Laser Propagation in the Maritime Environment

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I. INTRODUCTION

The Department of Defense hopes to employ laser technology as a category of weapons and countermeasures under the name of “directed energy” and “High-energy laser (HEL)” systems. With the country’s strong foundation in engineering and research, the United States are in a better position to exploit HEL systems than many other countries [1]. Current research efforts cover a spectrum of applications for laser systems mounted in aircraft, spacecraft, ships, and ground vehicles. Advantages of using lasers in place of other weaponry, such as kinetic weapons, include instantaneous and multi-target engagement, precision control, and reduced “logistics footprint” [1]. To employ laser systems though, researchers and developers must solve a series of engineering challenges; for instance, they must decide which laser sources are best, how to generate sufficient energy in the confines of the platform a laser system is mounted to, compensate for atmospheric effects on beam propagation, and optimize costs [1].

Some of the main reasons the Navy has in the employment of HEL include its engagement time and discriminatory capability. As described in a report by the Defense Science Board Task Force, an example of using a laser for the first example would be against fast and agile anti-ship missiles, where time to engage is very short; an example of the latter would be against patrol boats which can blend into civilian vessels, requiring greater precision than is sometimes offered by normal ordnance [1].

One of the unique challenges facing the employment of HEL for the navy is the nature of the operating environment. First, air in the maritime environment is denser than that over land or higher in the sky [1]. It is entirely possible for a laser beam’s energy to get absorbed before it reaches its target, other parameters such as humidity, pressure, temperature, and wind velocity contribute to skewing a straight-path from the laser's source to the target.

In that vein the aim of this project was to study the effects of maritime weather conditions on a laser beam's propagation. All of the aforesaid variables contribute to changes in the index of refraction of air. Fluctuation in index of refraction causes electromagnetic radiation, including visible light, to bend. Hence, a laser beam going through turbulent air at varying humidities and temperatures is less likely to hit its intended target. The goal of this project was to observe the differences of laser beam propagation in maritime environs versus 'normal' conditions and attempt to correlate simultaneously recorded weather data with measures of beam performance such as beam diameter, power delivery, and accuracy.

II. Basic Laser Mechanics

Laser light is generally of the same frequency and phase, or 'coherent,' and has a small angle of divergence. A laser beam can form from a device which is an 'optical cavity' filled with certain materials, 'gain media,' which amplify input energy emitted at certain frequencies [2]. The frequency of energy which will stimulate a gain medium is dependent on the chemical make-up of the medium. In any case, the following description gives a very basic explanation of how a laser light is created from such a device. The gain medium is stimulated with energy at a frequency of light which corresponds to the energy difference between ground state and an excited state in the atoms of the gain medium. Two processes happen when the gain medium absorbs energy at such a frequency: 1) electrons which absorb photons at that frequency move up to an excited state, and 2) electrons already in the excited state which receive such a photon get knocked back to ground state, emitting a photon which travels with the same frequency and phase as the original, and the original photon does not get absorbed by the atom [3]. This means there are two photons where originally there was one, so the process can continue. When more than half the atoms in a gain medium are at a simulated state then there is a surplus of photons for the amount of ground state atoms left; this is called population inversion [3]. At this point the excess photons escape an aperture in the optical cavity and produce visible light.

III. Helium Neon Lasers

The type of laser used in this research was a Helium-Neon laser (“HeNe”) emitting at 632.8 nm, commonly used in academic settings as a reliable basic laser. Helium-Neon lasers are the cheapest and most common gas lasers, built to operate at 632.8 nm (red), 543.5 nm (green), and 1523 nm (infrared) [4]. The mixture of gas within the tube is 85% helium, 15% neon at a pressure of 1/300 atmospheres [5]. The construction of the laser tube features a flat mirror on one end, 100% reflective, and can have either another flat mirror or a concave mirror at the other end [5]. Having two flat mirrors requires extremely precise alignment, so the HeNe laser usually comes with one flat mirror and one concave; the emission end mirror reflects 99%, transmits 1% [5].

IV. PROJECT HISTORY

The initial milestones set for the course of the project were to study laser behavior in 1) atmospheric conditions in the laboratory, 2) over a 100+ m water tank underneath Rickover Hall, and 3) across College Creek, a brackish water tributary to the Severn River. In the final lab set-up, data from a weather instrument would be taken in conjunction with power measurements of the laser at a target in an attempt to correlate effects of temperature, humidity, wind velocity, and pressure on beam performance.

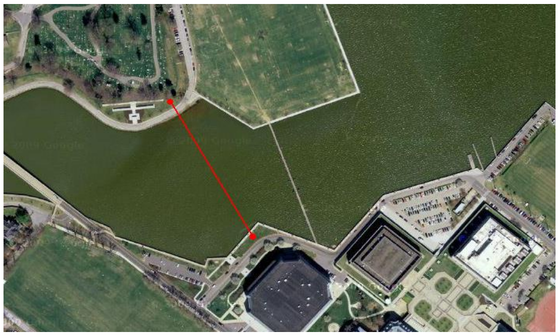

Fig. 1: College Creek. Drawn on is the prospective sight for experimental set-up.

Professor Montgomery of the USNA Physics Department contributed early in the project by recommending the Helium-Neon 632.8 nm laser and by instruction on basics of laser propagation. His supplemental notes gave detailed explanations deriving and explaining laser optics lens equations and equations for Gaussian beam propagation and included such key facts as the basic principle that lasers spread as they propagate due to 1) natural tendencies of Gaussian behavior and 2) aperture size, due to laws of diffraction.

Maury Hall experiment

The first experiment was conducted on the ground floor Maury lab room. A Helium-Neon laser was shot down the length of the lab room and beam diameter measurements were taken by ruler at 5 foot intervals,

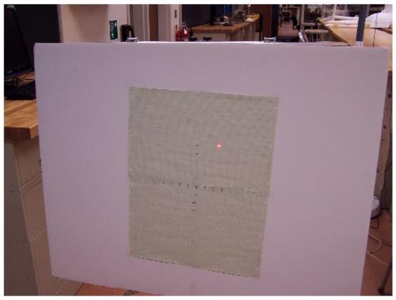

Fig. 2: target set-up in Maury lab room

ranging from 0 feet to 128 (due to discrepancies room layout). Then an experiment was performed outdoors, from 0 to 100 feet, measuring beam diameter and power.

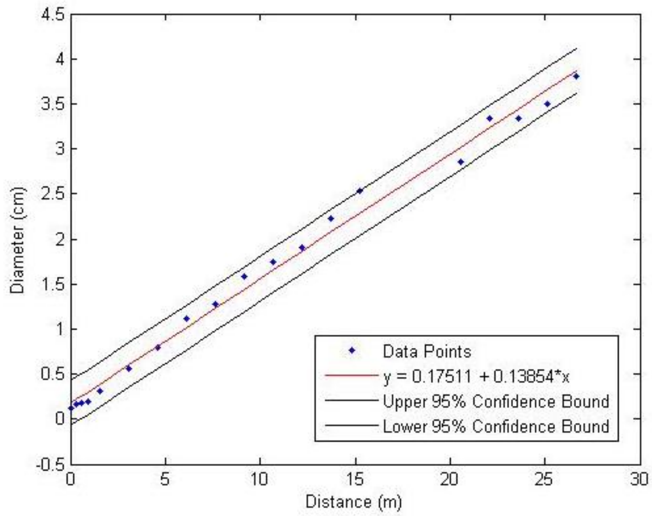

Figure 3: Data plot of measured beam diameter from the Maury experiment. A best-fit curve was applied using the Least Squares method, and a 95% confidence boundary was applied on either side. With 'y' in centimeters and 'x' in meters,
y = 0.17511 + 0.13854*x

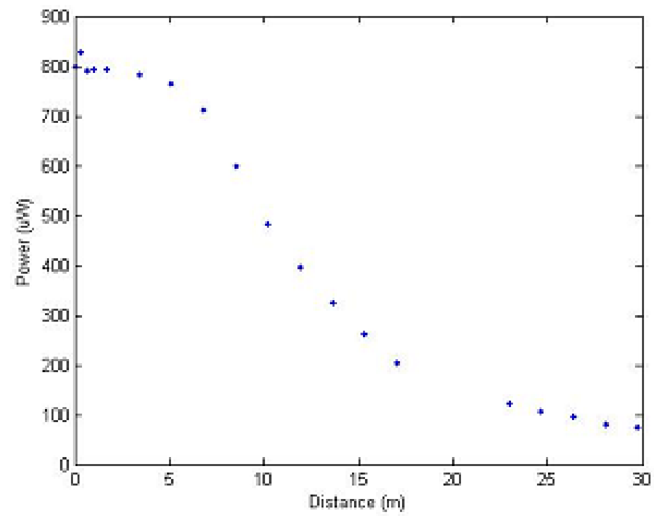

Figure 4: power measurements taken in the Maury experiment. Measurements were taken with a hand-held "Laser Check" power sensor, with an integrative viewing aperture.

Figures three (3) and four (4) show measured beam width and power measurements inside the Maury classroom. Each of these data sets was skewed by environmental factors and measurement errors. For instance, measurement of beam diameter is skewed at least two factors. First, it was measured visually with a hand ruler. Second, these were taken by visual inspection, so there was no way to reliably measure according to the definition of beam width, that is, the radial boundary where intensity is equal to $\frac{1}{e^2}$ the peak power at the radial center, for the *z* distance away from the origin.

For power measurements, one must consider that the lab room was not dark at all, since other students were using the same room; light at 632.8 nm came from other sources than the laser, such as from outside or from the lighting inside. Continuing, the power sensor was hand-held, and therefore subject to jitter, and from that power measurements were skewed since the viewing aperture did not take laser light at a perfectly normal incident angle. Furthermore, I took five power measurements at each distance and averaged them, and as the beam spread at larger distances, I measured at various locations inside the beam, but could not really document where I took the measurements. This means that the displayed power at each distance is not truly representative of the power at that distance, since power varies radially in addition to the 'z' distance from the laser, the axis formed coming straight out of the laser cavity.

Outdoor Experiment—Mahan Courtyard

For the outdoor experiment, measurements ranged out to 105 feet with 5 foot intervals along a walkway in the Mahan courtyard. Performance characteristics to be measured were beam diameter and power, as before. New factors arose which skewed

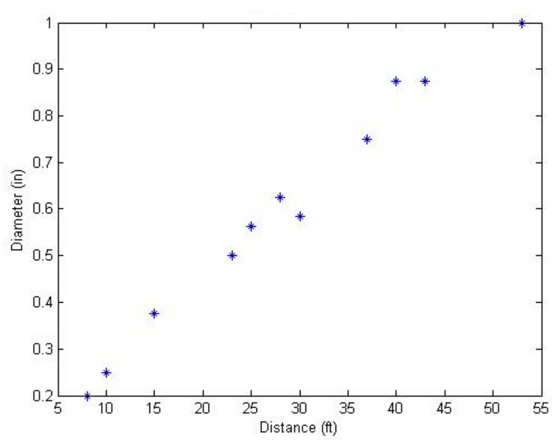

Figure 5: Diameter measured vs. distance in an experiment outside of Maury Hall.

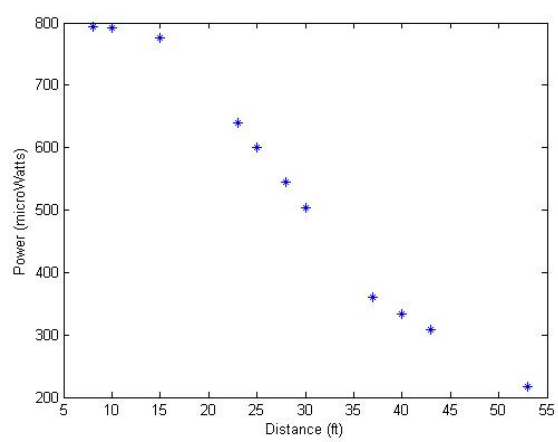

Figure 6: Power measured vs. distance in an experiment outside of Maury Hall.

measurements, however. The wind was strong that day, causing the target and/or the easel to fall over many times. Besides this, clouds and shadows from trees bending in the wind caused disruptions in getting accurate, consistent data both for beam width and power measurements. The beam growth chart (Fig. 5) shows very erratic changes in diameter which couldn't possibly be true; it is likely the differing levels of brightness outside threw those off. Strangely, power measurements (Fig. 6) did not seem wildly different from those in the first experiment. In any case, further outdoor experiments would require two power meters: one for the laser, and another next to it in order to subtract the power added by regular sunlight, so that the power received from the beam can be known.

Rickover Hydrolab Experiments

Following the experiments in and outside of Maury, the next step was to set the laser in an environment closer to the target environment, and the USNA Naval Architecture Technical Support Department (NATSD) stepped in to help. This department has several large water tanks which they use for testing ship models, which were pertinent to the laser research because 1) they provide a longer track to measure beam expansion, 2) they offer a environment closer to the conditions in which we wanted to observe laser, and 3) it was still relatively controlled. In contrast to the environment outside of Maury hall, where the wind kept knocking my target poster off its easel, there was no wind to contend with in the 'hydrolab.' Mr. Zseleczky, one of the staff in NATSD, granted permission to use the 300 foot long tank, and additionally he and Mr. Don Bunker built a frame suitable for hanging a target over the water tank's wall, suspending a target above the water.

In the hydrolab set-up beam diameter was measured from 1 m to 105 m. Distances were measured along the wall using a tape measure, and were set to 1,2,3,5, and 10 meters, and then at 10 meter intervals up to 100, and then an extra one at 105 m.

The actual experiment involved taking pictures of a target at various distances, as seen in the following photographs.

Figure 7: distance marker in Rickover Hydrolab

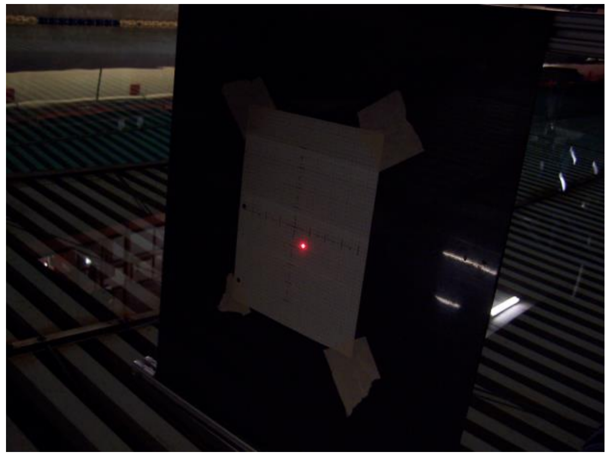

Figure 8: target and frame hung over the water tank

The target consisted of graph paper marked with an x-y grid and having hash marks at 1/5 inch intervals in black marker, to add contrast against the laser light in the pictures. To take measurements, the target was mounted to the frame and moved along the wall, while distances were recorded at each distance down the tank. No power measurements were taken since the power meter was expensive and hand-held, making it risky to try holding over the edge of a water tank.

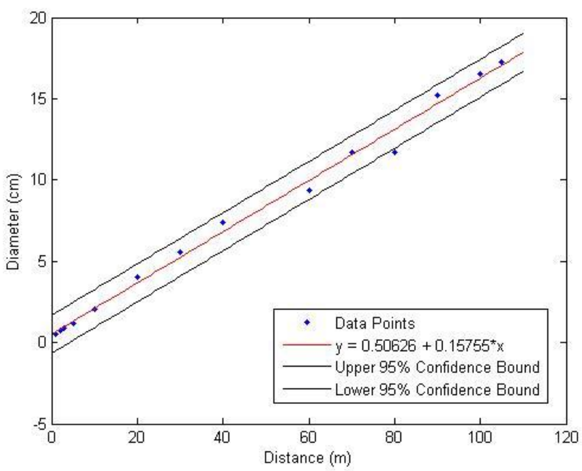

Figure 9: Diameter vs. distance measurements in the hydrolab. Data indicates more expansion than in the Maury lab room. With 'y' given in centimeters and 'x' in meters, the linear regression found gives:

$$y = 0.50626 + 0.15755 * x$$

For diameter measurements, I visually inspected the photographs I took during the experiment and estimated them as best I could, usually to the tenth of an inch. According to the data set, the diameter grew much more quickly than it did in the Maury lab room. While environmental factors such as humidity and temperature were different than in Maury, it is likely that the lighting in the hydrolab lent the most to the change in measured diameter. It was much darker in the hydrolab, allowing for more laser light to show up on the target, as opposed to the situation in Maury where ambient light could "drown out" the effect of the laser light on the target.

Data Analysis

The equation $I(r,z) = I_o\left(\frac{w_o}{w(z)}\right)^2 e^{-2\left(\frac{r}{w(z)}\right)^2}$ [6] can be used to describe the intensity at any point along a Gaussian laser beam's path given the following pieces of information: I_o, nominal intensity of the beam, w_o, beam waist (narrowest diameter of the beam), $w(z)$, beam width at point z away from the beam waist, and r, the radial distance from the translational path of the laser beam. Having measured $w(z)$ at various distances and being able to obtain I_o by dividing an initial power reading by the area of the beam at that point, it was still impossible to solve this equation without knowing w_o (I was unable to found it in the model specs). To compare the effects on power delivery between 'ideal' conditions in Maury and the humid environment in the hydrolab, it was necessary to solve this equation. The results from this equation would only be estimates, but for the purposes of this project, qualitative results were suitable in lieu of precise data.

One could theoretically find beam waist w_o empirically by rearranging the formula [7] $w(z) = \frac{\lambda z}{\pi w_o}$. Having values for z, w(z), and λ, one could rearrange this equation to solve for "w_o." The equation is actually an approximation representing an asymptotic approach in value as *w(z)* increases, so larger distances in the data sets were used.

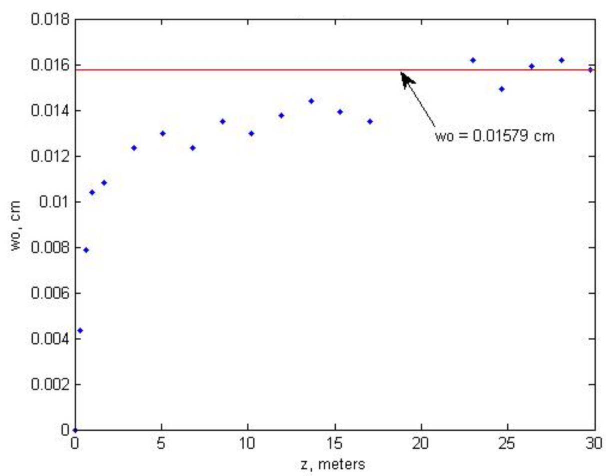

Figure 10: w_o, beam waist, empirically measured in the Maury lab room.

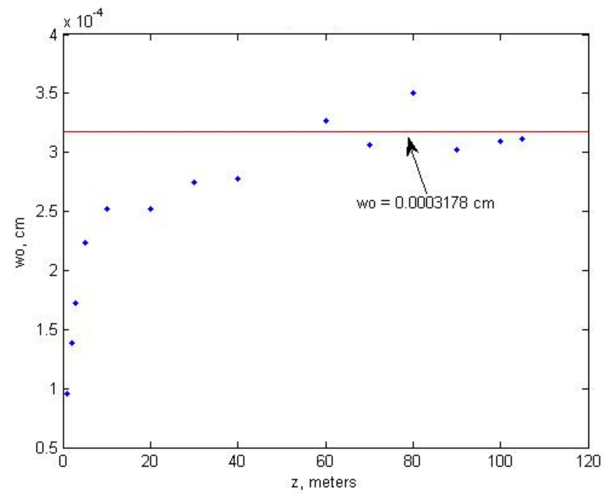

Figure 11: w_o, beam waist, empirically measured in the Rickover Hydrolab.

Experimental values differed by orders of magnitude from each other. While the specifications sheet for the laser, a Metrologic ML868, did not give a beam waist, it said that the beam diameter at the aperture is 0.066 cm [8] (meaning the beam waist must be smaller than 0.066 cm). When one notes the earlier discussion of diameter measurement discrepancies, the difference between each experiment and the accepted value appears to conform to theory. First, it seems extremely likely in the case of the Rickover Hydrolab, that the measured value of beam width is much larger than the conventional definition of diameter. Being larger, it would cause the calculated value of beam diameter to be much smaller, since smaller aperture size causes more expansion. It is also likely that the diameters measured in Maury were larger than convention has defined.

V. MATLAB PROGRAMS

Over the course of the semester several MATLAB programs were created to accommodate data recording and analysis, demonstrate ideal Gaussian beam propagation, and upload of data from a weather sensor. Each variety of program relied heavily on the creation and manipulation of large matrices.

The first variety stored and analyzed data for each of the experiments conducted in Maury and Rickover. Data sets were recorded as vectors for distance from source to target, beam diameter, and power readings. Power readings had five measurements for each distance, and so the program next used a double nested 'while' loop such that 1) power readings were summed for each row (using a column index) and then the sum was divided by 5, giving average power at each row. Beam diameter graphs were all fairly linear so the program includes code which used the Least Squares Method in matrix form to make a linear curve fit as well as make a 95% confidence interval bounds above and below the best-fit curve. The accuracy of the Least Squares confidence estimates are skewed however, by the fact that their 'confidence' is based on the assumption that beam widths adhered to the true definition of laser beam diameter, when in fact they weren't since they were measured by visual inspection.

The same programs include the beam expansion equation, $w_o = \frac{\lambda z}{\pi w(z)}$, solving for beam waist, w_o, and applying the same strategy as before. Again this is based off the idea that the experimental values of beam waist theoretically converge on the true value as distance from the source increases. Its validity is also skewed by the lack of conformity to the definition of beam diameter.

The second variety of program creates a matrix of power values based on the equation for ideal Gaussian propagation, $I(r,z) = I_o \left(\frac{w_o}{w(z)} \right)^2 e^{-2\left(\frac{r}{w(z)}\right)^2}$. Beam waist was actually displayed on the manufacturer's specification sheet, and I_o was calculated using the definition of intensity, $I = \frac{P}{A}$, power divided by area. Using specified nominal output for power and, the program finds area by converting beam waist into a radius and then used the formula for area of a circle. The values of "*w(z)*" and "*r*" generate in a double nested loop which could run through any number of values; "*w(z)*" relates to "*r*" by $w(z) = w_o \sqrt{1 + \frac{z^2}{{z_o}^2}}$. In the case of the following graph, I decided to run beam diameter "*w(z)*" out to ~10 m, and radial distance "*r*" up to 7 cm. The graph shows the log of power, since the power measurements taken at face value drop off so dramatically that the graph only shows contrast in the very bottom left corner. In any case, the graph indicates that the beam spreads according the principle mentioned earlier, asymptotically approaching a divergence angle specified by wavelength and aperture size.

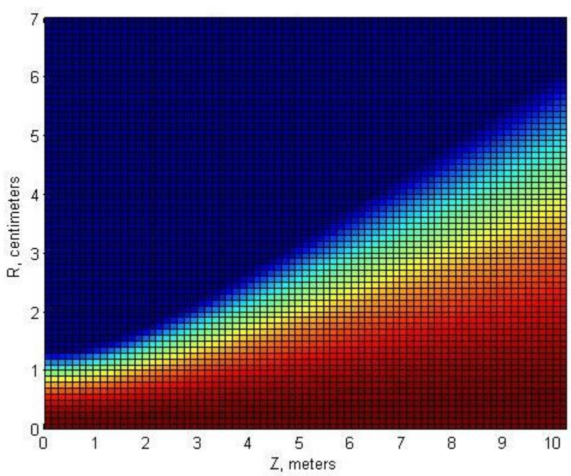

Figure 12: theoretical intensity distribution of a perfect Gaussian laser beam across 10 meters (logarithmic scale).

Besides creating the above graph, the program uses the section of the matrix measuring power at *r*=0, i.e. the radial center of the beam, and compares it with measured power from one of the experiments in Maury. The graph highlights some of the discrepancies mentioned earlier in relation to inaccuracies measuring power, that is, the presence of ambient light and the effect of jitter on the hand-held device, as well as the effect of averaged values instead of a constant measurement at the center of the beam. Also note that to get intensity from experimental power measurements, I divided all power measurements by the area of the viewing window in the power sensor.

The graphs of experimental vs. theoretical intensity look extremely different. This is because the power measurements given by the LaserCheck represented all power incident on the viewing window, not just the center of the beam. The act of dividing by area of the aperture window is another complicating factor, since that only gives the average area. To find exact intensity at a point, one would have to take the incremental power incident at one point and divide it by the incremental area of that point, *dA*.

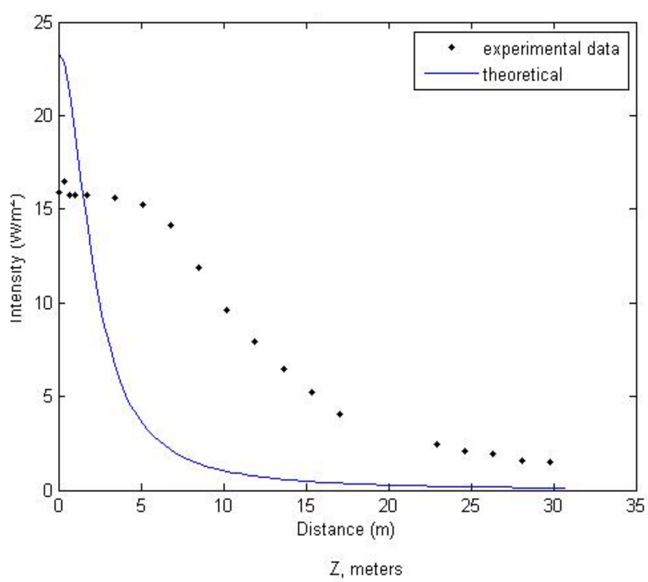

Figure 13: comparison of theoretical vs. experimentally measured intensity along the propagation axis, 'z'

This is impossible to do with the experimental data taken without claiming extreme license in manipulating the data. To try to better match the experimental data with what should be found in theory, another similar program takes the same piece code to generate the map of theoretical intensities and compares it with experimental data. It represented the region measured by the LaserCheck handheld power measuring device, which has an aperture radius of 0.4 cm. The regions boundaries are z=0 to z~30 m by r=0 m to r=0.004 m.

First it breaks up the area of the aperture into concentric rings. Then, at each increment of 'z,' it finds the theoretical intensity at each increment of 'r' out to the boundary at 0.004 meters. Then theoretical intensities are added to make a weighted average—at each coordinate (increments of 'z' and 'r'), the theoretical intensities of that (z,r) coordinate are multiplied by the area of the ring surrounding that 'r' coordinate, since 'z' has no effect on the area. That product actually gives a theoretical 'power' measurement, since it is the product of dI*dA. To find intensity, the sum of those dI*dA is divided by total area, the area of the aperture.

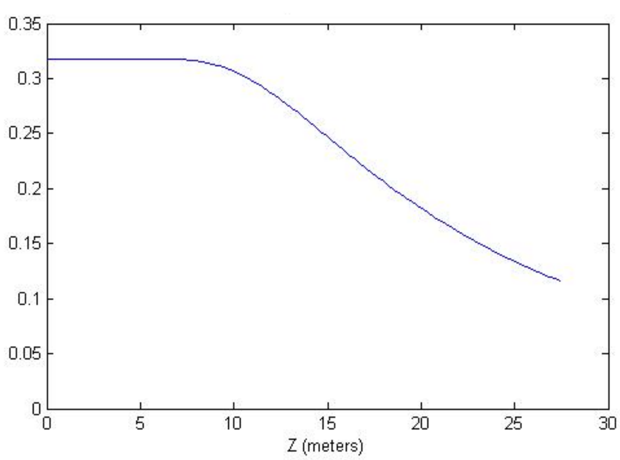

Figure 14: theoretical power measurement of a Gaussian laser beam with peak power of 800 µW through viewing aperture of Laser Check, which sums power over entire aperture.

The shape of the graph in Figure 14 resembles the shape of the experimental data in Figure 13 much more closely than the theoretical intensity shown in Fig. 13. However, the scale is much smaller. Admittedly, this is probably indicative that a part of the code is wrong. However, overall the process of "integrating" the theoretical intensity over the area of the aperture does make a step closer to making a more intelligible comparison of expected findings vice those found experimentally, since the reverse cannot be done from experimental data. In the case of my findings, multiplying the expected intensity values by a conversion factor of 50 makes the graphs easy to compare.

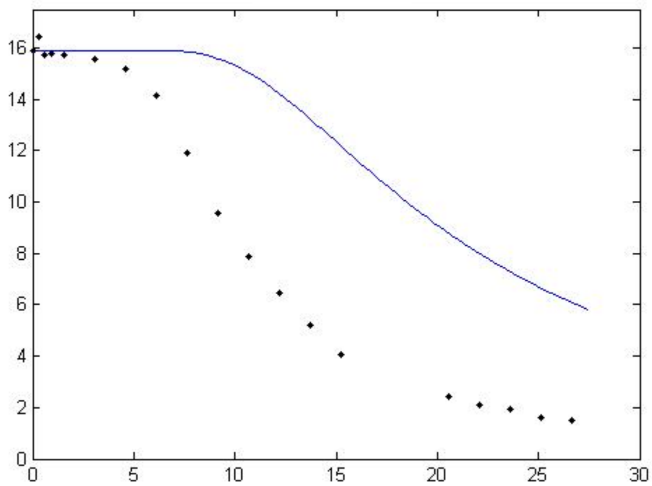

Figure 15: comparison between theoretical power (with conversion factor correction) and measured power via Laser Check.

One can observe, looking at Figure 15, that experimentally found intensity drops off faster than theoretically expected. However, a laser propagating through air, as in the lab room, encounters obstacles not seen in a vacuum, hence the ideal beam propagation formula will naturally return a higher intensity measurement than found in the real world.

The final type of program, to be used in the final experiment across College Creek, imports data from a weather instrument, the Vaisala WTX520. Information gets imported via an Excel file created after the instrument is done recording. After calling the program, the user is prompted to enter the file name of the excel spreadsheet. The entry is stored as a string and then referred into the argument of another embedded MATLAB program, "xlsread," which imports data from the sheet saved from the Vaisala instrument. It then stores the weather data according to the column of the spread sheet it was in (for instance, wind velocity was column two; any numbers in column two, below the header rows, would be stored in this matrix). Then it takes the data from the spreadsheet cells which contained the data and time. MATLAB has a program to convert certain spreadsheet formats of date and time into a date and time 'vector,' giving a slot to year, month, date, hour, minute, and second. Using all these vectors (wind velocity, air pressure, humidity, precipitation, and date/time) one could then record power data and be able to compare it with measured weather values taken at the same time.

VI. DEMONSTRATIONS

In the last 3 weeks of the semester two demonstrations were given about the project, one to the students of ES303H and another to professors and faculty working with Professor Avramov, including Professor Korotkova from the University of Florida.

ES303 Presentation

For the former, students in the honors controls course ES303H received a brief consisting of five PowerPoint slides which explained the rationale for the project, starting with the directed energy initiative conducted by the Defense Science Board Task Force and Office of Naval Research. The brief also introduced basic facts, for instance that lasers do not propagate in a perfectly straight line and how it is necessary to know a laser's propagation pattern through a given environment to successfully 'lase' a target. Afterwards the presentation showed experiments up to that point, illustrating findings with graphs, and then the idea for the final experiment, shooting a HeNe laser across

College Creek and measuring power delivery while measuring weather conditions. It concluded with information about related work such as that on jitter control for air platforms.

Presentation to Visiting Professor

In a demonstration to Professor Korotkova, she was shown the weather station and the program written for data upload, as well as results from previous experiments. While observing the weather instrument, Professor Korotkova observed that it did not have the resolution needed to show "beam wander." According to Professor Korotkova, it is the fluctuation of temperature, rather than the temperature itself, which causes distortion of a laser beam, and that these fluctuations are most often much smaller than tenths of degrees.

After that conversation Professor Korotkova, Professor Aurelia, and several others, were shown the Rickover Hydrolab and the experiment which had been run there. In the course of this Professor Korotkova made another observation: the beam at the target showed granulation and was visibly "wandering," shifting around on the target. She again attributed this to temperature fluctuations along the beam's propagation path.

VII. FURTHER RESEARCH AND DESIGN WORK

To carry on in a similar line of research, the follow up project will be to create a two-part system which represents a scaled-down version of a scenario where a stationary 'command post' communicates with a mobile unit via laser modulation. The problem would incorporate signal processing with tracking, which in turn involves balancing measured feedback with estimation of states. A laser mounted on a swivel would aim a beam at a power sensor mounted on a cart which can translate along one axis, simplifying a two or three dimensional space of motion.

The major difficulty in such a project, even simplified, will be coordinating the movement of the 'command' laser ("c-laser") with the movement of the cart. The control program will need to take input from both the command laser and mobile cart to know how much to rotate the c-laser. It would also need to know how far away the cart is from the c-laser to incorporate a correction factor, which would amplify the power output for the command signal so that power at the target mobile unit would remain at a constant level (not considering modulation).

VIII. Conclusion

Ultimately, this research laid the ground work for future research on lasers but did not achieve its original intent. As Professor Korotkova pointed out, the project is impossible to carry out successfully since one must have extremely precise instruments, which were not available this semester; however, these will be available for the following semester. Hopefully, another student will be able to pick up the skeleton of this project and bring it to fruition with the improved instrumentation.

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