

Understanding and Analysis of Underwater Laser Propagation for Communication Applications

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Course: ES485 Laser Propagation in the Maritime Environment

Abstract— The purpose of this study was to observe laser light propagation through a maritime environment and to understand the effects of that medium on data transmission fidelity. Data transmission was simulated through the use of an Optical Chopper, which physically broke the beam at a set frequency to simulate a digital signal being passed via carrier wave. Furthermore, two different types spread laser beams, Spatial Light Modulated and Gaussian, were compared to determine which was superior at delivering the most complete digital signal. Performance was measured in the percent bit error of the data transmission. As expected the turbid water transmission had significantly higher data bit errors than those in calm water.

INTRODUCTION

Problem Statement

Study the effectiveness of underwater data transmitting via laser beam propagation given varying environmental conditions. The prescribed constraints of the system were that only the equipment provided was used to conduct the experiment, a camera not a photodiode was used to take the data, a 632.8 nm red laser was used, and that the power of the lasers never exceeded 2 mW. The equipment used included a 30.8L cylindrical water tank, a Meadowlark Optics Linear Series Spatial Light Modulator, a 340M-GE - Fast Frame Rate VGA Monochrome Scientific Camera with Standard CCD Sensor, and EL-25-20X-A - 20X Optical Beam Expanders integrated into the mounted 2.0 mW, red Helium Neon HNL020L laser beam breadboard.

Motivation

Current underwater acoustic communication does not offer high data rates. The exploration of underwater optical wireless communications (UOWC) as a solution to the challenges of underwater communication is of considerable interest to scientists and the military alike. Communication between buoys, unmanned underwater vehicles (UUVs), ships, submarines, and divers can all benefit from UOWC especially if cheaper, more secure high data rate communication can be achieved¹. UOWC employs optical wavelengths to transfer information between dedicated point-to-point links. Optical waves offer advantages like high rates of data transmission, secure links, small scale of transceiver components. Optical wireless transmissions use modulated optical beams in order to establish short, medium, or high frequency communications. Performance and reliability is dependent on weather and oceanic conditions between the receiver and the transmitter.

BACKGROUND RESEARCH

¹ S. Arnon, "Underwater Optical Wireless Communication Network," *Optical Engineering*, 01-Jan-2010. [Online]. Available: <https://www.spiedigitallibrary.org/journals/optical-engineering/volume-49/issue-1/015001/Underwater-optical-wireless-communication-network/10.1117/1.3280288.full?SSO=1#ArticleLinkReference>. [Accessed: 06-Nov-2017].

Effects of Water Turbulence

The ocean is a complex medium and it has been proven that turbid water greatly affects the fidelity of the data transmission. A recent study, "Effects of underwater turbulence on laser beam propagation and coupling into single-mode optical fiber" by Frank Hanson and Mark Lasher look into the effects that a turbulent maritime environment has on a laser beam's coherence and intensity. Water is far denser than air and the ocean environment is far more turbulent than the lower atmosphere, as a result of these two factors the effect of the refractive index is far greater. So far, little research on the effects of underwater turbulence have been conducted, however some researchers have stated that a 17-point deformable mirror could help improve propagation through such a complex environment by focusing and adjusting the beam to compensate for the adverse conditions. This experiment by Hanson and Lasher thoroughly analyzes the relationship between beam diameter and the effects of turbulence on that beam. The experiment utilized both Gaussian and flat top laser beams which were shot through two meters of turbulent water. The water used was pure water via reverse osmosis, and this experiment did not take particulates such as salt into account. The laser used was a 532 nm, continuous wave laser which was variably expanded to different test diameters. Turbulence was induced via a circulating pump as well as through external heat sources. To quantify the results, images to the resultant spot where characterized and evaluated.

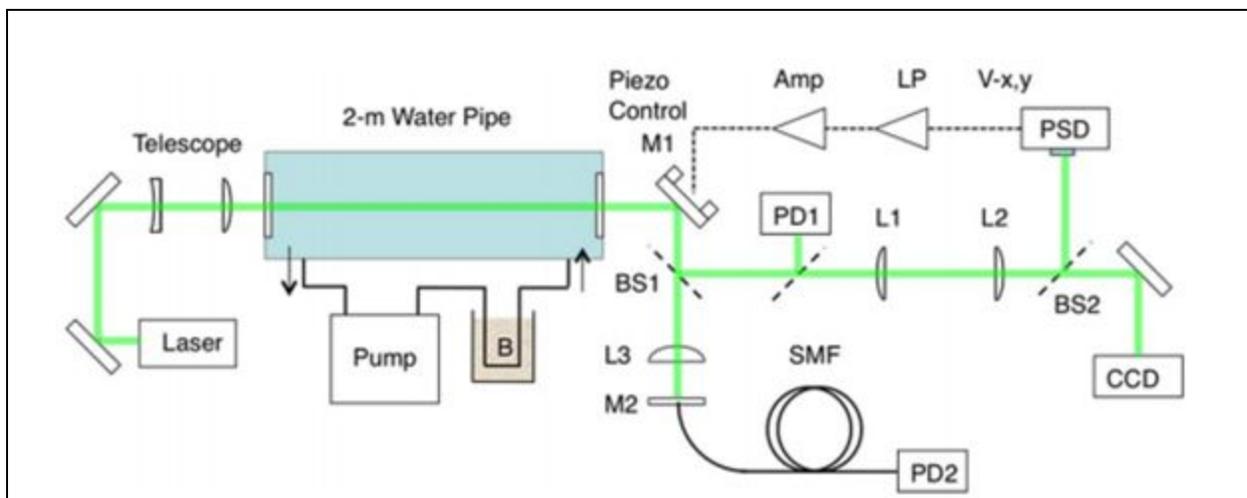


Figure 1. A diagram of the experimental setup. A heated water bath (B) was used in some cases to generate turbulence. A tip-tilt control loop, consisting of a PSD, LP filter, amplifier(Amp), and a piezo driven mirror (M1), was used to maintain coupling into the SMF. Focal plane images were recorded on the CCD camera.

This experiment concluded that "the results show the importance of beam size relative to the transverse coherence length (r_0)." It was found that for smaller beams, the degrading effects of the turbulence are reduced when compared with beams that were spread more.

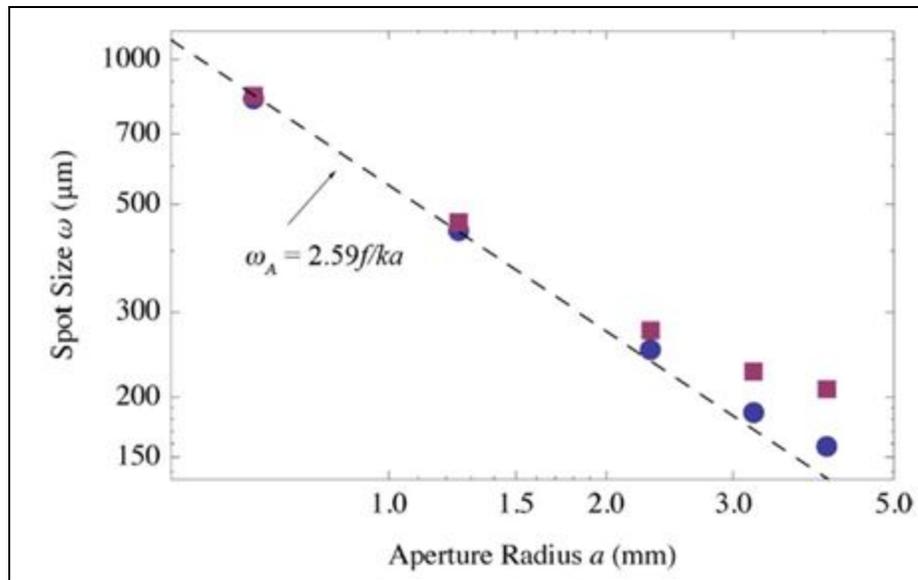
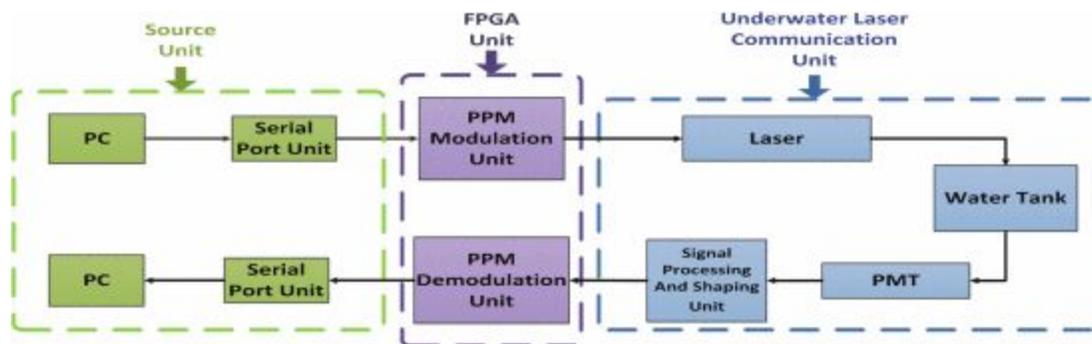


Figure 2. Spot Radius of flat-top beams of changing spread radius (a) propagating through calm water (•) and water with turbulence (•). The dashed line represents the spot radius for an ideal Gaussian fit.

Current Underwater Laser Communication Designs

Multiple organizations and independent parties have worked towards improving underwater laser communications. One example of current experimentation was published in OCEANS 2016-Shanghai. In the paper the authors describe the process they used in modulation. This team used Pulse Position Modulation (PPM). The advantages of using PPM according to the trials performed is a small pulse duty cycle and a high average power transmission efficiency, which is important when transmitting a large amount of bits at a high rate over a wide range of frequencies.



Schematic of experimental design

Another research team proposed an experiment similar in setup to our proposed experiment. Using Quadrature Amplitude Modulation(QAM)paired with orthogonal frequency-division multiplexing(OFDM), the team used a green light laser diode and a PIN detector to send signals through 2m of fresh water. QAM works by modulating the amplitudes of two carrier waves out of phase with each other by 90 degrees. OFDM uses large numbers of closely located orthogonal subcarrier signals that carry data over multiple channels. Every subcarrier is modulated with a standard modulation scheme at low symbol rates, in this case QAM, with the

total symbol rate remaining similar to single-carrier modulation schemes. QAM-OFDM is used commonly in optic-fiber transmission, and is being used increasingly in blue LD-based underwater optical communications(UWOC). The team demonstrated their proposed system can achieve 1.118-Gb/s optical signals using the aforementioned modulation scheme and can do so through 2-m of fresh tap water with a BER of 2.98×10^{-3} , which is very low by FCC standards².

EXPERIMENTAL TOOLS

Lasers

In order to determine the effects of water on laser propagation two 2.0 mW, red Helium Neon HNL020L lasers beam types are compared, one of a Gaussian Beam and one of a Gaussian Beam set through a Spatial Light Modulator (SLM). The 2.0 mW, red Helium Neon HNL020L lasers are mounted on a breadboard. As shown in Figure 3 below, the Gaussian beam is placed in line with a beam expander pointing straight down the tank. The Meadowlark Optics Linear Series SLM is placed at the exit of the Gaussian beam expander so both beams have the same transmission distance. The SLM Beam is placed in line with its own beam expander, however, it is angled to direct its beam in direct contact with the center of the SLM's reflective active area. This is done so that the SLM can flatten and modulate the intensities of the entire gaussian beam into the SLM pattern.

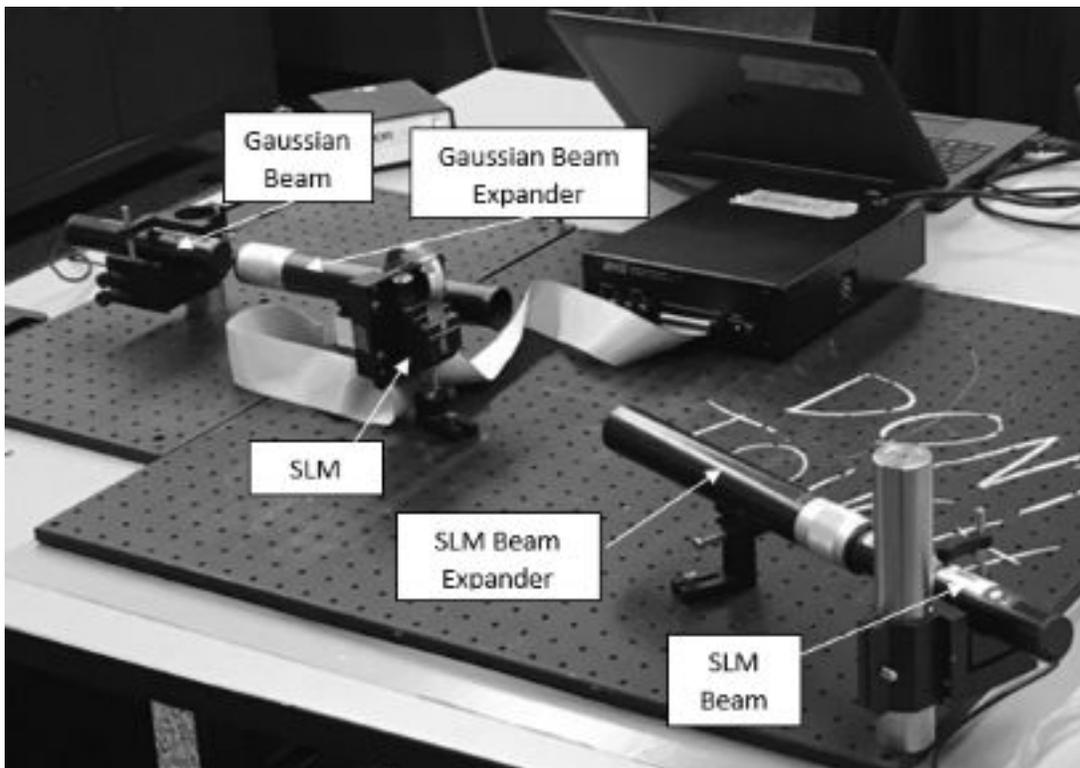


Figure 3. Lasers Breadboard set-up.

² Xu, Lin, Yu, Song, Kong, Qu, Han, Jia, Deng. *Underwater Laser Communication Using and OFDM-Modulated 520-nm Laser Diode*, IEEE Photonics Technology Letters, vol. 28, No 20, October 15, 2016

The 2.0, red Helium Neon (Model HNL020L) laser outputs a wavelength of 633 nm. In order to operate correctly it must be in an environment from -20 degrees celsius to 70 degrees celsius. The experimental water and air must maintain a temperature within this range of values. In order to mount this laser and adjustable laser mount was used so that the angle of propagation could be changed in slight increments. It is important to note the length and diameter of the laser head is 271.78 and 44.2 mm so that the mount can be set to properly grip the laser. The outputted power of the laser is 2.0 mW with a beam diameter of 0.63 mm.

An additional test is conducted using an Industrial Fiber Optics Laboratory Helium Neon Laser (Model IF-HN15M), 5.0 mW in which an audio signal is sent to determine the effects of the water on the propagation. The Industrial Fiber Optics Laboratory Helium Neon Laser, that is used for the audio signal propagation, emits a red beam and can be seen below in Figure 4. This test was completed as a intuitive test to see effects of turbidity on data transmission through water.

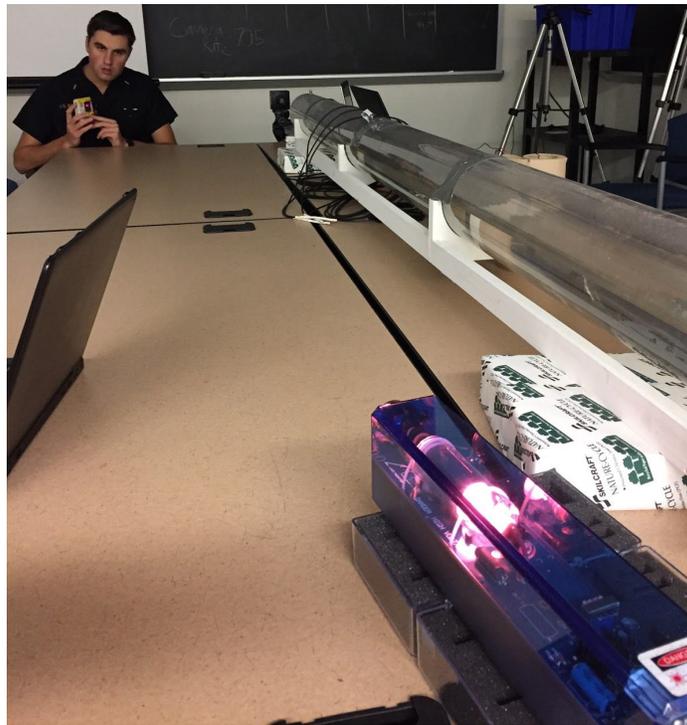


Figure 4. Secondary Experimental setup for Helium Neon Laser outside of the water tank to hear a sound profile of the audio signal outside of the water propagation.

The specifications for this helium neon laser include a 1.0 to 5.0 mW power output with a 633 nm wavelength and beam diameter of 0.47 mm. The operating temperatures for this laser are within 0 to 40 degrees celsius. The evaluation of the quality of the audio transmission sent by the Helium Neon Laser in both the air and the water are used as a proof of concept for the testing of the lasers in the tank.

SLM

The spatial light modulator used is the Meadowlark Optics Linear Series Spatial Light Modulator (SLM). The SLM used is designed for versatility and ease of use in optical laboratory environments. A SLM is a device that

modulates light according to a fixed spatial (pixel) pattern. The purpose of this piece of equipment is to modulate the intensity of a beam of light reflected off of the reflective screen. Shown in Figure 5 found below, the beam is centered on the reflective screen.



Figure 5. Spatial Light Modulator with beam (red dot) channeled on the reflective active screen of the modulator,

The screen itself, known as an array due to the fact it is an array of pixels, measures 6.14x6.14 mm and contains an active pixel range of 1-65,536 pixels. This range describes how many pixels can be used to modulate the intensity of the beam. The SLM mount comes with two integral pitch and yaw control knobs located above and behind the reflective screen. The pitch and yaw controls are used to adjust the SLM to either match the incident light or adjust the reflected beam in a desired direction.

The SLM is controlled via graphic user interface on any computer, via cable. Using the provided software, a user can control the duty cycle and pattern of the reflected light. Patterns are pre-loaded with the software, and the user may select whichever pattern of modulation best suits their experiment. The modulation pattern that is used is shown below in Figure 6. It's purpose is to create a distinguishable light and dark area of the transmitted beam for measurement.

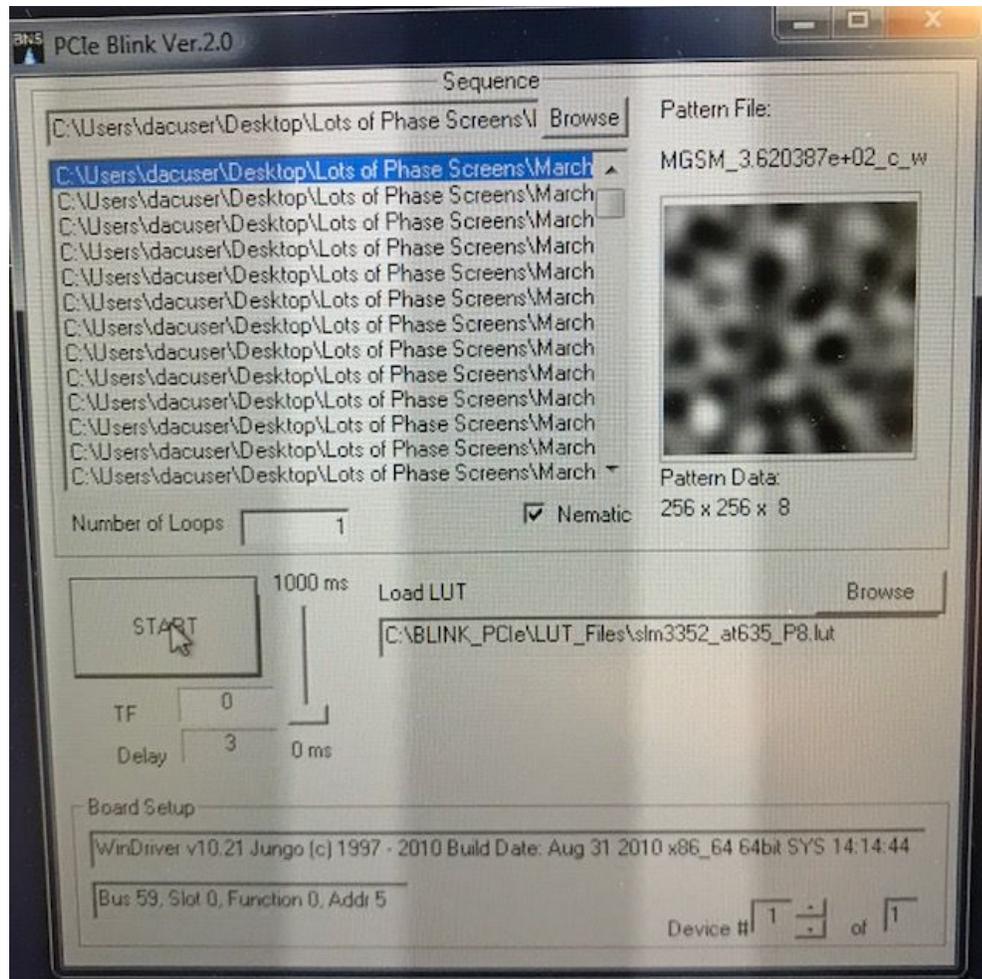


Figure 6. Software Screenshot of SLM.

Aside from selecting a modulation pattern, the only other selection a user must make is the delay setting, which simply has the SLM wait for the allotted time before beginning the modulation process. A 3 ms delay, which translates to 333 frames per cycle, is used and pattern file MGSM_3.620387e+02_c_w because of its even dispersion being suited for the lasers being modulated.

Optical Chopper

In order to modulate light from the continuous beam, a ThorLabs MC2000B Optical Chopper was used. The motor speed control design allows for the precise maintaining of the chopping speed and phase. The instrument uses a slotted chopper blade/wheel to periodically interrupt the beam of light while still maintaining the integrity of the beam's intensity as shown in Figure 7.

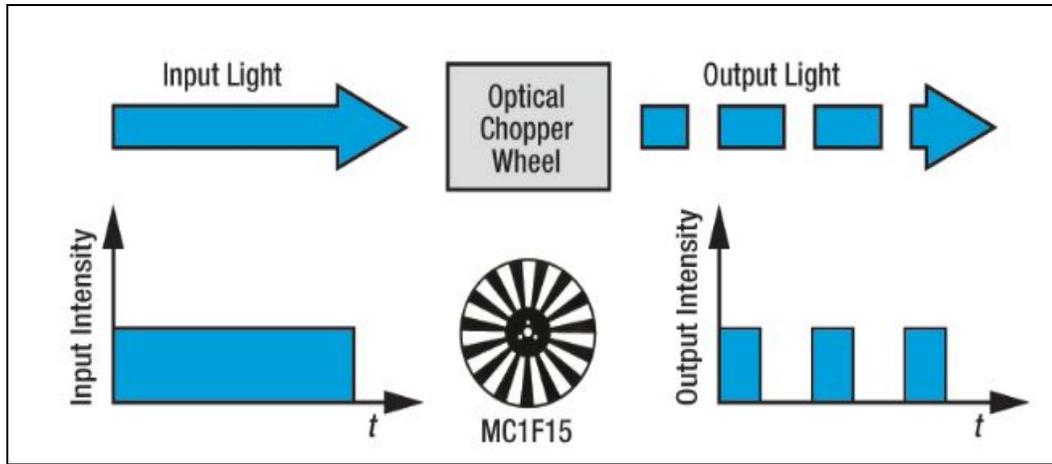


Figure 7. Operational diagram of an Optical Chopper³

The MC1F10HP³ blade model used in conjunction with the MC2000B Chopper system has a frequency range of 20 Hz-1000 Hz for the inner ring and a frequency range of 200 Hz- 10 kHz for the inner ring. The model is dual frequency blade that offers 10/100 slots. As shown in Figure 8, the chopper was set up to intercept the beam before it entered the water tank. In order to utilize the widest portion of the slot, a Thorlabs ID37Z/M Mounted Zero Aperture Iris is paired with the Optical Chopper. It features an aperture range of 0.0 mm to 37.0 mm. This chopper/iris combo is used to keep the size of the beams uniform.

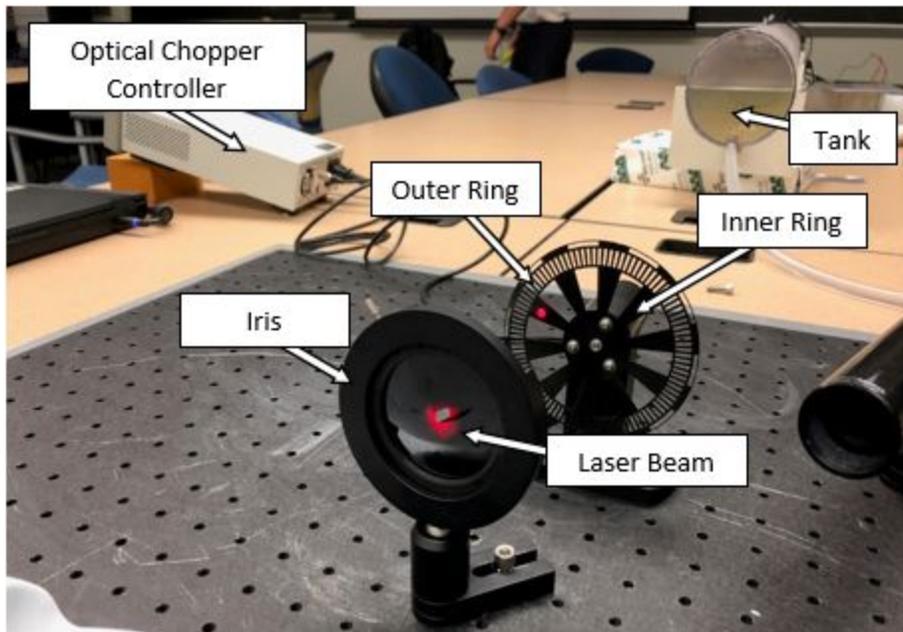


Figure 8. Optical Chopper System and Iris mounted in experimental configuration.

Tank

³“Optical Chopper System and Chopper Wheels.” *ThorLabs*, www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=287.

The fresh tap water, the medium of choice, is contained in a horizontal cylindrical tank formed from clear acrylic plastic. The tank measures 243.84 cm long, with an outer diameter of 13.97 cm, and inner diameter of 12.7 cm, making its volume 30888.9 cm^3 , or 30.88 L. For the duration of the experiment, the tank is filled approximately half-full of water. At the end of the tank opposite the laser platform, a length of tubing connects to the top of the tank, through which a pump cycles water when activated, draining from the near end of the tank. The pump runs on a DC voltage of 13.8 V. As seen in Figure 9, the tank is placed in between the breadboard setup containing the laser equipment and the camera.

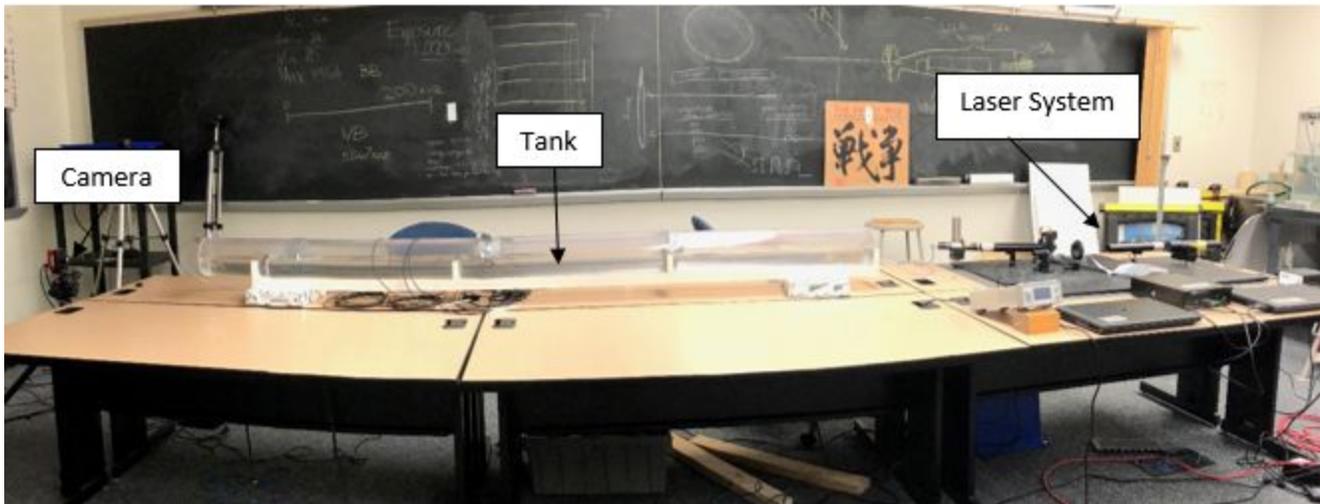


Figure 9. Experimental workspace containing the laser beam breadboard setup, tank, and camera

Camera

The camera used is a ThorLabs 340M-GE Fast Frame VGA Monochromatic Camera with CCD sensor, GigE. The camera can manage up to a maximum of 705 frames per second and has the capability of measuring up to 12 bits of intensity per image. The camera served as the receiver for data and was pointed directly into the path of the beam at the end of the water tank. The camera would measure both the intensity and timing of the laser light that reached the end of the tank, allowing for the received data to be analyzed and compared to what was transmitted. In order to reduce noise as well as to protect the camera's retina sensor, a red filter is used to shut all wavelengths of light that were not in the wavelength of red light. In order to simulate a digital signal, an optical chopper was used to physically break the laser beam in effect returning 1's and 0's through bright and dark spots.

EXPERIMENTAL PROCEDURE

Set-Up

Our setup consisted of multiple components illustrated in Figure 10 below. The main components in the setup were a camera, water tube, laser with expander, SLM, laser (alone), iris, spinner, and two breadboards in order to mount the equipment. This was seen as the ideal setup for our multiple experiments changing frequency as well as choosing whether to test SLM or Gaussian beam propagation through the tube because we did not have to change any setup on a day to day basis to get data. This was important because it helped improved the efficiency of the data collection by not losing extra time from the setup and teardown of the necessary equipment in our experiments. The conditions of the water, and distances, were kept constant throughout the entire experiment to ensure that the data was precise.

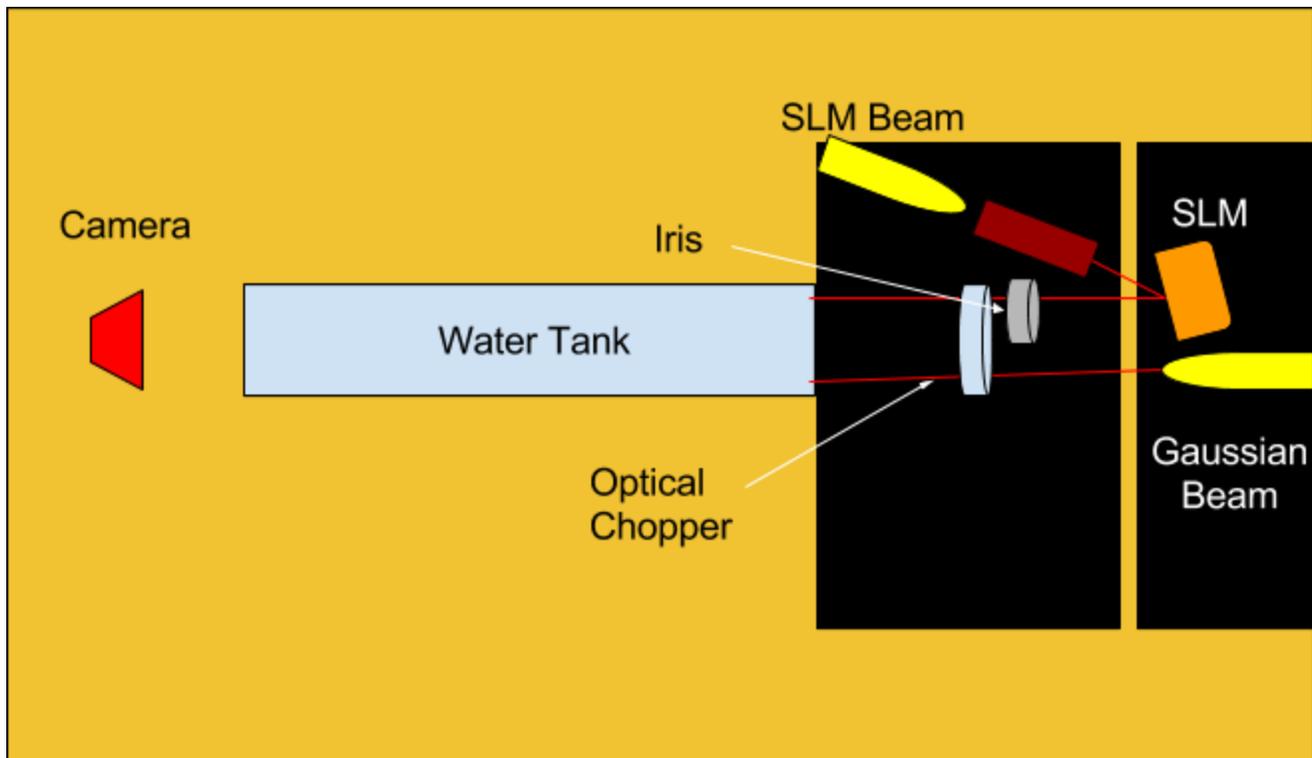


Figure 10. Illustrated experimental setup.

The basic setup consisted one laser shot through a expander to an SLM. This beam was directed using slight adjustments of the SLM as well as the laser in order to get the perfect beam through the water, ensuring that we did not hit off the surface of the water or the walls. This was important because if we hit off the walls this would have caused extra lost in propagation because it would be refracting off the inner tank walls or the water surface. Due to the wave properties of light the beam would refract off the plastic edges of the tank and continue down the tank, while some light would refract through the plastic edge. The iris was specifically used in order to decrease the size of the beam so that the laser dot size was smaller than the black inner part of the spinner. This helped to ensure that the data we received was correct and that the beam was oscillating at the correct frequency without having any light when the spinner was in the correct position to block it. This also helped to define our data better because the high intensity point were a lot greater than the low intensity points, when no light was hitting the camera.

The Gaussian Beam as seen in Figure 11 below, was set up so that the beam would start at the start of where the SLM beam reflected off the SLM. This ensured quality of data because it kept the distance that we shot the lasers at constant throughout all trials of data. The SLM in this setup was used in order to modulate the intensities of reflected light into a random pattern to see the effects of using this rather than just using the gaussian beam.

For the entire laser setup we incorporated two breadboards one with the laser, expander, spinner, and iris, and one with the laser and the SLM next to each other. This was the setup that was created in order to account for a breadboard that wasn't long enough for both combinations. In both case the laser beam were propagated through the tube into the center of the camera. The camera was mounted to a tripod to adjust in order to get the entirety of the beam.

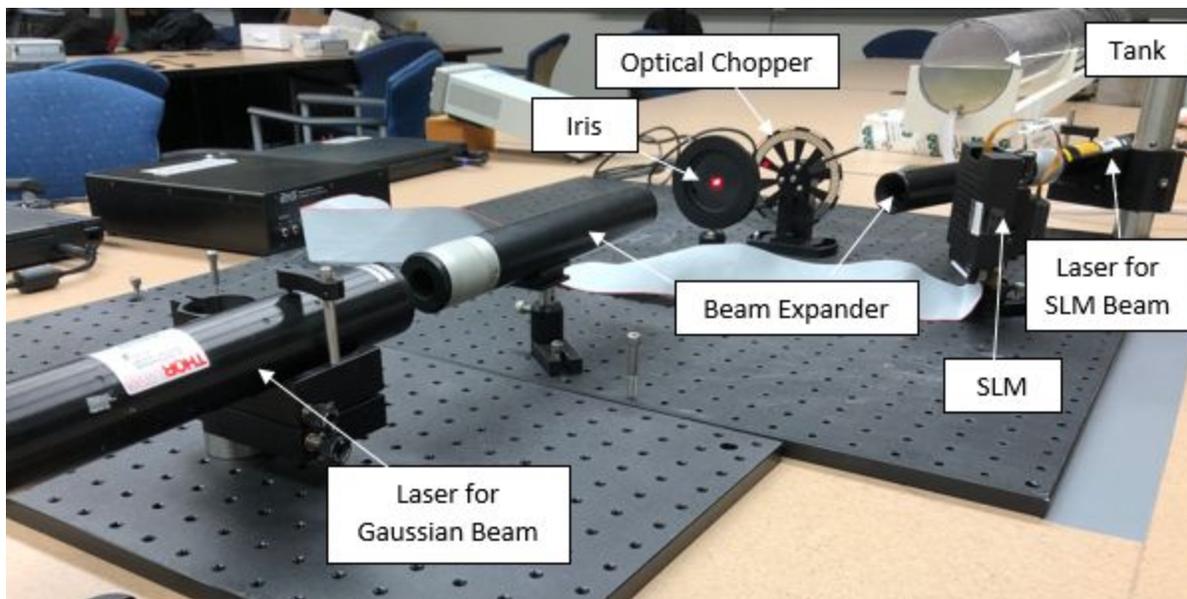


Figure 11. Breadboard set-up. Note the SLM is not in the correct position for its individual testing, rather it is moved out of the way so the Gaussian Beam can be sent through the Iris onto the Optical Chopper.

Some difficulties that we came across when creating this setup of the lasers was that with the setup we needed a long breadboard in order to fit both lasers as well as the beam spreader. Another challenge that we faced was getting the correct height and direction of the beams so that they would go directly through the tube without hitting the walls or the surface of the water. To account for this challenge we ensure to keep everything that was used in the same location after a days of work.

Data Collection

To begin, the laser of interest is turned on and aligned to shoot down the length of the tank and into the lens of the camera without bouncing off the top or sides of the tank. Next, the chopper is set at the desired data

transmission rate (ie. number of Hz), but not started. All ambient light is removed from the room and the camera's setup calibration parameters are entered. An exposure time of 3.000 ms is chosen which allows for a maximum frame rate of around 330-335 frames per second (fps). Although this is nearly half the fps that the camera is capable of, this speed is used because it is the maximum speed the camera can consistently run without dropping frames. Next the minimum and maximum light intensity values are entered at 815 and 1550, respectively, with a gain of 84. All of these values are determined experimentally to allow for appropriate contrast of the dark and bright laser spots when the ambient light is eliminated. After the camera's parameters are entered, the laser is shone onto the camera and the laser's brightest spot is located and its x and y coordinates are written down. In order to decrease the likelihood of dropped frames even more, the camera's frame is reduced to capture only nine pixels centered around the x and y coordinates of the brightest spot. If the Spatial Light Modulator (SLM) is being used, it is started at this point. In either circumstance, the optical chopper is started and the camera begins to record the data transmission. After around 2000 frames are captured, the recording process is stopped and recorded as a .tif file. If there are any dropped frames, the data must be retaken, as dropped frames could severely impact the quality of the received information, thus skewing the results in favor of poor transmission.

Due to the limitations of the Camera's frame rate, the tested frequencies had to be carefully selected. In order to see clear data transmission we had to at a minimum have at least 2 data points captured per frequency shift. For example we needed to see the pattern of one's and zeros so the minimum Frame rate to frequency ratio we could have was two. The maximum frame rate we were able to achieve with our camera was around 332 FPS. So to achieve the ratio above the maximum frequency to be tested could be no more than 166Hz. When data was being streamed at this rate, this meant that the camera was able to take two shots: a 1 and a 0, per frequency cycle. After that the lower multiples of this frequency were used; 83, 42, and 21 Hz. By using lower multiples we are doing two things, making sure that the data doesn't fall out of sync and giving the camera double the amount of data points per frequency cycle each iteration. For example at 83 Hz, the camera is recording 4 readings per cycle, 8 at 42 Hz, and 16 at 21 Hz.

Data Analysis

Data analysis is conducted in MATLAB. The data is initially uploaded as a tiff file and processed (See Appendix, Section A) to be represented as a 3x3 array of individual intensity values the length of the total frames captured. The received data is then thresholded so that it can be represented as a series of 0's and 1's. Using the average of the received data, a threshold is created assigning any data point above the average a 1 and any data point below the average assigned a 0.

In order to compare the transmitted and received data, the received data must be indexed to start at the same point as the transmitted. Through manual indexing, the necessary values are removed from the received data array. The equivalent data points are deleted from the non-thresholded received data array. Each new array is saved and stored as a '.mat' file for further data analysis

A representation of the transmitted signal for each frequency is generated for comparison. Using the relationship between the known frequency value and camera rate the number of one's expected in each byte of data is calculated as shown in Equations (1) and (2).

$$period = 1/frequency \tag{1}$$

$$num\ ones = 0.5 * period/camera\ rate \tag{2}$$

An array representing one byte of data is generated (See Appendix, Section B) and repeated for the length of the received data using the calculated number of ones found in Equation (2) . An equal amount of zeros are generated for the array.

RESULTS

The intensity measurements, and a comparison plot of the thresholded received data and the transmitted data are plotted for each frequency, beam type, and scenario and are found below in Figures 12-27 (See Appendix, Section C). Only the first 150 frames of data are analyzed.

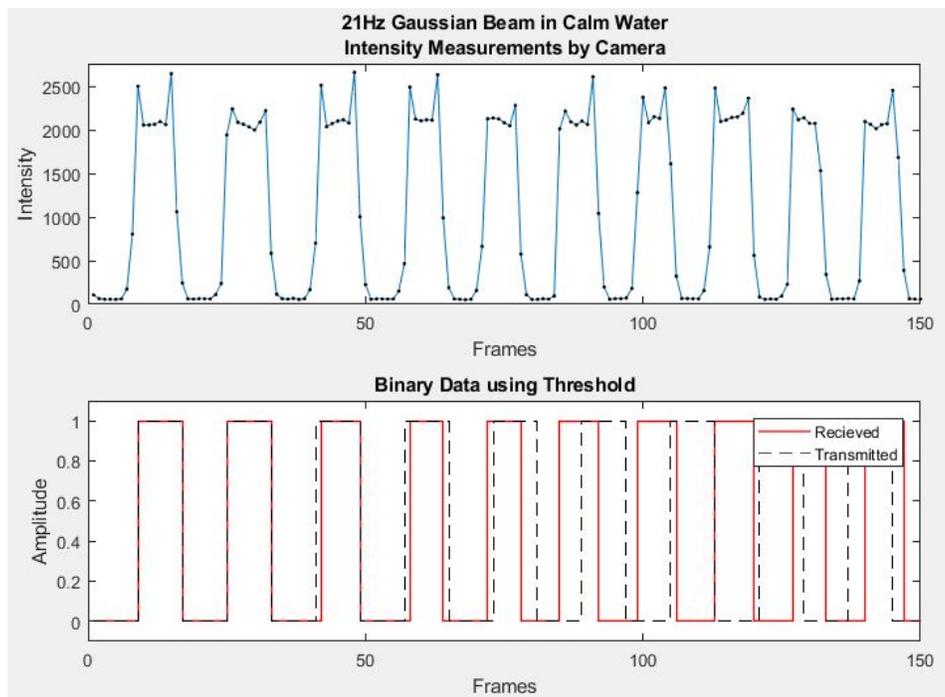


Figure 12. Plot comparing transmitted and received data for 21 Hz Gaussian Beam in Calm Water.

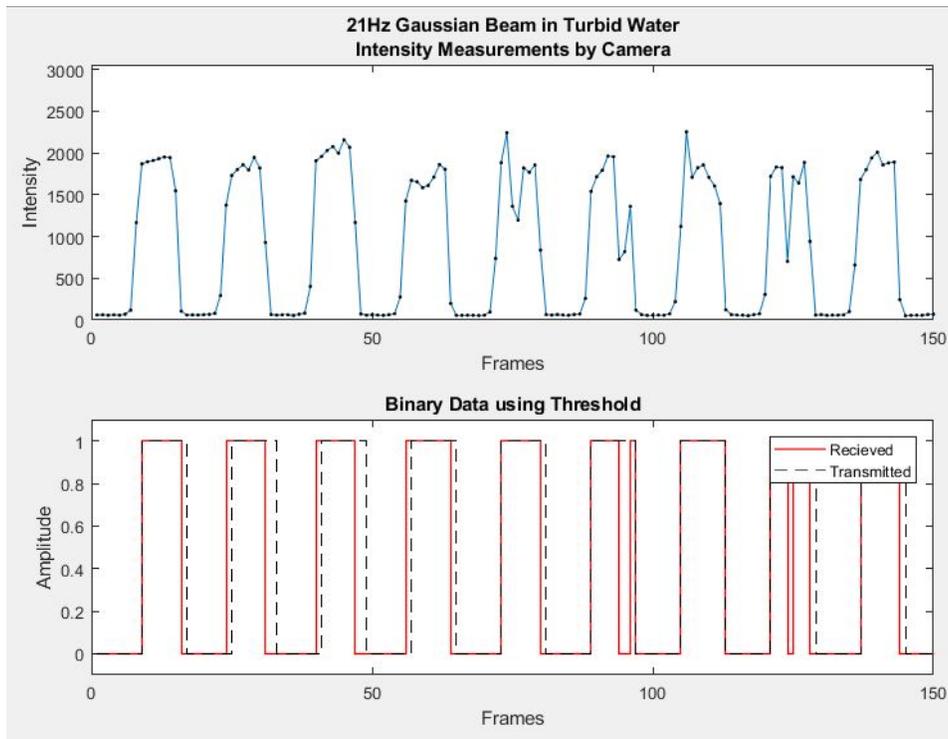


Figure 13. Plot comparing transmitted and received data for 21 Hz Gaussian Beam in Turbid Water

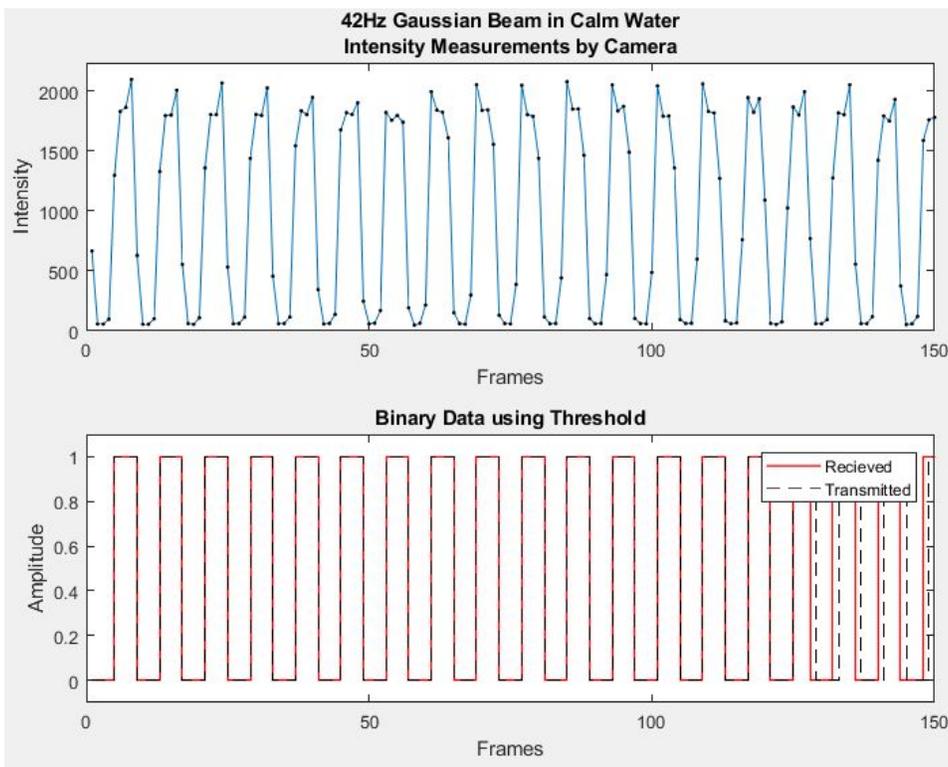


Figure 14. Plot comparing transmitted and received data for 42 Hz Gaussian Beam in Calm Water

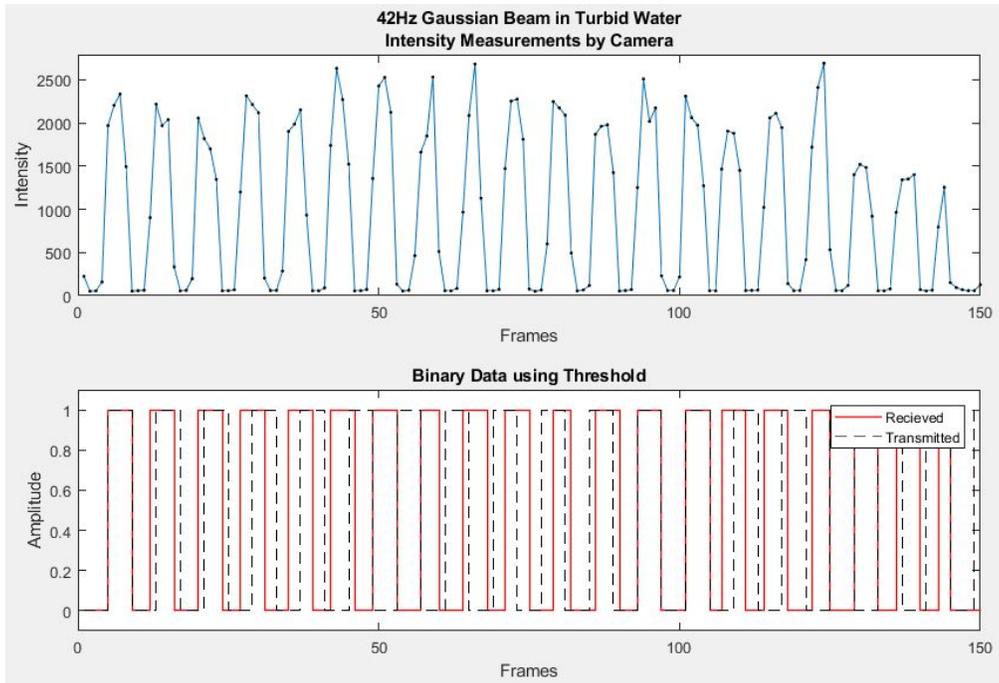


Figure 15. Plot comparing transmitted and received data for 42 Hz Gaussian Beam in Turbid Water

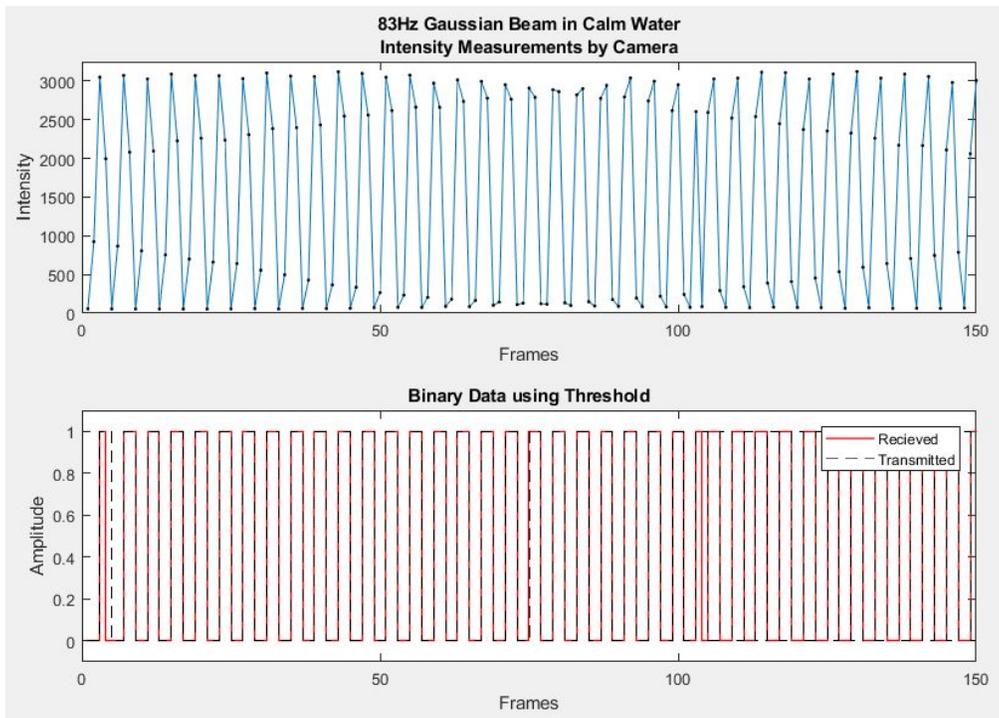


Figure 16. Plot comparing transmitted and received data for 83 Hz Gaussian Beam in Calm Water

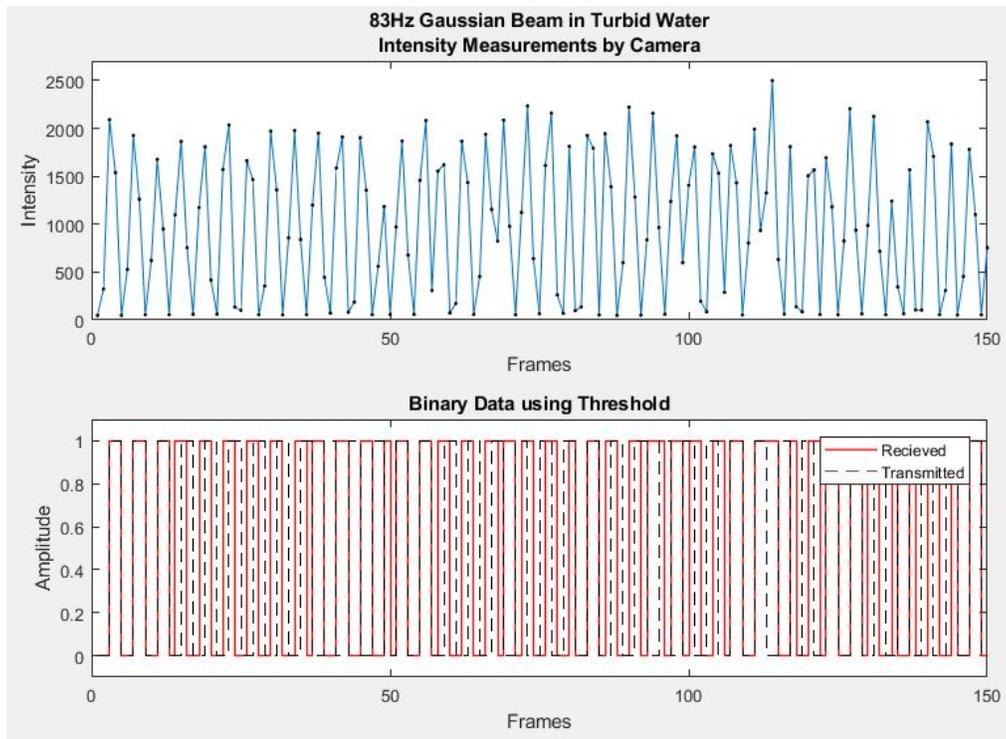


Figure 17. Plot comparing transmitted and received data for 83 Hz Gaussian Beam in Turbid Water

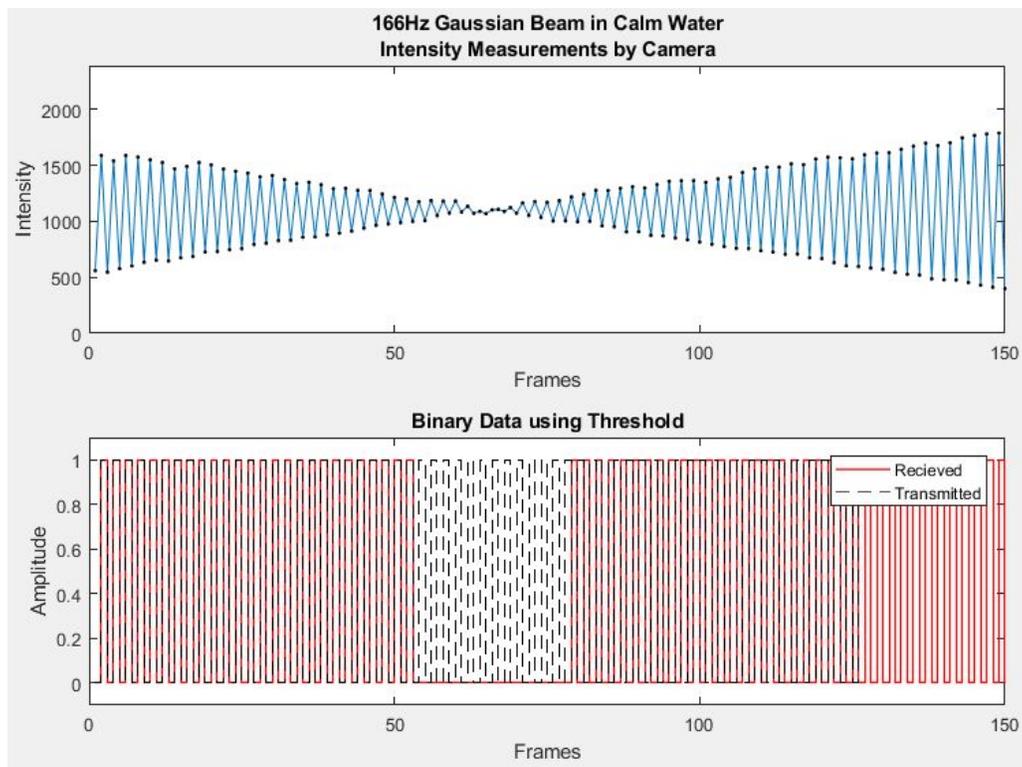


Figure 18. Plot comparing transmitted and received data for 166 Hz Gaussian Beam in Calm Water

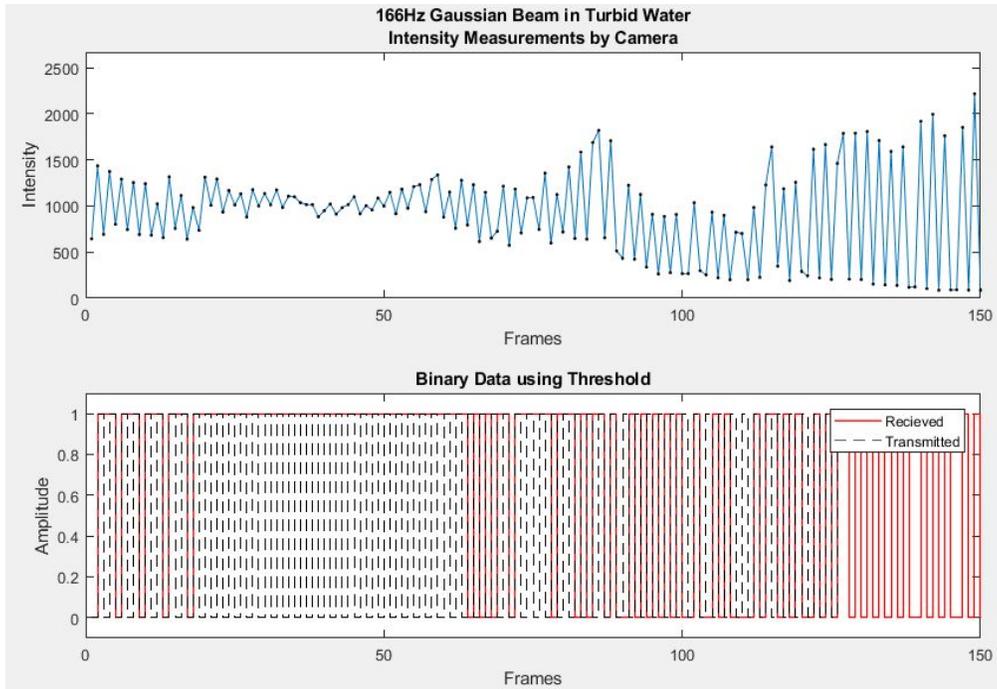


Figure 19. Plot comparing transmitted and received data for 166 Hz Gaussian Beam in Turbid Water

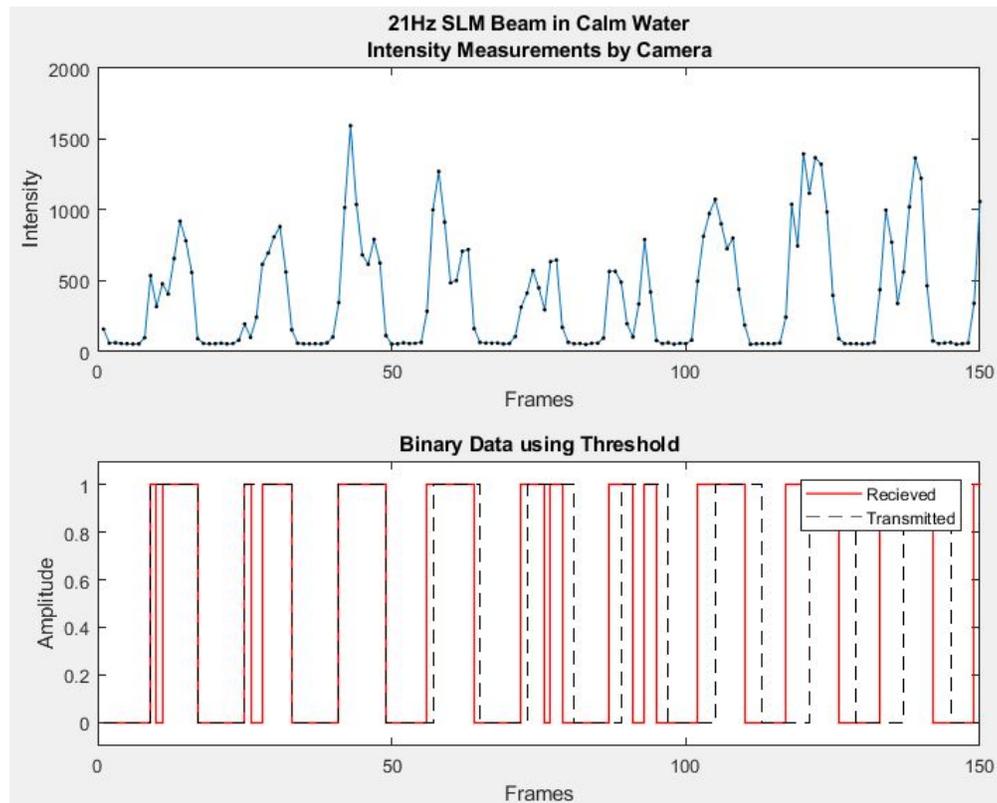


Figure 20. Plot comparing transmitted and received data for 21 Hz SLM Beam in Calm Water

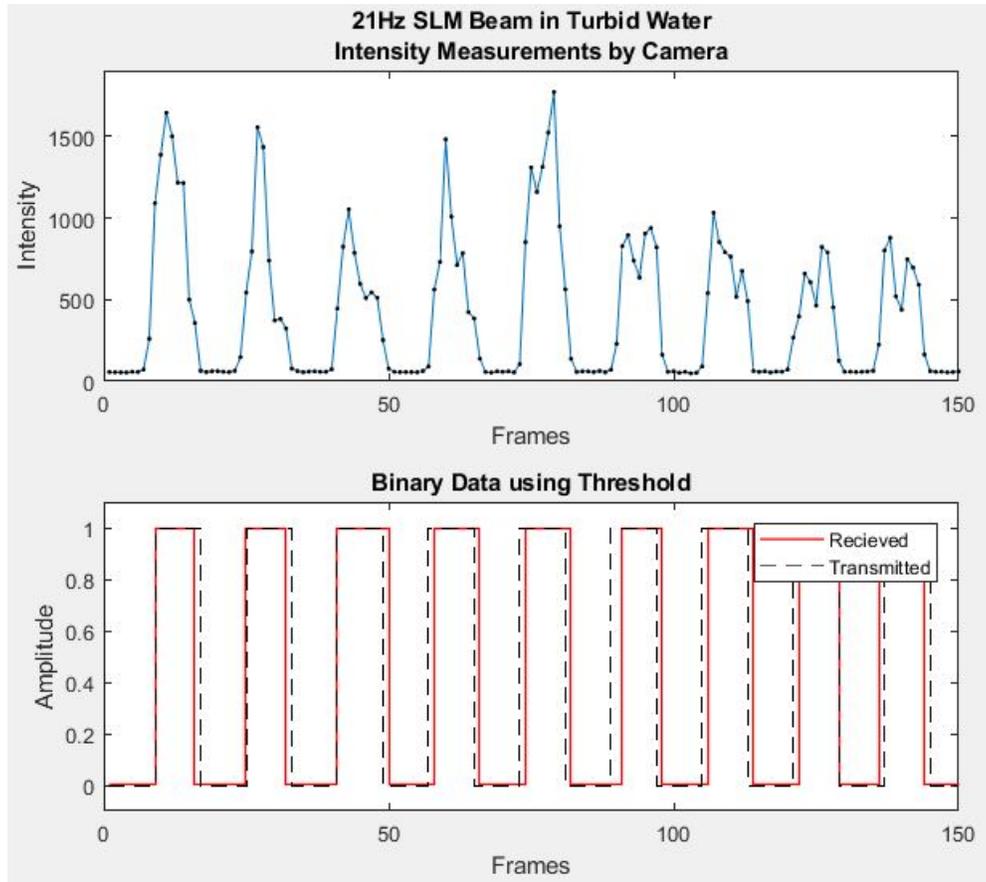


Figure 21. Plot comparing transmitted and received data for 21 Hz SLM Beam in Turbid Water

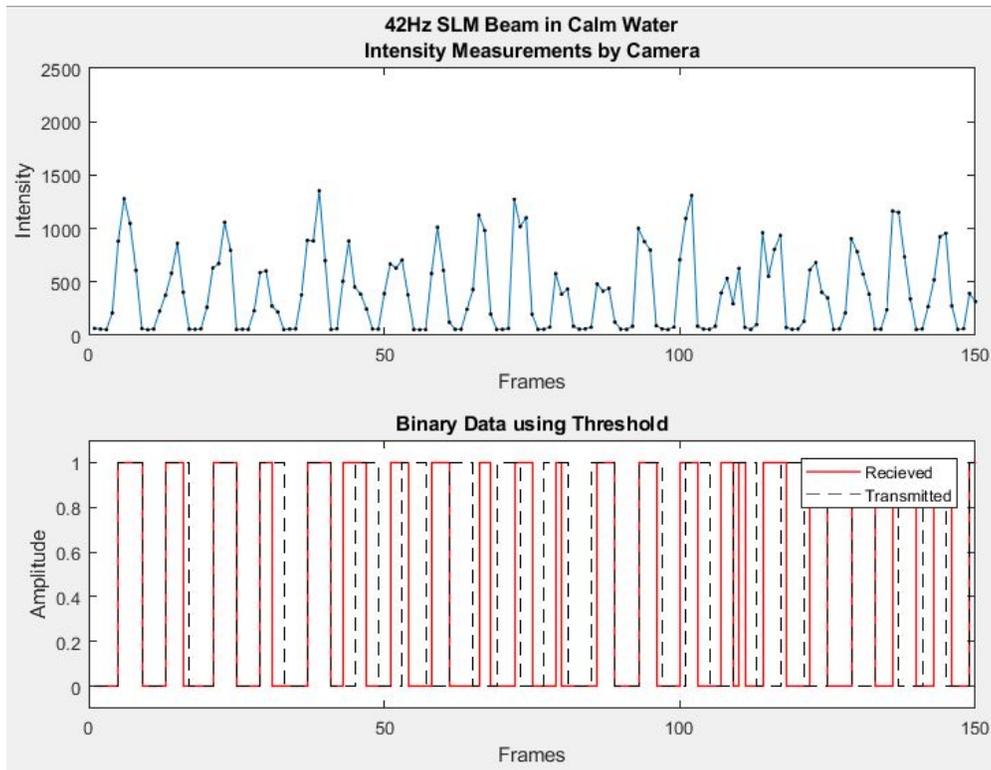


Figure 22. Plot comparing transmitted and received data for 42 Hz SLM Beam in Calm Water

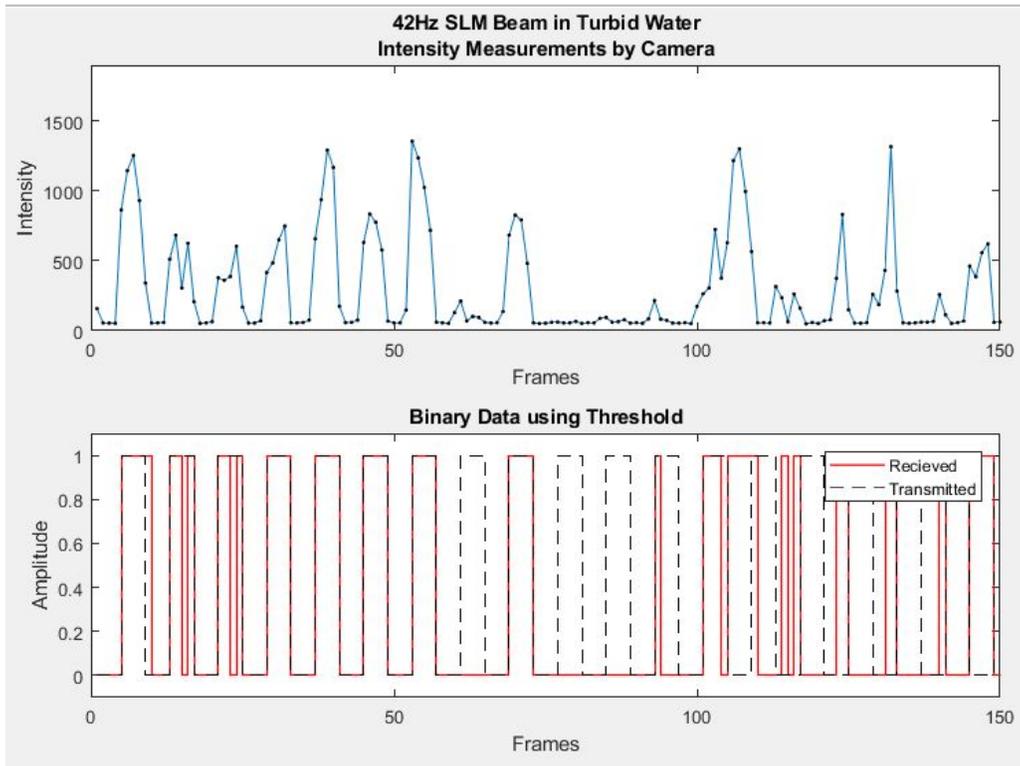


Figure 23. Plot comparing transmitted and received data for 42 Hz SLM Beam in Turbid Water

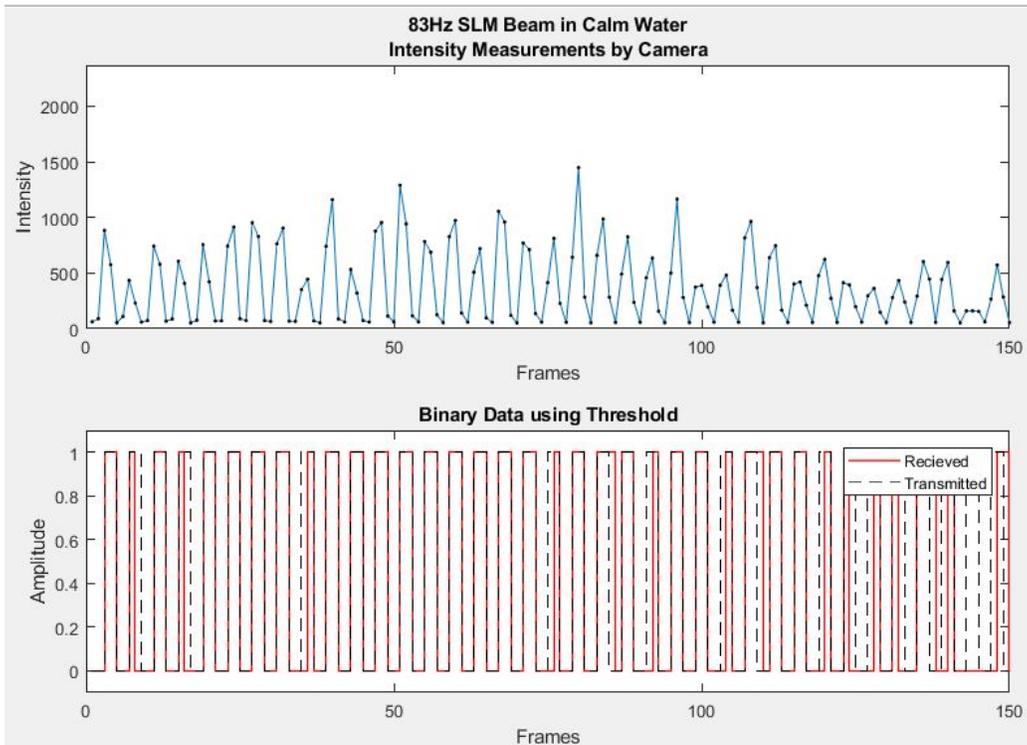


Figure 24. Plot comparing transmitted and received data for 83 Hz SLM Beam in Calm Water

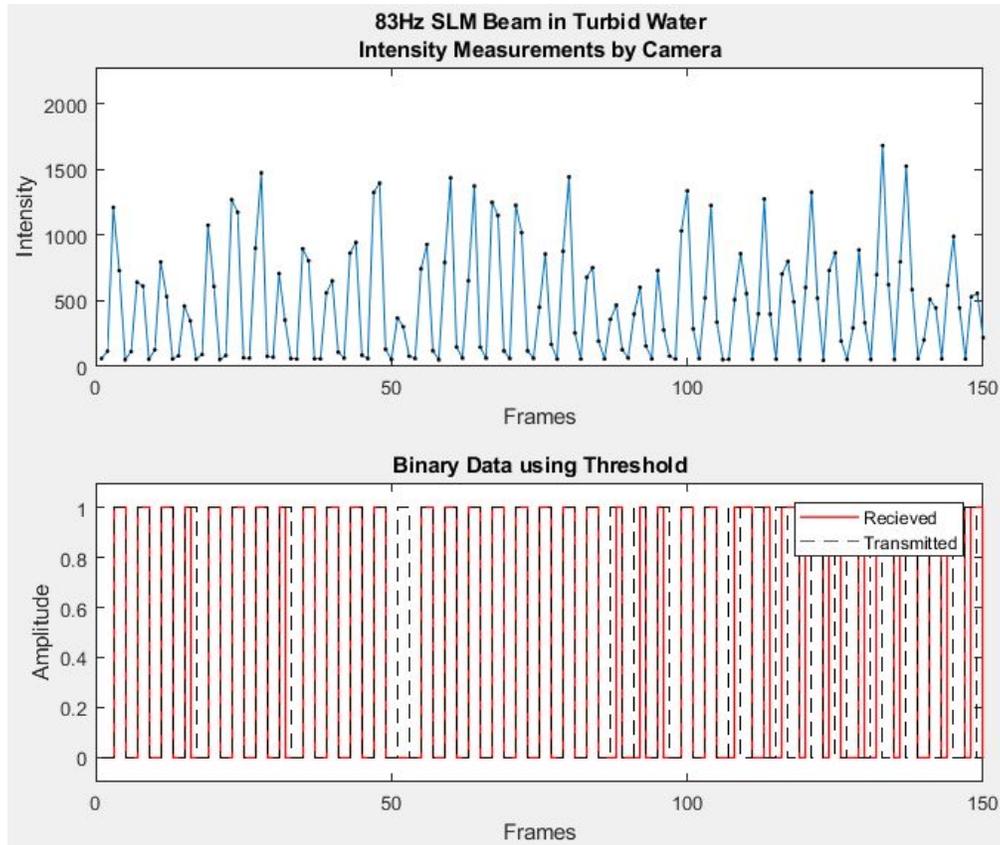


Figure 25. Plot comparing transmitted and received data for 83 Hz SLM Beam in Turbid Water

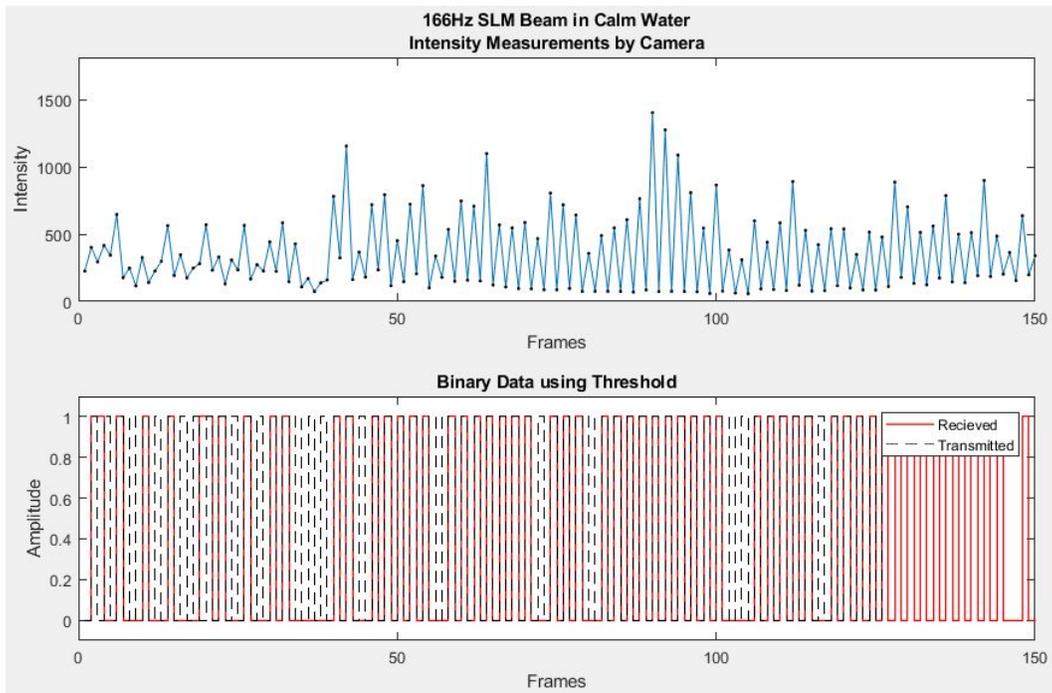


Figure 26. Plot comparing transmitted and received data for 166 Hz SLM Beam in Calm Water

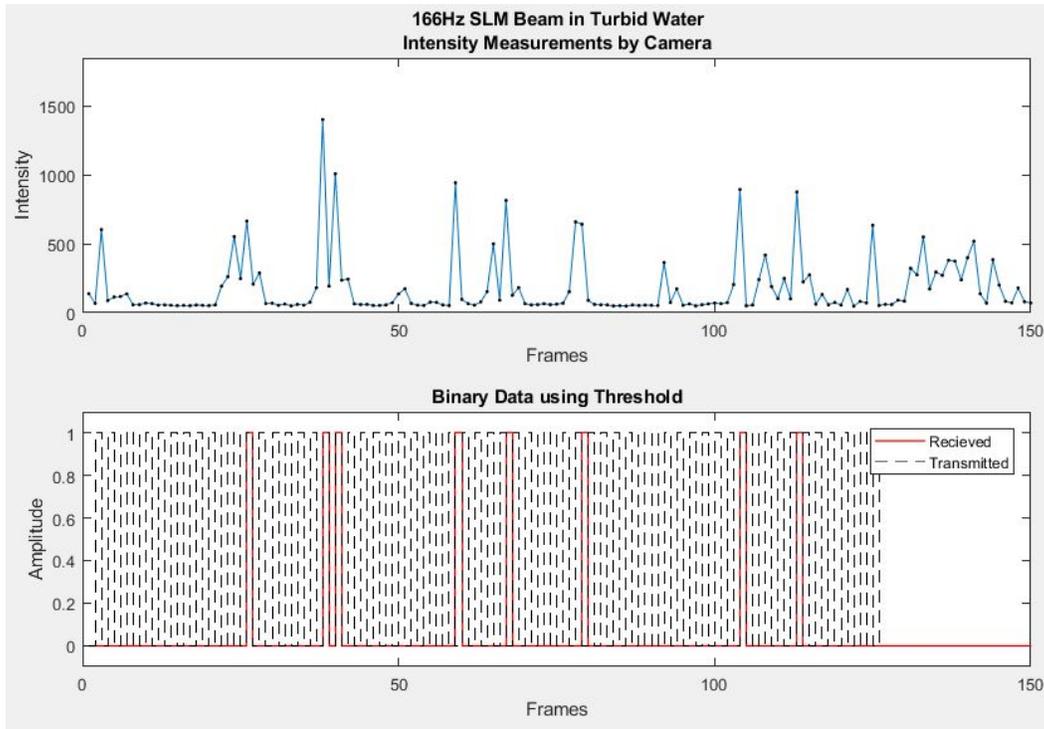


Figure 27. Plot comparing transmitted and received data for 166 Hz SLM Beam in Turbid Water

Through intuitive means, each plot of the beam intensity was analyzed for bit errors. The number of errored peaks was totaled and used to calculate the bit error percentage tabulated in Table 1.

Table 1. Tabulated Results of Bit Error Percentage for each beam type.

	Calm				Turbid			
	21 Hz	42 Hz	83 Hz	166 Hz	21 Hz	42 Hz	83 Hz	166 Hz
Gaussian Beam	0%	0%	3.7%	25.0%	33.33%	30.0%	21.43%	50.68%
SLM Beam	22.22%	47.62%	32.43%	66.20%	33.33%	52.17%	43.24%	80.0%

A plot of the percent bit errors was plotted (see Appendix, Section D) for each beam type at each tested frequency shown below in Figure 28.

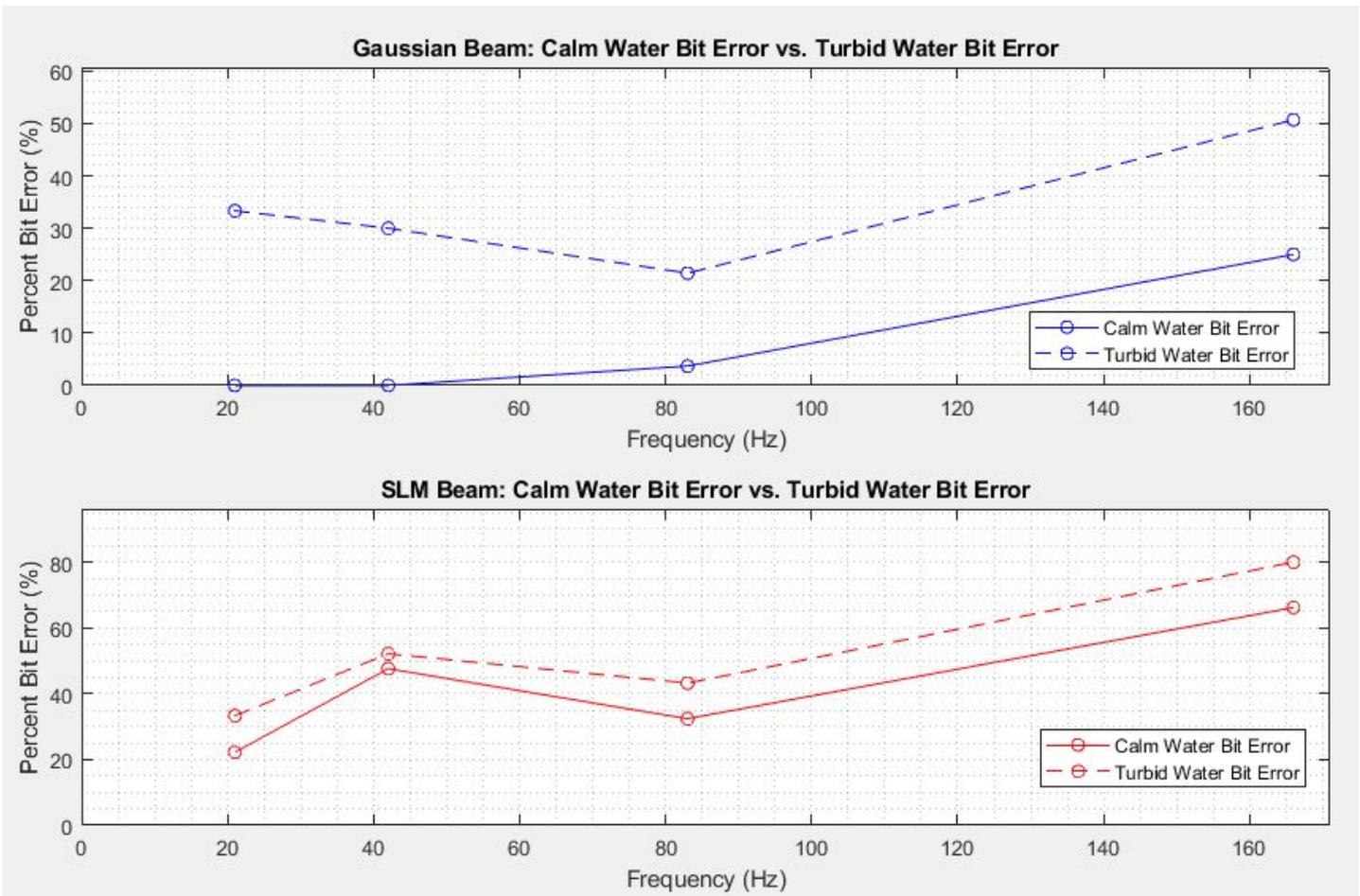


Figure 28. Plot of the percent bit error for each beam type.

CONCLUSION

The influence of water turbidity on the propagation of a laser is key in the study of the influence of the environment on laser propagation. Our experimental studies explains how turbidity can have a drastic impact on the propagation of the laser beam through water. This was found using intuitive analysis of the binary data from the intensities of light. Additionally, it was found that at higher frequencies, more errors occurred between transmitted and received data.

There is an obvious advantage seen in the use of the Gaussian Beam over the beam that underwent Spatial Light Modulation. However, a trend shared by both is the consistency of error seen between the 42 Hz and 83 frequencies. The error stays between 40% and 60% at those frequencies. As the frequency increases a sharp increase in bit error can be seen in both the Gaussian Beam and the SLM Beam. The additional experimental trial, with an inputted audio signal, turbidity was treated as a proof of concept test. The turbidity again had a great effect on the transmission of audio data through the water. The effect was heard in the change of sound once the turbid water was turned on. Without turbidity, however, there was little effect on the audio transmission.

Based on the data obtained throughout the conducted research it can be seen the effects of the environment on the propagation and from this the limits to the practical applications that lasers can serve in the sense of data transmission. The experiment serves as a foundation from which more studies can be conducted. One that includes a spread of more frequencies and additional environmental conditions like temperature, salinity, and water contaminants. The United States Navy and other groups alike would be interested to see the validity of data transmission through laser propagation. This experiment is a testament to the idea that laser beam propagation has potential to serve as a means for link to link data transmission, however, the most advantageous frequency and and beam type need continued investigation.

REFERENCES

“Optical Chopper System and Chopper Wheels.” *ThorLabs*,
www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=287.

S. Arnon, “Underwater Optical Wireless Communication Network,” *Optical Engineering*, 01-Jan-2010. [Online].

<https://www.spiedigitallibrary.org/journals/optical-engineering/volume-49/issue-1/015001/Underwater-optical-wireless-communication-network/10.1117/1.3280288.full?SSO=1#ArticleLinkReference>

APPENDIX

Section A

```

name= ['NON_SLM_21Hz.tif'];

FileTif = name;
InfoImage=imfinfo(FileTif);
mImage=InfoImage(1).Width;
nImage=InfoImage(1).Height;
NumberImages=length(InfoImage)
FinalImage=zeros(nImage,mImage,NumberImages,'uint16');

z=1;
ax=1;bx=NumberImages-1;

for i=ax:bx
    FinalImage(:,:,z)=imread(FileTif,'Index',i);
    b=double(FinalImage(:,:,z));
    x(i)= mean(mean(b));

    average = mean(x); %average value of received data

%Thresholding of received data
if x(i) > average+100 %if received is above average+100 then represented as a 1
    xx(i)=1;end
if x(i)< average-100 %if received is above average-100 then represented as a 0
    xx(i) = 0;end

```

```
end
```

Section B

```
load('21Hz Data.mat'); %Enter desired data to upload

frequency = 21; %indicate frequency being analyzed
period = 1/frequency;
camera_rate = 0.003; %camera rate

frame_cap = 150; %cap on frames to be analyzed/plotted
num_ones = (0.5*period)/camera_rate; %number of ones in transmitted data
z = [1:round(num_ones)]; %number of ones expected in one bit of data
y = [zeros(size(z)), ones(size(z))]; %one bit array of transmitted data

%creation of array of transmitted data the length of the received data
for ii = 1:length(y):frame_cap
    for jj = 1:length(y)
        ylnew(ii+jj-1) = y(jj);
    end
end
end
```

Section C

```
%plot of raw received data
fig = figure('Name','Final Project Graphs');
axs(1) = subplot(2,1,1,'Parent',fig);
plot(x,'Parent',axs(1)); axis([0 150 0 (max(max(x))+100)]);
hold on;
plot(x,'k.','Parent',axs(1));
hold on;
title(axs(1),{num2str(frequency),'Hz SLM Beam in Turbid Water'};'Intensity Measurements
by Camera');
xlabel('Frames');ylabel('Intensity');

%plot of binary received vs. transmitted data
axs(2)= subplot(2,1,2,'Parent',fig);
stairs(xx,'r','LineWidth',1,'Parent',axs(2)); axis([0 150 -0.1 1.1]);
hold on;
stairs(ylnew,'--k','Parent',axs(2));
hold on;
title(axs(2),'Binary Data using Threshold');
xlabel('Frames');ylabel('Amplitude');
legend('Recieved','Transmitted');
```

Section D

```
frequencies = [21 42 83 166]; %Array of frequencies tested
```

```
%Bit Error = number of peaks with errors/total number of peaks
%Arrays of bit errors for Gaussian Beam
Gaussian_Calm = ([ (0)/10 (3)/18 (1)/27 (5)/67 ])*100;
Gaussian_Turbid = ([ (3)/9 (12)/20 (18)/39 (12)/63 ])*100;

%Arrays of bit errors for SLM Beam
SLM_Calm = ([ (4)/9 (12)/20 (11)/36 (74)/79 ])*100;
SLM_Turbid = ([ (5)/9 (15)/18 (21)/36 (74)/78 ])*100;

%Plot of Bit Errors for each type of beam
figure(1)
subplot(2,1,1);
plot(frequencies,Gaussian_Calm, 'b-o');
axis([0 (max(frequencies)+5) 0 (max(Gaussian_Turbid+10))]);
hold on
plot(frequencies,Gaussian_Turbid, 'b--o');
hold on;
xlabel('Frequency (Hz)');ylabel('Percent Bit Error (%)');
legend('Calm Water Bit Error', 'Turbid Water Bit Error');
title('Gaussian Beam: Calm Water Bit Error vs. Turbid Water Bit Error');
grid minor;

subplot(2,1,2);
plot(frequencies,SLM_Calm, 'r-o');
axis([0 (max(frequencies)+5) 0 (max(SLM_Calm+10))]);
hold on
plot(frequencies,SLM_Turbid, 'r--o');
hold on
legend('Calm Water Bit Error', 'Turbid Water Bit Error');
xlabel('Frequency (Hz)');ylabel('Percent Bit Error (%)');
title('SLM Beam: Calm Water Bit Error vs. Turbid Water Bit Error');
grid minor;
```