red, approximately 630 nm in wavelength. The speed of propagation is dictated by a simple equation, $V = f \cdot \lambda$ (Eqn 1. Velocity equation), where λ represents the wavelength of the EM wave, *f* represents the frequency of the oscillations between the electric and magnetic fields and V is the velocity of the light. The velocity equation can be altered by substituting *c*, speed of light in a vacuum. The equation becomes a consistent method for determining the frequency of propagated laser light, based upon the 630 nm wavelength and constant speed of propagation, but this only applies to vacuum environments.

The paraxial equation describes the behavior of light as an EM wave in a vacuum, $\nabla^2 A + k^2 A = 0$, where ∇ represents a Laplace operator, k represents the wave number of the light, and A represents the amplitude of the light [5].

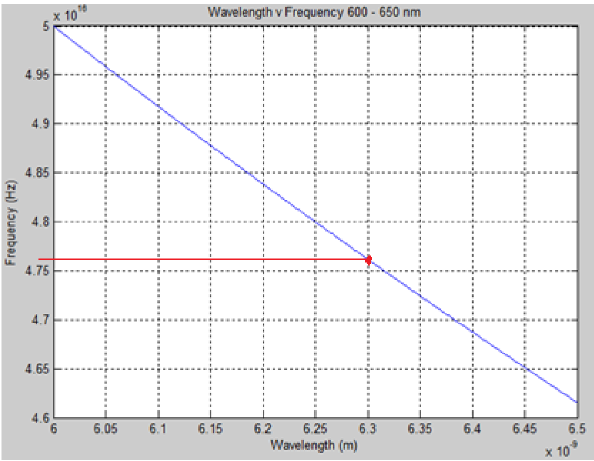


Figure 1 - Focuses exclusively on the light that will be propagated from the laser. This graph demonstrates the relationship from the velocity equation. A red dot marks where the laser light for this research project is.

The red light is centered around 630 nm, as stated above, this equates to a frequency of approximately 4.76 Terrahertz. This means that the photons in this laser light have an energy of approximately 3.155 picojoules. 4 mW laser light will be used in the experiment. 4 mW and 3.155 picojoules do not necessarily align. In order to calculate energy, power and energy will be multiplied together. Through calculations, it can be determined that $1.27x10^{16}$photons leave the laser every second, or conversely every $7.85x10^{-17}$seconds a single photon will leave the laser. With a power of 4 mW, applied over $7.85x10^{-17}$seconds, $P \cdot t = E$, the energy of a single photon to be 3.155 pJ can be obtained. This relates to this research because an accurate measure of the energy to expect on the sensor is desirable.

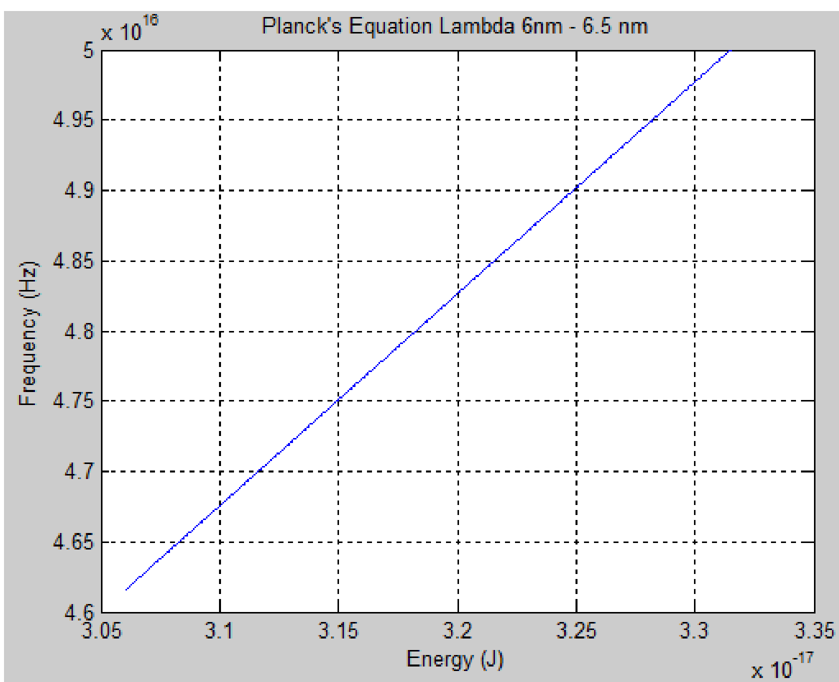


Figure 2 – Representation of the laser light in terms of Planck's Equation, or the Energy equation.

Beam Wander

An interesting property of laser light is beam wander. Beam wander is the physical change in the propagation path of a light beam. Lasers may take a curved path to the target and upon impact with the target, the point may move around the target itself [9]. As can be seen by figure 3 [7], beam wander increases with distance.

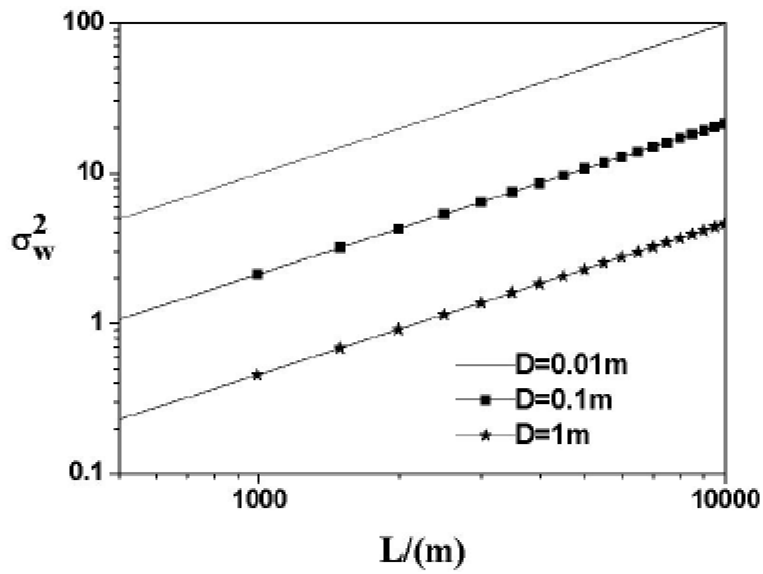


Figure 3 –Relation between beam wander and propagation distance on a horizontal path. σ_w^2 is a measure of how much the beam wanders over the distance. L/(m) is the distance propagated and D is the diameter of the beam being propagated, showing that a larger bema wanders less. [7]

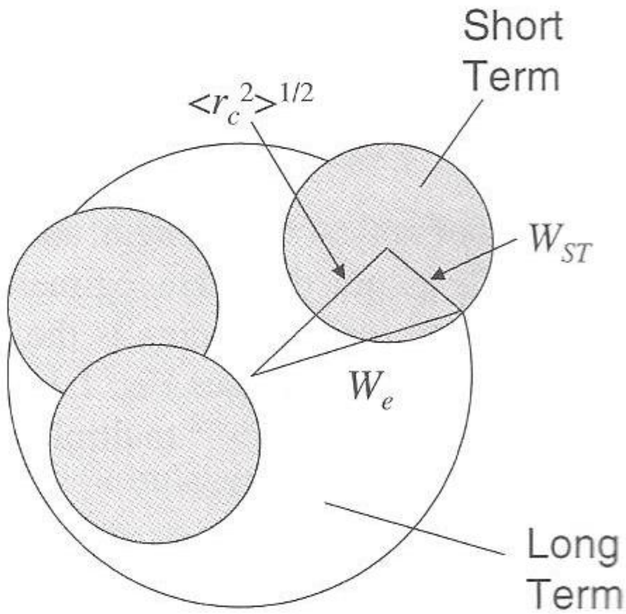


Figure 4 – Physical representation of beam wander on the target [8].

The amount of beam wander is calculated based upon the triangle displayed in the above figure. $<r_c^2>$ is determined based off of the Pythagorean Theorem and the values W_e and W_{ST}. The W_e term is the distance from the center of the average location of the laser to the edge of the current location of the laser beam. W_{ST} represents the diameter of the laser outwards to the intersection of the average area of the laser. W_{ST} represents a short term measurement and W_e is the longer term measurement. Atmospheric turbulence will affect the results that are obtained in the experiment. Scintillation and wind, altitude, temperature, and humidity will all come into effect.

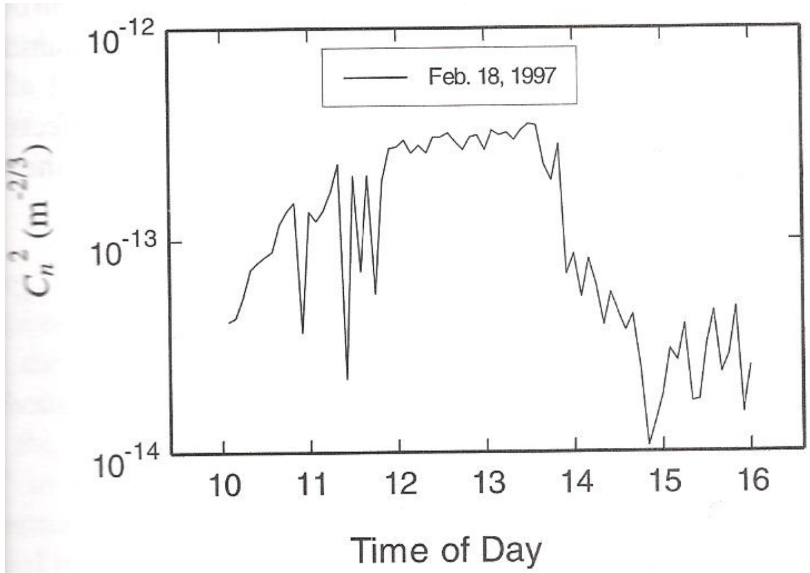


Figure 5–Amount of turbulence approximately 1.5 meters off the ground. The refractive-index structure (C_n^2) is a measure of the atmospheric turbulence [8].

A C_n^2 of 10^-12 is considered strong turbulence and there is less turbulence closer to the ground [8]. The above C_n^2 plot only applies to the specific area where it was recorded and the season (central Florida during a warm season), but the principal is similar and will be observed in the trials for this research project.

$$C_n^2 = 0.00594\left(\frac{v}{27}\right)^2 * (10^{-5} * h)^{10} * e^{\frac{-h}{1000}} + (2.7 * 10^{-16}) * e^{\frac{-h}{1500}} + A * e^{\frac{-h}{100}}$$

The above equation, the Hufnagle-Valley (H-V) method, is the generally accepted method of calculating C_n^2 [8].

In our research so far, beam wander has been roughly measured to find interesting results. For the multiple 5 meter trials, and expected for remaining trials at 50 meter and 100 meter, the beam had minimal wander. In the below graphs, each data point represents the location of maximum intensity for one specific frame from a single shot of the laser. The X and Y axis are the pixels of the frame for that shot and the Z axis represents the frame count.

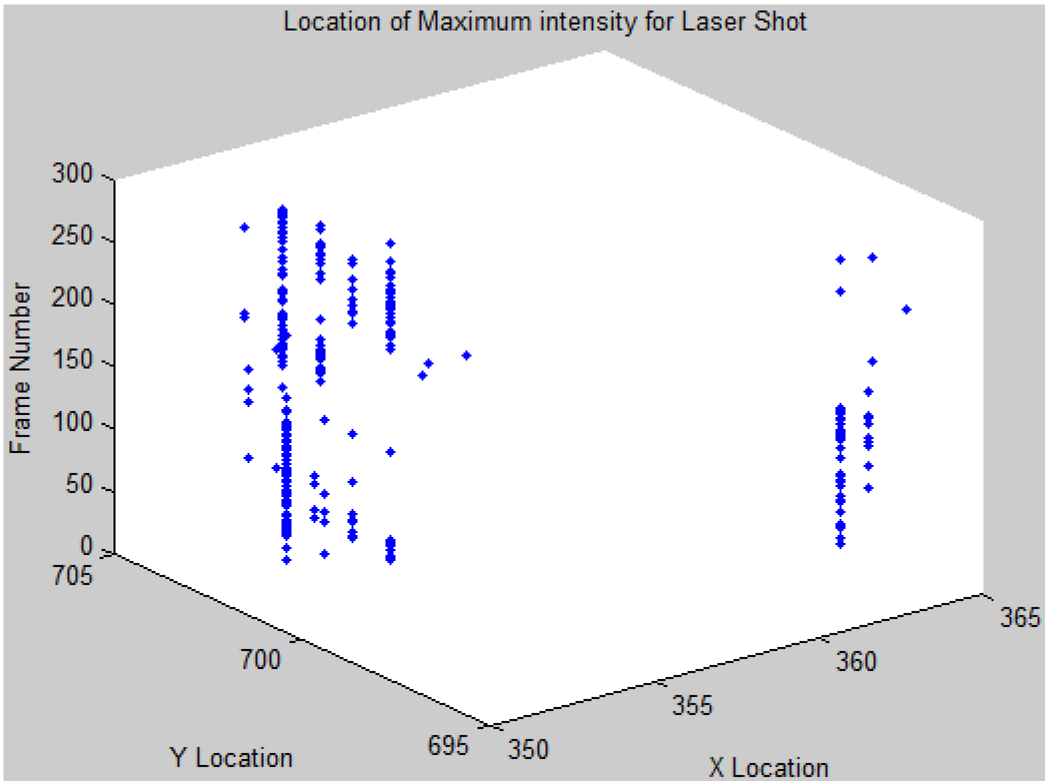


Figure 6 -Trial run with beam wander. There is no distinct mode of points where the maximum intensity accumulates. However, all the maximum points are within an area of 150 square pixels. Each pixel is 4.65 µm x 4.65 µm. This data was obtained from a 5 meter laser propagation on Gaussian screen set 1, SLM correlation width of 16.

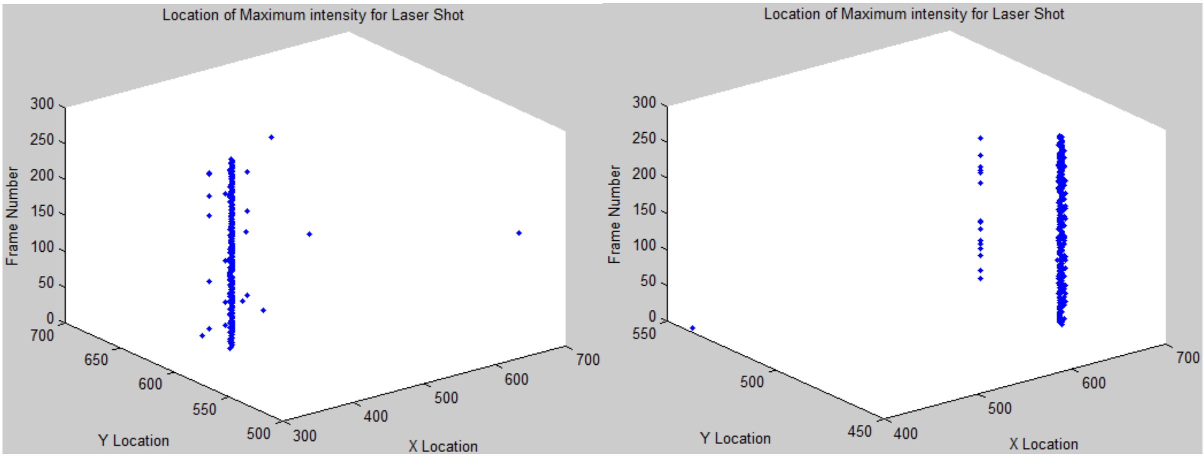


Figure 7 – Two different representations of a unimodal distribution for the maximum intensity of the laser. A unimodal distribution shows minimal beam wander for the specific trial.

The above two graphs show a good representation of unimodal distributions. There is one clear accumulation point for the maximum intensity. If the single outlier in either graph is removed, the data spread is approximately 18 square pixels on the left figure and 20 square pixels on the right figure. The above two trials had significantly less beam wander compared to the first trial. These graphs were obtained from a 5 meter propagation with SLM screen correlation width 1 and 4, both from Gaussian set 1.

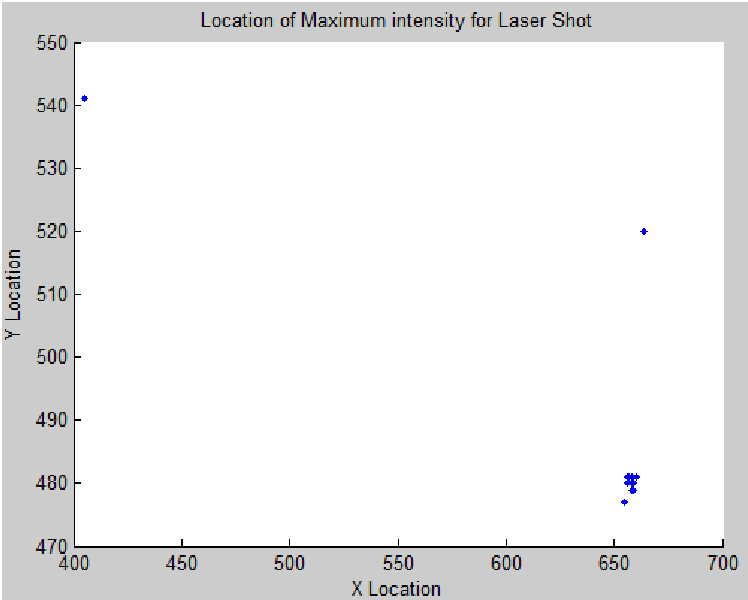


Figure 8 - View down the Z-axis for the right graph from figure 7. As can be seen, when eliminating the outliers, there is extremely minimal data spread with an obvious accumulation point for the maximum values.

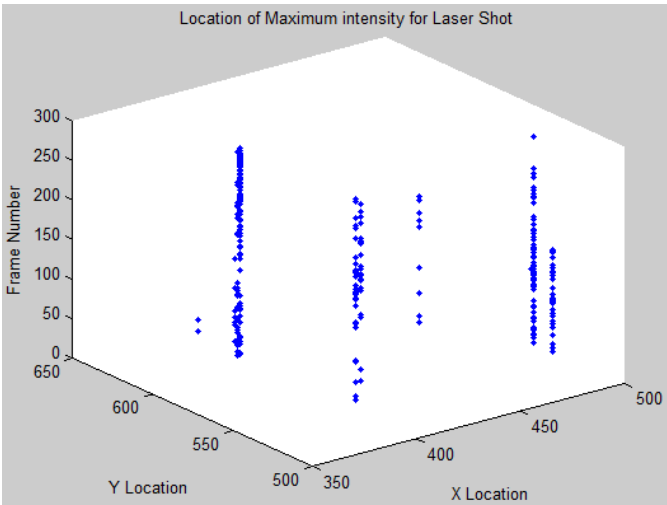


Figure 9 -Multi modal distribution for the maximum value in the frame. There are multiple locations where data points accumulate. From 5 meter propagation, Gaussian set 1, SLM 4.

SLM #	Distance	Xbar	Ybar	STD X	STD Y	STD Hypot	DistX(µm)	DistY(µm)	Hypot Dist(µm)
set2									
4	50	732.55	521.9	3.49	7.99	8.72	16.23	37.15	40.56
set3									
16	100	360.85	1137.22	52.87	141.83	151.37	245.87	659.52	703.86
128	50	317.14	343.73	168.53	184.56	249.93	783.65	858.21	1162.17

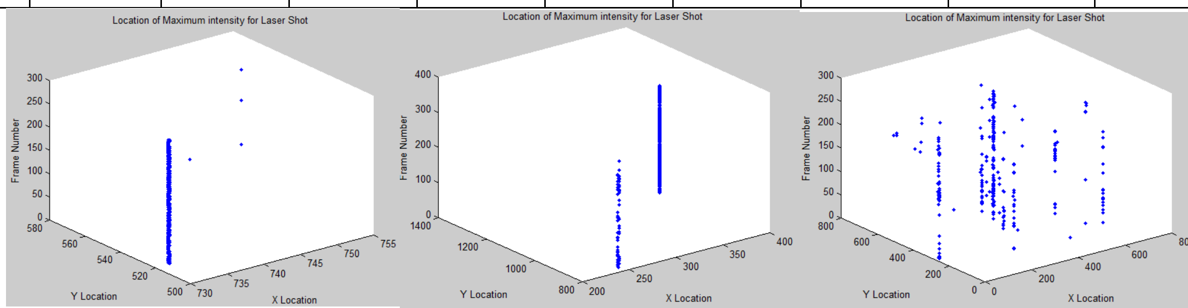


Figure 10 - The above table shows the beam wander results from three different shots with the laser. The graphs below, from left to right, correspond to the table from top to bottom. The left graph shows minimal beam wander with a single location of maximum intensity. The middle graph shows small beam wander with two locations of maximum intensity. The final graph shows maximum beam wander and no discernible location where the maximum intensity accumulates during the laser shot.

Beam wander and the distance from the average center of the beam will show how much the specific laser was moving in the experiments run for this project. Minimizing beam wander will be necessary for laser technology to be utilized as a weapons system.

EM Waves

EM waves are physically able to propagate through space by the means of induced electric and magnetic fields, according to Faraday's law. The electric field and magnetic field are perpendicular to each other and the path of propagation, the perpendicular magnetic field is generated. The magnetic field generates instantaneously through space and an electric field and vice versa. For EM waves, in plain terms, amplitude describes the brightness of the light, wavelength dictates the color, and the phase is the polarization, which is not detectable by the naked eye. This induced electric and magnetic field property can be seen in figure 6.

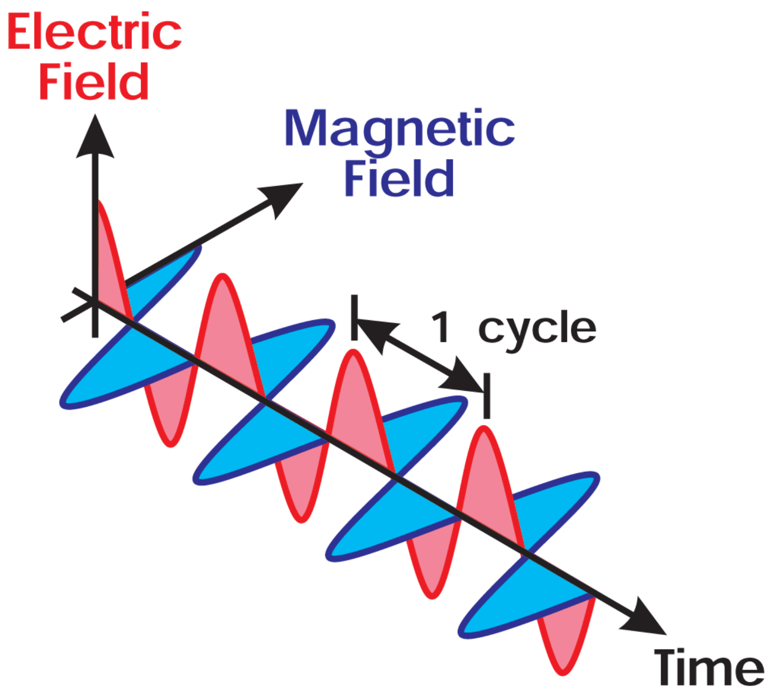


Figure 11 – This is a representation of a basic EM wave propagation, demonstrating that the Magnetic and Electric fields are perpendicular to each other and the propagation path [6]

HE- NE LASER

The He-Ne laser was developed in 1961 by Ali Javan and it will be used in the research and project. An approximate mixture of 20% Helium and 80% Neon is sealed into a "tube," generally glass. The Neon gas is in the majority because the Neon serves as the primary propagation medium for the laser. In order for the laser light to be generated, the gas mixture must be energized, or stimulated. This stimulation is accomplished through the means of a simple electric current, the current is carried through the Helium. This raises the energy level of the majority of the Helium atoms, the 3rd energy level. This higher orbital of Helium is very close to Neon's 2nd level, thus making an energy transfer between the Helium and Neon easier (on an atomic level). From this point, population inversion is easily accomplished, this means that more photons to be emitted than absorbed. The inversion between photons absorbed and released makes it possible for the laser light to be emitted and propagate form the laser generation source. The light leaves in the form of a coherent, monochromatic, external beam of light.

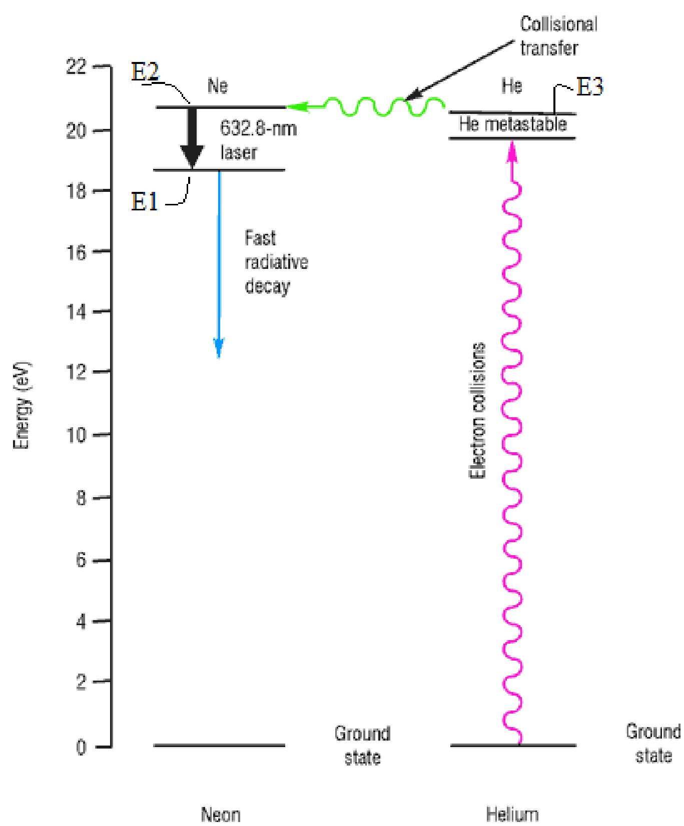


Figure 12 – The process of atom excitation and emission of laser light

III. Data and Analysis and Statistics

In order to obtain data from the laser, the laser light is received using the DCx camera as the target. The camera records the live feed of the laser and this video is converted into individual frames (discussed in detail in Appendix A). The intensity of the laser light on these screens over time can be measured. This measurement is accomplished with MATLAB programming, plotting, and data analysis tools. The specific intensity of pixels in the light are analyzed as well as the intensity over all the pixels in the frame. MATLAB is used to calculate the mean and variance of these intensity measurements, for both the frame and pixel. For this stage of the research, the attenuation factor used was 10^4.4 for the 5 meter trials, and 10^4.0 for the 50 meter and 100 meter trials.

The center of the pixel range was [512,640] (all pixels will be referenced in x,y 512,640 would mean the 512^{th} pixel in the x direction and the 640^{th} pixel in the y direction). The total pixels recorded by the DCx camera are [1024,1280]. In future runs of the experiment with the DCx camera, a method to ensure that the laser impacts the camera at the same spot on the lens and that the spot be the exact center of the camera must be devised.

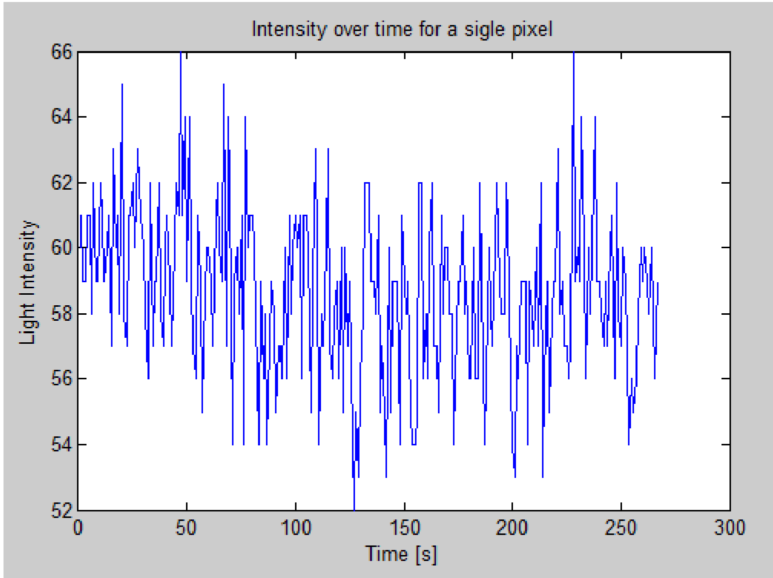


Figure 13 - average intensity for pixel 512,800 for one shot of the Gaussian laser

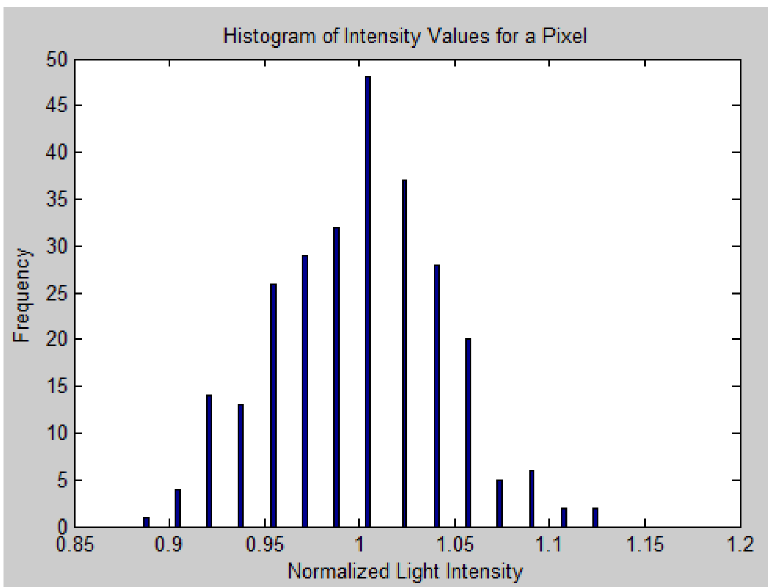


Figure 14- histogram of intensity values for pixel 512,800

This average intensity was a very good result because the data can be seen to center around a specific value, which can also be seen from the histogram of this data, approximately

60. The intensity histogram for pixel [512,800] confirms the time sequence plot that the average is centered around one value. The bell curve distribution shape is the desired result for a histogram from a Gaussian laser beam. As can be seen above, this data falls into a bell curve shape. These two graphs show the ideal result for an average laser shot, they were obtained from a Gaussian beam, screen set 2, correlation width 16.

Light Intensity Fluctuations measured over a Distance

It can be seen in the 50 meter propagation test (set 2 with SLM Correlation Width of 16), the behavior of the laser light is extremely similar to the behavior of the light in the original 5 meter trials, except the intensity is approximately one-quarter what it is in the shorter trials. When the distance lengthens to 100 meters, the intensity gets even smaller.

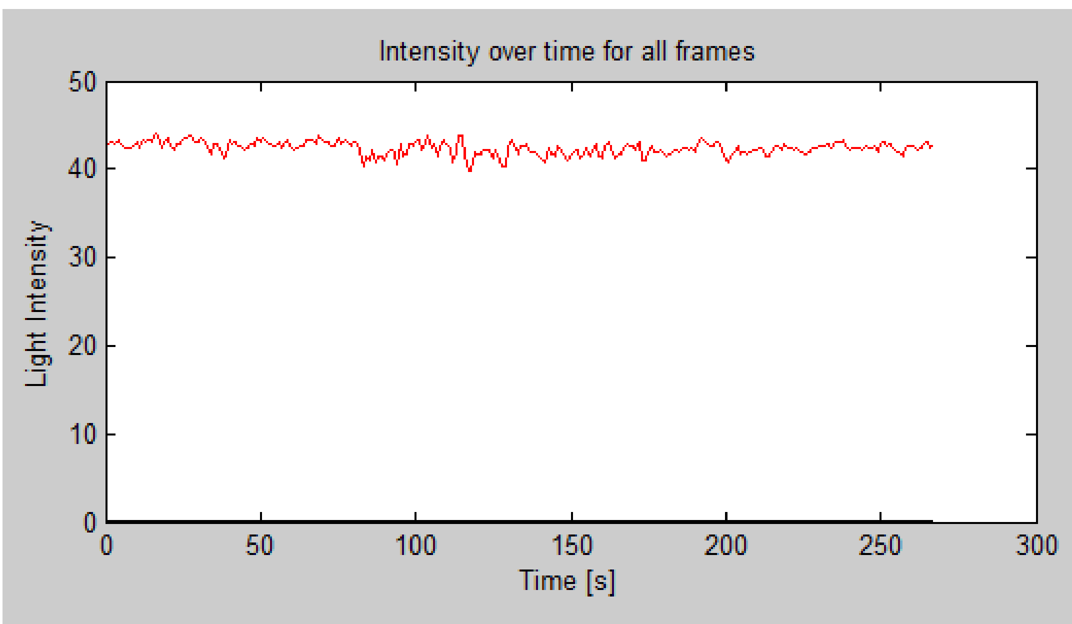


Figure 15 – Average intensity of a frame for the Gaussian trial at 50 meters propagation, the average value of this plot is 42.39.

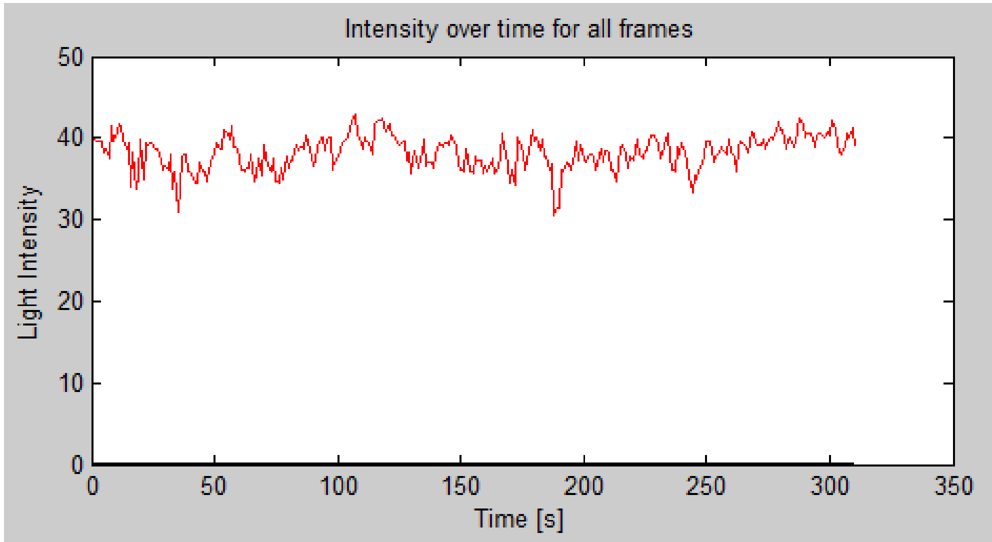


Figure 16 – Intensity over time for the frames from the Bessel trial at 50 meters with an equivalent Beta value. The intensity of the Bessel beam is slightly lower than it was on the Gaussian shots, but similar behavior.

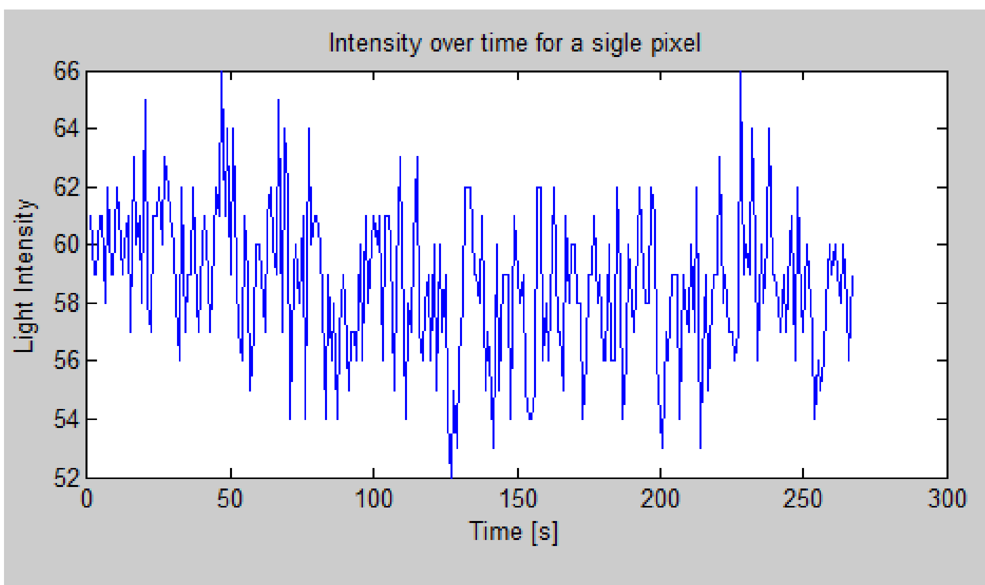


Figure 17- Average intensity for just one of the pixels in the 50 meter, Gaussian propagation, the average intensity in this plot is 58.66.

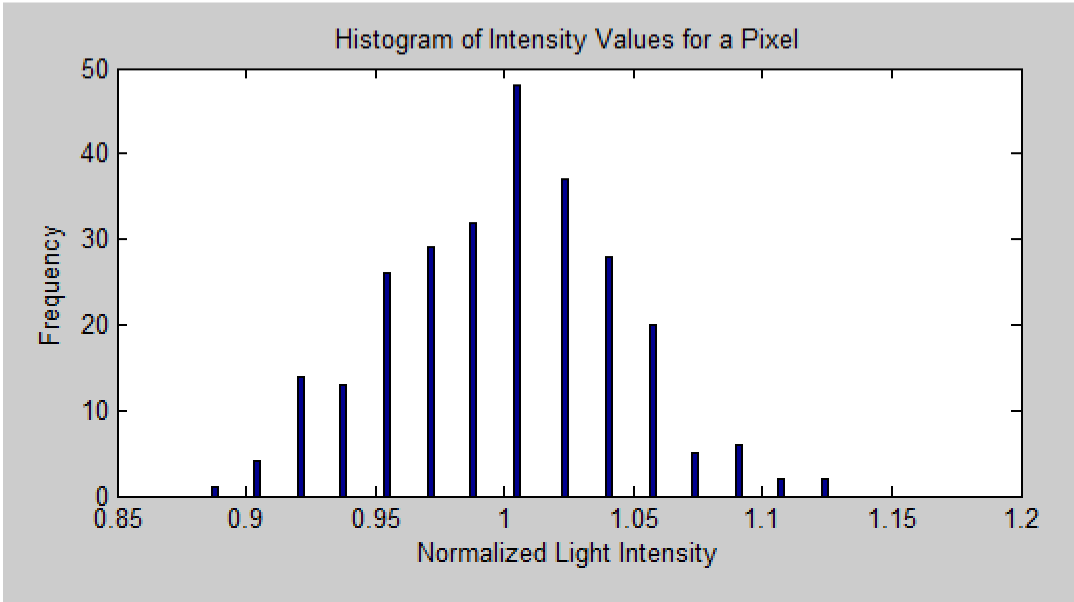


Figure 18- Histogram for the above propagation, similar to the original 1 meter propagations and 5 meter propagations, the distribution is unimodal and seems to be mostly symmetric.

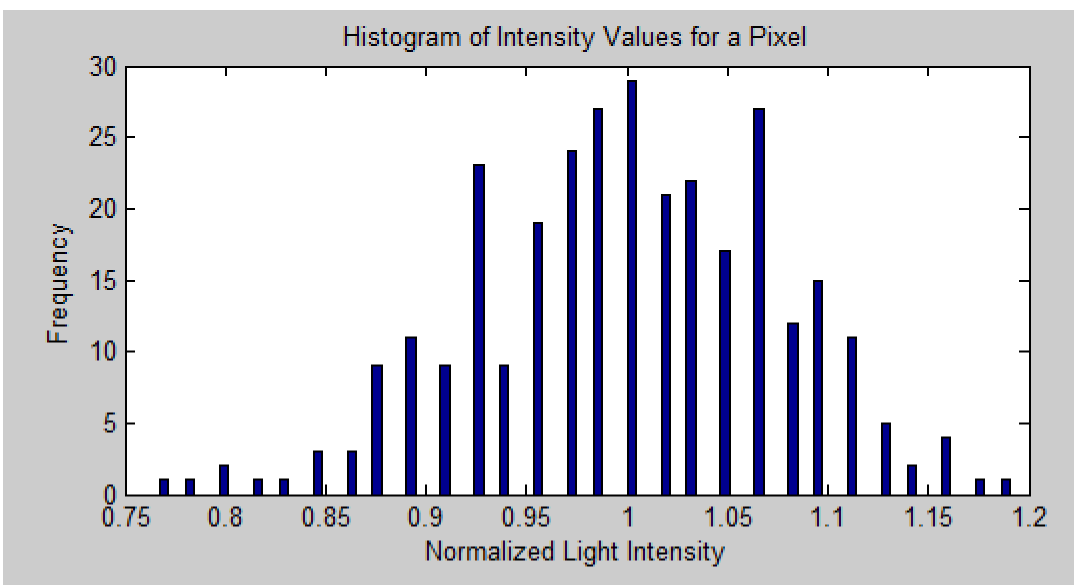


Figure 19 – Unimodal distribution from a Bessel screen with a beta value equivalent to SLM 16. The distribution is more widely spread, but it is still a bell curve.

V. MATLAB Code

The MATLAB code that has been used to produce these results can be found in Appendix B.

This code analyzes all of the frames from the laser video that is taken. The code can then produce a 3D surface plot of intensity. In addition, the code will record the intensities for one specific pixel over the course of the video. From the intensity information, a histogram of intensity values is produced and a time sequence showing how intensity changes over the video is displayed. For this single pixel, the maximum value of the pixel's intensity is printed. The same data is recorded for the minimum intensity, but this is not plotted because it is not overly useful data. The code has also been designed to record the average intensity of a frame over time. This average for the whole frame is plotted against time along with the corresponding histogram. It can determined if the intensity is unimodal, bimodal or has no defined mean. It can be seen how close the intensity data matches a Gaussian distribution bell curve.

This MATLAB code also conducts a basic statistical analysis of the intensity information. For a single designated pixel in the frame, the average intensity, variance of intensity, and standard deviation of the intensity are printed. The intensity of each frame is recorded along with the pixels. The average intensity for a frame, the variance of intensity, and standard deviation of intensity, calculated from all frames, is displayed. The final bit of statistics calculated is the variance for a frame. The variance of intensity over the frame is recorded for each individual frame and plotted against time. Ideally the variance of an individual frame will not change over the course of the laser shot. The variance of a frame is different than the average variance because each frame is different. The average variance is calculated with respect to the average intensity of the entire laser shot. The variance of a frame is calculated with respect to the average intensity of that specific frame. With a perfect laser shot the variance of each frame would be identical to the average and the variance of frames over time would not change.

Finally, the MATLAB code determines the pixel location of the maximum intensity for each frame. This location is recorded in two matrixes, one for the X location and one for the Y location. The average X and Y locations and the standard deviation of the X and Y locations of the maximum intensity are calculated and reported in a figure as well as a plot versus time of the maximum intensity location.

This code will help us reach the project objectives because the patterns of behavior in the laser light will be determined. Through the statistical analyses, surface plots, and ability to evaluate individual pixels of the laser light, how the laser operates and potentially how the laser will operate in different conditions will be explained.

VI. Experimental Method and Experiment

The following pictures document the basic experimental setup and show how the laser is expanded and measured.

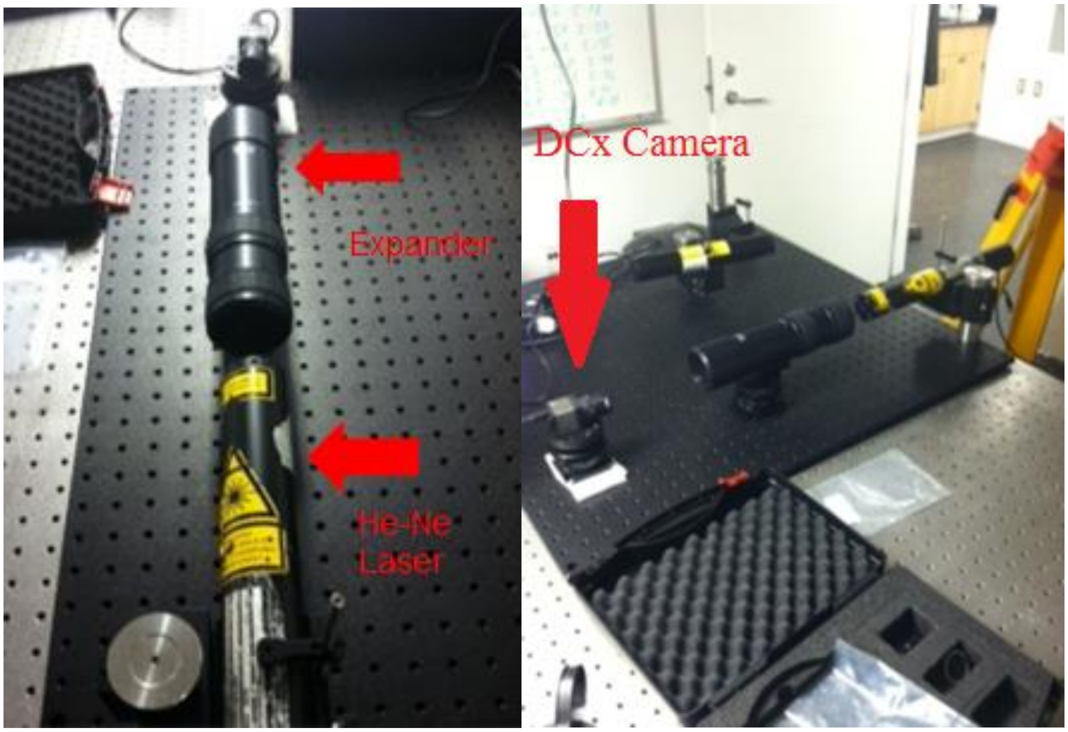


Figure 20- a) Laser alignment with the expander b) Alignment with the DCx camera

Figure 21 – Path of the laser light as it travels from the expander to the SLM and then from the SLM to the DCx camera for recording.

The above pictures depict the most basic form of this experiment, the following pictures will detail how this experiment was completed over 50 and 100 meters.

Figure 22 – Laser, expander and SLM were arranged on the tripods, this is the same experiment as depicted in Figure 21 above, except it is now easily aligned over greater distances.

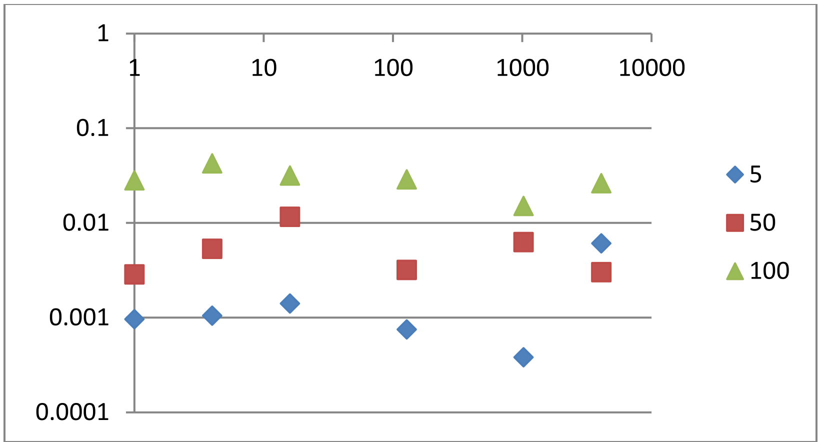
Figure 23 – The camera on a tripod set up for field experiemnts, the tripod system allowed for an extremely simple alignment of the laser, expander, SLM and camera over the long distances.

VII. Results

From the research, it appears that using different screens with the same statistical values will produce statistically similar results. Over the three distances and 3 sets, all the results between sets and distances resulted in statistically similar results. It was also learned from the research that for all trials, the black intensity was greater than the intensity of the screen, with the exception of some of the Bessel trials in set 2.

For the following 4 sets of results, the distances are in meters for each different trial (green triangles, red squares, blue diamonds). The horizontal axis represents the level of coherence based upon the SLM Correlation width or equivalent Beta value. A Higher value represents more coherent light while a smaller value represents less coherent light. The vertical axis shows the variance of light or the intensity of the light, based upon the graph. The intensity is based off of values 1 – 255, 255 showing the maximum intensity that can be recorded by the intensity sensor. There are 256 levels of intensity that can be recorded by the sensor. For each of the four sets of graph, there are four graphs in each set. The first graph is the variance of intensity of a single pixel in the frame, the second graph is the variance of intensity for the frame as a whole. The third graph is the mean light intensity for the pixel point, the final graph is the mean light intensity for the whole frame.

The following graphs resulted from Gaussian Screens Set 1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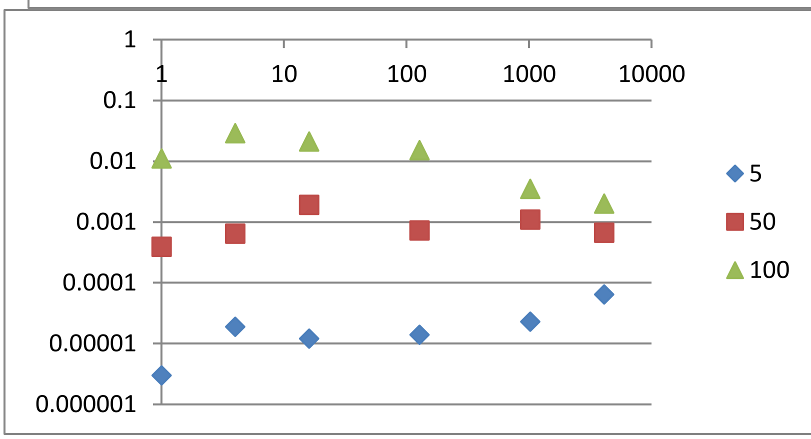
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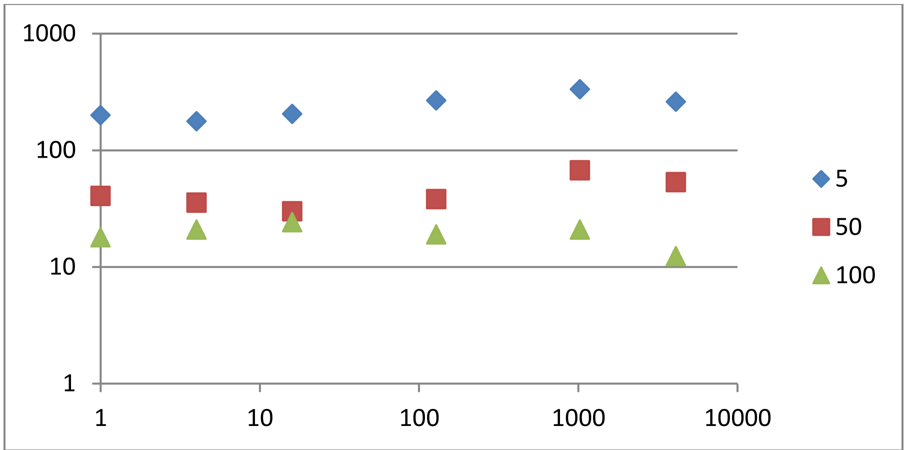
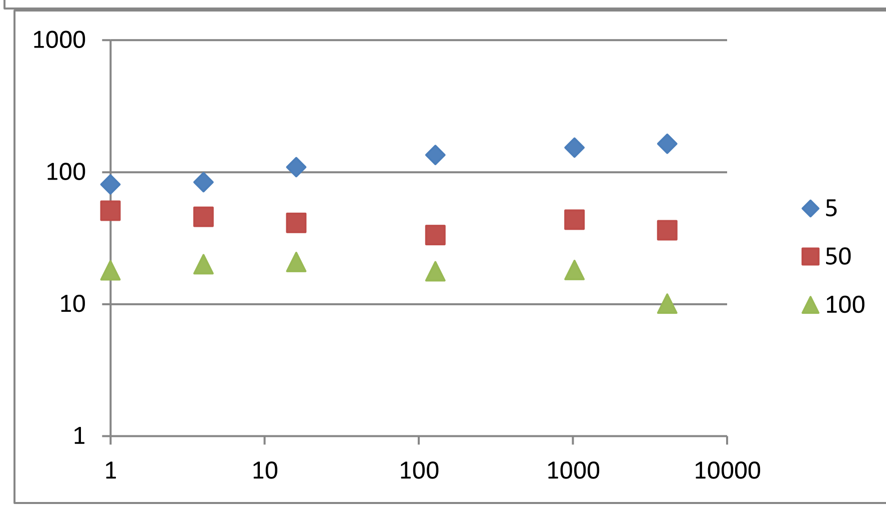
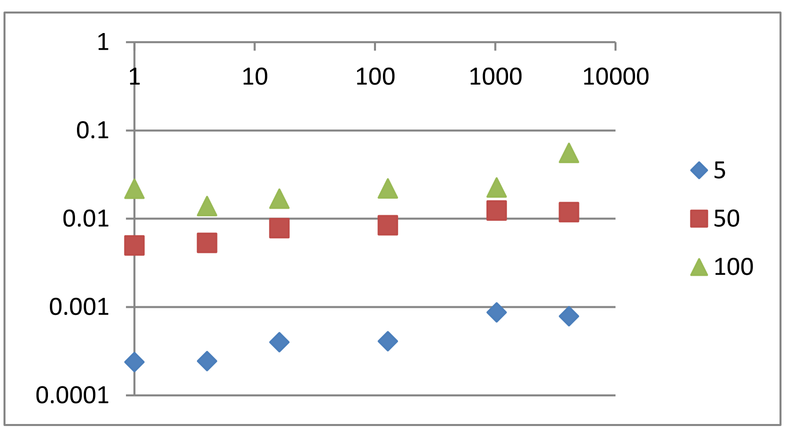
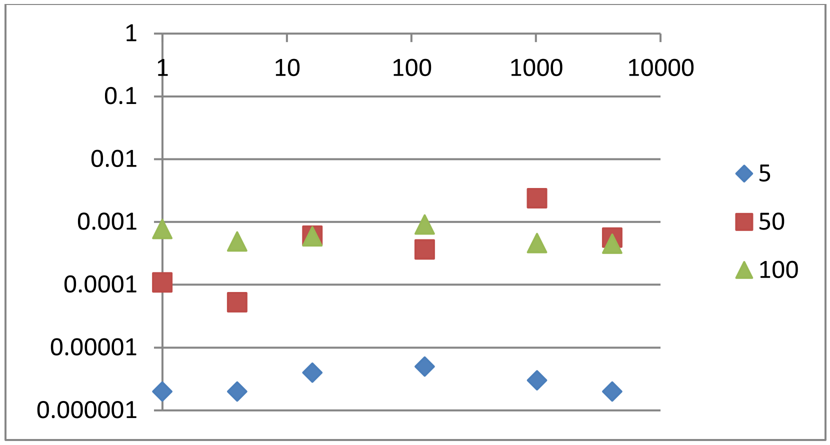
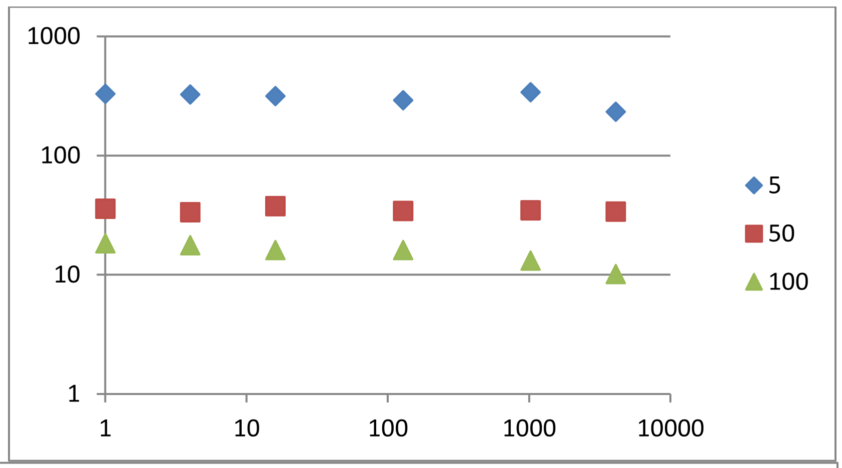




The next set of graphs came from Bessel Screens set 1




1
0.1
0.01
0.001
0.0001
0.00001
0.000001
1
10
100
1000
10000
5
50
100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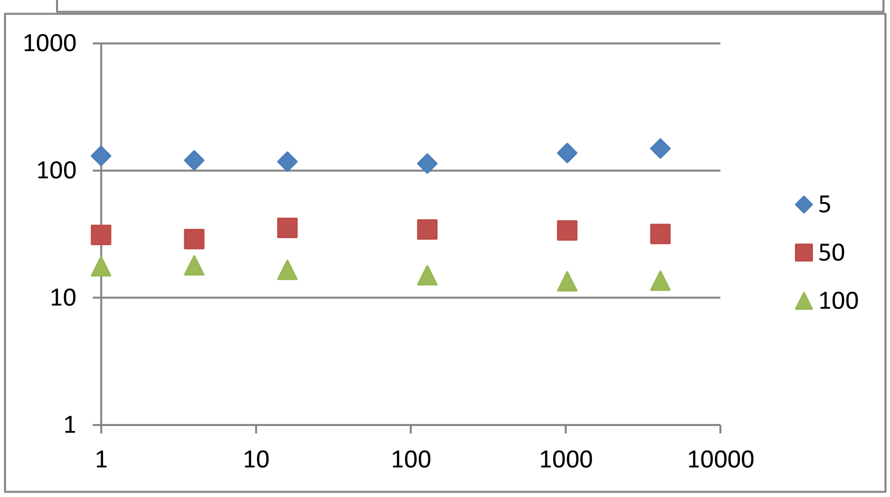
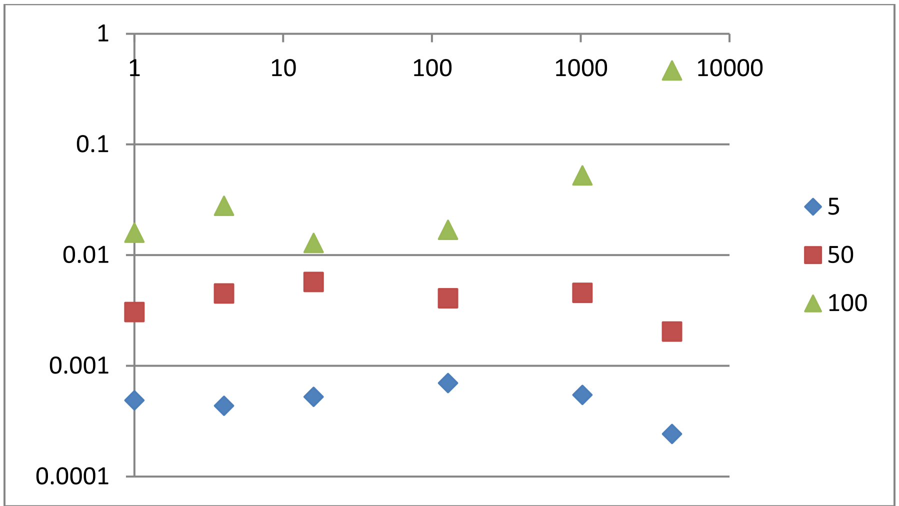
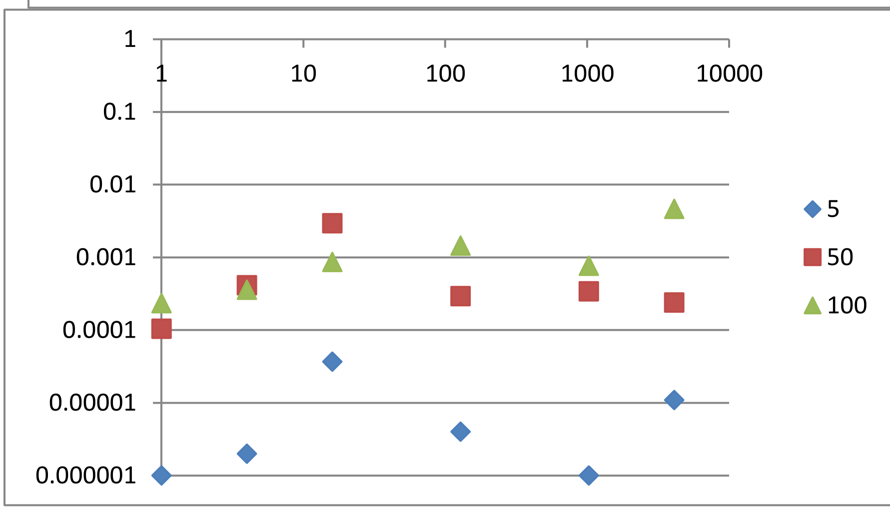
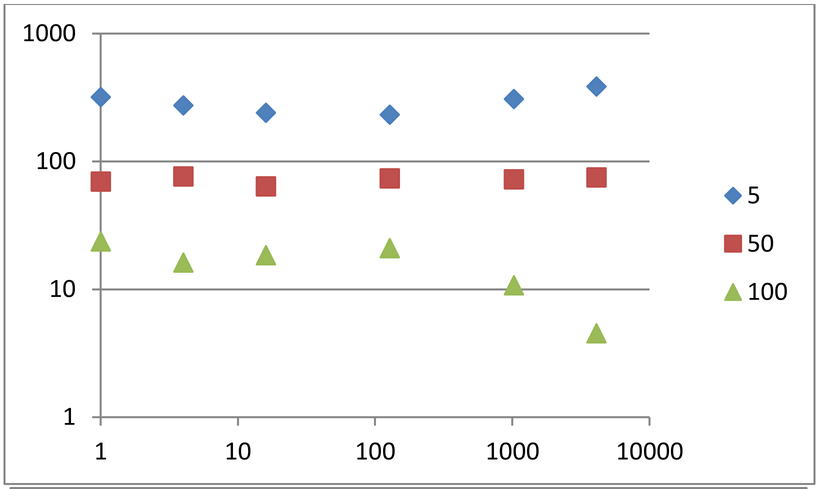
100
10
1
1
10
100
1000
10000
5
50
100

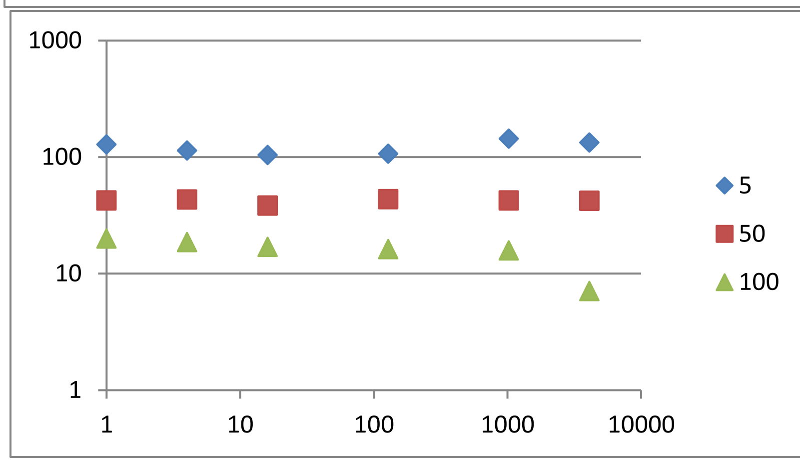

1000
100
10
1
1
10
100
1000
10000
5
50
100

The next set of graphs came from Bessel Screens set 2

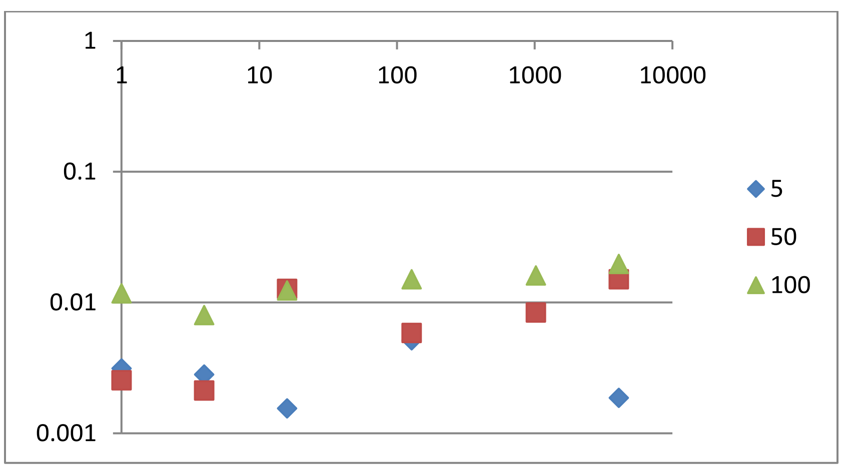


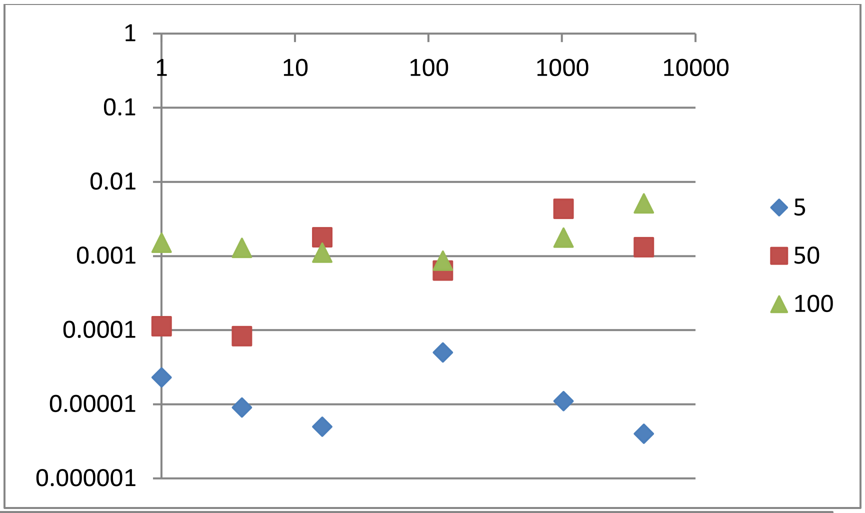


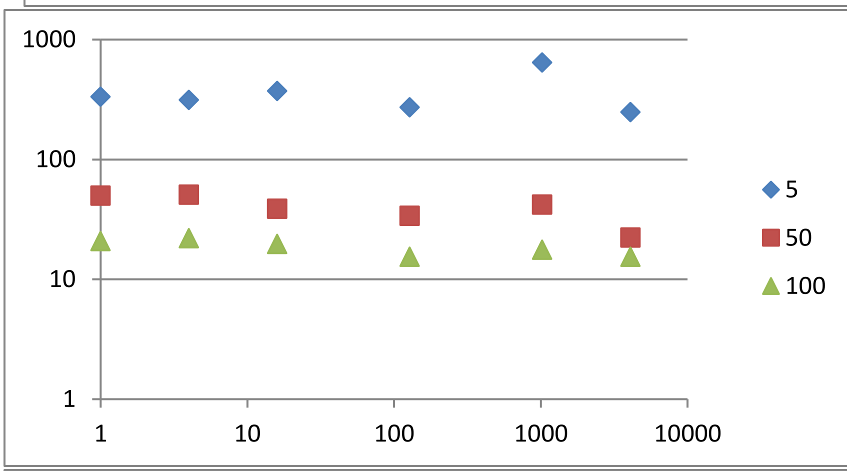


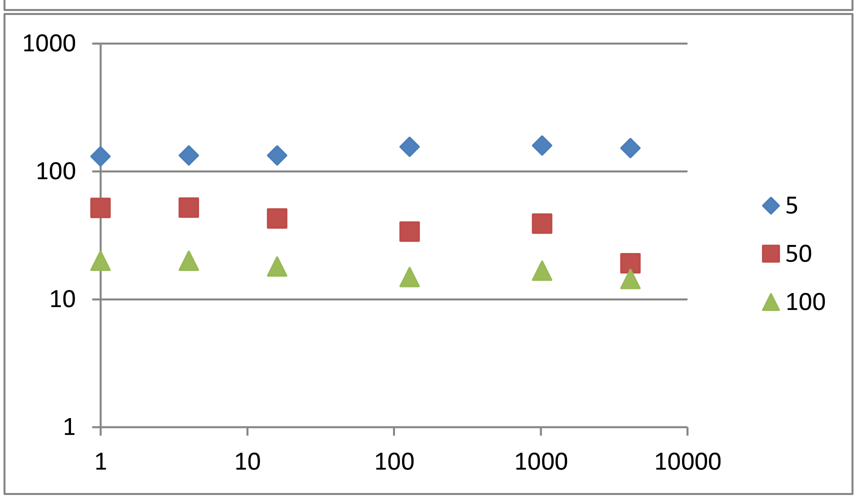


The next set of graphs came from Gaussian Screens set 3









All the above graphs represent the data that was collected during the trials with the laser. The following are the general patterns and conclusions that were drawn from this data.

- At 5 meters, with the Gaussian beams, the variance was reduced with all three sets of screens, only Bessel set 1 significantly reduced the variance intensity
- At 50 meters Bessel and Gaussian sets 1 and 2 reduced variance significantly, but not set 3
- At 100 meters Gaussian screens were not able to reduce the variance by any significant amount. The Bessel screens had moderate success at 100 meters, only reducing variance in half of the trials, but these screens were the most consistent.

These conclusions are summarized in this table

Gaussian Beams

Distance / Screen set	Set 1	Set2	Set3
5	X	X	X
50	X		
100			X

Bessel Beams

Distance / Screen set	Set 1	Set2	Set3
5	X		
50	X	X	
100	X	X	X

An “X” mark signifies that the variance was reduced in half, or more, of the trials for a specific set. For example, with a Gaussian beam, using screen set 1, at a distance of 50 meters, the variance of intensity was reduced in half or more of the 6 trials. The 6 trials being screens, 1, 4, 16,128, 1024, 4096.

The following are the data tables from the research

Gaussian Set 1

	pix var				pix mu		
Distance/Screen	5	50	100		5	50	100
black1	0.002486	0.003229	0.017894				
1	0.000963	0.002864	0.028202	1	199.5237	40.72	18.01444
black4	0.000521	0.003793	0.010574	4	177.5352	35.684	20.9639
4	0.00105	0.005324	0.042801	16	205.575	30.044	24.21661
black16	0.000591	0.003734	0.006834	128	267.7632	38.136	19.01278
16	0.001415	0.011588	0.031602	1024	333.567	67.3	20.9393
black128	0.000316	0.002547	0.004205	4096	260.475	53.52198	12.34824
128	0.00075	0.003202	0.028958				
black1024	0.00023	0.003226	0.008236				
1024	0.000383	0.006282	0.015204				
black4096	0.023117	0.001045	0.029112				
4096	0.006089	0.003031	0.026339				
	frame var				frame mu		
	5	50	100		5	50	100
black1	0.000022	0.001325	0.008156				
1	0.000003	0.000392	0.011064	1	80.82751	51.01313	18.09648
black4	0.000005	0.000667	0.003134	4	83.88826	45.83148	20.0677
4	0.000019	0.000639	0.029026	16	109.2981	41.21903	20.88478
black16	0.000015	0.002037	0.001816	128	134.7273	33.28031	17.71497
16	0.000012	0.001906	0.021067	1024	153.7544	43.5357	18.12684
black128	0.000018	0.001059	0.000916	4096	164.3306	36.22956	10.11948
128	0.000014	0.000725	0.015153				
black1024	0.000024	0.001166	0.001602				
1024	0.000023	0.001093	0.003508				
black4096	0.000028	0.000085	0.026566				
4096	0.000064	0.000668	0.002007				

Bessel set 1

	pix var				pix mu		
Distance/Screen	5	50	100		5	50	100
black1	0.000242	0.003414	0.028244				
1	0.000238	0.004986	0.0219	1	328.5429	35.78662	18.3718
black4	0.000233	0.003312	0.013193	4	324.6908	33.46497	17.66346
4	0.000243	0.005329	0.013889	16	315.1995	37.6879	16.14103
black16	0.000227	0.006014	0.013771	128	292.0953	34.27389	16.17949
16	0.000399	0.007831	0.016856	1024	340.251	34.72293	13.1859
black128	0.000204	0.011086	0.009441	4096	233.7656	33.96815	10.16987
128	0.00041	0.008394	0.021937				
black1024	0.000279	0.008258	0.01815				
1024	0.000865	0.012372	0.022659				
black4096	0.000234	0.009834	0.08155				
4096	0.000788	0.0119	0.055774				
	frame var				frame mu		
Distance/Screen	5	50	100		5	50	100
black1	0.000005	0.000316	0.000347				
1	0.000002	0.000109	0.000772	1	130.1858	31.2217	17.70186
black4	0.000015	0.00029	0.001069	4	120.4439	29.00442	18.02817
4	0.000002	0.000053	0.000491	16	117.3429	35.46998	16.61436
black16	0.00002	0.000433	0.00225	128	113.2465	34.50305	15.00454
16	0.000004	0.000608	0.000589	1024	137.7901	33.76188	13.48888
black128	0.000006	0.000303	0.000443	4096	148.7352	31.71338	13.61833
128	0.000005	0.000364	0.000917				
black1024	0.000016	0.000534	0.000258				
1024	0.000003	0.002382	0.000461				
black4096	0.000001	0.000817	0.002436				
4096	0.000002	0.000564	0.000451				

Gaussian Set 2

	pix var				pix mu		
Distance/Screen	5	50	100		5	50	100
black1	0.006416	0.001537	0.011737				
1	0.004566	0.001614	0.021246	1	268.1531	65.50936	21.34967
black4	0.003861	0.000888	0.050708	4	286.3674	65.73034	12.19935
4	0.016494	0.001351	0.079725	16	305.3488	58.65543	18.49673
black16	0.001675	0.001439	0.026963	128	204.0691	51.19101	20.60458
16	0.013533	0.002	0.013076	1024	184.8278	46.58427	16.99346
black128	0.026205	0.00118	0.003991	4096	227.5175	38.28839	16.12418
128	0.010719	0.003118	0.00889				
black1024	0.010546	0.001282	0.005054				
1024	0.02177	0.003016	0.013465				
black4096	0.010259	0.001434	0.006102				
4096	0.008829	0.0047	0.016637				
	frame var				frame mu		
Distance/Screen	5	50	100		5	50	100
black1	0.00002	0.000127	0.002194				
1	0.000037	0.000265	0.014323	1	127.5855	54.57683	14.43054
black4	0.000021	0.000113	0.053501	4	123.6305	48.60227	12.55424
4	0.000008	0.000257	0.043452	16	125.3328	42.38544	16.60574
black16	0.000019	0.000559	0.020537	128	153.4999	41.58026	18.83912
16	0.000009	0.000326	0.001319	1024	174.5312	47.38932	15.45097
black128	0.000011	0.000378	0.001288	4096	175.5045	38.80985	14.58134
128	0.000016	0.000844	0.001351				
black1024	0.000021	0.000064	0.0016				
1024	0.000027	0.000215	0.002474				
black4096	0.000011	0.000089	0.001701				
4096	0.000007	0.000506	0.005561				

Bessel Set 2

	pix var				pix mu		
Distance/Screen	5	50	100		5	50	100
black1	0.000246	0.004396	0.02027				
1	0.000488	0.003056	0.016022	1	318.7591	69.75807	23.71186
black4	0.00029	0.005223	0.047632	4	273.8683	76.21936	16.2
4	0.000437	0.004507	0.027907	16	239.7034	63.84194	18.43729
black16	0.000263	0.008478	0.018349	128	231.877	73.8871	20.93559
16	0.000525	0.005742	0.012914	1024	307.6455	72.36452	10.77627
black128	0.000325	0.004146	0.007924	4096	384.9243	75.17742	4.538983
128	0.000699	0.004067	0.016931				
black1024	0.000254	0.004219	0.024698				
1024	0.000548	0.004567	0.052523				
black4096	0.000257	0.002017	0.025785				
4096	0.000243	0.002045	0.467436				
	frame var				frame mu		
Distance/Screen	5	50	100		5	50	100
black1	0.000003	0.0002	0.001405				
1	0.000001	0.000105	0.000235	1	128.0327	42.46556	19.91694
black4	0.000002	0.000413	0.001305	4	113.4153	43.13614	18.61892
4	0.000002	0.000415	0.000361	16	103.8241	38.2048	16.94454
black16	0.000004	0.005729	0.001165	128	106.7904	43.44282	16.20189
16	0.000037	0.002942	0.000868	1024	143.9812	42.40559	15.76664
black128	0.000002	0.000718	0.00101	4096	132.9646	42.00492	7.097375
128	0.000004	0.000293	0.001448				
black1024	0.000003	0.000327	0.00021				
1024	0.000001	0.000343	0.000766				
black4096	0.000001	0.000346	0.000278				
4096	0.000011	0.00024	0.004675				

Gaussian Set 3

Distance/Screen	pix var				pix mu		
	5	50	100		5	50	100
black1	0.003968	0.001862	0.051915				
1	0.003141	0.002557	0.011817	1	332.1348	49.78339	20.74183
black4	0.01452	0.002043	0.006042	4	312.5504	50.70036	22.04248
4	0.002821	0.002129	0.008033	16	372.7252	38.69314	19.66667
black16	0.004937	0.001841	0.006175	128	272.2774	33.84477	15.4183
16	0.001553	0.012741	0.012376	1024	640.5309	41.98556	17.62418
black128	0.00089	0.005496	0.006105	4096	247.269	22.25949	15.36275
128	0.005148	0.005884	0.015095				
black1024	0.000485	0.005553	0.006593				
1024	0	0.00841	0.016127				
black4096	0.000778	0.012711	0.013729				
4096	0.001877	0.015138	0.01982				
	frame var				frame mu		
Distance/Screen	5	50	100		5	50	100
black1	0.000013	0.000086	0.047019				
1	0.000023	0.000113	0.001515	1	131.4937	51.84608	20.0009
black4	0.000011	0.000251	0.00118	4	133.4733	52.25068	20.02237
4	0.000009	0.000083	0.001285	16	133.8139	42.88046	18.07064
black16	0.000009	0.000098	0.001762	128	155.5546	33.86851	14.96502
16	0.000005	0.001797	0.001108	1024	159.3451	39.01121	16.78246
black128	0.000005	0.001465	0.000877	4096	152.0468	19.18901	14.41301
128	0.00005	0.000634	0.000865				
black1024	0.000021	0.00096	0.000573				
1024	0.000011	0.004318	0.00177				
black4096	0.000012	0.000641	0.003213				
4096	0.000004	0.00132	0.005108				

Bessel Set 3

	pix var				pix mu		
Distance/Screen	5	50	100		5	50	100
black1	0.00028	0.003145	0.009026				
1	0.000414	0.006582	0.009943	1	272.0025	25.98052	20.17221
black4	0.00022	0.004303	0.008546	4	271.011	23.82792	17.39879
4	0.000467	0.007756	0.011746	16	255.981	25.40909	14.93656
black16	0.000289	0.008036	0.011751	128	225.1774	22.16234	8.1571
16	0.000536	0.011314	0.018088	1024	308.3175	18.54546	16.62538
black128	0.00043	0.008517	0.011903	4096	106.2181	6.987013	16.55589
128	0.000716	0.017189	0.106106				
black1024	0.000274	0.014238	0.015854				
1024	0.000931	0.029969	0.015278				
black4096	0.000397	0.023862	0.013349				
4096	0.003891	0.428761	0.012777				
	frame var				frame mu		
Distance/Screen	5	50	100		5	50	100
black1	0.000002	0.000118	0.00347				
1	0.000013	0.000329	0.000765	1	121.6043	34.55052	16.93927
black4	0.000002	0.000046	0.000415	4	114.3939	31.097	14.23232
4	0.000003	0.001786	0.002004	16	103.9636	30.246	12.13221
black16	0.000002	0.000321	0.002302	128	105.4091	28.29139	8.478256
16	0.000016	0.000694	0.00687	1024	143.5096	24.44323	14.70067
black128	0.000001	0.000255	0.002606	4096	124.7908	12.37585	14.33487
128	0.000025	0.00139	0.012403				
black1024	0.000003	0.011039	0.00138				
1024	0.000002	0.003996	0.000925				
black4096	0.000009	0.001692	0.001058				
4096	0.000002	0.127517	0.000681				

VIII. Conclusions

After this phase of research has been completed, several conclusions can be drawn. The research needs to be continued to expand on what was learned from this project. . Further research needs to be conducted on how exactly these relationships work between SLM screen, intensity, and variance so that intensity can be maintained while still reducing variance. Using an SLM to propagate a laser can give you the ability to reduce variance, but at the cost of intensity. It is also relevant to note that analyzing information for pixels is unreliable and unnecessary compared to analyzing information from each frame. Unless all the pixels in the frame are analyzed, looking at a single pixel for analysis is not overly useful. Comparing a single pixel to the frame can provide insight to which pixels behave the same as the frame as a whole, but that analysis is rendered obsolete after a new trial is set up as the pixel identities will be rearranged and the spot that was analyzed is not different in the next trial. If the pixels are not compared to the frame and only a single pixel is evaluated, then this information is a very narrow view of the laser as a whole and is still not overly relevant. This research has provided useful insight into how an SLM can change a laser beam over a propagation distance. The research must be continued in the future. An SLM is a very useful tool to minimize variance of intensity for a laser beam and could prove useful in allowing directed energy weapons to be used in a maritime environment on a significant scale.

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Appendix A

In order to properly set up the experiment, multiple things must be taken into consideration, aligning all the equipment, properly operating the computer programs, and then preparing the data for analysis. It is strongly recommended to use tripods for the laser, expander, SLM (Spatial Light Modulator), and camera, it makes alignment a far simpler process. Make sure to fully open the legs of the tripods for maximum stability of the equipment.

Gather Equipment

-Laser, control box for the laser, power cord, tripod, activation key

-Expander, tripod

-SLM, ribbon cable, tripod, control box, power cord, laptop with proper programs installed

-DCx camera, USB connector cord, laptop with proper programs installed and MATLAB

Setting up and aligning the laser, expander, and SLM

The laser needs to be given approximately 30 minutes to fully warm up and stabilize at the steady state power level. It is suggested to immediately turn on the laser before starting to operate computer programs or align the laser, expander and SLM, to optimize the set up time with the laser warming up. In order to turn on the laser, take the laser's control box and plug in the power cord and connect it to a wall outlet. Then take the white connector from the laser and connect it to the laser's control box. Turn the key on the control box and a red light should turn on, pass your hand over the laser path to make sure that the laser is properly outputting a beam. Make sure that the laser's polarization arrow is pointed in the direction of the propagation and that the arrow is facing upwards and visible from the top of the laser. The polarization arrow is on the emitting end of the laser, it is a yellow and black sticker with an arrow on it.

Aligning the equipment- In order to gather good data, the laser must fully escape the expander without reflecting or refracting inside the expander. Place the laser as close to the expander opening as possible and get the laser to propagate as close to the center of the expander opening as possible. Place an object in front of the expander and verify that the whole beam is propagating through. This can be confirmed when observing the beam on the exit end of the expander, the beam will be a full circle, with no reflections, and no dim or dark spots. Adjust the expander so that the beam size is maximized while not being larger than the reflecting window on the SLM. If the beam from the expander is larger than the reflecting window on the SLM, there will be artifacts on the camera which will skew the data. Now, take the SLM and align the reflecting window of the SLM with the beam from the expander. It is strongly suggested that the cords for the SLM already be plugged into the SLM, otherwise, if the SLM is aligned before attaching the cables to the control box, the SLM will likely become misaligned after the connection is made and the alignment will have to be redone. After aligning the beam to the reflecting window and properly adjusting the size of the beam with the expander, if necessary, twist the SLM about its vertical axis to direct the beam towards the intensity sensor while keeping the alignment with the beam from the expander. Make sure that the angle between the expander beam and the reflected beam from the SLM is minimized (ideally less than 10 degrees), this will maximize the effectiveness of the SLM in changing the phase of the light.

At the intensity sensor (camera), place the camera such that the reflected beam from the SLM is hitting the center of the camera. After longer distance propagations, the beam will have expanded to a size much larger than the window of the camera, attempt to center the beam on the camera as much as possible.

Setting up the camera

At the end of the propagation distance is where the camera should be placed. Connect the USB cord to the back of the camera and proceed with aligning the camera. It is strongly suggested to tape down or otherwise secure the camera's cord from the back of the camera. If not secured, the cord produces a small tension, but it is enough to move the camera and ruin the alignment, with the cord secured, the camera will remain stationary with less difficulty. Plug the other end of the USB cord into the computer to be used for the recording. Turn on the laptop, if the laptop is already on that is fine, and open the program uc480 viewer. Make sure to apply the proper filters to the camera so as not to saturate the sensor, or worse, destroy the camera. It is a trial and error process of determining how much filtration will be needed at what distance and power level for the laser, but make sure that proper filters are on the camera before shooting the laser at the camera. The ideal amount of filtration keeps the sensor from saturating at all times, but maximizes the intensity as close to 255 as possible. The camera is now ready for use.

Setting up SLM

In order to properly make the SLM alter the phase of the light, the proper set up procedures must be taken. The following steps refer specifically to the BNS (Boulder Non Liner Systems) SLM, these specific steps may not produce desirable results in other brands of SLM. Connect the ribbon cable from the SLM to the control box. Connect the control box to the PCI express cord, do not connect the PCI cord to the laptop yet.

1. Make sure the laptop is off before plugging in the SLM's power cable. Once the laptop is off and disconnected from the SLM in all ways, plug in the SLM's power cord to power the control box.
2. After powering the control box, plug in the PCI Express Card from the SLM into the laptop to be used and make sure that the card is properly lodged in the slot and fully connected. Boot the laptop. If the laptop is turned on before the SLM box, the two devices will not interface properly.
3. Log into the computer and open PCIBlink or whatever program runs the SLM.

When the program fully loads, the SLM is ready for use.

Operating computer programs – mainly SLM and camera

There are two primary programs that will be used on the laptops to properly run the experiment and collect data, these programs are the uc480 viewer and the PCIBlink, these operate the camera and SLM respectively.

-uc480 viewer

Once the camera has been properly set up and this program is opened, click on the miniature play button in the top left of the program. The main window of the program will now display a black and white image of what the camera is seeing. If the laser is aligned with the camera, the white of the laser beam will be seen, if the laser is not aligned, all that should be seen is a black screen. Use the feedback on the screen to make sure that the laser is properly aligned with the camera, attempt to get the whole beam inside the camera's view screen, or at least have the center of intensity in the center of the camera's field of vision. Move the camera as necessary to have the laser properly impact the camera.

Once the camera has been aligned to properly view the laser, you are ready to record. Click on the ‘cut scene’ icon on the top bar of the program, this will bring up a window to allow you to film the laser. Click the “create…” button. Name the file and save it where desired. Bring the JPEG quality up to 100 on the next screen. Click on “record”. When the run has finished, click on “stop” and then click on “end.” This will end and save this recording. When you are ready to record a new video of the laser, begin the process again with the “create…” button. Repeat as many times as necessary. In the screen that displays while the camera is recording, check the size of the video, after approximately 30 seconds of recording, the video file should be approximately 200 MB, if the video is significantly smaller, then the camera is not actually recording the laser at all and is recording too low of an intensity to accurately measure.

-PCIBlink

After the SLM has been properly set up and PCIBlink is loaded, click on the “Browse…” button on the top right of the program window. Find the screens that you desire to modulate the laser beam with. Click on “select”. The images that you select must be 512x512 and be in a *.bmp format. If you have more than one screen in a single folder, the SLM will cycle through these images, if you want only a single change to the laser at a time, put each image file in a separate folder. In order to make sure that the SLM is actually changing the laser, place an object in front of the beam before selecting the screen to modulate the laser with, after selecting the screen, there will be an obvious difference between the laser from before selection and to after selecting the operating the screen. If you watch the laser the whole time, you should actually see the laser changing on the object. If the laser on the object does not change from before selecting the screen to after selecting the screen, there is a problem with the SLM and the computer must be rebooted and all the SLM setup procedures must be repeated. If the SLM goes idle for 5 minutes or more, you will also be required to reboot the computer and restart the SLM setup procedures. Once you have confirmed that the SLM is actually working, you can prepare your runs with the beam. You need to know how long your laser shot is supposed to last, based upon this time you will select the delay and number of loops for the SLM to run through. The delay is the delay between images (normally you will only have one image in the folder), the loops is how many times the SLM will cycle through your list of images (again, only one image in the list). With a 1000 ms delay between images (maximum delay possible) and 100 loops, it will take the SLM 100 seconds to run through that program (with only one image in the list). If there were two images it would take the SLM 200 seconds. Based upon how long your trials need to be, set the appropriate delay and loop numbers, but take into account human error and starting the recording on the other end. Give yourself approximately 10 seconds of leeway time. If your run is supposed to be 30 seconds long, set the SLM to cycle for approximately 45 seconds, the extra 15 seconds will allow you to start the SLM, then start the recording on the camera and stop the recording on the camera before the SLM stops properly displaying images. After the proper delay and loops have been set, click on the "start" button at the bottom left of the program window. Repeat for the next desired screen and trial runs.

Operating video to jpg program

The DC camera outputs *.avi files, in order to convert these to files easily read by MATLAB, a conversion program is necessary, the proper program can be downloaded from http://www.dvdvideosoft.com/products/dvd/Free-Video-to-JPG-Converter.htm

Once open, this program is simple to use. Click the "Add Files…" button and find the files that were recorded from the camera. Add all files that you desire to convert for analysis. Select the amount of frames you want to retrieve from the video, for best analysis you should select all frames, but if you require less data you can also elect to capture frames every n^{th} frame, every x seconds, or pull x frames from the video. When you have selected all the videos to convert and the proper frames to pull, type the location of the output files. Then click "Convert".

Running the experiment

In order to get good data, after properly following the above steps for setup, you must do the following to properly utilize the proper setup. Set the SLM to run your desired screen and record data for 30 seconds, convert this data into pictures and analyze the data with the MATLAB or other processing program. If the data is good (intensity values span at least 50 levels and max out at approximately 200, adjust filters as necessary, no sudden changes in intensity, intensity can never be zero), run the screen again and gather data for approximately 3 minutes. Check the data with your processing program again, if the data is still good, save this data. Otherwise, repeat the gathering procedure.

Appendix B

Data Analysis

```
%% Initialization
clear
format compact
format short


%% Global vars

frames = 309; %total frames to be analyzed by the program
```

```
% specific pixel location to be reviewed by the statistics portion of
% program
x = 512;
y = 640;

%% average of all frames
startx = 1; %// row
stopx = 1024;
starty = 1; %// column
stopy = 1280;
k = 0;redsum = zeros(1024,1280); %// Average of all pixel values to zero

 widthx = 150;
 widthy = 150;

% startx = x-widthx; %// row
% stopx = x+widthx;
% starty = y-widthy; %// column
% stopy = y+widthy;
% k = 0;redsum = zeros(stopx-startx+1,stopy-starty+1);

%% Stastics portion
%make an array for the time sequence
time = 1:1:frames; %^^^^^^^^^^^^^^^^^%SAZ%%%%%%%%% recalcualte using how many
frames per second and how long was test)
Ipixspot = 1:1:frames; % used to plot a time sequence for intensity of a
pixel
Iframes = 1:1:frames; %used to plot a time sequence for intensity over whole
frame
Imaxframes = 1:1:frames; %used to determine max intensity of a a whole frame
IpixNorm = 1:1:frames; %Normalizes intensity for a pixel then a frame
IframeNorm = 1:1:frames;
IMaxframeNorm = 1:1:frames;
Varframes = 1:1:frames; %used to plot the variance of each frame for all
frames
VarframeNorm = 1:1:frames;
VarDiffFrames = 1:1:frames; %calculate the difference between the variance of
each individual frame and the average variance
VarDiffFramesAbs = 1:1:frames; %absolute difference between variances

%% Load data
%f=['.jpg'];n=['4096'];
f=['.jpg'];n=[input(' ','s')];
%// Load data and sum pixel values
%// Modify this loop to conform to whatever file format the data uses


for a = 1:frames %change the k in commands to a to see if same data appears
    st = [n,' ',sprintf('%03u',a),f];
    s1 = double(importdata(st));
    s = (s1(:,:,1) + s1(:,:,2) + s1(:,:,3))./3;
    %// Display k to show the script is not frozen
    %// Use k as an index instead of a in case a does not match up with
    %// frame numbers
    k = k + 1
```

```
    %// Sum all pixel values

    Ipixspot(k) = s(x,y);
    sazframe(k)=sum(sum(s(stopx-startx+1,stopy-starty+1)))/(((stopx-
startx+1)*(stopy-starty+1))-1);
    intensityframe = 0;
    maxi = 0;
    test = 0;
    for stern = startx:1:stopx
        for bow = starty:1:stopy
            intensityframe = intensityframe + s(stern,bow); %sum of intensity
for all pixels in the frame
            test = s(stern,bow);

            if(test>maxi)
                maxi = test;
                xloc = stern;
                yloc = bow;
            end
        end
    end


    Iframes(k) = intensityframe/(((stopx-startx+1)*(stopy-starty+1))-1);
%normalize the value of intensity in a frame and assign that value as the
intensity for that frame

    %maximum values of intensity and location of intensity
    Imaxframes(k) = maxi;
    Imaxframesloc(1,k) = xloc;
    Imaxframesloc(2,k) = yloc;

    sumframe = 0;

    for sternv = startx:1:stopx
        for bowv = starty:1:stopy
       sumframe = sumframe +(Iframes(k)-s(sternv,bowv))^2;
        end
    end

    Varframes(k) = sumframe/(((stopx-startx+1)*(stopy-starty+1))-1);
%intensity variance for a single frame,k, compiled for all frames - able to
be plotted
    VarframeNorm(k) = Varframes(k)/mean(Varframes);


    redsum = s(startx:stopx, starty:stopy) + redsum;

end


%Normalize the values for intensity

redsum = redsum/(k-1);
```

```
sprintf('Evaluating Pixel %d,%d',x,y)
sprintf('Picture size is %d pixels by %d pixels', widthx*2,widthy*2)

%% mean and std dev of intensity

    meanI = mean(Ipixspot)
    meanIw = mean(Iframes)

    %Normalize intensity data
    for e=1:frames
        IpixNorm(e) = Ipixspot(e)/meanI;
        IframeNorm(e) = Iframes(e)/meanIw;
        IMaxframeNorm(e) = Imaxframes(e)/meanIw; %Most intense pixel value
for the whole frame
    end

    meanInorm = mean(IpixNorm)
    meanIwnorm = mean(IframeNorm)

varianceINorm = var(IpixNorm)
varianceIwholeNorm = var(IframeNorm)
meanvarianceNorm = mean(Varframes)


    for d=1:frames
        VarDiffFrames(d) = VarframeNorm(d)-mean(VarframeNorm);
        VarDiffFramesAbs(d) = abs(VarDiffFrames(d));
    end

maxIntPixNorm = max(IpixNorm) %Max intensity for the specific pixel x,y

varDiffmean = mean(VarDiffFrames);
varDiffmeanabs = mean(VarDiffFramesAbs)
n


%% Mean and Std Dev for max location

Imaxframeslocx = Imaxframesloc(1,:);
Imaxframeslocy = Imaxframesloc(2,:);

meanx = mean(Imaxframeslocx);
meany = mean(Imaxframeslocy);

stdx = std(Imaxframeslocx);
stdy = std(Imaxframeslocy);

stddist = sqrt(stdx^2+stdy^2);

%the size of pixels on the DCx camera is 4.65 micrometers x 4.65
%micrometers, this will show how far from the average center of the beam
%the laser deviated on average.
```

```matlab
distx = stdx*4.65;
distxmilli = distx*10^-3;
disty = stdy*4.65;
distymilli = disty*10^-3;
diststd = stddist*4.65;
diststdmilli = diststd*10^-3;

%% Plotting
%  figure(1)
% surf(redsum)
% title('Averaged intensity fluctiuations of laser light')

figure(2)

subplot(2,2,1)
plot(time,Ipixspot)
title('Intensity over time for a sigle pixel')
xlabel('Time [s]');
ylabel('Light Intensity');

subplot(2,2,3)
hist(IpixNorm,100)
title('Histogram of Intensity Values for a Pixel');
ylabel('Frequency');
xlabel('Normalized Light Intensity');

subplot(2,2,2)
plot(time,Iframes,'r');hold on;plot(time,sazframe,'k');hold off;
title('Intensity over time for all frames')
xlabel('Time [s]');
ylabel('Light Intensity');

subplot(2,2,4)
hist(IframeNorm,100)
title('Histogram of  Intensity for frames');
ylabel('Frequency');
xlabel('Normalized Light Intensity');

figure(3)
plot3(Imaxframesloc(1,:),Imaxframesloc(2,:),time,'.');
title('Location of Maximum intensity for Laser Shot');
xlabel('X Location');
ylabel('Y Location');
zlabel('Frame Number');

% figure(3)
% subplot(1,2,1)
%
% plot(time,VarframeNorm)
% title('Normalized Variance of Intensity for a frame over all frames');
% xlabel('Time[s]');
% ylabel('Light Intensity');
%
% subplot(1,2,2)
% plot(time,IMaxframeNorm,'r');hold on;plot(time,varianceINorm,'k');hold off;
```

```
% title('Maximum Intensity for pixel over all frames');
% xlabel('Time[s]');
% ylabel('Light Intensity');
%
%
% figure(4)
% subplot(1,2,1)
%
% plot(time,VarDiffFrames)
% title('Difference between average variance and variance of frame');
% xlabel('Time [s]');
% ylabel('Difference');
%
% subplot(1,2,2)
% plot(time,VarDiffFramesAbs)
% title('Absolute Difference between average variance and variance of
frame');
% xlabel('Time [s]');
% ylabel('Difference');

figure(7)
text(0,0, sprintf(...
    'Evaluating Pixel %d,%d\nPicture size is %d pixels by %d
pixels\nIntensity for pixel: %f\nIntensity for frame: %f\n\n\nVariance of
Pixel Intensity: %f\nNormalized Pixel Intensity: %f \n\n\nVariance of Frame
Intensity: %f\nNormalized Frame Intensity: %f \n\n\nMaximum Intensity for
pixel: %f\n \n\n\n\n\n\n\n\n\n\n\n\n\n\n' ...
    ,x,y,widthx*2,widthy*2,meanI,meanIw, varianceINorm,meanInorm,
varianceIwholeNorm, meanIwnorm, maxIntPixNorm))

figure(8)
text(0,0, sprintf(...
    'Max Location Analysis\nXbar: Pixel %f\nYbar: Pixel %f\n\nSTDx: %f
pixels\nSTDy: %f pixels\nSTDHypotenuse: %f pixels\n\nDistance in X: %f
micrometers      %f mm\nDistance in Y: %f micrometers      %f mm\n Hypot
Distance: %f micrometers    %f mm\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n' ...
    ,meanx, meany,stdx,stdy,stddist, distx,distxmilli,
disty,distymilli,diststd,diststdmilli))
```

Make Correlation Width Screens

```
I = normrnd(0,1,512,512);
    [y,x] = meshgrid(1:length(I),1:length(I));
    r = length(x)/2;
    c = length(x)/2;
    rho = sqrt((x-r).^2 + (y-c).^2);
    Corr_width_2 = 64; %this is the only thing i change, when I want a screen
with 128 or 4096, that is the number I change
    window = exp(-rho.^2/Corr_width_2);
    GSB = conv2(window,I);
    GSB_512 = GSB(256:767,256:767);
    GSB_512 = GSB - min(min(GSB_512));
    GSB_512 = GSB_512./max(max(GSB_512));
    jj = jj+1;
```

```
    figname = sprintf('GSM_%d_corr_width_%d_Gaussian.bmp', jj,
round(Corr_width_2)):
    imwrite(GSB_512,figname, 'bmp');
```

Make Bessel Screens

```
I=[zeros(512/2,512/2) zeros(512/2,512/2) zeros(512/2,512/2)
zeros(512/2,512/2);
    zeros(512/2,512/2) normrnd(0,1,512/2,512/2) normrnd(0,1,512/2,512/2)
zeros(512/2,512/2);
     zeros(512/2,512/2) normrnd(0,1,512/2,512/2) normrnd(0,1,512/2,512/2)
zeros(512/2,512/2);
    zeros(512/2,512/2) zeros(512/2,512/2) zeros(512/2,512/2)
zeros(512/2,512/2)];


% Generate distance grid
[y,x] = meshgrid(1:length(I),1:length(I));       % Svetlana used a
1:length(I), then centers

    % calculate the distance from (r,c)
    r = length(x)/2;                                   % choose center of grid
    c = length(x)/2;
    rho = sqrt((x-r).^2 + (y-c).^2);                   % distance from center,
careful as rho very big drives the window function to zero rapidly



Beta = .025;
window_bessel = besselj(0,Beta*rho);

% convolution of window function with Gaussian Random Number grid
GSB = conv2(window_bessel,I);  % origibnal!!

GSB=GSB- min(min(GSB));GSB = GSB./max(max(GSB));

GSB1x = conv2(window_bessel,I,'same');

GSB1=GSB1x- min(min(GSB1x));GSB1 = GSB1./max(max(GSB1));%imshow(GSB1); %this
is the center part necessary for processing in slm


% taking central selection of randomized values for SLM use
GSB_512 = GSB1(256:767,256:767);
GSB_512 = GSB_512 - min(min(GSB_512));
GSB_512 = GSB_512./max(max(GSB_512)); % this process shifts the values to [0
1] in order to maximize the imwrite resolution (creates a bitmap)


% Save figures as fig files (saveas) and/or bitmap (imwrite)
jj = jj+1;
figname = sprintf('GSM_%d_Beta_%f_Bessel.bmp',jj,Beta);
```

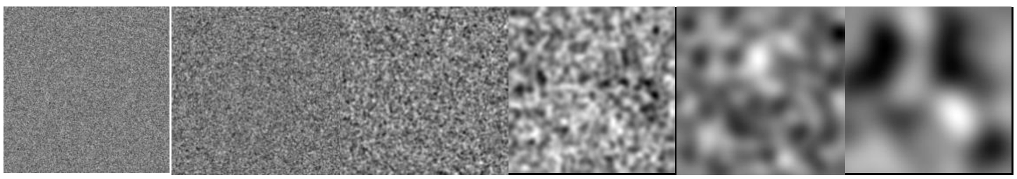
```
imwrite(GSB_512,figname, 'bmp');
```

Appendix C

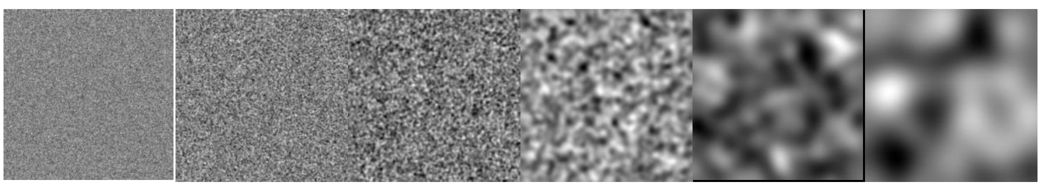
The screens are displayed left from right in increasing correlation width order, 1, 4, 16, 128, 1024, 4096. The Bessel screens with the equivalent beta to the correlation width are also displayed left form right. The equivalent beta values used are 5, 1, 0.45, 0.25, 0.05, 0.025.

Gaussian Screens used

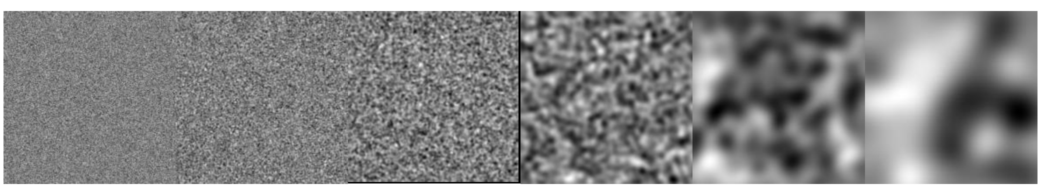
Set 1



Set 2

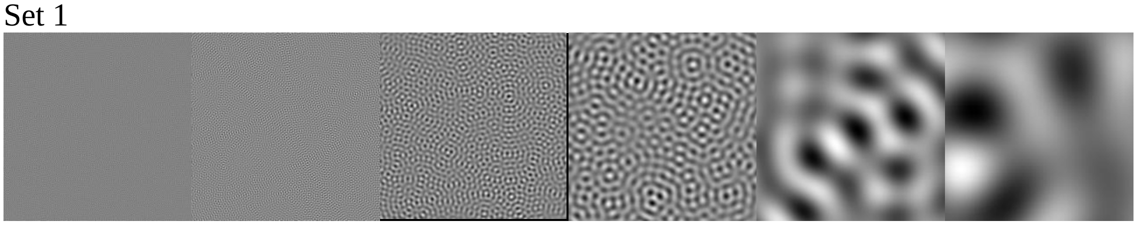


Set 3

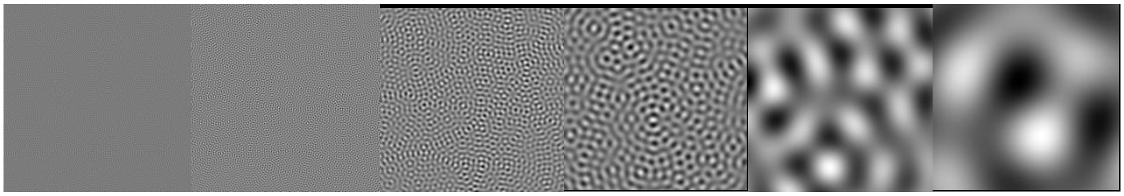


Bessel Screens used

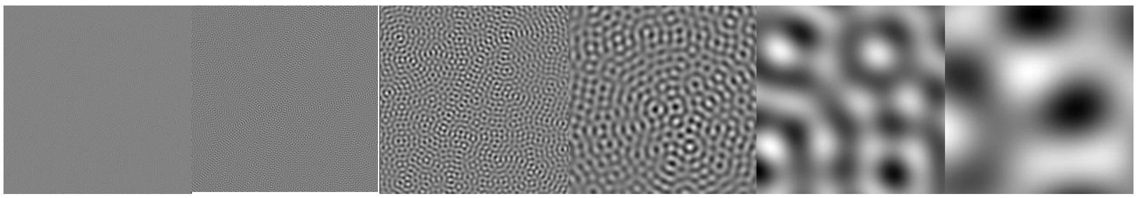
Set 1



Set 2



Set 3



Appendix D

Legend
B - Black had a higher value compared to the Screen
S - The Screen had a higher value compared to black

Ideal results for this project
S should be in the Intensity Column
B should be in the Variance Column

A single box is represented by two letters
The first letter is the result for the pixel
The second letter is the result for the frame
Frame results where evaluated as more valuable for this research

Set 1

Gaussian Beams

5m

	Intensity	Varaince
1	BB	BB
4	BB	SS
16	BB	SB
128	BB	SB
1024	BB	SB
4096	BB	BS

Bessel Beams

5m

	Intensity	Varaince
1	BB	BB
4	BB	SB
16	BB	SB
128	BB	SB
1024	BB	SB
4096	BB	SS

50m

	Intensity	Varaince
1	BB	BB
4	BB	SB
16	BB	SB
128	BB	SB
1024	BB	SB
4096	BB	SS

50m

	Intensity	Varaince
1	BB	SB
4	BB	SB
16	SB	SS
128	BB	BS
1024	SB	SS
4096	SS	SB

100m

	Intensity	Varaince
1	BB	SS
4	BB	SS
16	BB	SS
128	BB	SS
1024	BB	SS
4096	BB	BB

100m

	Intensity	Varaince
1	BB	BS
4	BB	SB
16	BB	SB
128	BB	SS
1024	BB	SS
4096	BB	BB

Set 2

Gaussian Beams

5m

	Intensity	Varaince
1	BB	BS
4	BB	SB
16	BB	SB
128	BB	BS
1024	BB	SS
4096	BB	BB

50m

	Intensity	Varaince
1	BB	SS
4	BB	SS
16	BB	SB
128	BB	SS
1024	BB	SS
4096	BB	SS

Bessel Beams

5m

	Intensity	Varaince
1	BB	SB
4	BB	S=
16	BB	SS
128	BB	SS
1024	BB	SB
4096	SB	BS

50m

	Intensity	Varaince
1	SS	BB
4	SS	BS
16	BB	BB
128	SS	BB
1024	BB	SS
4096	BB	SB

100m

	Intensity	Varaince
1	BB	SS
4	BB	SB
16	BB	BB
128	BB	SS
1024	BB	SS
4096	BB	SS

100m

	Intensity	Varaince
1	SS	BB
4	BB	BB
16	BB	BB
128	SB	SS
1024	BB	SS
4096	BB	SS

Set 3

Gaussian Beams

5m

	Intensity	Varaince
1	BB	BS
4	BB	BB
16	BB	BB
128	BB	SS
1024	XB	XB
4096	BB	SB

50m

	Intensity	Varaince
1	BB	SS
4	BB	SB
16	BB	SS
128	BB	SB
1024	BB	SS
4096	BB	SS

100m

	Intensity	Varaince
1	BB	BB
4	BB	SS
16	BB	SB
128	BB	SB
1024	BB	SS
4096	BB	SS

Bessel Beams

5m

	Intensity	Varaince
1	BB	SS
4	BB	SS
16	BB	SS
128	BB	SS
1024	BB	SB
4096	BB	SB

50m

	Intensity	Varaince
1	BB	SS
4	BB	SS
16	BB	SS
128	BB	SS
1024	BB	SB
4096	BB	SS

100m

	Intensity	Varaince
1	BB	SB
4	BB	SS
16	BB	SS
128	BB	SS
1024	BB	BB
4096	BB	BB

For the above tables, correlations between sets and correlations between the larger value (Black or screen) will be annotated here.

Correlations between statistically similar sets

For 5 meters – Gaussian Sets 1, 2, and 3 had similar results, as did Bessel Sets 2 and 3.

For 50 meters – Gaussian Sets 2 and 3 had similar results, as did Bessel Sets 1 and 3.

For 100 meters – Gaussian Sets 1 and 2 had similar results, as did Bessel Sets 1, 2, and 3.

Desirable results – with respect to the results from the analysis of frames, not pixels.

Desirable results were determined by having a majority of variance values that were smaller with the SLM screen than the black comparison. Marginal results were when half of the values were smaller with the screen and half were larger than the black comparison. Undesirable results were when a majority of the variance values with the SLM screen were larger than the black comparison. If results were not desirable or marginally desirable, they were undesirable. All tests were undesirable in terms of intensity, so those results are not specifically laid out.

For 5 meters – Gaussian sets 1 and 3 showed desirable results, set 2 showed marginal results. Bessel set 1 showed desirable results, set 2 showed marginal results.

For 50 meters – Gaussian set 1 showed desirable results, set 3 showed marginal results. Bessel set 2 showed desirable results, set 1 showed marginal results.

For 100 meters – Gaussian set 3 showed marginal results. All three sets of Bessel showed marginal results.