Exploration of Multiple Wavelength Laser Beams Propagating Underwater

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ABSTRACT

Laser beams propagating through complex media commonly experience degradation. This experiment investigates the effects of using laser beams with different wavelengths propagating along the same path as a method of mitigating distortion. We recorded intensity measurements of both a red and green laser after passing through a temperature and flow controlled underwater path and explored the effects of wavelength diversity on laser scintillation. Specifically, temperature variations were induced in a 243cm long water tank, containing 500 liters of deionized water using three heating sources. Experiments were performed with a triple pass through the tank for a total propagation length of 980cm. The final experimentation yielded repeatable and significant reductions in the scintillation of the multiple wavelength beam compared to its individual component beams.

Keywords: wavelength diversity, underwater laser propagation, scintillation

1. INTRODUCTION

With specific reference to communication systems employed by the United States military, laser communication systems stand to offer significant improvements in not only signal transmission security, but the data transfer speed as well. These communication systems could have direct implementation underwater, between divers, submarines, and unmanned underwater vehicles (UUVs). Current undersea communication systems do not frequently rely on wireless systems, particularly when the large transfer of data is imperative to mission success, such as with UUVs, and are slow and unsecure when they do opt for wireless transmission.

Laser link communication systems offer significant improvements over traditional solutions, including increased security and the data transfer speed. Despite these possible advantages, significant barriers in laser propagation have kept the technology from seeing widespread implementation as a means of communication in the US military today. The major challenges facing laser propagation center on overall loss of beam intensity, as well as intensity fluctuations on target over long distances and through different media. In terrestrial environments, there are considerable challenges presented by not only the environmental obscuring effects from airborne particulates, but also the varying of the index of refraction due to temperature gradient changes. These changes affect the beam path and results in constructive and destructive interference upon reception. Similarly, laser beams underwater experience significant challenges in propagation, however there has been significantly less investigation on beam propagation underwater.

2. BACKGROUND

Along a laser beam propagation path, small changes to the index of refraction within the propagation medium create a phenomenon known as optical turbulence. It is one of the main constraining factors for the propagation of laser beams through complex media because of the intensity fluctuations it causes within a beam profile. The beam is pulled apart and no longer united. This is due to the changes in the index of refraction along the beam path, which ultimately results in varying interference patters on the receiver.

In communications systems, the presence of optical turbulence can have a significant effect on the intensity fluctuations of the beam on the receiver, affecting quality or feasibility of the transmission of data. The underwater environment is particularly susceptible to optical turbulence due to high variability in environmental conditions, such as temperature and

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salinity. Additionally, the underwater domain is less susceptible to use of high powered lasers due to the possibility of thermal blooming, which occurs when the propagation medium absorbs energy from a propagating beam and is significant altered in its properties, generally seen as a temperature spike. Because of these issues, both conservation of the beam intensity levels and reduction of scintillation are topics of extreme importance when discussing the feasibility of complex underwater laser systems. Comparatively, there has been markedly less investigation on beam propagation underwater than in the atmosphere, likely due to the difficulty in the set up and control of test beds. This is despite the possible advantages that beam transmissions could bring to the underwater environment, such as advancements in laser communication systems between unmanned underwater vehicles and their control units.[1]

One method that has been investigated to cut down on the high degree of intensity fluctuation of laser light on reception, is wavelength diversity[2]. Wavelength diversity involves the use of co-aligned laser beams with diverse wavelengths propagating along the same path onto the same receiver. Existing literature, primarily theory and numerical simulations on wavelength diversity, focuses on propagation through an atmospheric environment[3]. The theory behind wavelength diversity is based on the way in which laser beams interact with the medium along their propagation path. If two beams have enough wavelength diversity, they will be affected differently and will create inherently different irradiance patterns on the receiver. Where one beam falters, the other beam may be able to fill in, and visa versa. Figure 1 depicts the received irradiance patterns form a green and red laser influenced by turbulence along the propagation path.

Our experiment seeks to explore the relationships between changing environmental conditions in the propagation medium and the implementation of wavelength diversity as a means of reducing overall intensity fluctuation on the receiver after propagation through a turbulent medium.

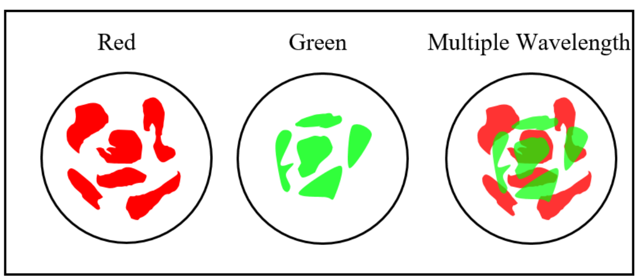

Figure 1. Irradiance Pattern on Receiver for Green/Red/Multiple Wavelength Beams through turbulence

3. EXPERIMENTAL SET-UP

To analyze the effects of multiple wavelength propagation underwater, two laser light beams are propagated through a water tank and captured using a charge coupled device (CCD) camera system. Two HeNe lasers, each operating at different wavelengths, one red (633 nm), and one green (543 nm) were directed into, and combined with a beam splitter creating a co-propagating multiple wavelength beam. The water tank that the beams propagate through has a variable and controllable temperature as well as flow provided by heating sources. The heating sources use feedback controllers to regulate the heat they output as water is circulated about an internal heating element. This paper specifically studies the effects of the temperature and water movement on laser beam intensity fluctuations. The experimental set up is show in Figure 2.

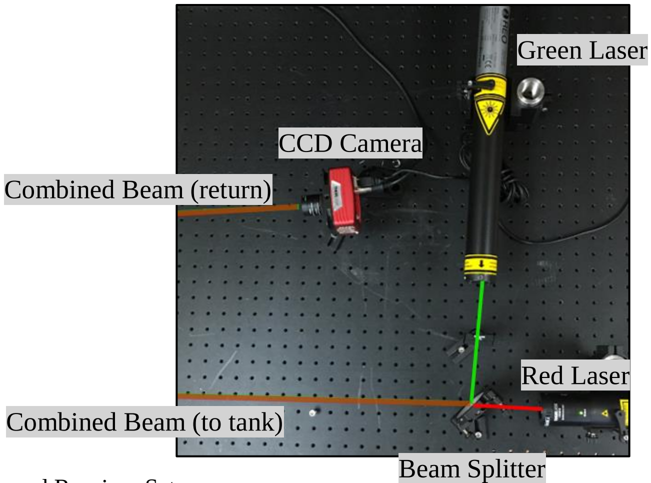

Figure 2: Laser Source and Receiver Set up

Laser light intensity was recorded for an approximate duration of ~12 seconds at 55 frames/second, for a total of ~600 frames per collection, with an exposure time of 17.725 ms and with a 480x640 pixels, 16 bit camera... Additionally, the laser light was attenuated using neutral density filters so that the camera sensor was not saturated.

3.1 Initial Experiments

Initial experimentation was conducted in a 75 liter tank, measuring 75x30x30cm, and was filled to half volume with freshwater. A mirror was placed on the side opposite to the beam entry to double the propagation path length. The tank was made of bonded and sealed acrylic sheets assembled on the bottom and sides of a rectangular prism, with no sheet on the top side leaving the tank open for manipulation. The total beam path from aperture to collection camera is 475cm, with approximatelym175cm through the water. The single heater was affixed to the side of the tank in the corner near the mirror, 7.5cm at the closest point to the beam path. An overhead diagram of this tank can be found in Figure 3.

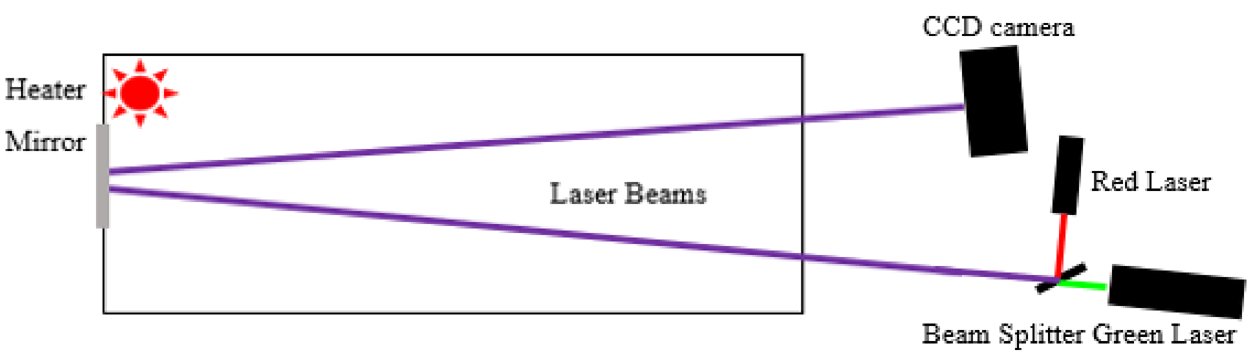

Figure 3: 75 Liter Tank Experimental Set Up Overhead Diagram

The experiment consisted of data collection at specific incremented temperature settings on the heating elements. Beginning at room temperature (70ºF), the temperature was incremented 10ºF each iteration through 100ºF. At each interval, data was collected for just the red beam, then just the green beam, then the combined beam. Ultimately, the conclusion that was reached was that the beam path had to be extended to allow ample amount of time in the propagation medium for the beam to demonstrate the desired effects. Additionally, closer proximity to the heater and more heaters in a larger volume of water were also desired, as this would create a greater degree of control over the environmental conditions we sought to manipulate.

3.2 Extended experiments

Based on the initial testing, extended experimentation was planned and carried out. Experimentation in a different environment was required due to the variation in results and lack of repeatability from the initial experimentation. The development of a comprehensive test bed became an integral part of the experimentation. To resolve the issues from the first experiment, a much larger 800 liter tank was used to create a longer propagation path, with more controllability over the environmental modifications. The tank was made of cast polyethylene with dimensions 43x76x243cm. This tank was filled with approximately 500 liters of deionized water. An entry and exit window were created using machined window mounts and fitted pieces of optical quality acrylic. Access points are added in the roof to allow access and manipulation of items inside the tank. Two mirrors, one at each end, are mounted so as to provide the means to create a multi-pass environment, doubling the available beam path seen in a single pass system. Total path length underwater was approximately 980 cm. The setup of the lasers, beam splitter, and camera are in the same design as those in the initial experiment. Three heating elements are used due to the increase in total water volume, with each heater being placed through the roof access points, within 2 inches to the beam paths at all three points. Figure 4 shows the test bed in the laboratory setting.

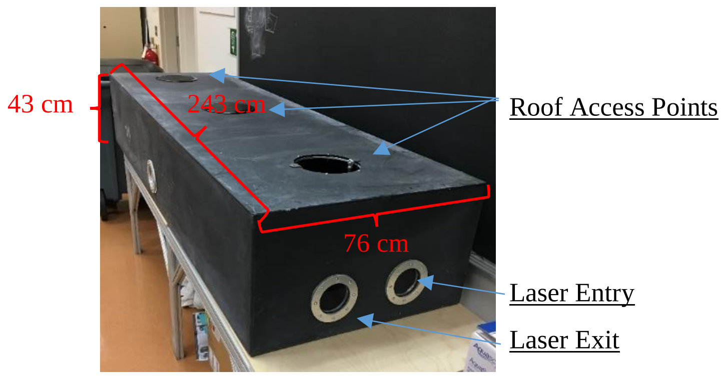

Figure 4. Experiential test bad for laser underwater research.

Figure 5 shows an overhead diagram of the beam path and heater placement.

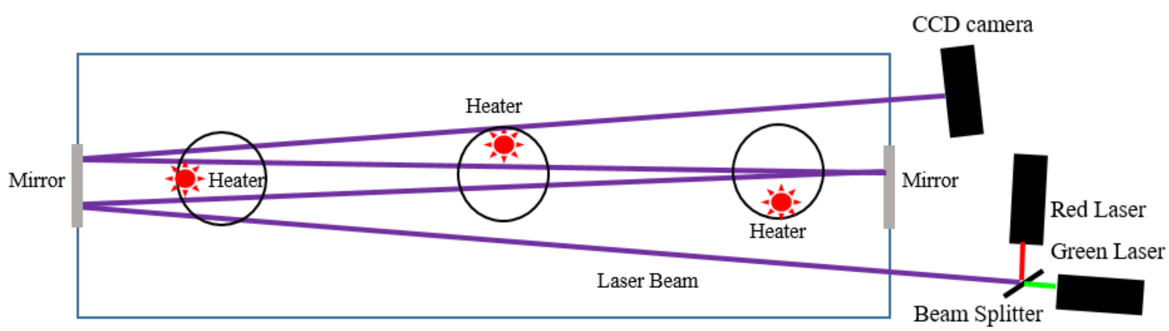

Figure 5. Laser propagation path underwater with the heat sources placement.

The experiment consisted of evaluating the propagation of red, green and multiple wavelength beams through several environmental scenarios. Specifically, the water temperature was set to room temperature (70ºF), and then the temperature was incremented by 5ºF each iteration through 95ºF. At each interval, intensity fluctuations at the receiver were collected for just the red beam, then just the green beam, then for the multiple wavelength beam.

4. Data Collection and Analysis

4.1 Data Collection

Laser light intensity fluctuations across the image sensor of a CCD camera. Data was downloaded onto a laptop computer as a series of .tif screens, which were each analyzed individually. In each pixel of the 480x640 resolution screen captures, intensity fluctuation were recorded. The background intensity value for the CCD camera was determined experimentally, and was subtracted from the values. From these, the scintillation was calculated as a statistical measure as the normalized variance of the intensity fluctuations. These were then averaged across the beam profile as an average for each pixel throughout the collection. Pixels with a mean irradiance value greater than or equal to $\frac{1}{e^2} * Max\ Intensity$ were considered within the beam profile as per the traditional definition of the spot size of a laser beam. This helped particularly to avoid the issues with intensity fluctuation spikes at the edge of the beam profile due to low saturation, and also created what is called a masked beam profile. Figures 6 and 7 are two angles of an ideal result of masked beam intensity profile.

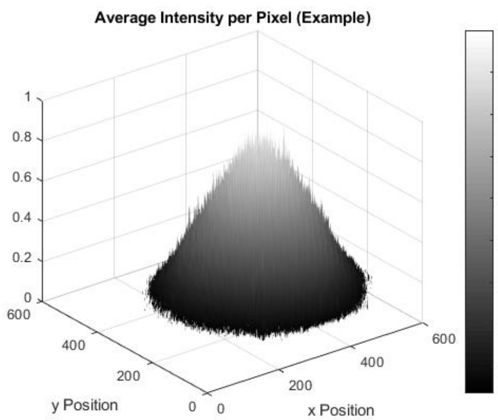

Figure 6. Beam Profile Side View

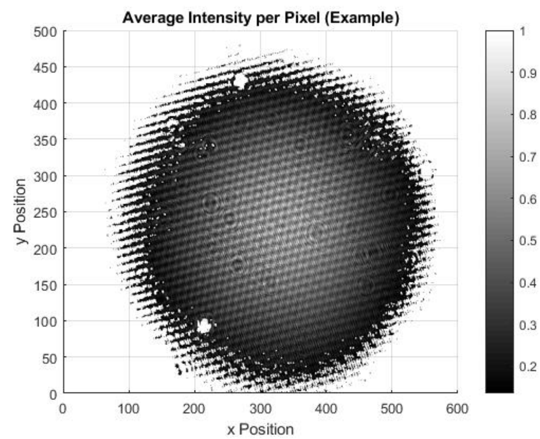

Figure 7. Beam Profile Receiver Planar View

The scintillation index of a beam is the resulting normalized variance of irradiance fluctuations. The normalized variance is computed for a laser beam upon arrival at the receiver, and this value effectively describes the frequency of irradiance fluctuations. Below is the equation for the calculation of scintillation index, denoted as SI and where I is the irradiance of the optical wave and I_{avg} is the average irradiance on that particular screen

$$SI = \frac{<I^2> - <I_{avg}>^2}{<I_{avg}>^2} \tag{1}$$

This unit-less value is determined from the readings by the camera at the end of the tank receiving the beam. The normalized variance, or scintillation index, can be computed as a statistical value for beams of all powers and spot sizes, allowing the value to be compared across a wide array of beam types and sizes. In doing so, scintillation index was used to compare the performance of the beam intensity fluctuations for all beams used in this experiment.

The heat sources had to be placed in such a way that they were in a very close proximity to the beam path. This ultimately resulted in a large amount of turbulence being generated around each of the heater, shown in Figure 5 as the red circular objects with traces coming off. To account for this and to try and track the impact that the temperature alone was having on the propagation performance, two data collections were conducted at each temperature interval. The “agitated” collection was done with the heating element turned on, and after it had reached a steady state heat output. The “calm” collection was conducted after the water had ample time to settle with the heater turned off, which was standardized at a 5 minute interval. Figures 8 and 9 showcase the typical beam profile for each of these cases.

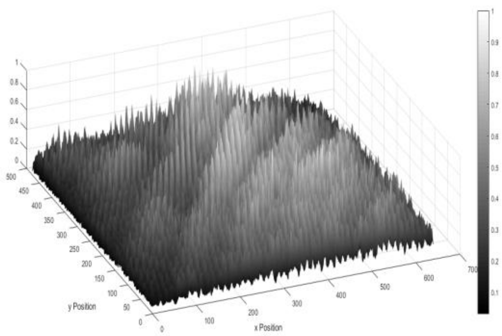

Figure 8. Calm Tank Green Beam Profile (70^{o}F)

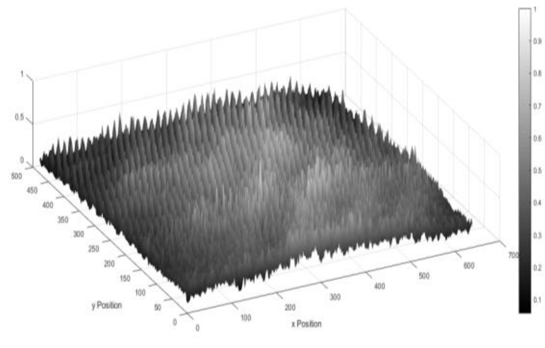

Figure 9. Agitated Tank Green Beam Profile (70^{o}F)

4.2 Data Analysis

Because the theory of multiple wavelength propagation improving scintillation performance has to do with minute changes in the index of refraction over the beam propagation path, as well as the effect as a function of wavelength, it is very much possible that too short a path length would not result in scintillation reduction. The beam path was increased by more than 500% in the second experiment, and the results were much more conclusive.

Table 1 shows in detail the results of the data collection at each of the temperature settings, with distinction between the turbulent and calm turbulent settings. Scintillation calculated as a unit-less value, and intensity is stored as a measure of charge recorded from the receiver, which uses the incident photons to create a measurable electrical charge.

Scintillation						
	70F	75F	80F	85F	90F	95F
Red Calm	0.0078	0.1088	0.2926	0.3754	0.3113	0.6336
Standard Deviation	0.0076	0.0835	0.1762	0.1723	0.1676	0.3492
Green Calm	0.0616	0.1175	0.2900	0.5690	0.4916	0.9937
Standard Deviation	0.0868	0.0926	0.1798	0.2660	0.1795	0.4491
Both Calm	0.0004	0.0984	0.2467	0.2434	0.4333	0.5533
Standard Deviation	0.0003	0.0920	0.1482	0.1329	0.1767	0.2766
Red Agitated	0.0089	0.0667	0.2919	0.7014	0.7526	0.8299
Standard Deviation	0.0115	0.0511	0.1127	0.1295	0.2163	0.1821
Green Agitated	0.0165	0.1045	0.3322	0.8291	0.8370	1.5024
Standard Deviation	0.0189	0.1249	0.1361	0.1975	0.1462	0.3824
Both Agitated	0.0107	0.0663	0.2388	0.5822	0.3972	0.8096
Standard Deviation	0.0127	0.0739	0.0993	0.1337	0.1199	0.2520
Intensity						
	70F	75F	80F	85F	90F	95F
Red Calm	899.3565	777.1502	664.6414	685.7734	822.8711	472.4281
Standard Deviation	310.53	294.09	261.02	185.56	194.71	183.12
Green Calm	2865.8602	2122.7952	2180.5239	1380.1393	1481.1217	937.2033
Standard Deviation	1113.70	878.32	751.41	479.79	476.96	362.71
Both Calm	3417.2260	2873.2188	2540.6331	2685.0828	2331.2792	1226.2385
Standard Deviation	1281.90	1065.90	1010.45	683.40	722.27	394.59
Red Agitated	962.4209	914.9258	724.9596	685.4959	378.1893	512.4732
Standard Deviation	304.06	292.07	258.98	258.87	109.94	103.29
Green Agitated	2442.0617	1993.8349	1725.8987	1549.5102	1628.3403	905.2385
Standard Deviation	996.82	790.70	711.85	473.14	483.78	406.57
Both Agitated	2899.5192	2380.9301	2303.2392	2067.5316	2320.7106	1626.5954
Standard Deviation	1004.94	925.79	850.49	816.39	943.50	516.77

Table 1. Scintillation and Intensity Data from Experimentation.

The data from the table is compiled in the following figures (10, 11, 12 and 13), displaying scintillation or intensity vs temperature for both calm and turbulent data.

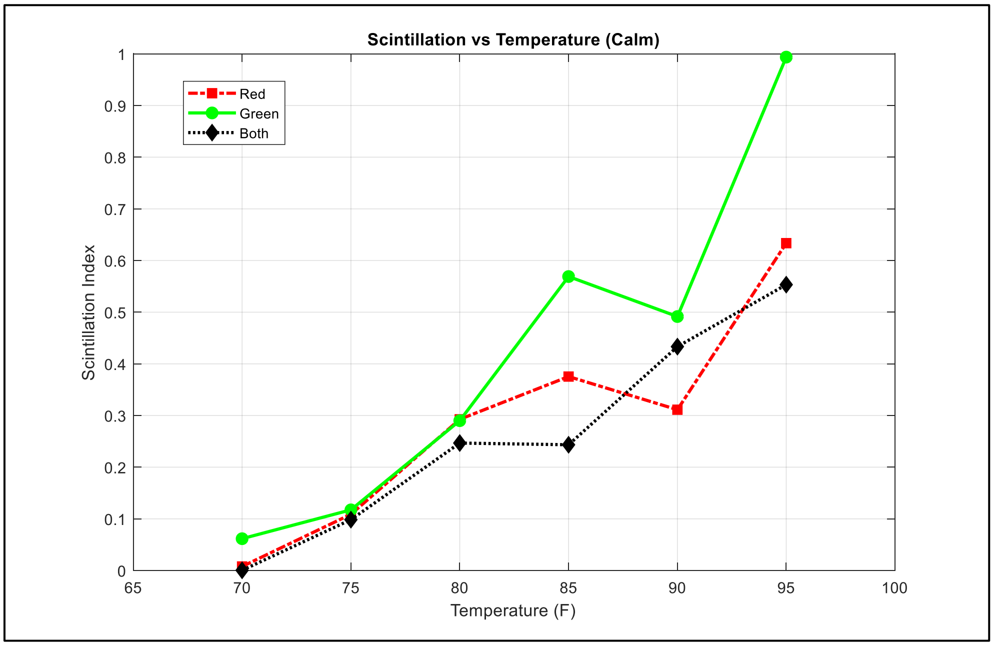

Figure 10. Scintillation vs Temperature (Calm)

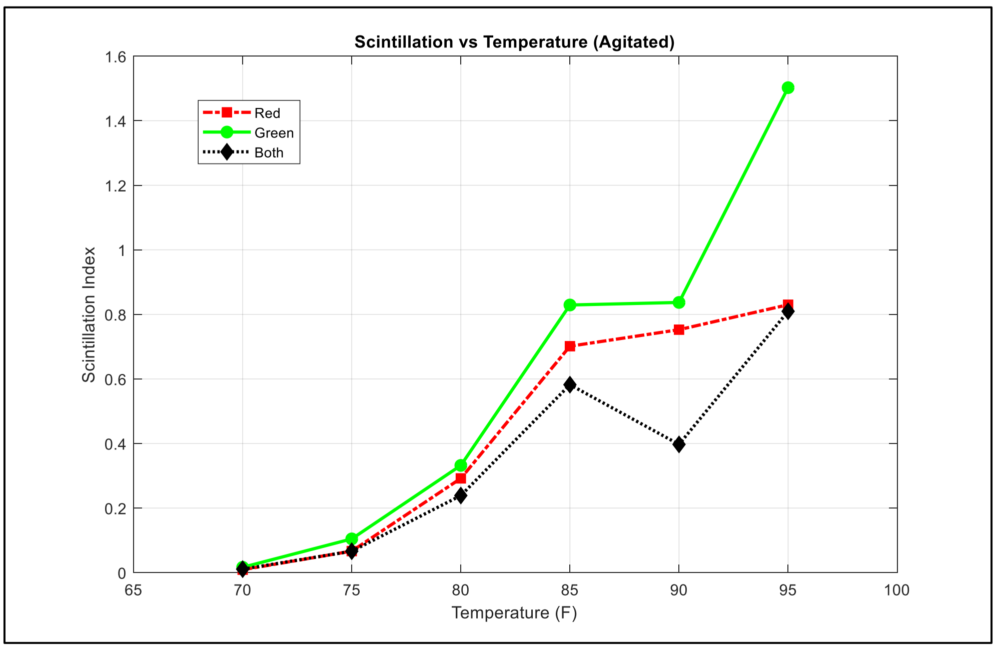

Figure 11. Scintillation vs Temperature (Turbulent)

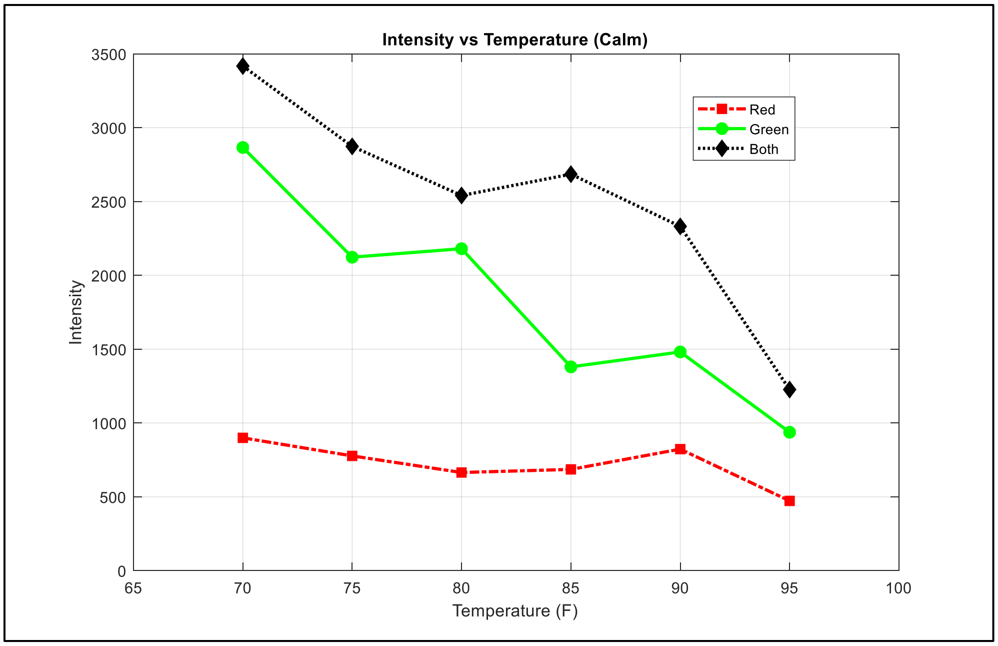

Figure 12. Intensity vs Temperature (Calm)

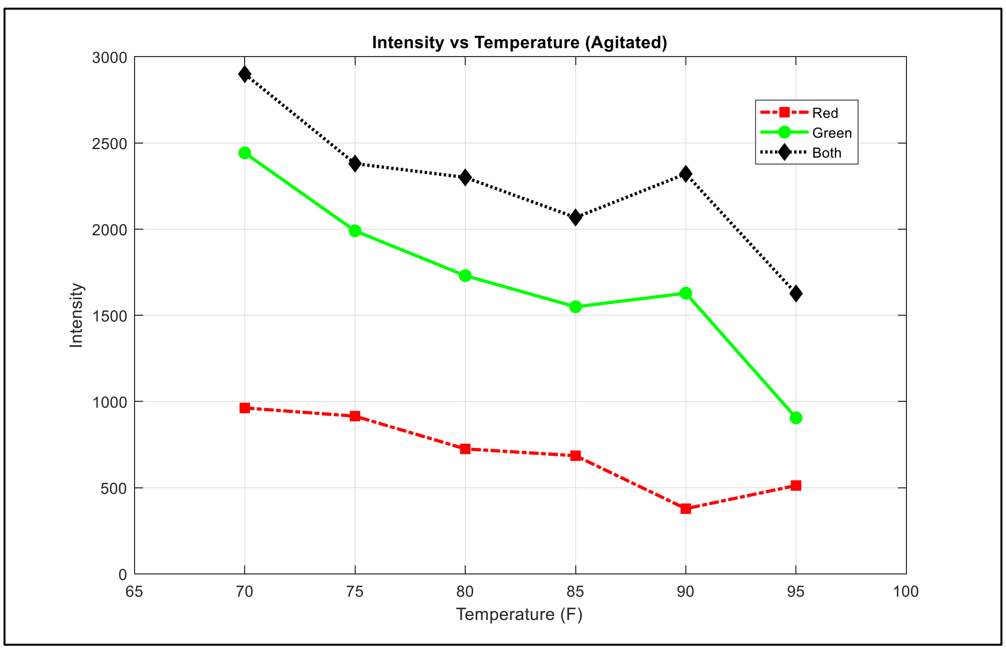

Figure 13. Intensity vs Temperature (Agitated)

The data analysis shows clear trend lines. Most notably, the multiple wavelength beam consistently outperformed the other beams with respect to scintillation reduction, with the exception of one temperature setting. For the turbulent environment, there was an overall average reduction in scintillation by 27.77%, while the calm environments yielded an average reduction of 31.05%%. At almost every temperature increment, the green beam performed the worst, despite markedly less absorption as it propagated through the environment when compared to the red beam.

Additionally, the beams all performed comparatively worse as the temperature increased in both calm and turbulent conditions, demonstrating the theory about increased optical turbulence as the temperature of the system increased. The effects of temperature increase on the beams overall reduced the intensity while increasing the scintillation, providing a much worse environment for something such as communications.

These values and deductions come with a caveat due to the high value of the standard deviation calculated along with them. Due to the high degree of beam spread and turbulence, it was repeatedly a difficult process to keep the beam centered on the receiver on the camera, and as such, the resulting standard deviations are higher than desired. If possible, mitigation of these affects would provide more comprehensive data, however every effort was made to keep the beam centered as it got progressively more turbulent as the experimentation went on. Each of these collections were repeated multiple times under identical experimental set ups to test the repeatability of measurements, since even minute changes to the heater placement or beam orientation from collection to collection would result in discernable changes.

5. CONCLUSION AND FUTURE WORK

Current laser communication systems have not yet been refined enough for feasible application in the underwater domain. Possible advances in the understanding of laser types which could be more conducive to underwater propagation, such as multiple wavelength beams, could make underwater laser communication possible in the future. Advances must focus on not only the preservation of laser intensity, so as to travel longer distances, but also on the minimization of intensity fluctuations, which are detrimental to the success of a communications system.

This paper explored the performance of a red-green multiple wavelength beam in a series of scenarios, and compared the performance of this beam to the performance of its component beams. The motivation for the experimentation comes from the theory that laser beams with different wavelengths will interact with changes in refractive index along the propagation path differently, which could ensure higher and more sustained saturation of the receiver compared to a beam of a single wavelength. Ultimately, this experiment has yielded the intended result as an investigation of the effects of propagation of multiple wavelength laser beams in the underwater environment. A second, larger tank was used to refine the experiment since the beam needed a longer propagation path in the environment, often with more kinetic turbulence in the environment as well. As temperature increased, the amount of scintillation and overall reduction in intensity also increased. The reduction in scintillation caused by the use of the multiple wavelength beam, however, was constant across all of the experimental environments and conditions. The combined beam was consistently slightly higher intensity than the sum of the other two beams, which also supports that more of the light was hitting the receiver than if either beam had been propagated on its own.

While the experiment has proven useful, there are a number of new issues raised from the developments that have been made. Looking for ways to reduce the standard deviation of measurements would be important to finding more and more meaningful data. Further experimentation into the effects of temperature gradients which change linearly would be valuable, and the addition of particulate matter in the tank to act as “scatterers” would be an interesting next step. Additionally, looking at the effects of two beams that are further away on the EM spectrum would also be valuable in helping to determine the true effects of wavelength diversity and the possible advantages it may have.

6. ACKNOWLEDGEMENTS

Funding for this project was supported by the Office of Naval Research (ONR).

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