UNDERWATER OPTICAL COMMUNICATION

Project thesis

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CERTIFICATE

This is to certify that the thesis titled "**Underwater Optical Communication**" is a bonafide record of the work done by **Ankit Atree** in the Department of Electrical Engineering, Indian Institute of Technology Madras, under my guidance and supervision, in partial fulfillment of the requirements for the award of the degree of Master of Technology in Electrical Engineering. The contents of this thesis, in full or parts have not been submitted to any other institute or university for the award of any degree or diploma.

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ANKIT ATREE

Abstract

The purpose of this thesis was to explore communications between a transmitter unit submerged underwater and a receiver unit in free space by using visible light lasers. While underwater communications are conventionally done using acoustic methods, underwater to free space communication is a fairly unexplored area of research. Further, underwater acoustic communications have certain inherent disadvantages owing to which the proposed method can also be used for communications between a submerged transmitter and a submerged receiver. Concepts from Free space optics were first applied to the underwater scenario to gain insight into the losses likely to be encountered. Subsequently, suitable transmitter and receiver configurations were studied and assembled. Post setting up the link in a wave flume tank, experiments were undertaken to study the effects of the turbulent underwater channel and the Air - Water interface on a laser beam. Methods to mitigate this turbulence were studied and the results brought out. A marked increase in the amount of data captured is observed by using suitable optical arrangements (light diffuser, Fresnel lens) along with the receiver.

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CHAPTER 1
Introduction

1.1 Overview

Underwater Communications have a vast range of applications in today's world. In the military field, a submerged submarine needs to communicate with other submarines/ ships/ UAV's/ land based units on a regular basis. Underwater Communications play a vital role here. In addition, commercial applications include oil rigs, deep sea diving and any application which needs a sensor submerged in water. While short range underwater links can be established using wired links, longer ranges necessitate the use of wireless methods.

Conventionally, underwater wireless communications have been undertaken using acoustic means. The propagation of sound in water is fairly well studied and systems using sound as a communication source have existed for a while now. However, the propagation of sound in water is highly dependent on Temperature, Pressure and Salinity [1]. As a result, the presence of thermoclines (temperature gradients) and haloclines (salinity gradients) in the ocean cause sound waves to refract when encountering these boundaries. This can drastically change the direction the sound is moving in or even channel the sound and propagate it for long distances (thousands of meters). Further, temperature, pressure and salinity are parameters which not only vary from place to place in the ocean, but also vary at the same place at different times of the day. In addition, higher frequency sound in attenuated much faster than lower frequency sound [2]. The fastest available acoustic modems work only at a few hundred kilo bits per second. Thus acoustic communications fall short when the requirement is to reliably communicate high bandwidth data (video, plots etc). This has lead to research towards finding alternate sources of communication in the underwater channel.

1.2 Background

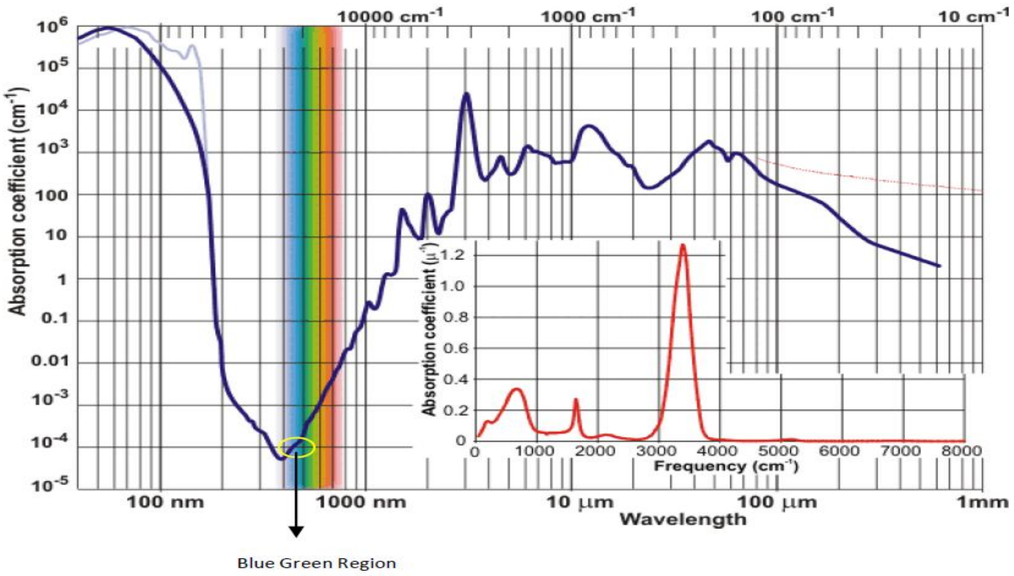


Figure 1.1 : Absorption coefficients of Electromagnetic Radiation in water at various wavelengths [3]

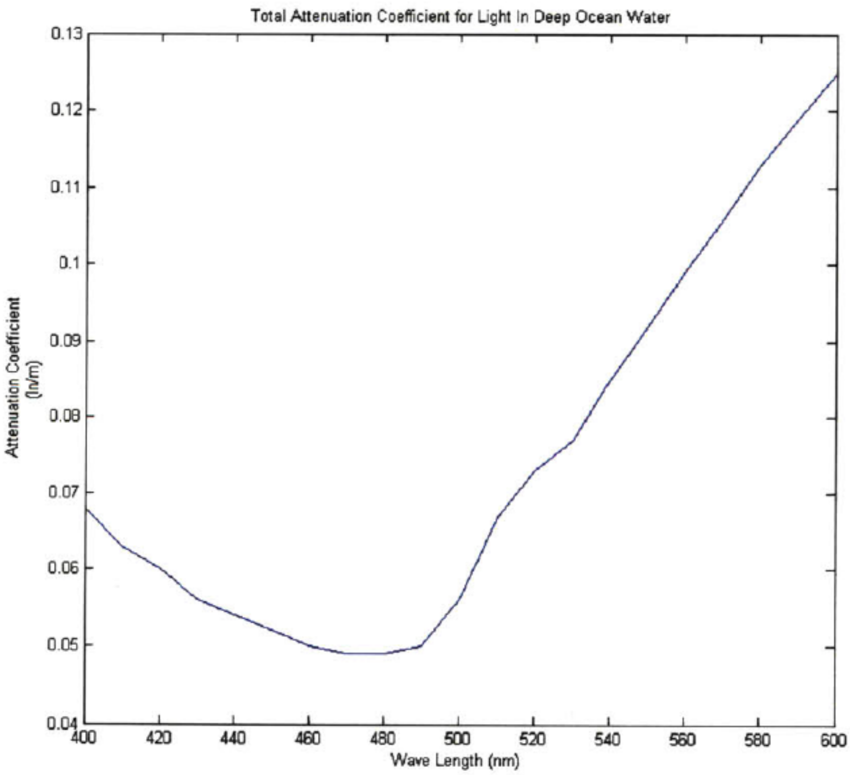


Figure 1.2: Absorption coefficients of visible light wavelengths in water [4]

Figure 1.1 shows the absorption spectrum of Electromagnetic Radiation in water. As is evident from the figure, Electromagnetic Waves suffer very large attenuation in water as compared to free space. However, the graph has a dip near the visible region which indicates lower attenuation coefficients for the visible region. Even within the visible region which is shown in Figure 1.2, we can see that the region between 440nm-540nm (mostly Blue/ Green) has the least absorption in water. Thus, it is theoretically possible for Blue/ Green light to travel considerable distance in water. Propagation of Blue/ Green light in free space is fairly well studied and the effects of the atmospheric channel including Attenuation (Absorption and Scattering) and Turbulence (Beam Wander and Scintillations) are predictable to a certain extent [5]. However, similar research for light propagation in water is still at a nascent stage and thus the exact effect that the channel has on the light beam is still a mystery.

Ocean waters contain organic and inorganic materials that influence the absorption and scattering of light. The complexity of the problem increases as, the concentration of organic and inorganic materials is not uniform and varies with the place and time. There needs to be a general model that takes into consideration these variations and to estimate the total light attenuation for different ocean conditions, since its essential to know the signal losses in the medium before designing a communication link. In addition to this, the scenario becomes more challenging if the optical beam needs to cross over the Air Water interface. Heavy turbulence exists at this interface which leads to the optical beam being thrown about over large distances. Communicating in such a state requires precise pointing and tracking systems along with suitable receiver optics to be able to capture the beam.

CHAPTER 2

THE UNDERWATER CHANNEL

2.1 <u>Introduction</u> Prior trying to develop an Underwater Communication Link, it is important to study the Optical Properties of the medium to understand the kind of effects that the channel may have on the light beam. One of the reasons for inadequate knowledge about the optical properties of water is perhaps inadequate knowledge about the exact composition of sea water. Natural water contains particles with size ranging from water molecules of size 0.1 nm to small organic particles of size 1 nm, phytoplankton's size ranging from 1µm to 100's of µm. Each of these particles contributes in some way to its optical properties.

2.2 <u>Losses encountered by an Optical Beam in water</u> The losses faced by an optical beam while propagating in water can be broadly classified into Attenuation and Turbulence. Attenuation can be further classified into Absorption and Scattering, while Turbulence can be further classified into Beam Wander and Scintillations.

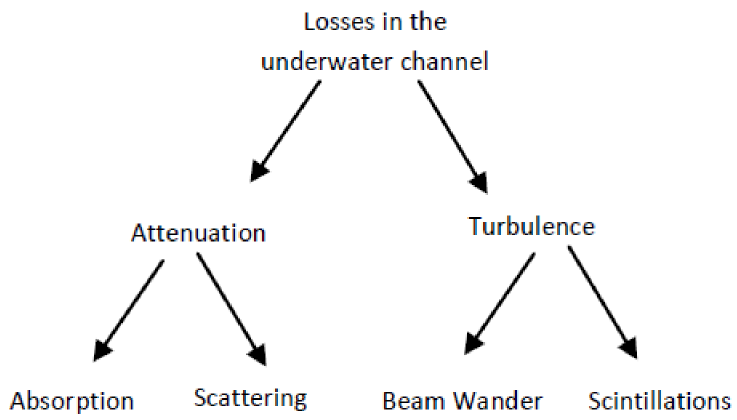


Figure 2.1: Classification of losses faced by an optical beam in water

2.2.1 <u>Absorption</u> refers to the loss of energy that is suffered by an optical beam when it interacts with the water molecules and other particulate matter present in water. As mentioned earlier, water consists of a large number of particulate matter and each particulate matter has its own absorption spectrum. One of the most commonly found dissolved constituent of sea water is chlorophyll, whose absorption of light was studied by Jerlov [6]. For the purpose of classification of types of water, Jerlov classified them on the basis of the chlorophyll content. The absorption spectrum of pure seawater and absorption by a few types of chlorophyll is shown in the Fig 2.2 and 2.3. Further, at different parts of the ocean, due to varying composition of these particulate matters, the absorption is likely to be different.

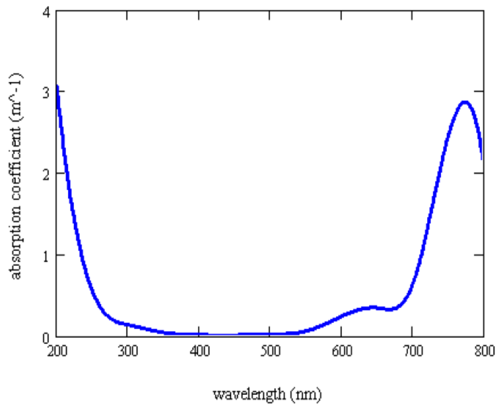


Figure 2.2: Absorption spectrum of pure sea water [7]

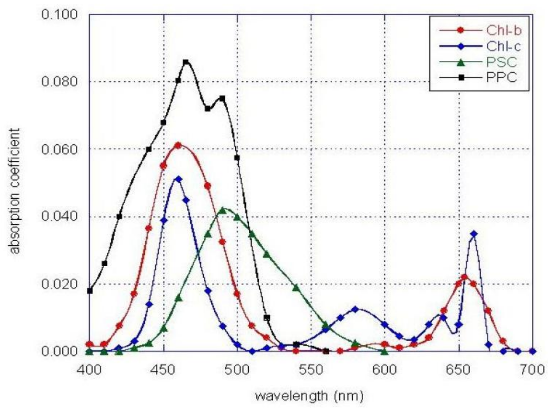


Figure 2.3: Absorption spectrum of types of chlorophyll [7]

It can be seen from the above figures that while pure seawater absorbs blue/ green light minimally as compared to other wavelengths, the absorption of light by particulate matter varies for different kinds of particles.

2.2.2 **Scattering** of light is basically the deviation of photons from their straight trajectory caused due to non uniformities in the medium. Scattering is not principally a loss of energy, as no part of the energy is actually lost, however it results in the energy spreading out over a larger distance. For wavelengths in the visible region, photons would experience Rayleigh scattering from particles of size much smaller than the wavelength of light while Mie scattering would occur for particles of size equal to or larger than the wavelength. The difference between the two lies in the fact that while Rayleigh scattering scatters uniformly in all directions, Mie Scattering is predominantly forward directional.

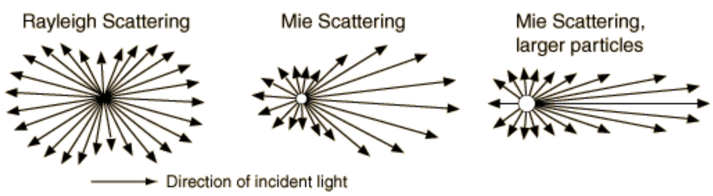


Figure 2.4: Rayleigh scattering and Mie scattering [8]

2.2.3 **<u>Turbulence</u>** Turbulent ocean flow causes variations in temperature, pressure and salinity. These parameters in turn result in localised variations in refractive index of the medium. Figure 2.5 depicts the variation of refractive index with temperature, pressure and salinity. It can be seen that while refractive index falls off with rising temperature, it rises linearly with salinity and pressure. Further, refractive index also depends on the wavelength of light [9]. These localised variations in refractive index cause the entire water medium to act as if consisting of a large number of lenses of varying sizes. These lenses of varying sizes can be thought of as eddies which cause the incident beam to be refracted. Eddies of size smaller than the incident beam will cause localised irradiance fluctuations in the beam. This happens because a part of the total beam gets refracted and upon emerging out of the eddy, interferes with the original beam. This interference may be constructive or destructive depending upon the phase difference between the two beams. This in turn leads to areas of high and low irradiance within the laser beam called as Scintillations. Figure 2.6 shows the image of a laser beam which has traversed 60 m from the source. The picture was taken on the rooftop of IITM Electrical Department. The localised irradiance fluctuations can be clearly seen in the picture.

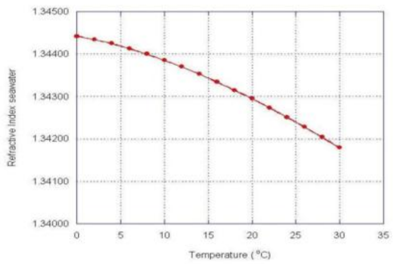


Figure 2.5 (a): Variation of Refractive index of water with Temperature [10]

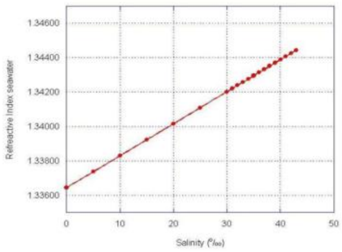


Figure 2.5 (b): Variation of Refractive index of water with Salinity [10]

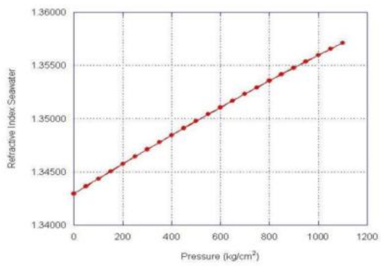


Figure 2.5 (c): Variation of Refractive index of water with Pressure [10]

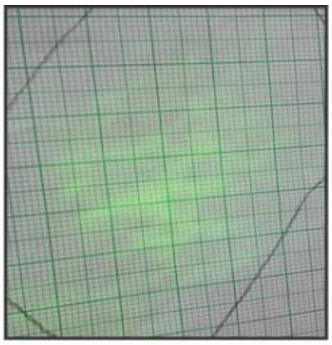


Figure 2.6: Scintillation (Picture taken on IITM Electrical Department Rooftop)

2.2.4 **Beam Wander**

Eddies of size larger than the optical beam would cause the entire beam to be deflected. This would manifest itself in the form of a wandering of the beam also known as Beam Wander. An illustration of Beam Wander is given in Fig 2.7. Beam Wander would result in alignment issues at the receiver and would require precise pointing and tracking systems to overcome.

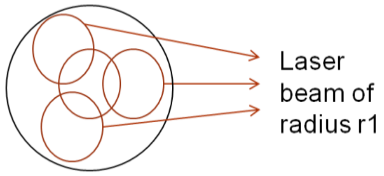
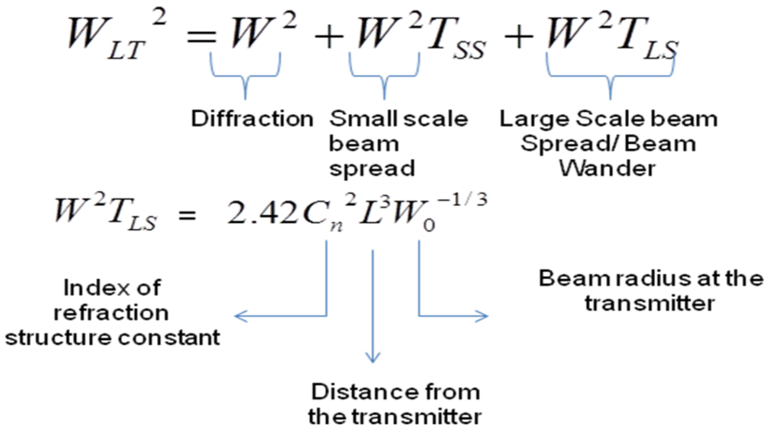


Figure 2.7: An illustration of Beam Wandering



As seen in the figure above, W_{LT}^2 is the long term beam radius which includes the deflections of the beam due to beam wander. It can be broken down into smaller components each attributable to diffraction, small scale beam spread and large scale beam spread/ beam wander [5]. This large scale beam spread can be expressed as a function of the distance from the transmitter, the beam radius at the transmitter and a function C_n^2, which is known as the index of refraction structure constant. Knowledge of this constant can give a fair idea of the effect of turbulence on the beam.

To get an idea about the time scale of the turbulence caused due to Beam Wander and Scintillation, if the Laser Beam has a transmitting aperture diameter of D and turbulent eddies flow across the beam with a velocity v, then the time scale of deflections would be of the order of $D/|v|$ [11]. Turbulence of time periods smaller than this would be because of scintillation.

2.3 Additional Sources of interference In addition to the losses discussed in the previous section, there are a multitude of other sources of interference which the optical link might encounter. These include:-

2.3.1 Solar Interference This interference would particularly exist in the top layers of the water channel, e.g. euphotic zone of the ocean. This would manifest itself in the form of background noise at the receiver. Appropriate filters for the transmitted wavelength would reduce the effects of background radiation considerably.

2.3.2 Multi-Path Interference Multi-path interference is caused when scattered photons are re-scattered back towards the receiver, thereby creating dispersion and spreading in the received signal. This phenomenon, which is routinely experienced in RF communication, is a relatively explored area of research in the field of optical communication, however the effects of such interference on an underwater optical link is unknown.

2.3.3 Physical Obstructions Physical obstructions such as fish or other marine animals will cause momentary loss of signal at the receiver. Appropriate error-checking and redundancy measures must be taken to assure that lost data is retransmitted.

2.3.4 Turbulence at the Air Water interface An optical beam reflecting/ refracting from the water surface would further experience heavy turbulence at the surface which would require suitable and precise beam tracking systems along with suitable optical arrangements to be able to capture the beam. In a scenario where the beam is required to interact with the Air Water interface, the turbulence faced would far exceed the turbulence due to beam wander or scintillations.

CHAPTER 3

TEST SETUP

3.1 One of the first challenges in the project was to locate a suitable experimental area for conducting the experiments. A suitable water tank with enough space to work in was a primary criterion. A survey was done of the tanks within the campus. This included certain water tanks in the Mechanical Engineering Department and a few tanks in the Ocean Engg Department. Finally, the Wave Flume Lab in the Ocean Engineering Department was chosen. The lab houses a glass walled fresh water tank with dimensions of 20 m x 0.5 m x 0.7 m. This particular lab was chosen for the following reasons:-

(a) The lab had sufficient area to work around the water tank where the associated accessories of the link would be kept.

(b) The water tank was easily accessible from all sides to allow for easy setup of the waterproof modules in the tank.

(c) Since the walls of the tank were made of glass, it was convenient to observe the optical beam and make necessary alignments.

(d) The tank had a wave maker installed which could be used to generate turbulence externally thereby simulating real time conditions.

Figure 3.1: Water Tank at Wave Flume Lab in Ocean Engineering Deptt at IIT Madras

3.2 <u>Proof of principle</u> The first step towards establishing an underwater link was to try and demonstrate a proof of principle. The aim was to show that communication in an underwater medium could be established by using Blue/ Green laser. A green laser pointer (output < 10mW, 532 nm) was used as a transmitter and a Silicon Phototransistor (L14G2) connected in a Trans-Impedance configuration was used a receiver. Both the transmitter and receiver were kept outside the water tank and reflecting mirrors were used to make the laser beam travel a distance of about 8 m in the tank. The link was successfully established thus paving the way for the rest of the project.

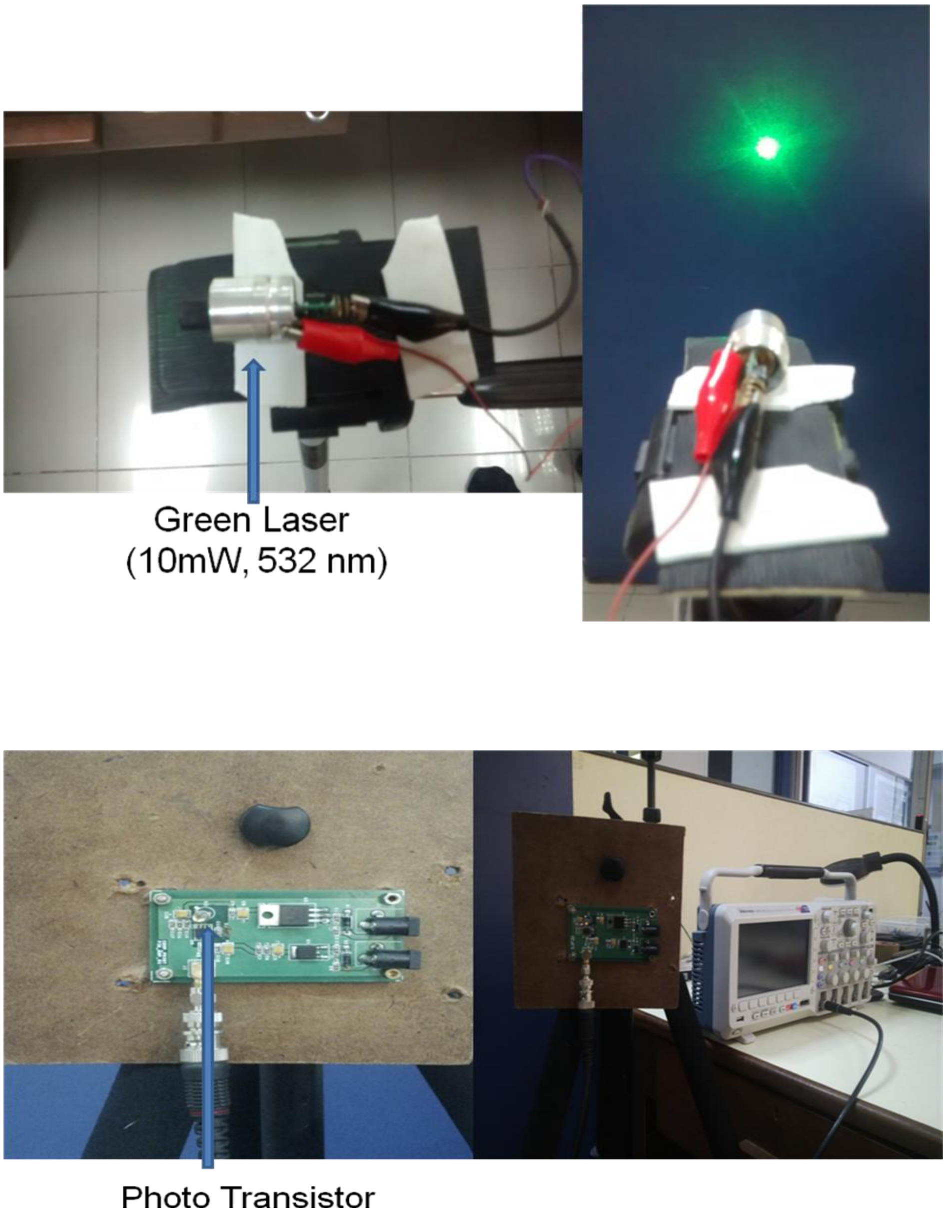


Figure 3.2: Transmitter and receiver configuration for demonstrating proof of principle

3.3 Transmitter Setup

Having demonstrated a proof of principle, we set about trying to establish the actual link. The requirement from the transmitter was to have a fairly focussed beam of enough power to be able traverse the entire length of the tank. Based upon these requirements, a Green Laser Pointer (power < 50 mW, 532 nm, Continuous Wave output) was procured. Since the laser was a continuous wave laser, there was a requirement of a driver circuit to be able to pulse the laser at the required frequency. A driver circuit was designed in house for this purpose. The entire process of disassembly and rewiring of the commercially procured Laser Pointer is placed at Appendix A.

Once the laser circuit along with the driver was ready, it was decided to make the laser setup waterproof so as to be able to keep the transmitter inside the water tank and thus remove the requirements of using reflecting mirrors as they tend to bring in additional turbulence and thus would hinder in undertaking a detailed study of the channel effects on the laser beam. A step by step breakdown of the waterproofing procedure of the transmitter is placed at Appendix B. Once the transmitter setup was ready, it was taken to the water tank in the Wave Flume lab and was checked for its functioning. Figure 3.3 and 3.4 depict the assembly and final setup of the transmitter. A clear Green Laser beam can be seen to be emanating from the transmitter.

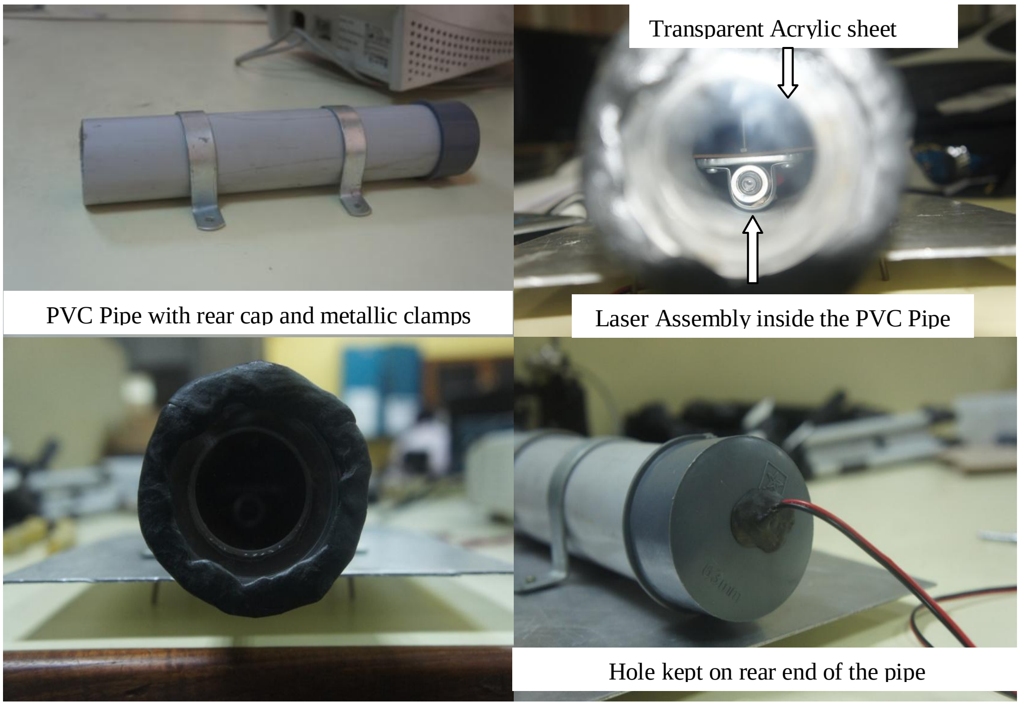


Figure 3.3: Assembling the transmitter

Figure 3.4: Final Transmitter Setup

3.4 <u>Receiver Setup</u> With the transmitter in place, the next step was to work on the receiver. The same receiver circuit as the one used for demonstrating the proof of principle was used for the final receiver as well. The circuit was assembled inside a PVC box of a suitable size using securing bolts. Appropriate holes were drilled on the sides of the box to allow the power supply cable and the SMA to BNC cable to pass through. The receiver used was a Silicon Phototransistor (L14G2). The receiver circuit used an OPA 656 as the amplifier. A hole of an appropriate size was drilled in the front casing of the receiver box to allow the laser beam to fall on the detector. The entire assembly was mounted on a tripod as shown in Fig 3.5. The receiver circuit diagram is placed at Appendix C.

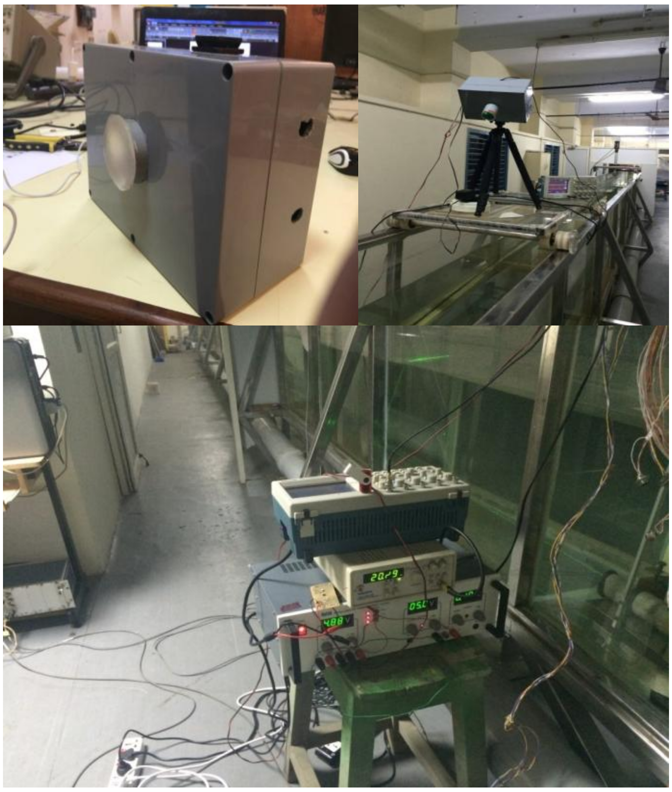


Figure 3.5: Final Receiver Setup

3.5 Link Bandwidth With the transmitter and receiver setup in place, the first experiment was to try and calculate the link bandwidth. For this purpose, the distance between the transmitter and receiver was kept to be 12 meters. The transmitting frequency was increased sequentially and the corresponding peak to peak function observed on the oscilloscope was noted. The observed link bandwidth was found to be 380 kHz.

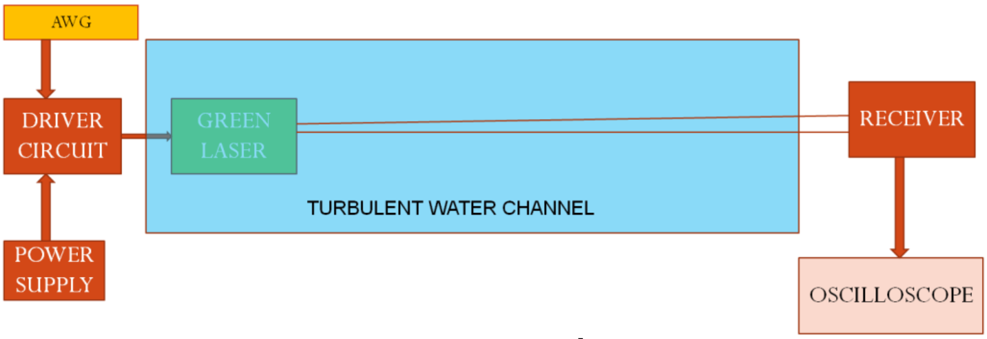


Figure 3.6: Experimental Setup

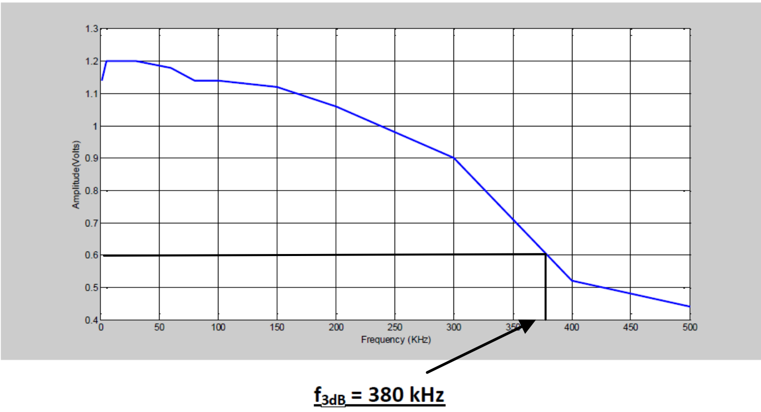


Figure 3.7: Link Bandwidth Plot

CHAPTER 4

Experimental Work and Results

4.1 <u>Introduction</u> With the link in place, the next step was to start experimenting and collecting data. The aim of the experiments was to try and observe losses encountered in a real time scenario in the water channel and try and mitigate its effects. The experiments were restricted to the study of losses due to turbulence only as a detailed study of the losses due to absorption and scattering would require a sea water tank which was not available within the campus.

4.2 <u>Inducing Turbulence</u> In order to simulate real time Ocean like conditions, the wave maker installed in the tank was accessed via a MATLAB interface. A screenshot of the MATLAB interface is shown in Fig 4.1. The interface allows a user to control two parameters of the generated wave. These parameters are wave height and wave period. If the turbulence is thought of as a sine wave, then wave height would represent the amplitude of the wave, whereas the wave period would represent the time period of the wave (depicted in Fig 4.2). The Wave Height could be adjusted between 1cm - 7cm whereas the wave period could be adjusted between 0.75 sec - 4sec. The limits exist due to limits on the mechanical motion of the metal plate which creates the waves. The water in the tank is confined in one axis and thus the turbulence observed was also confined in one axis (the vertical axis). In the ocean, this may not be the case and thus we are likely to experience turbulence along multiple axes.

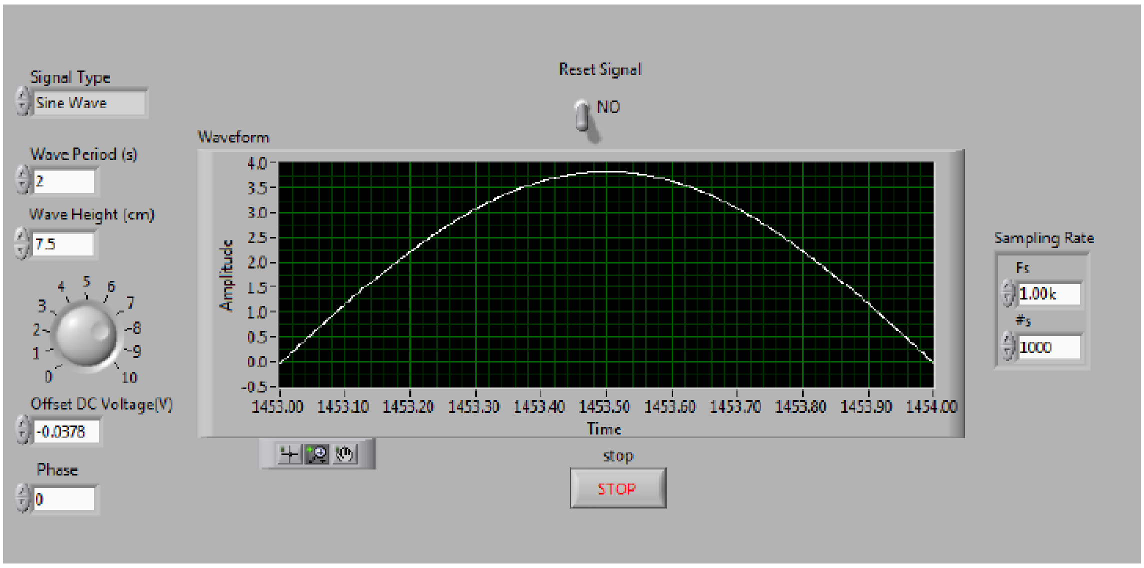


Figure 4.1: MATLAB interface to control wave height and wave period

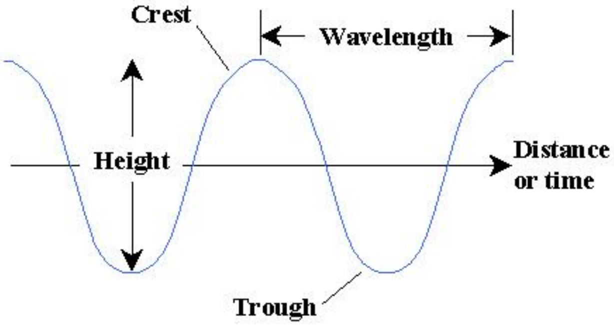


Figure 4.2: Turbulence Parameters

4.3 <u>Effects of induced turbulence</u> In order to observe the amount of turbulence that is experienced in an underwater environment and at the Air - Water interface, the laser beam was made to pass through the Air - Water interface after travelling about 10 meters in water. The wave height was increased sequentially and the amount by which the beam wandered was noted by measuring the distance by which the beam moved on a graph page. The results are plotted in Figure 4.4.

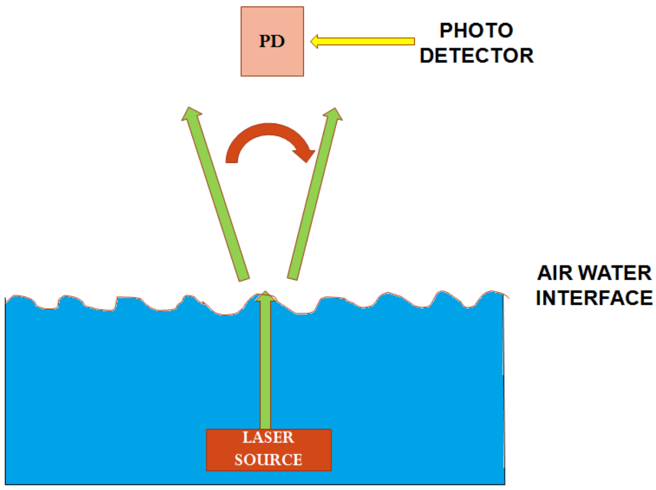


Figure 4.3: Turbulence at the Air Water Interface

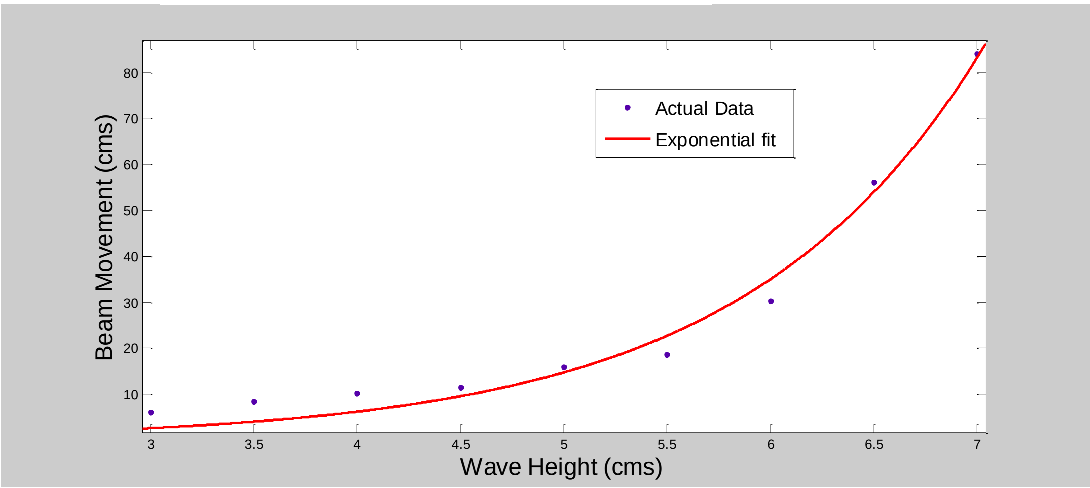


Figure 4.4: Beam movement as a function of wave height

As can be seen from the plot above, the amount by which the beam moves post crossing the water surface increases almost exponentially with increasing wave height. Since the photosensitive area of the detector (few mm) is relatively very small as compared to the distance over which the beam moves, only a fraction of the beam is actually captured by the detector over a period of time. To depict this in real time, the set up of Figure 3.5 was used and the response of the photo detector was captured using an Oscilloscope. The oscilloscope traces are plotted in Figure 4.5. The short term turbulence (occurring over time periods of few hundred microseconds) can be attributed to Scintillation while the turbulence occurring over larger periods can be attributed to beam wander. In addition, we also see the effect of the laser beam crossing the air water interface which causes only a small portion of the beam to be captured over a period of time.

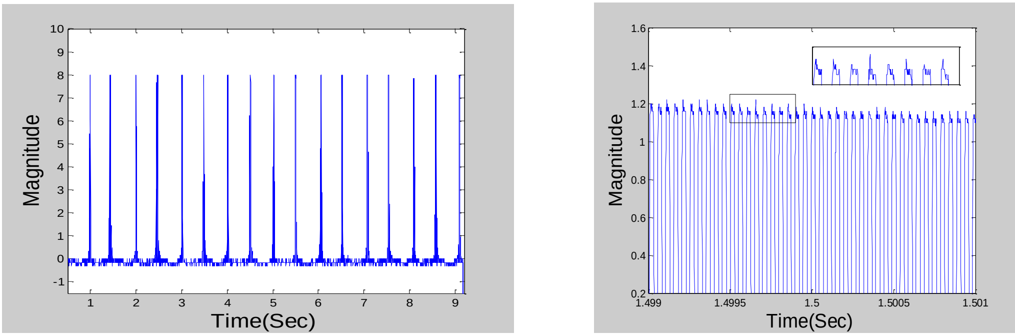


Figure 4.5: Depicting the effect of beam wandering due to refraction at air-water interface (left) and the effect of turbulence (right)

4.4 <u>Reducing Optical Turbulence Effects</u> The heavy turbulence that the Laser beam encounters particularly at the air water interface, renders it unfit for communication as it would lead to very high Bit Error Rates. Therefore, ways to reduce the optical turbulence effects were investigated. There are various ways in which these effects can be mitigated.

(a) Increasing the size of the receiver aperture offers an effective and simple way to reduce scintillations. This method is called as “Aperture Averaging” and is fairly well studied and applied for free space optics and thus a similar method could also be utilised for mitigating scintillation effects for underwater optics. The aim is to keep the receiver aperture larger than the laser beam diameter.

(b) A light diffuser can be used as a beam expander to counter beam wander. A light diffuser would spread out the incident light equally in all directions thus allowing for detection of at least a part of the incident beam even if it wanders over a larger area.

(c) Multiple transmitters and receivers can be used to capture a larger part of the beam (MIMO).

(d) A combination of all the above techniques can be used to counter turbulence

4.4.1 <u>Light Diffuser</u> A light diffuser would act as a beam expander thereby mitigating the effects of beam wander to a certain extent. A scattering plate was used a light diffuser in the experiments conducted. Figure 4.6 shows the scattering plate used. Scattering of light upon falling on the scattering plate can clearly be seen in the picture. Prior using the scattering plate for countering beam wander effects, an experiment was carried out to find out by how much the scattering plate increases the field of view of the receiver. A green laser beam was incident on the scattering plate with the photodetector placed behind the scattering plate. The angle of incidence of the laser beam was varied in steps to try and simulate real time beam wander and the corresponding response of the photodetector (peak to peak voltage) was captured. Figure 4.7 shows a plot of the peak to peak response of the receiver with varying angle of the incident beam with and without the scattering plate. It can be clearly seen that the field of view of the receiver increased by using the scattering plate.

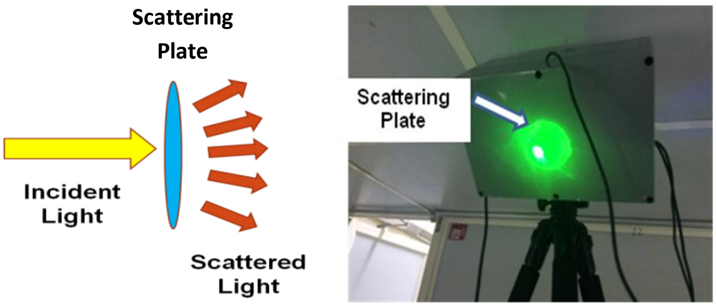


Figure 4.6: Scattering Plate used as a Phase Diffuser

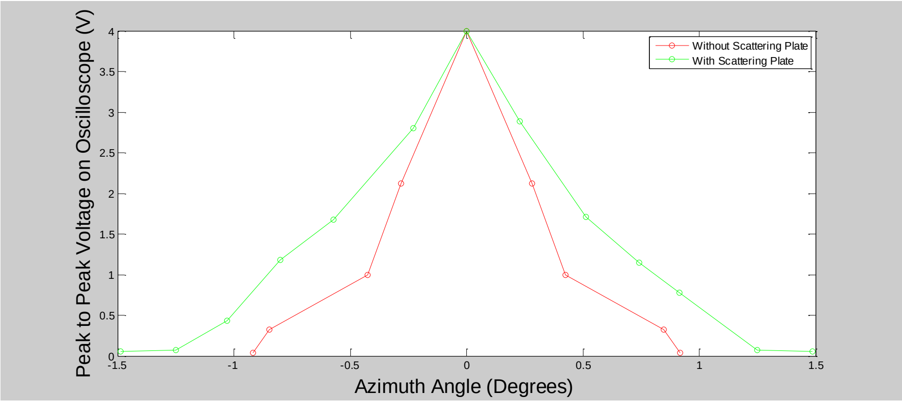


Figure 4.7: Field of view of photodetector with and without Scattering Plate (Data Normalised)

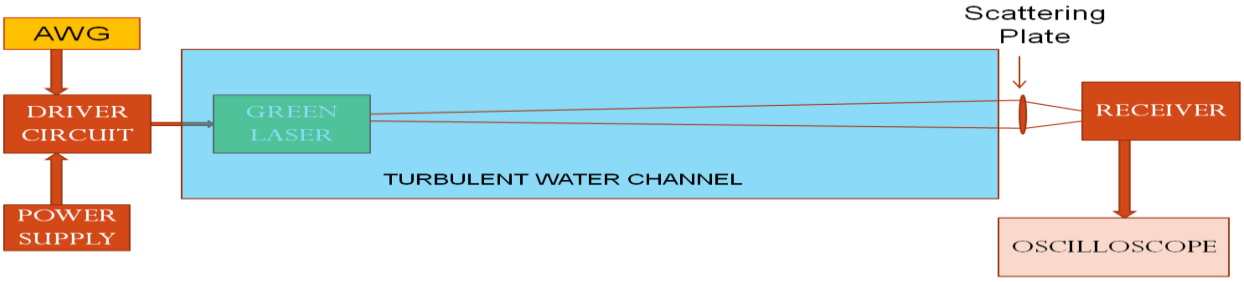


Figure 4.8: Experimental setup with scattering plate

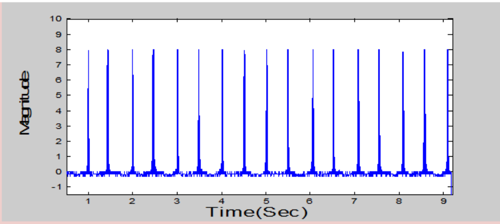
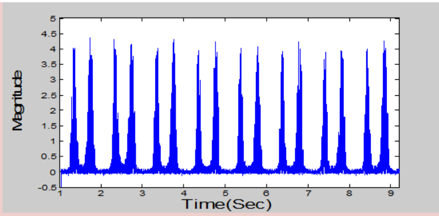
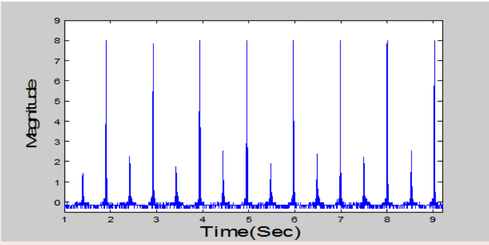
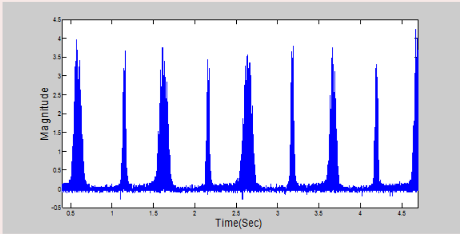
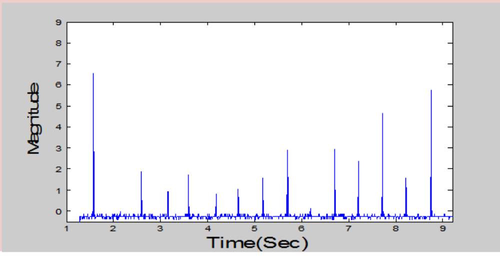
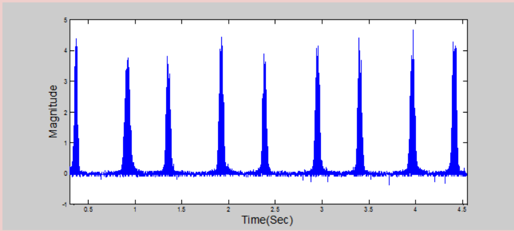
Wave Height (cms)	Long Term Turbulence (Without Scattering Plate)	Long Term Turbulence (With Scattering Plate)
1cm		
1.5 cm		
2 cm		

Table 4.1: Comparison of long term turbulence with and without scattering plate

The results obtained with the scattering plate are tabulated in table 4.1. It is evident that with the scattering plate, we are able to capture a larger portion of the beam thereby improving the probability of detection. However, scattering reduces the intensity of light falling on the receiver and thus it results in a tradeoff between receiver sensitivity and signal variance.

4.4.2 **<u>Fresnel Lens</u>** While we were able to capture a larger part of the beam by using a scattering plate at low values of turbulence i.e.at low wave heights (till 2cm), at wave height's beyond 2cm, the beam went outside the aperture of the scattering plate and thus an additional lens was required prior to the scattering plate. A Fresnel lens was used for this purpose. A Fresnel lens is basically a plate with concentric rings with varying thickness and is particularly useful for applications requiring large apertures and small focal lengths, as they can be made much thinner as compared to comparable conventional lenses. In order to depict the advantage of using a Fresnel lens in the setup, an optical setup similar to the one being used for our experiments was simulated in OSLO66 EDU. Snapshots of the simulation are shown in Figure 4.11. A Fresnel lens acts like a focusing lens converging all light falling upon it to its focal point. This is clearly evident from the snapshots as even as the beam traverses the entire length of the Fresnel Lens, it is till focused at the receiver. For our experiments, a Fresnel lens of dimensions 175mm x 250mm x 0.4 mm and focal length of 50 cm was used. Prior conducting the experiments, the Fresnel lens was characterised by using a setup similar to the one explained in section 4.3.1. The results are plotted in Figure 4.10. Once again, the increase in the field of view of the receiver can be clearly seen from the plot.

Figure 4.9: Use of Fresnel lens to increase receiver aperture

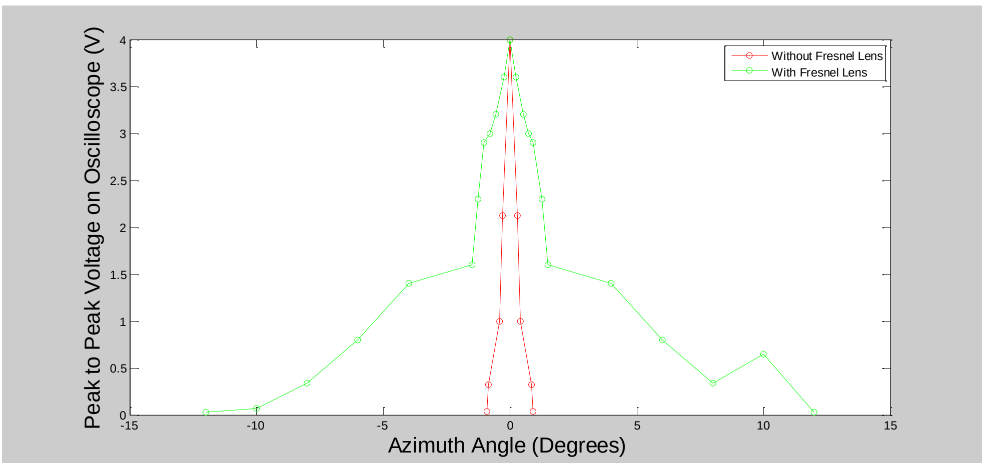


Figure 4.10: Field of view of photodetector with and without Fresnel lens

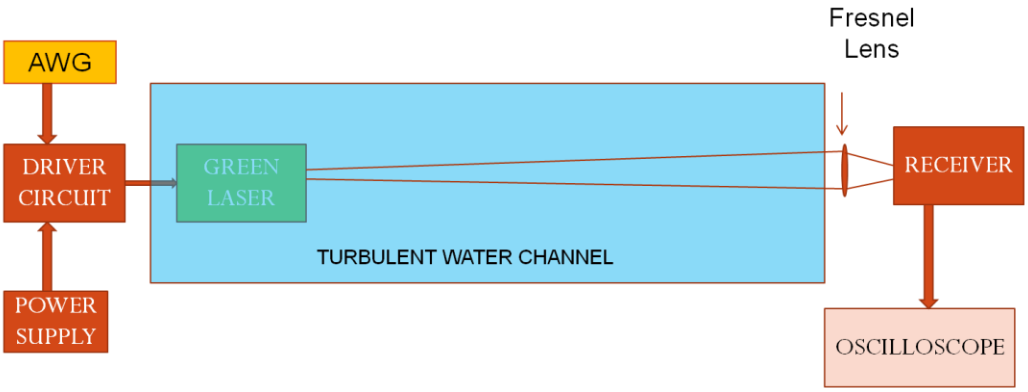


Figure 4.11: Experimental setup with Fresnel lens

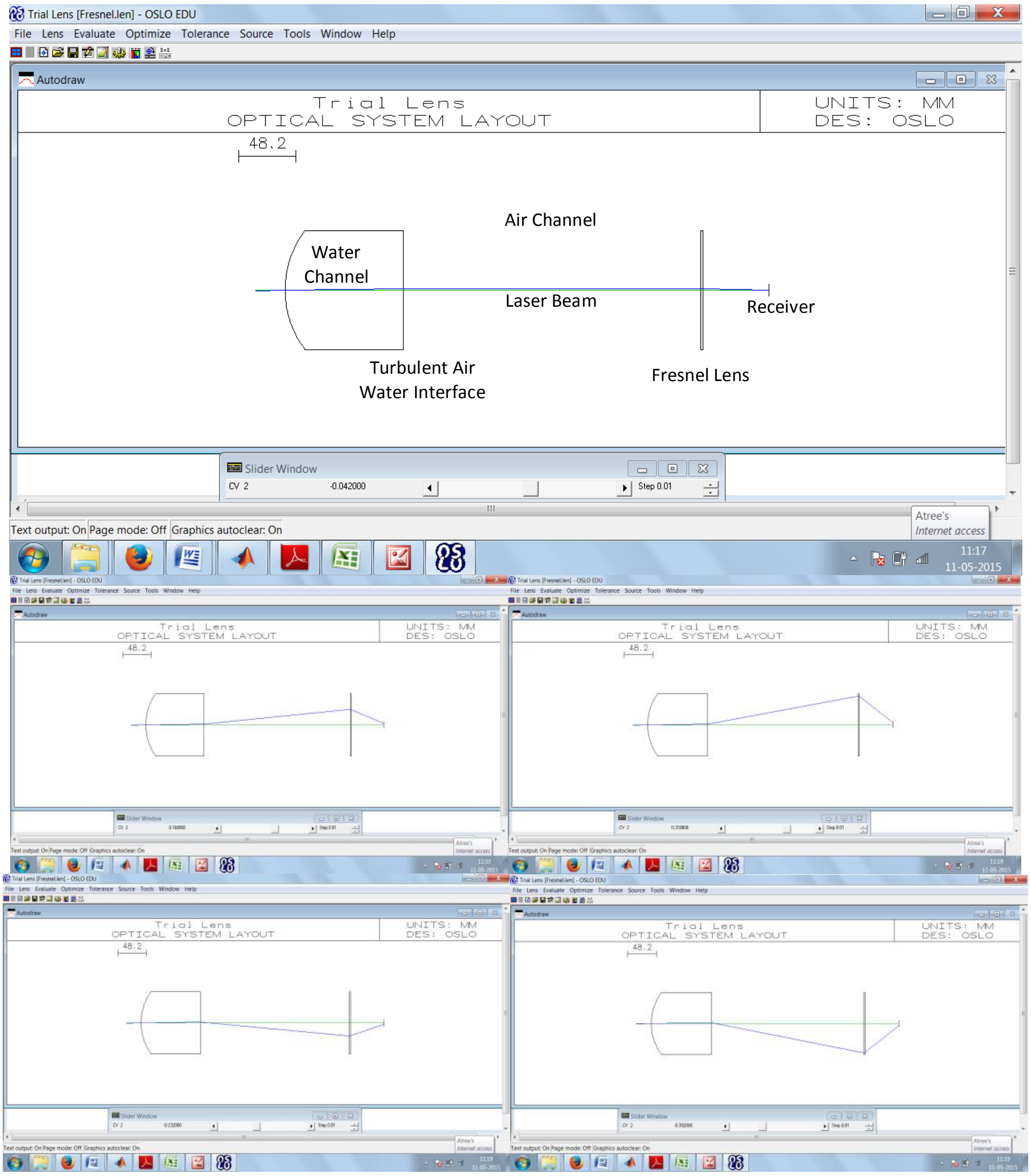
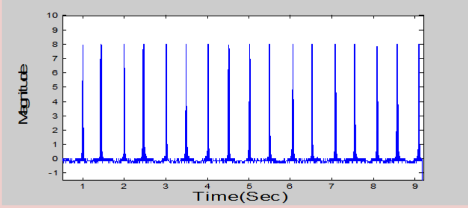
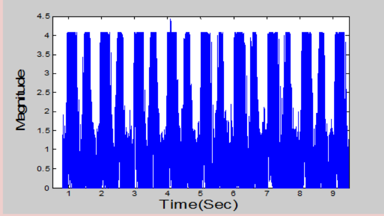
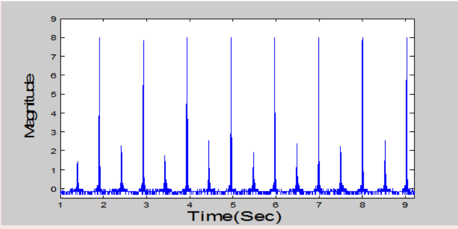
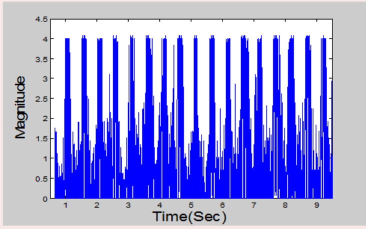
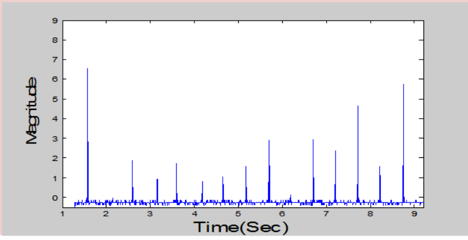
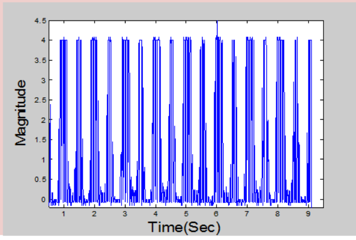


Figure 4.12: Snapshots of OSLO simulation depicting the beam being captured inspite of turbulence at the Air - Water interface

The experimental setup with the Fresnel lens is shown in Fig 4.11. The results obtained are placed in Table 4.2.

Wave Height (cms)	Long Term Turbulence (Without Fresnel Lens)	Long Term Turbulence (With Fresnel Lens)
1cm		
1.5 cm		
2 cm		

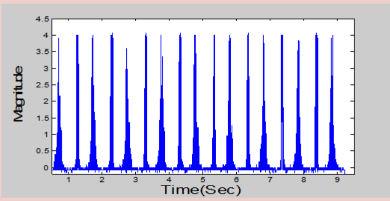
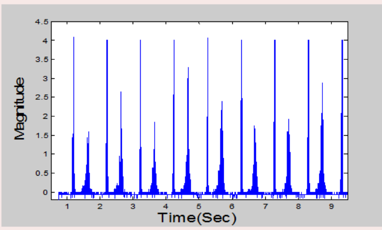
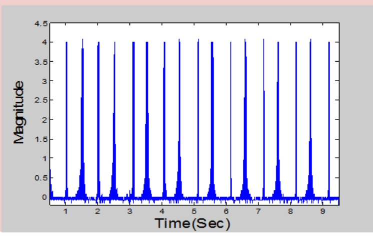
Wave Height (cms)	Long Term Turbulence (With Fresnel Lens)
4cm	
5cm	
6 cm	

Table 4.2: Comparison of long term turbulence with and without Fresnel lens

As is evident from the results, we were able to capture an even larger part of the beam by using a Fresnel lens. Further, we were able to capture the beam for wave heights beyond 2 cms as well. However, as it can be seen, particularly at higher turbulence levels (4cm wave height and above) that there are still large pockets of time over which no data is captured. In order to overcome this limitation, a combination of a Fresnel Lens and Scattering plate is used in the next section.

4.4.3 A combination of Fresnel lens and scattering plate

In order to capture larger parts of the beam at higher turbulence levels as well, a combination of Fresnel lens and scattering plate was used. The results for the same are tabulated in Table 4.3.

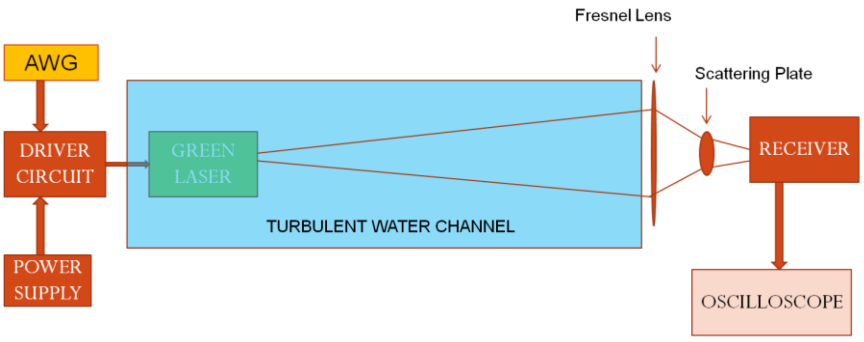


Figure 4.13: Experimental setup with a combination of Fresnel lens and Scattering plate

A comparison with the results obtained for the case when the Fresnel lens was used alone clearly shows an increase in the part of the beam which we are able to capture over a period of time. The aim in this setup was to ensure that the beam remains within the aperture of the scattering plate even at higher turbulence levels.

4.4.4 SIMO Configuration

While using a Fresnel lens and a scattering plate together did allow for capture of larger parts of the beam, a disadvantage of using a single receiver was that when the beam was incident on the edges of the scattering plate, the scattered light did not reach the detector resulting in the that part of the beam not being captured. This is evident from Figure 4.14. To overcome this limitation, a system comprising of 2 receivers was designed. By using two receivers, data can be captured even when the laser beam is incident on the edges of the scattering plate as is eveident from Figure 4.14 (b). All parameters (receiver bandwidth, gain) of the second receiver board were kept exactly same as the first one. As discussed in section 4.1, since the turbulence was limited along the vertical axis, the second receiver was mounted such that the detectors were aligned along a vertical axis. This can be seen in Figure 4.15. The beam was captured separately from both receivers and the output was combined during post processing. The results obtained are tabulated in Table 4.4. It was observed that by

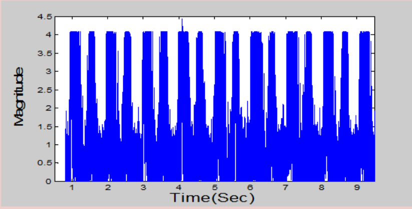
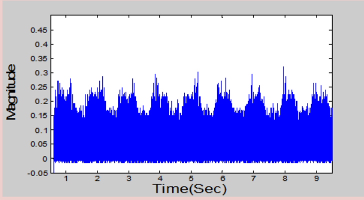
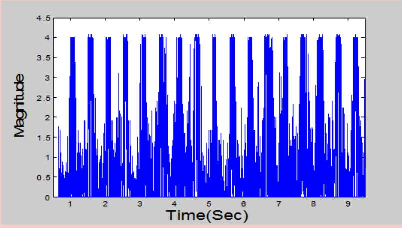
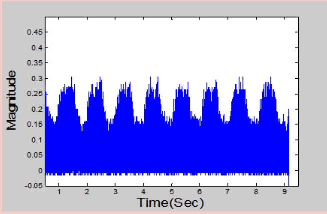
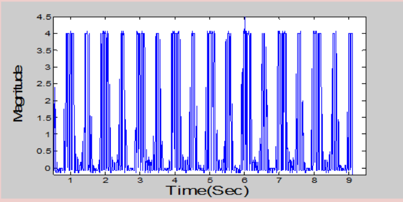
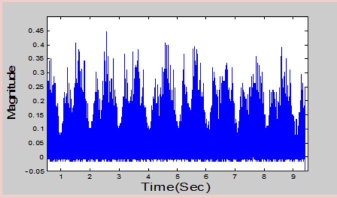
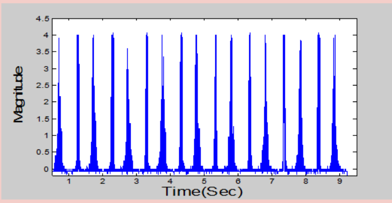
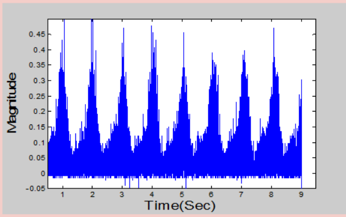
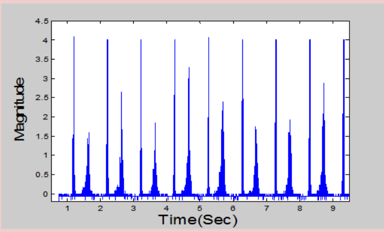
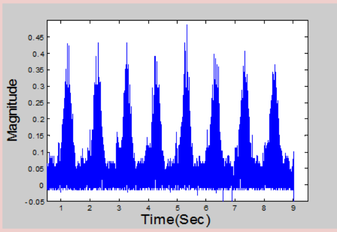
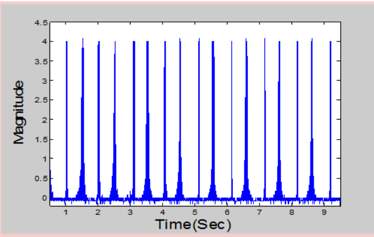
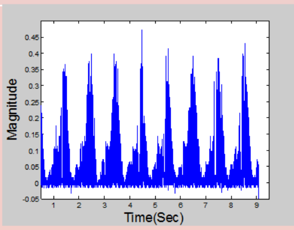
Wave Height (cms)	Long Term Turbulence (With Fresnel Lens)	Long Term Turbulence (With Fresnel Lens & Scattering Plate)
1cm		
1.5 cm		
2 cm		
4cm		
5 cm		
6 cm		

Table 4.3: Comparison of long term turbulence with Fresnel lens and with a combination of Fresnel lens and scattering plate

mounting the detectors on a vertical axis, the response of the two detectors peaks alternately and thus by combining the response of both the detectors during post processing, we are able to capture a much larger part of the beam as compared to the earlier scenarios.

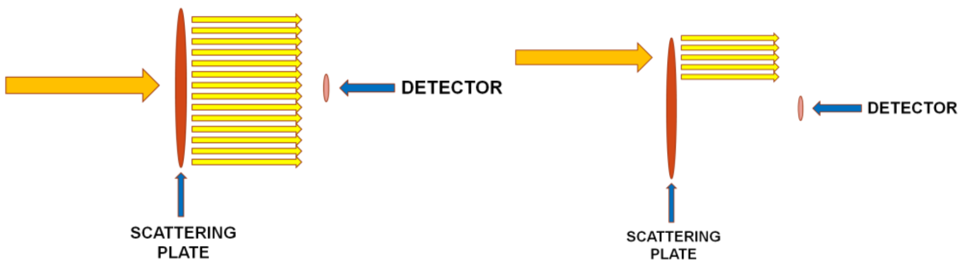


Figure 4.14 (a): Using a scattering plate with a single receiver
(Notice that when the beam falls on the edge of the scattering plate, the scattered light does not fall on the detector)

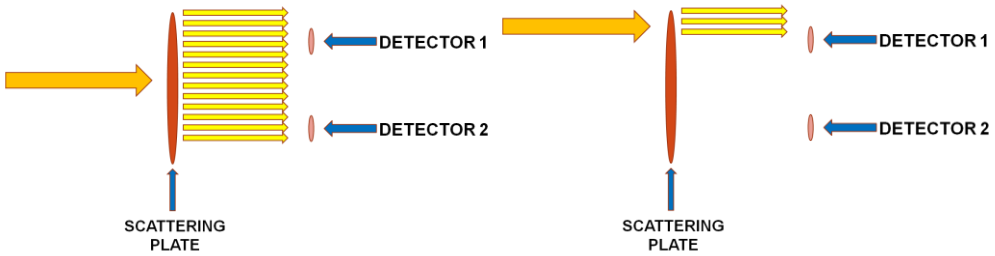


Figure 4.14 (b): Using a scattering plate with two receivers

Figure 4.15: Multiple receivers with detectors aligned along the vertical axis

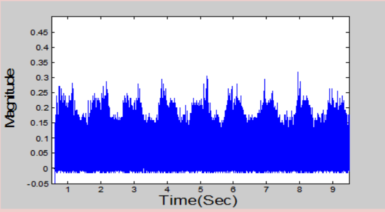
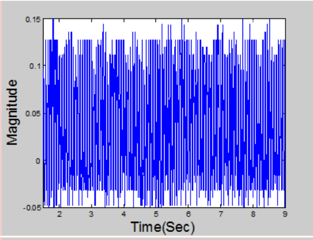
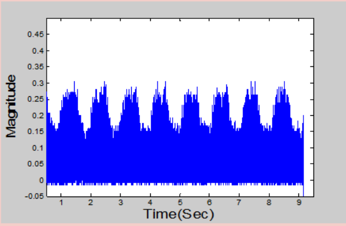
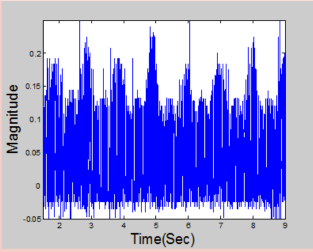
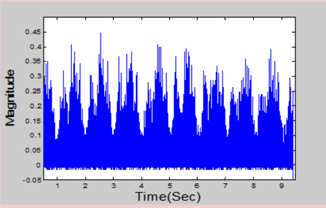
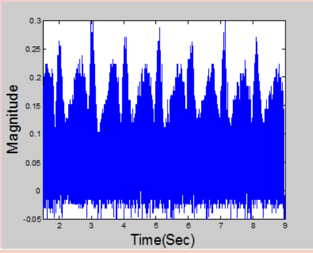
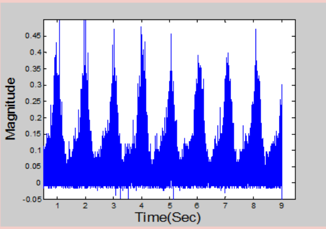
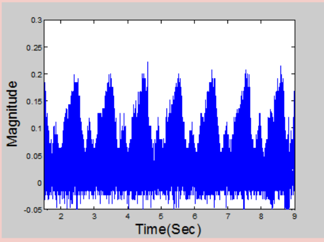
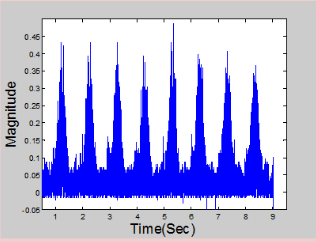
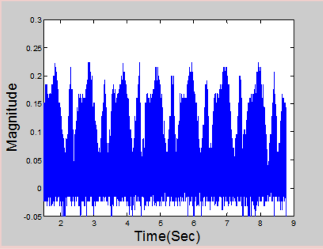
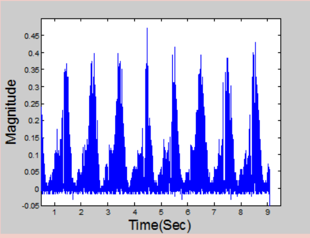
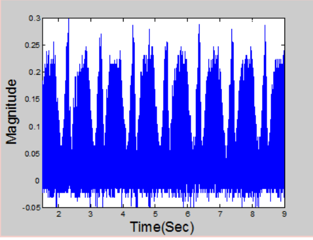
Wave Height (cms)	SISO (With Fresnel Lens and Scattering Plate)	SIMO (With Fresnel Lens and Scattering Plate)
1cm		
1.5 cm		
2 cm		
4cm		
5 cm		
6 cm		

Table 4.4: Comparison of long term turbulence with SISO and SIMO configurations

4.4.5 SIMO Configuration with Multiple Fresnel Lenses Even though the wave maker was capable of generating waves only till a wave height of 7 cm, in a real time scenario, chances of facing higher turbulence do exist and thus, an attempt was made to propose a system configuration which could work even in very high turbulence conditions. A system using multiple Fresnel lenses should be able to capture higher turbulence levels. To demonstrate the same, two Fresnel lenses were combined by bolting them at the ends. Since the two Fresnel lens are displaced along a vertical axis, their focal points too would be displaced along a vertical axis. Thus two separate receivers were mounted along a vertical axis such that the detectors were lying at the focal point of each of the Fresnel lens. The setup is shown in Fig 4.16. The data in this case is captured only for turbulence levels of 5 cm and above. This is because only at this high turbulence levels, the beam traverses both the Fresnel lenses. The results are tabulated in Table 4.5. A comparison of the data sets with the earlier used SISO configuration shows that the pockets of time over which we are not capturing data has reduced considerably, thus allowing us to capture a much larger part of the beam.

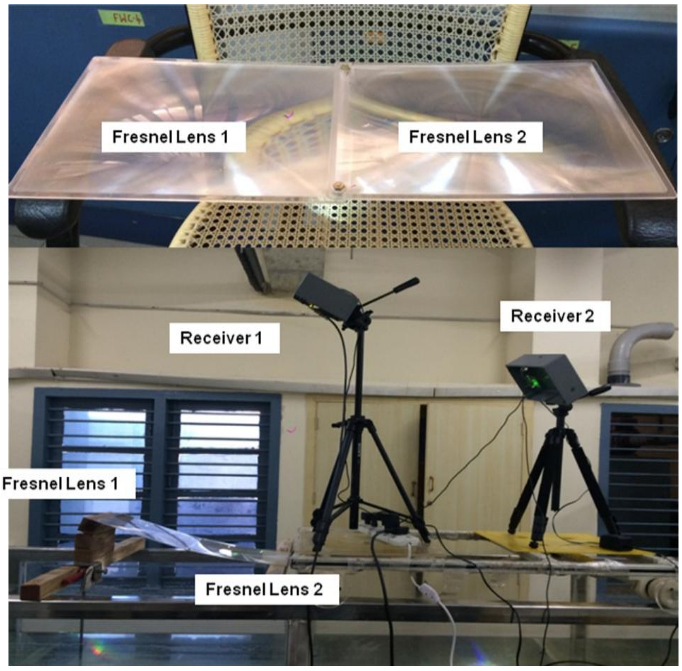


Figure 4.16: SIMO Configuration with Multiple Fresnel Lenses

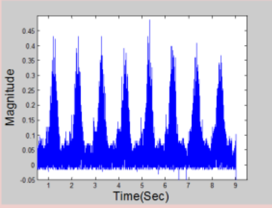
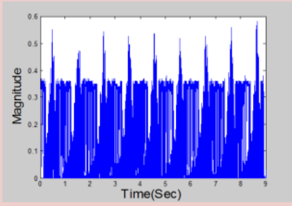
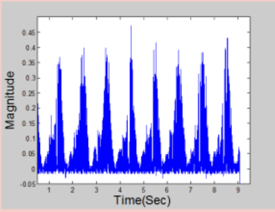
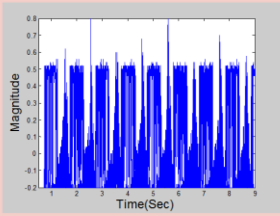
Wave Height (cms)	SISO	SIMO
5cm		
6 cm		

Table 4.5: Comparison of long term turbulence with SISO and SIMO configurations (SIMO configuration with 2 Fresnel lens)

CHAPTER 5

Conclusions and Future Scope

5.1 <u>Conclusion</u> This research is a building block for future Underwater Free Space Optics. The research has mainly focussed on using suitable optical elements to mitigate the effect of large scale turbulence observed when an optical beam interacts with the Air - Water interface. Underwater turbulence like beam wander and scintillation have also been studied. Since ways to mitigate both scintillation and beam wander already exist for free space optics, the same can also be applied to the underwater scenario. However, large scale turbulence like the one which an optical beam faces at the Air - Water interface is unlikely to be faced in a Free Space scenario. Thus the methods proposed in the research are likely to aid in designing of Underwater Optical Systems particularly where the optical beam interacts with the sea surface. As has been brought out in Chapter 4 of the thesis, the large scale turbulence encountered at the Air – Water interface can be mitigated by using suitable optical arrangements. Using multiple receivers can further increase the amount of data being captured. Further, even though the experiments conducted were carried out with a single laser source, using multiple laser sources could entail capturing even larger parts of the data.

5.2 <u>Future Scope</u> The requirements of an underwater to free space wireless link would arise in a wide array of scenarios. Some of these are **:-**

(a) Military applications
(b) Underwater sensor network and observatories
(c) Security and harbour inspections
(d) Maintenance and surveying of underwater pipelines and oil rigs
(e) Autonomous underwater vehicle communications
(f) Remotely operated vehicle telemetry

Most of these applications benefit from standout features of optical communications which include High data rates, Wireless operation, Conservative power budget, Low cost and reproducibility, High Fidelity of data transmission. Thus to give an impetus to the research in Underwater Optics, the following is recommended as a future scope:-

(a) Careful experimentation of signal attenuation in natural seawaters.
(b) Power measurements for seawater with different quantities of phytoplankton.

(c) To build a complete digital communication link and perform BER measurements for different water conditions.

(d) Addressing the issue of pointing and tracking. Exploring options like beam steering and adaptive optics as possible solutions.

(e) Experimenting with multiple laser sources as a means to nullify large scale turbulence effects.

Acoustical communications will still stand as the primary source of underwater communications, but the research has shown the optics may have a place in the underwater environment as well in the times to come. In applications which require the beam to interact with the sea surface, optical communication holds strong advantages over acoustic communications.

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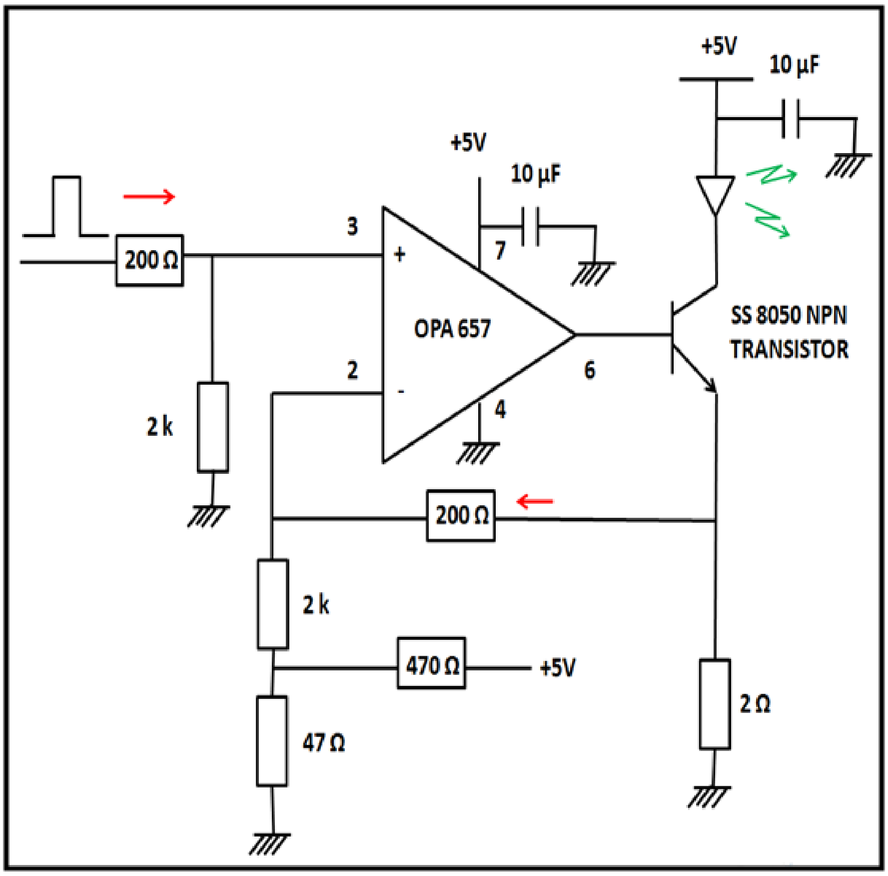
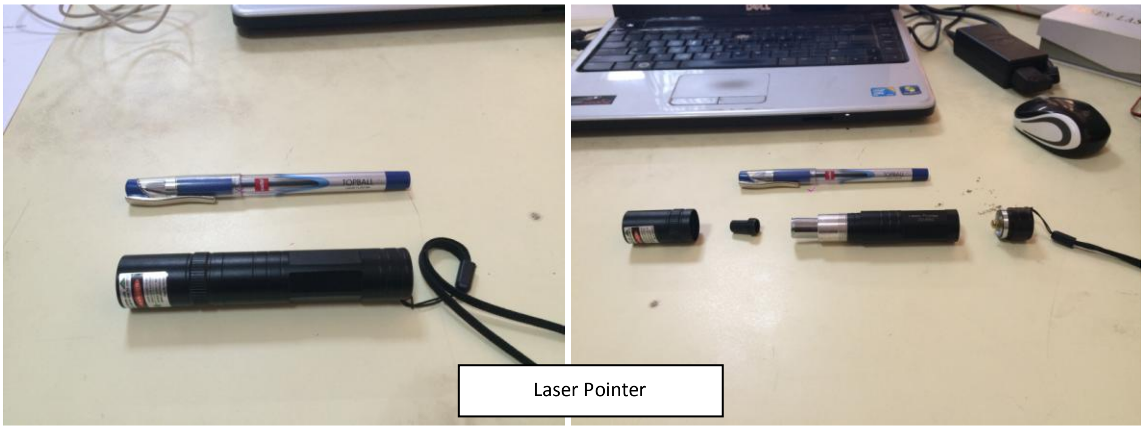
Appendix A

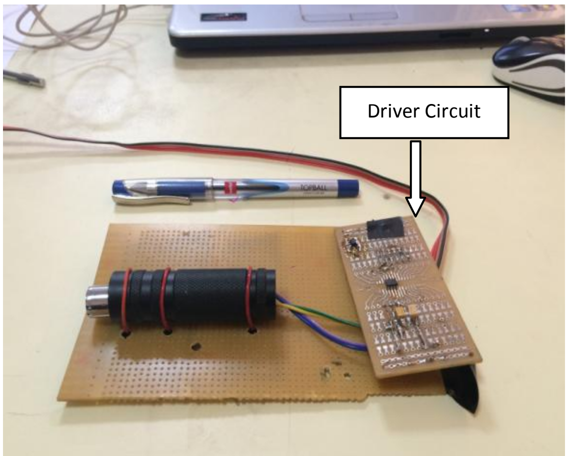
Transmitter Driver Circuit Assembly

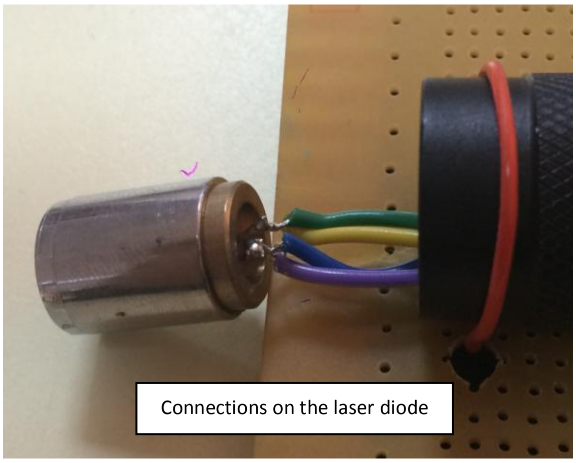
Since the laser procured for the project had a CW output, one of the initial challenges in the project was to make the laser output pulsed. An external driver circuit was required for this purpose. The driver circuit was made using OPA 657. The circuit diagram of the driver circuit is placed in the figure below.



A pictorial representation of the assembly of the driver circuit is given in the figures on the next page. The diode connections were accessed by removing the laser pointer from its housing and the driver circuit was then soldered onto the diode directly thereby bypassing the existing connections of the laser pointer.


Laser Pointer


Driver Circuit


Connections on the laser diode

Appendix B

Waterproofing the Transmitter

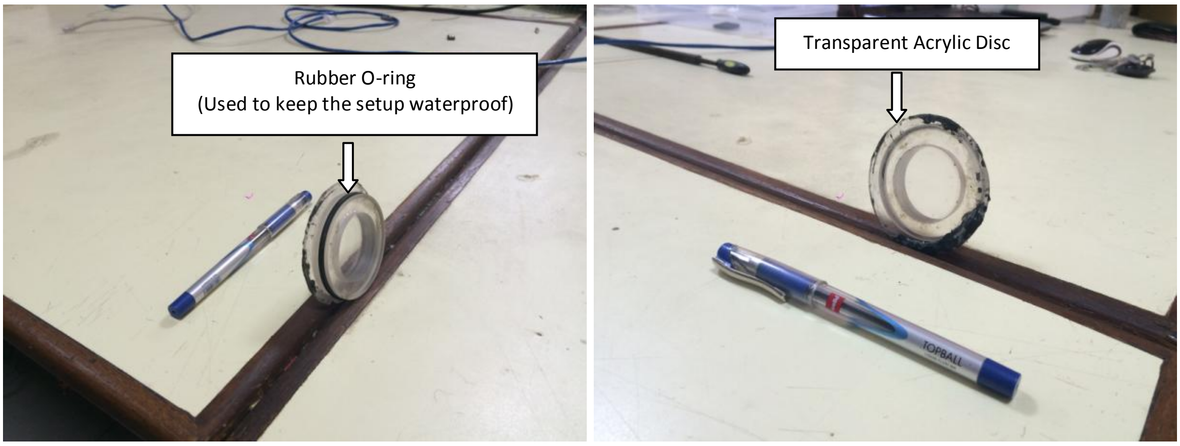
The project involved using a Waterproof Submerged Transmitter unit. A step by step breakdown of the waterproofing process is brought out here for reference:-

Step 1 - Housing

For the purpose of housing the transmitter, a PVC pipe of length 45 cm, diameter 3.5 cm and thickness 2mm was used. Such pipes are easily available at hardware stores. The thickness of the pipe would be governed by the depth to which the transmitter unit is to be submerged. Since the project required submerging the transmitter unit till a depth of only about 0.5 meter, the effect of pressure acting on the pipe was considered negligible and thus only a 2mm thickness pipe was used.

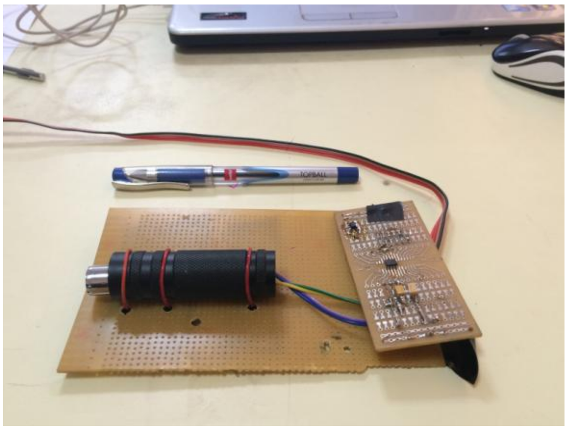
Step 2 – Making one end of the housing transparent

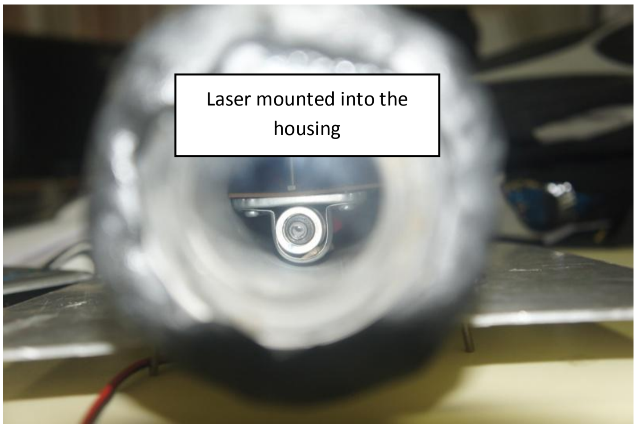
Since the laser was to be mounted within the PVC housing, one end of the housing was to be kept transparent to allow the laser beam to emerge out. For this purpose, a transparent acrylic sheet was cut to the size of the PVC pipe using a lathe machine. The challenge was to mount the disc onto the end of the pipe while maintaining the water tight integrity. For this purpose, the acrylic disc was pasted onto a plastic disc using a water tight adhesive (choloform). The disc was then mounted onto the end of the pipe using a rubber O-ring. The O-ring ensured that the mounting onto the PVC pipe was waterproof.



Step 3 – Mounting the laser

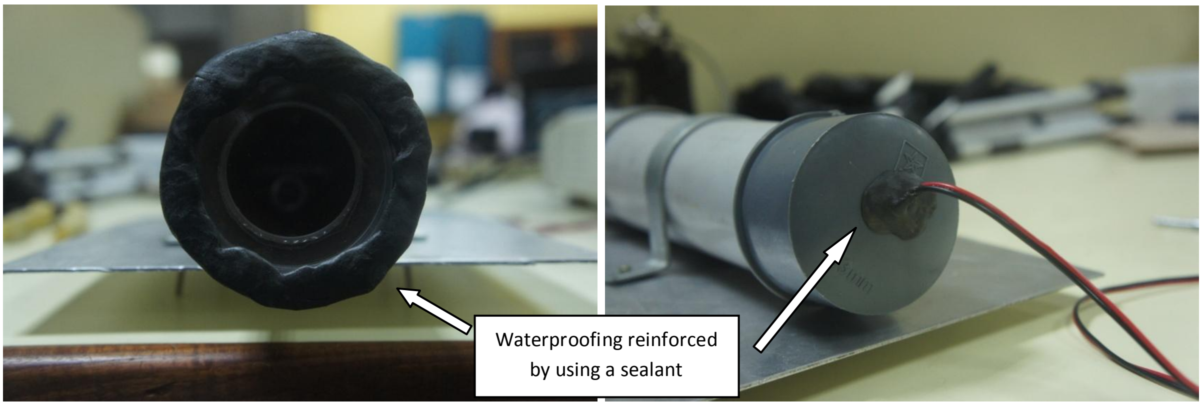
Once the housing was ready, the next step was to mount the laser onto the housing. For this purpose, the laser was secured onto a plastic board as shown in the figure below. The board was cut to a size so as to snugly fit into the housing.





Step 4 – Final Touches

With the laser mounted onto the housing, the transmitter setup was ready. The rear end of the pipe was closed by using a PVC cap (available at any hardware store). In order to reinforce the waterproof integrity of the setup, a sealant (M-seal) was put both at the front and rear end of the pipe. In addition, a hole was kept on the rear end of the pipe to allow the power supply to the laser to pass through. In order to make the process of putting the transmitter in and out of water easier, a frame was fabricated with metal bars on the side to support the weight of the transmitter. Further, in order to ensure that the transmitter unit stays submerged and static even in turbulence, additonal weights were installed on the ends of the frame. The image below shows the final transmitter setup.


Waterproofing reinforced
by using a sealant


Weights bolted at the
end of the frame to keep
the setup stable
Final Transmitter Setup

Appendix C

Receiver Schematic