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Harbor Security System

Timothy Jonathan Brown
University of New Hampshire - Main Campus, tjz63@wildcats.unh.edu

Matthew Birkebak
University of New Hampshire - Main Campus, mts54@wildcats.unh.edu
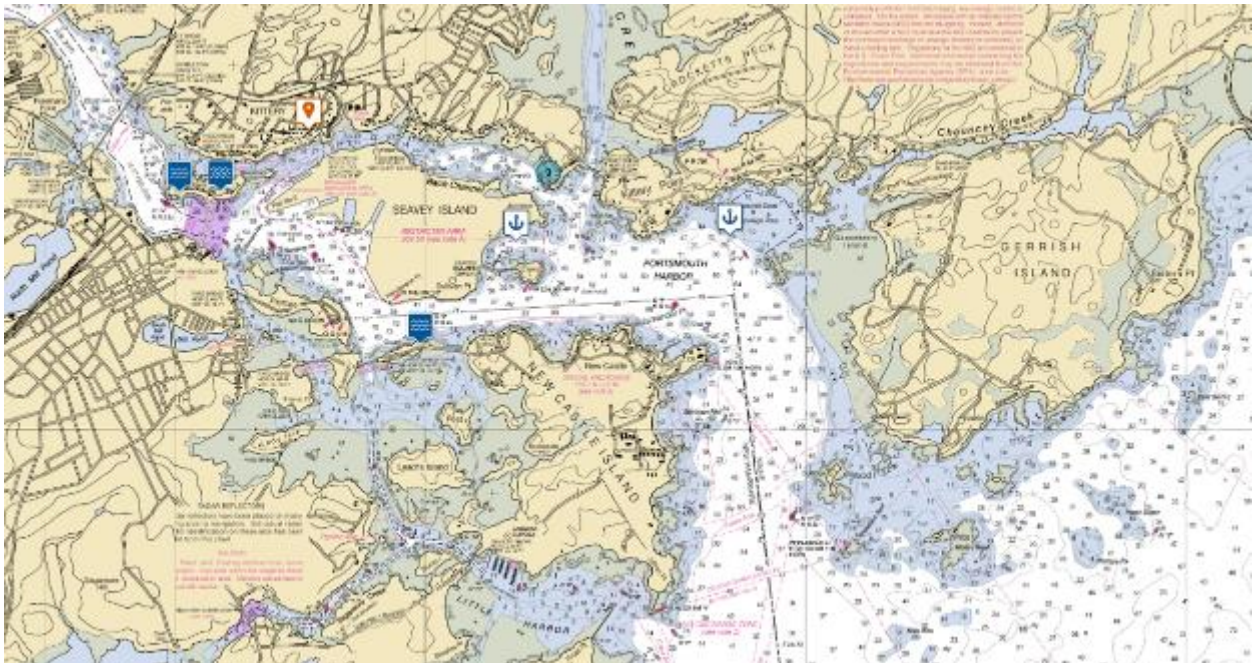
Harbor Security System

MATTHEW BIRKEBAK (CONSTRUCTION LEAD)   TIMOTHY BROWN (CONTROLS LEAD)

mts54@wildcats.unh.edu   tjz63@wildcats.unh.edu

Advisors: Shachak Pe'eri, May-Win Thein, Firat Eren

Abstract

Harbors and ports provide the infrastructure for commercial trade and naval facilities. It is vital to ensure the safety of these locations. The Harbor Security System provides an optical 'gate' using underwater lasers and photodetectors. This system allows monitoring of both surface and submarine vessels traveling into and out of the harbor. Also, the system provides real time alerts when unauthorized vessels enter the harbor. This project provides a proof of concept for a Harbor Security System to be implemented in Portsmouth Harbor. A scaled model of the detection system was constructed and tested. This detection system is capable of detecting surface and submarine vessels along with their velocity and length. Results of the study showed that the average error of the size estimate was 15% and the average error of the velocity estimation ratio(slope) was 9%.

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Introduction

Problem Statement

Portsmouth Harbor is home to several commercial shipping centers and a military base (Portsmouth Naval Shipyard) that manufactures submarines. Commercial, Military, and Submarine traffic through Portsmouth harbor (New Hampshire, USA) must be constantly tracked and recorded for the identification of rogue vessels entering the harbor and provide information to aid in harbor maintenance and upkeep.

Current Options

With the most recent technologies there are still very few methods developed to monitor the boat traffic in a harbor. Several common options are outlined below.

Vessel Identification

AIS (Automated Identification System) is currently being used to track many commercial vessels. It is contingent on the captain of the ship acquiring, installing, and running a GPS (Global Positioning System) inside their vessel. It is a definite aid to tracking harbor use, but it should not be the only means of tracking vessels. Also, it is anticipated that a rouge vessel will not report its location.

Visual Identification

It is possible to use a camera or personal to manually record the traffic through a harbor. Although this approach allows full identification of a surface vessel, this method is both inefficient and has major drawbacks including lack of visibility at night and during storms, inability to detect submarines, and lack of ability measure size and speed of traffic.

Acoustic Monitoring

It is also possible to use sonar to monitor boat traffic. The problem with this method is the large amount of acoustic background noise generated by a harbor. The background noise includes wave action, vibration from moving vessels, and other sonar units.

Active Optic Detection Systems

A more refined solution to detecting commercial, military and submarine traffic through Portsmouth Harbor is an optic detection system. A laser detection system involves laser sources that are coherent active light sources and light detectors with a high sampling rate to determine when a vessel passes through the grid. The detection system operates similarly to an elevator door detector shown in Figure 1. The light field generated by the lasers effectively creates a 'gate' that can sense when and object is passing through.
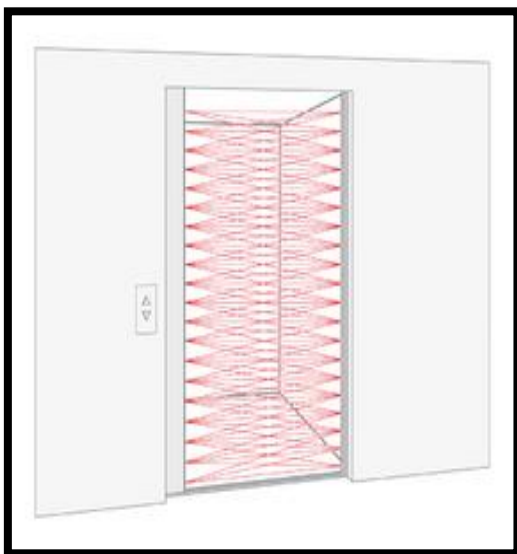
FIGURE 1 - EXAMPLE LASER GATE (TELCOSENSORS)

A laser gate detector is the most viable option for a security system and this report outlines the factors and construction necessary to develop this system. The laser detection system will be designed for Portsmouth Harbor, and a location will be chosen. The constraints of this project are a budget of 1000$ and a time limit of two school semesters. Accordingly, the design of the laser detection system for Portsmouth harbor was be scaled down and tested in the Jere Chase Ocean Engineering Wave and Tow Tank as a proof-of-concept that will provide more insight on the effectiveness of a laser detection system and test potential components for a full scale system in different natural conditions (Figure 2).

FIGURE 2 - JERE CHASE OCEAN ENGINEERING WAVE AND TOW TANK (WW (CENTER OF COASTAL AND OCEAN MAPPING)

1) Portsmouth Harbor Environmental Factors

The following environmental factors are specific to Portsmouth Harbor and were used in the design and conceptualization of a laser detection system. The area was analyzed to determine the dimensions of relevant traffic, specific concerns based on the local environment, and the best location and size for a laser detection system.

Traffic

The traffic in the Harbor can be divided into recreational, commercial, and military. Recreational vessels are not considered as paramount to detect because there relative size, environmental impact, and threat potential is significantly lower than a cargo ship or a submarine. The commercial traffic in Portsmouth harbor derives from multiple commercial facilities along the inlet to Great Bay Estuary. The military traffic is either naval ships or submarines. A diagram displaying the location and types of traffic in Portsmouth harbor is shown in Figure 3.
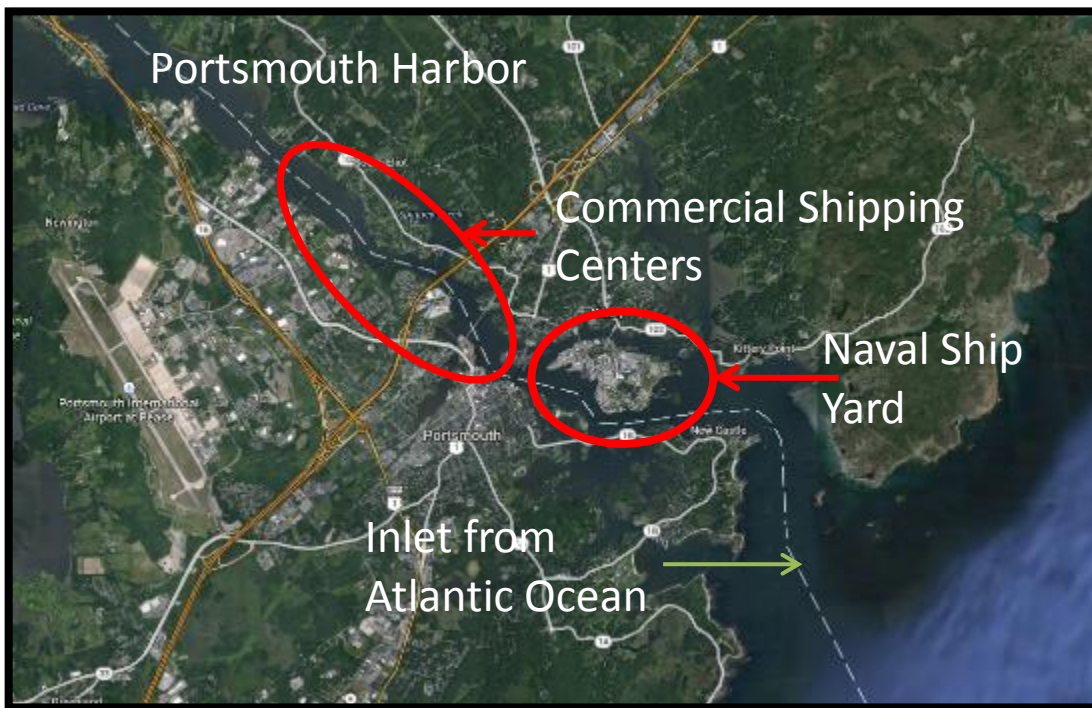
FIGURE 3 - SOURCES OF TRAFFIC IN PORTSMOUTH HARBOR (GOOGLE)

Commercial Traffic

The commercial traffic along Portsmouth harbor is from several commercial facilities along the inlet to Great Bay estuary. An example of a Commercial industry in Portsmouth Harbor is shown in Figure 4 with a length of a boat tied to land of 221 m.

FIGURE 4 - COMMERCIAL INDUSTRY IN PORTSMOUTH HARBOR (GOOGLE)

Boats that are have a large length require a large draft as well. The draft of a vessel is the distance that is submerged in the body of water when the boat is traveling (See Figure 5).
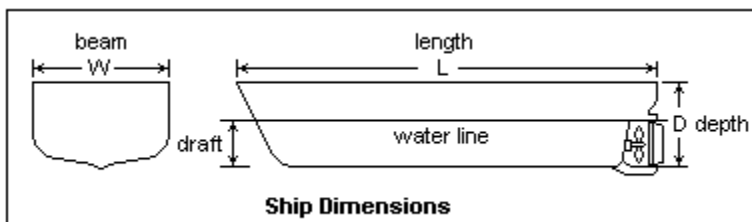
FIGURE 5 - SHOWS DRAFT OF A VESSEL (CALVERT, 2003)

A vessel spotted using AIS (Automatic Identification System) tracking in Portsmouth harbor online at www.marinetraffic.com (MarineTraffic) called Decisive had a draft measuring 23.622 feet (7.2 m).

The draft of a vessel of this size and weight will vary between 5 and 9m depending on the weight of the cargo. A draft of this size will be considered the average range of shipping vessels.

Military Traffic

The military traffic will be focused on naval vessels with a draft larger than 4.5m and submarines. Because submarines cannot be spotted visually they pose one of the highest threats to the harbor. Submarines are also capable of carrying dangerous payloads or counter intelligence personal. Monitoring submarine traffic is the most important reason to focus on harbor security. The detection system must extend deep enough into the water column such that submarines will be detected. The array must also be designed such that a submarine vessel with a small draft will be detected.
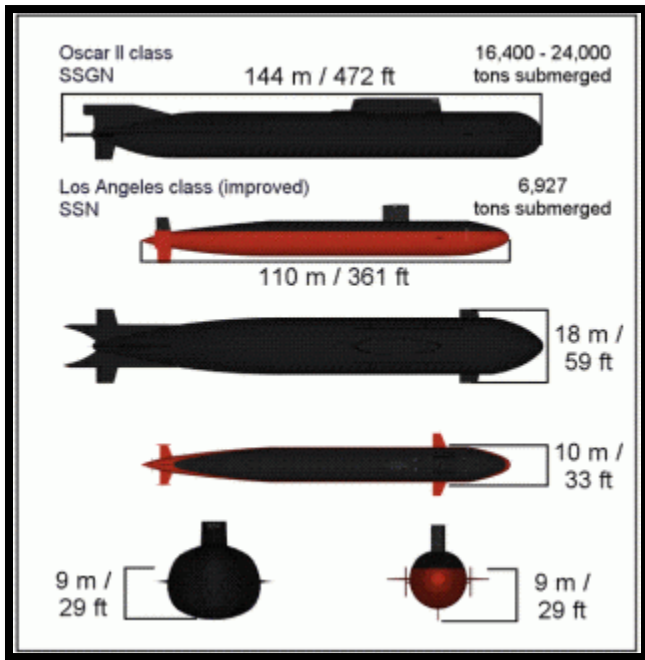
FIGURE 6: SUBMARINE DIAGRAM (FAS.ORG)

The average military submarine has a draft between 7 and 10 m (See Figure 6). From The US Naval Museum larger vessels, such as the USS Ohio has a draft of 10.1 m. On the smaller end of the spectrum is the Dolphin submarine has a draft of 6 m.

Sediment and Turbidity

Sediment in the water column can cause scattering and attenuation of a laser beam. The average diffuse attenuation coefficient in the water column in Portsmouth harbor was used according to a 2005 study (Pe'eri et al, 2011). This average diffuse attenuation coefficient value was determined between August and October to be .2 m^{-1}. Although, there are certain sea states that can cause false detections in an optical detection system. These sea states include tides, runoffs, turbidity currents, and anytime there is an algal bloom or increase in material, organic or inorganic in the harbor.

Because of these highly variable conditions, the detection system will have periods of time in which it will have optimal operating conditions, and times with reduced performance when many false detections may occur. For example, the periods in which the detection system will have optimal operating conditions are during flood tide, or when the tide is rising and flowing in from the ocean, and during the winter months. The periods in which the detection system will more likely to have false detections will be during ebb tide, or when the tide is receding and carrying runoff past the detector system out to the ocean. Seasonal conditions will also affect the reliability of the system. Spring and autumn are also seasons with expected reduced performance of the system as the water during these periods are more likely to have debris and runoff silt. Sediment and organic matter is more likely to be washed into the estuary during these months and have the potential to lessen the clarity of the water.

It is crucial to construct an adaptive control algorithm for times when the detection system performs in sub-optimal conditions. The control system will adapt to turbidity currents, which travel with the current and possible runoff during ebb tide.

Location of System (theoretical)

The settings of the experiments will be scaled accordingly to the location of the optical detection system based on a number of specifications, including distance from harbor mouth, tidal range, width of harbor at the given point, upstream runoff, and water column obstacles. First, the system must be close enough to the harbor mouth such that all vessel destinations are behind the detection system, i.e., all vessel must pass through the "optical gate" in order to get to their destination. Closer proximity to fresh water will also decrease false detections due to turbidity and other runoff.

The system must set at a depth such that at mean lowest low tide all the components of the system will still be submerged. Tidal datum mean lower low water (MLLW) is based on a dataset collected over the past 19 years from Fort Point Station (the location of the Naval Ship Yard) provides that the maximum flood tide is 10.4 feet (3.7 m) above MLLW. For this reason the system should be mounted just near the MLLW. This will prevent the system from ever being exposed to the above sea environment while allowing it to detect vessels with a minimum draft of 15 feet (~4.5 m).

Another factor in the choice of location is the width of the harbor. Bernoulli's fluid flow equation states that as the diameter decreases the fluid flow rate increases. This principle can be applied in the case of the harbor. As the width of the channel decreases, the flow through that section increases. Faster flow rates are advantageous for the system because strong currents will allow sediment plumes to pass faster through the channel. Thus, less likelihood of a false detection (less masking of the laser beam) by the system. Narrower channels also require less ranging distance, leading to a better signal (i.e., stronger signal-to-noise ratio).

The final requirement for the detection system is that it must be capable of spanning the width of the harbor without any physical obstacles such as rocks or shoals. The light field should have a uninterrupted path. Bathymetric data was used to check that geographic features would not obstruct the path of the laser system.

Based on all of these factors, the channel section between Kittery Point, Maine and Salamander Point, New Hampshire was selected as the model location for the detection system (Figure 7 - Portsmouth Harbor Laser Detection System Location).

Location Chosen	Salamander Point to Kittery Point
Distance	2030 ft (619 m) (From Google Maps Measure Tool)
Max Depth	50 ft (15 m)
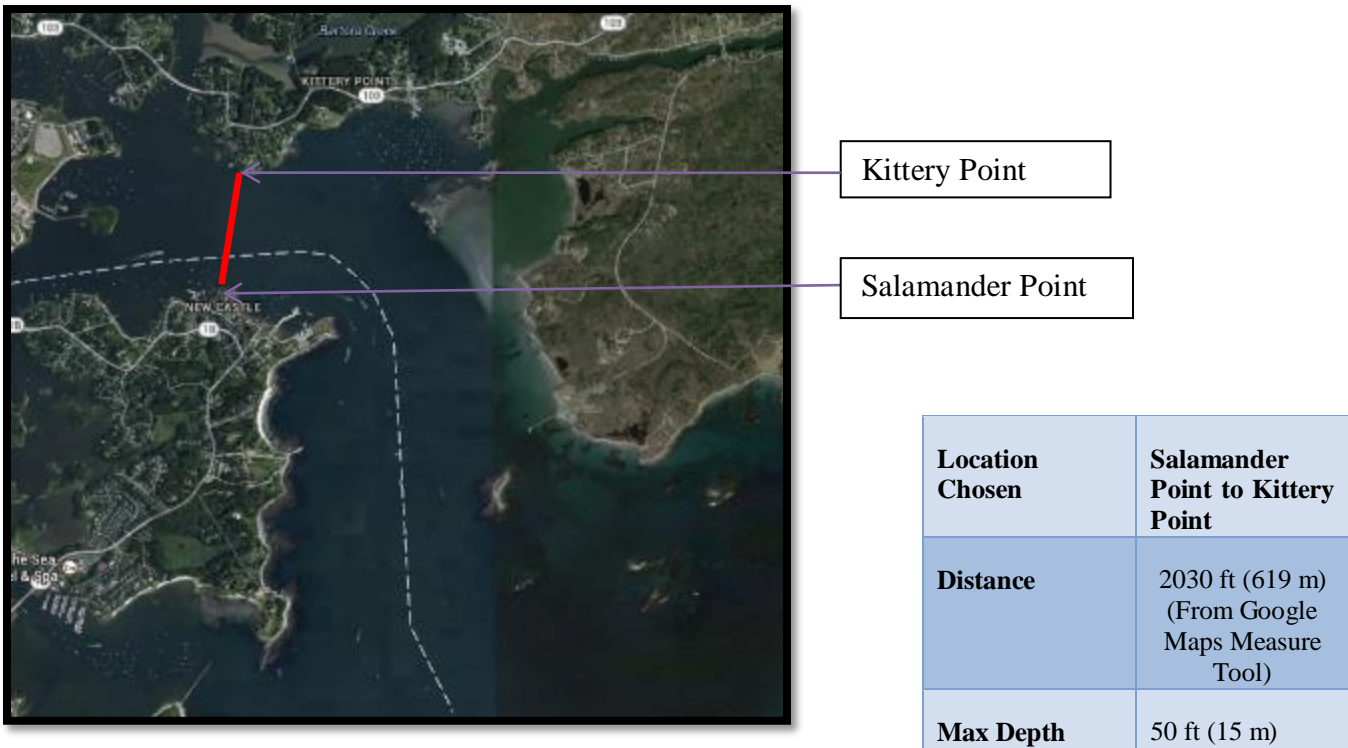
FIGURE 7 - PORTSMOUTH HARBOR LASER DETECTION SYSTEM LOCATION (GOOGLE)

Dimensions of System

The dimensions of the security system can be broken into three components. Height is defined as the depth below the water surface. Width is the span the light field must cross from one side of the harbor to the other. Finally length is the dimension parallel to the water flow through the harbor.

The size of the laser output rig and the detector rig can be determined by the length and draft of the traffic coming in (draft > 4.5 m at mean high tide), the size and location of submarines, and the bathymetry of the harbor. Detector rig should be longer than the average submarine passing (~30 m). The detector system should be designed for the smallest size submarine, which is 6 m in height. Submarines operate using sonar and are especially costly. Submarines typically surface when pulling into port. If a submarine remained submerged it would need to remain above the bottom of the harbor and below the draft of a possible ship above it to remain safe. Based on this conclusion the security system need not monitor within 20ft (6 m) of the harbor floor. The Portsmouth Harbor bathymetry is shown in Figure 8 from a NOAA chart.
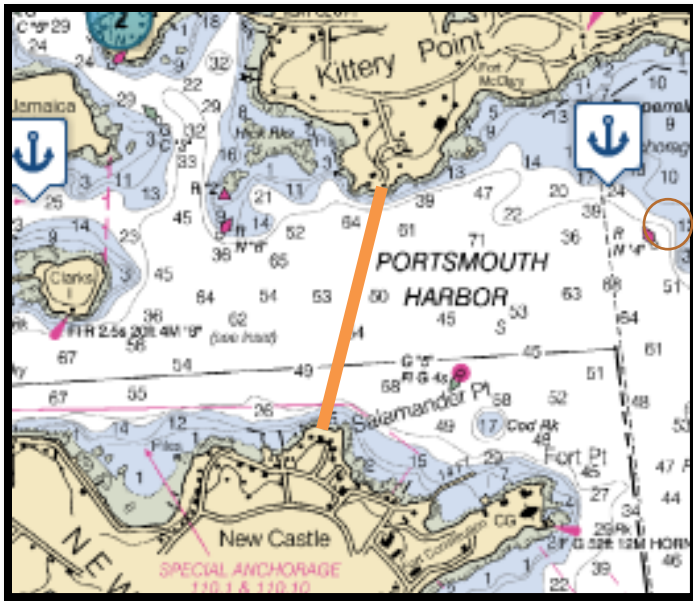
FIGURE 8 – BATHYMETRIC CHART OF PROPOSED LASER SYSTEM LOCATION (NOAA CHART 13283)

The deepest depth across the harbor entrance that can be used for the laser system is 15.5 m. The smallest submarine height would be between 3 to 6 meters below the surface of the water. Any larger submarine would surface to navigate the harbor.

The size of the laser detection system should be able to measure a maximum of 6 meters below the mean water
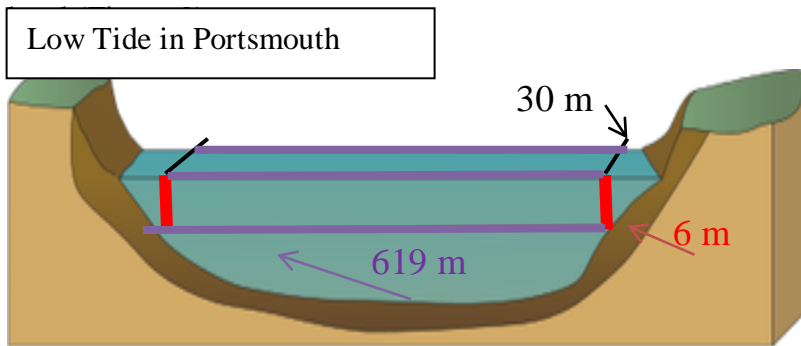
FIGURE 9 – SIMPLE DEPICTION OF LASER SYSTEM SIZE (INTEGRATION AND APPLICATION NETWORK)

The final dimensions of the area this particular system at the specified location in Portsmouth Harbor are reported in Table 1.

Dimension	Depth Below MLLW	Length horizontal
Detector Array Size	6 m	30 m

TABLE 1: ARRAY DIMENSIONS

Feasibility of System

Laser Power

Lasers are known to be dangerous and hazardous. In the application of the laser detection system the safety of marine life and possible human exposure is of paramount concern. The National Environmental Policy Act (NEPA) holds standards for the maximum permissible exposure a human can be exposed to before permanent eye damage. The primary concern with a laser at 532nm is damage of the retina from prolonged exposure. Since there are no distinct guidelines for laser exposure underwater, a laser system that follows NEPA guidelines for human maximal permissible light exposure in air will be used as a basis. Before continuing with a full scale project an ecological professional should be contracted.
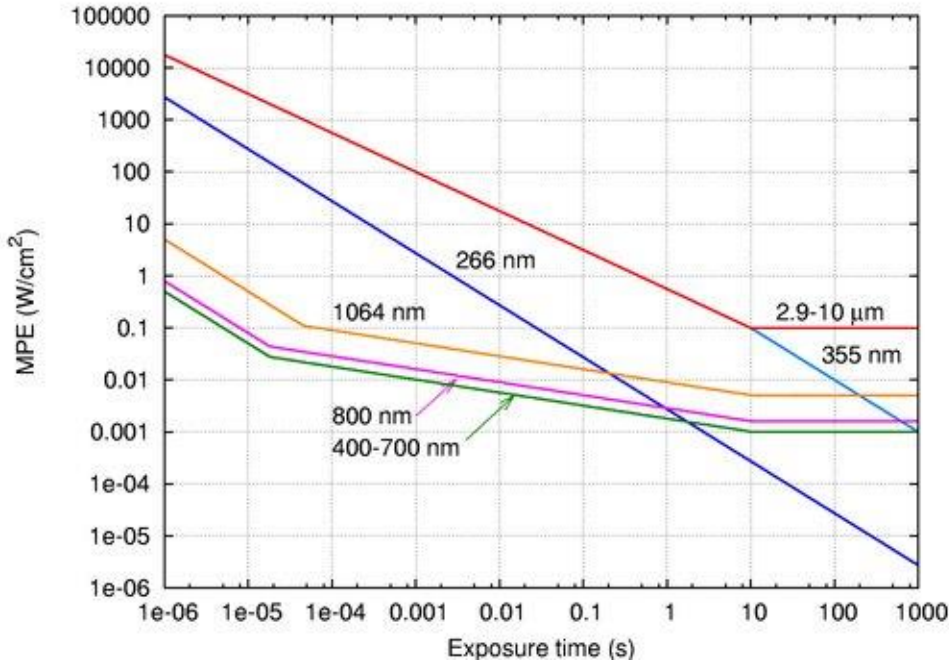
FIGURE 10: MAXIMUM PERMISSIBLE EXPOSURE   (HAN-KWANG, 2007)

The maximum permissible exposure is calculated based on laser power (W/cm^2) and duration (Figure 10.) For a continuous beam laser an exposure time of 0.25 seconds will be considered (the average time for human blink reflex according to Shahani et al (1970)). In this case a 532nm laser should not exceed a maximum of 5mW/cm^2. Pulsed lasers can have a much higher MPE because they can pulse at incredibly small time periods. Therefore, the laser to be used in the Portsmouth harbor should be a pulsed laser. The laser used in the proof of concept scaled project will be a continuous beam for budget reasons.

The attenuation coefficient average from August to October over 2005 surveys was 0.2m^{-1} (Pe'eri et al, 2011). Using the attenuation coefficient and a 5mW/cm^2 laser Equation 1 gives that the maximum distance a laser can travel is ~ 62 m for a photodetector sensitive down to 200nW.

$$I = I_o e^{-kx} \; or \; x = -\frac{\ln\left(\frac{I}{I_o}\right)}{k} \qquad \text{Equation: 1}$$

Where x represents the distance traveled through water, k represents the attenuation coefficient at a particular wavelength and I is the irradiance.

A continuous beam laser strong enough to cross the harbor would be above the MPE standards. To travel a 100m distance needed to span a gate a 9W laser would be required using equation 1. This could prove eye safe if a pulsed laser with 1 microsecond pulse was achieved. Many lasers (ND: YAG for example) can operate on nanosecond pulse width making this the desired solution.

Environmental Factor Conclusions

<div align="right">TABLE 2</div>

Design of Laser Security System	Affected by which Environmental Characteristics	What is the result in design
Feasibility of System	NEPA laser power guidelines, sediment and turbidity, Limited use of AIS	Permissible Pulsed 9W laser -> yields ~ 100 m of travel in Portsmouth Harbor. Attenuation coefficient is .2
Location of System	Laser Power, Tide, Draft of Traffic, Bathymetry	Laser placed across 619 m section between Naval Ship yard and inlet Depth> .67 m below mean water level at Seavey Island
Size of System	Draft of Traffic, Size of Submarine, Depth of submarine travel, Bathymetry Chart	6 m vertical in water column by 30 m horizontal in water column

2) Design and Construction of Harbor Security System

The optical detection system as outlined in the Environmental Factors section requires two primary subsystems to function: 1) a laser powered transmitter system to generate the light field through whitch harbor traffic would pass (the laser's light field acts as a gate that is broken when objects pass through it) ; and 2) an array of photodiodes in a pattern that will be able to detect shadows casted by marine traffic passing through the light field. From specifications defined in the Environmental Report, the harbor security system should be able to detect boats with a minimum draft of 4.5 meters and submarines with a draft of 6 meters. The system must also be able to span a waterway of approximately 600 meters, while meeting NEPA standards.

The materials and components have been carefully selected to meet the detection conditions (vessel size and environmental parameters). The transmitted laser pulses must have sufficient power to span the distance of the waterway even in turbid conditions. The photodiodes must be capable of detecting the light field projected by the laser and should have a contact area large enough to avoid small sediment particles from blocking the incident light. Finally, the size and shape of the detection system should ensure that vessels of the specified sizes will be detected by the system.

In order to test the logistics and implementation of the laser detection system, a scaled version of the system was implemented. The detection system was tested in the Chase Ocean Engineering Wave and Tow Tank as a proof of concept analysis. The scale model closely resembles the proposed full size design based on a scaling factor in the length dimension of 1:60. Due to the constraints of the Chase Ocean Engineering Wave and Tow Tank, the following scaled system dimensions were selected (Table 3):

Dimension	Depth Below Surface	Span Across Tank	Length
Size	1 m	3.7 m	.5 m

TABLE 3: SCALED DIMENSIONS

Key components in the detection system

Transmitter Array
The primary role of the transmitter array is to generate a light field that is of the correct size to cast a shadow on all passing vessels. The overall power of the light should be capable of spanning the distance as well as remaining waterproof for extended amounts of time. The transmitter array includes: a light source in the system

is a 532 nm laser to generate the detection signal, a laser-line generator prism to the laser expand the laser beam and increase the area of effect of the system, and a water-proof housing to protect the electro-optical elements.

Laser

The laser used in this system is a Z-Bolt Emerald Greeen 532 nm (green) laser emitter (Figure 11). A 532 nm laser was selected due to its ideal properties in underwater environments. According to the Jerlov curves defined by Pe'eri et al. (2011) the diffuse attenuation coefficient of light in Portsmouth Harbor at 500 to 550 nm has lower values compared to longer wavelengths (yellow and red). The laser pointer used for this system is rated waterproof up to 300 feet(91m).

FIGURE 11: LASER POINTER (Z-BOLT)

The physical dimensions are with AA batteries. This small size laser allows flexibility in the design of the transmitter unit. Based on laboratory tests to evaluate the characteristics of laser, it was found that the laser emits a beam with a divergence of .042 mRad and a power of 4.2 mW. This small divergence helps minimize power loss due to the inverse square law of an expanding beam.

Powell Lens

The Powell lens (laser line generator) is a small prism that takes a small laser beam and generates a fan like output of the light through internal reflection (Figure 12). The angled portion of the prism can be adjusted to alter the angle of the output fan (Figure 13. The Powell lens allows for a controlled expansion of the laser's beam and the ability to aim it at multiple targets oriented on the line. In this case the beam was aligned horizontally and incident on 5 photodiodes. The benefit of using this method is that lasers are needed to transmit over a larger number of photodiodes. Less laser sources also reduces the hardware costs as well as power consumption, and simplifies the optical design (i.e., less alignment procedures).
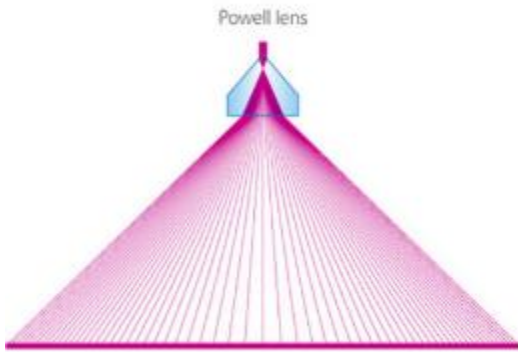
FIGURE 12: POWELL LENS DIAGRAM

(ALTECHNA)
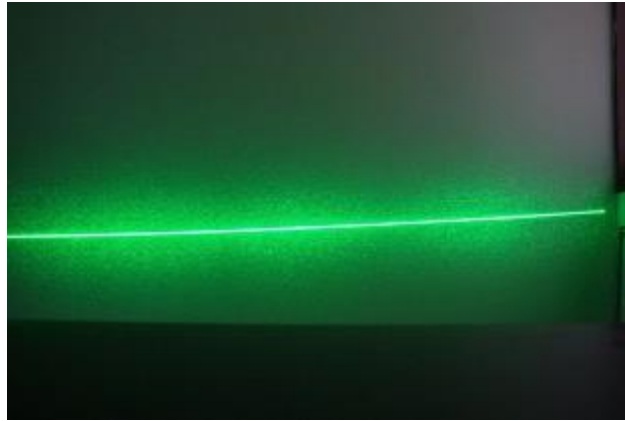
FIGURE 13: LASER LINE GENERATOR IMAGE

Waterproof Housing

The laser line generator rig is designed to hold a laser line generator, specifically the Powell lens in alignment with the output of the underwater dive laser. The laser line generator is sensitive to rotational misalignment. The ranging of the dive laser is only sensitive to rotational misalignment that may indicate a manufacturing error and will result in the inclination of the dive laser output. The dive laser used was measured in laboratory conditions and was found to have a negligible rotational misalignment for the use in this experiment. The laser-line generator rig was designed to be easily taken apart, prevent misalignment of the laser line generator, and have the potential to be waterproof. A model of the rig was designed in Solidworks (Computer Aided Design [CAD] format) using the physical dimensions of the dive laser and the dimensional drawings of the laser-line generator (Figure 14).
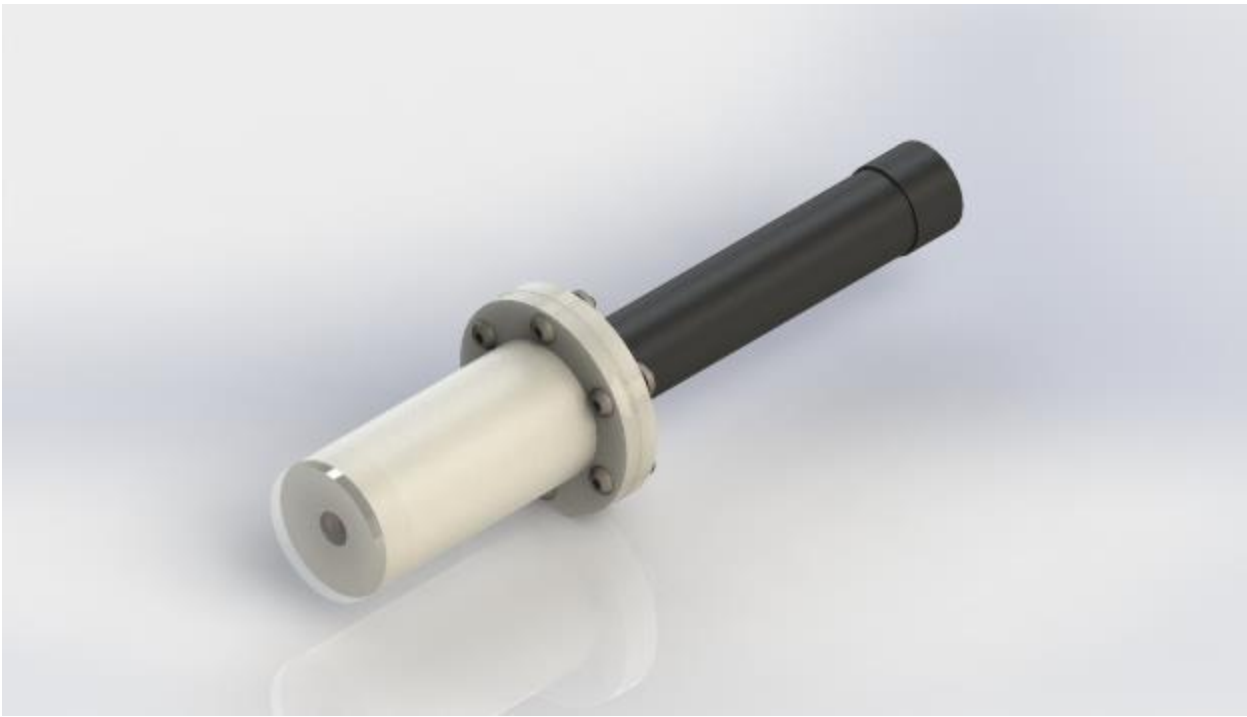
FIGURE 14 - LASER LINE GENERATOR RIG PHOTOREALISTIC RENDERING DEVELOPED IN SOLIDWORKS

FIGURE 15 - LASER LINE GENERATOR CROSS SECTION

The waterproof laser housing allows all components of the transmitter array to be held in place. Figure 15 shows a cross section diagram of the housing. It is important to note that the laser line generator can be placed into a small slot next to the clear acrylic plastic. The laser can then be placed and secured by watertight seal at the rear of the structure. Figure 16 shows the housings inner contour made to hold the laser tightly in place without slipping.

Laser Line Generator Design Considerations

Powell Lens setting

JB waterproof welded

Tight fit

Optional O-ring
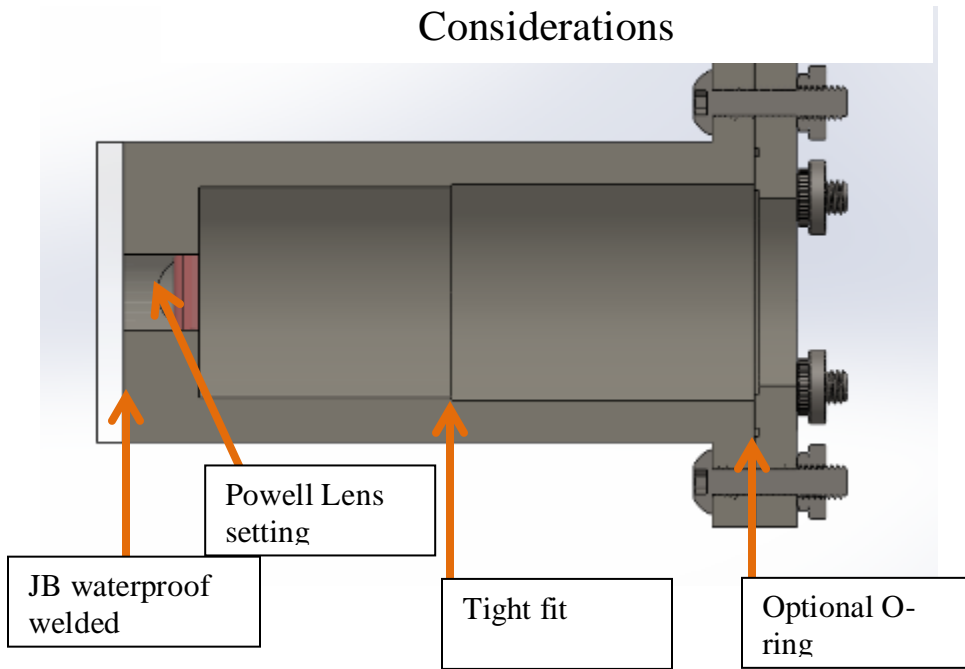
FIGURE 16 - LASER LINE GENERATOR DESIGN CONSIDERATIONS
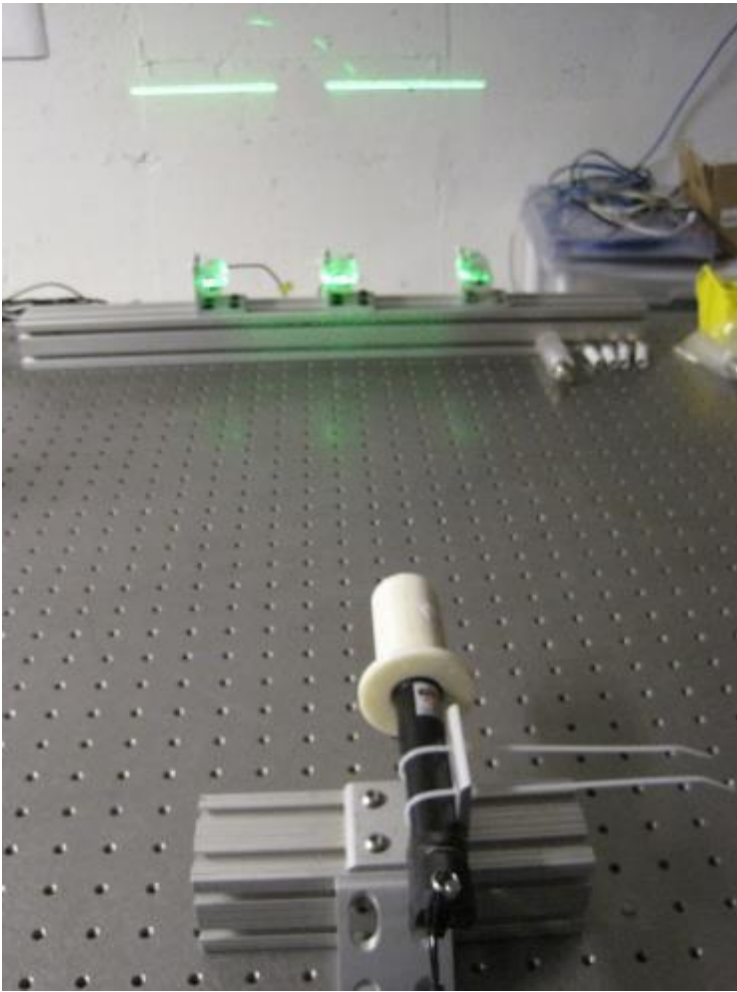
FIGURE 17 - EXAMPLE IN AIR-TEST WITH LASER LINE GENERATOR

Figure 17 provides an example of how the scale transmitter array functions. When held in place it is capable of producing a fanned laser beam. The components will stay in place without rotation or slippage from vibration and movement. This will prevent misalignment of the system. The laser and housing were also secured to an 80X20 mount that could be secured to other stationary surfaces.

Detector Array

The detector array consists of an array of photodiodes arranged in a square grid pattern. The photodiodes were placed in water-proof housing for protection. The dimensions of the detector array are such that that they are fully covered by the laser footprint. When the connection is broken by a vessel passing through the system, the output drops indicating a detection.

Photodiode

Photodiodes can convert light into an electrical current. The incident photons excite electrons in the silicone of the photo detector. In turn, the electrons begin to flow and produce current. The voltage output of a photodiode is dependent on several factors including the incident light power, the quantum efficiency of the silicone diode, the temperature of the silicone, and the construction of the associated electrical circuit.

Figure 18:PD1A (ThorLabs)

For this detection system the ThorLabs PD1A photodiode was chosen (**Error! Reference source not found.**). his photo detector uses a silicone diode which is known to be highly sensitive in the visible light spectrum (See Figure 19). The transmitter is a green laser (532 nm) therefore this detector is well suited to work with this signal (responsivity of .33 A/W).
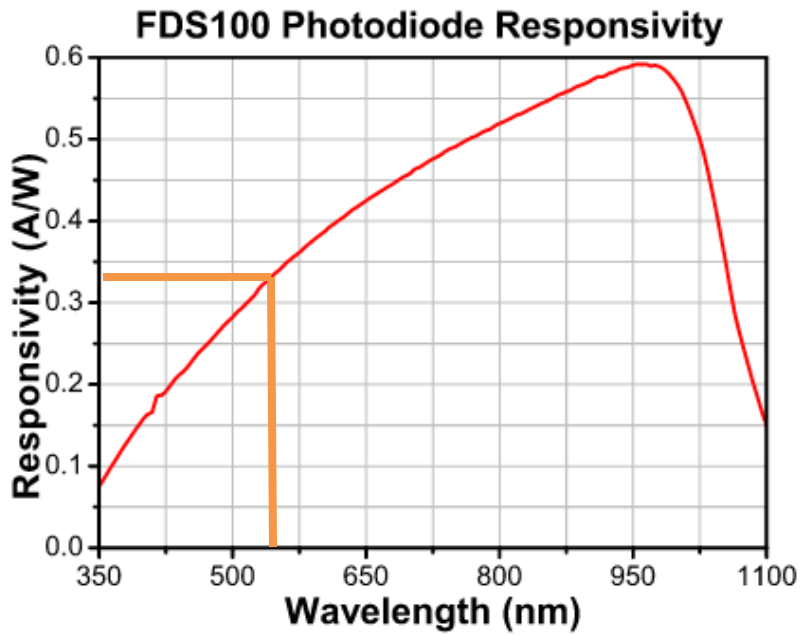
FIGURE 19: THORLABS RESPONSIVITY CURVE (THORLABS)

FIGURE 20 shows the electrical diagram for the Thor Labs PD1A Photodiode. The current produced by the photo detector flows through the circuit and the load resistor is used to measure a voltage output that corresponds to the amount of light that is measured.
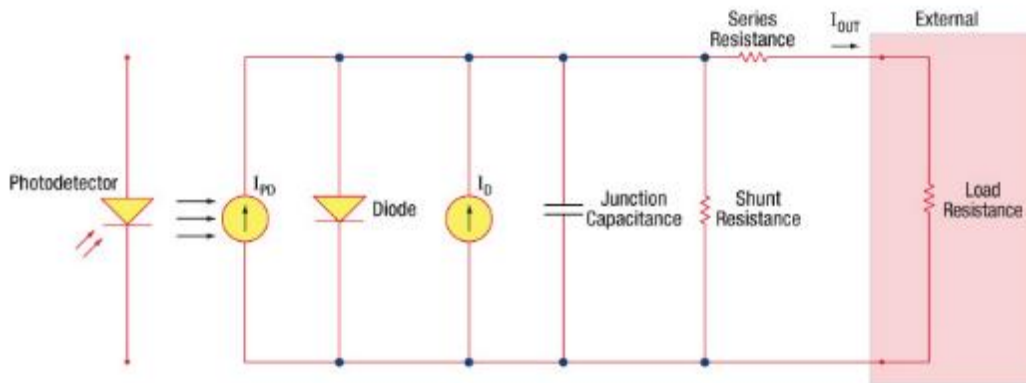
FIGURE 20: ELECTRICAL DIAGRAM OF PHOTODIODE CIRCUIT (ThorLabs)

This photodiode was also selected for its relatively large diode size. The larger silicone diode patch creates a larger target for the laser beam, decreasing the likelihood of misalignment. This diode can be placed on a reverse bias circuit to further increase the magnitude of the output (Figure 21). A bias voltage of 5V was applied from the voltage Through empirical mea surements, it was found to be useful to apply a 5V reverse as an input voltage to increase the scale of the output. This circuit was used on diodes for all consecutive experiments.
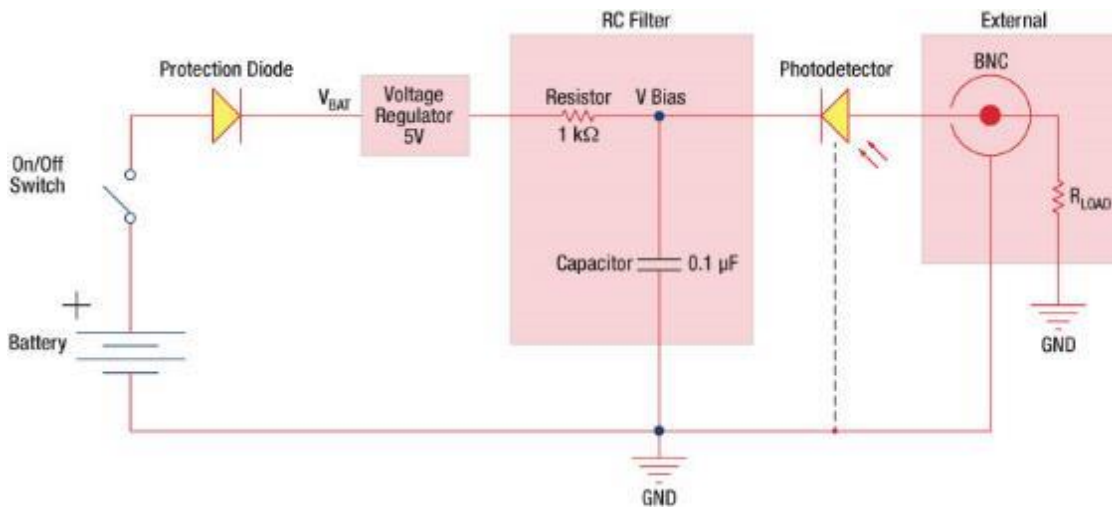
FIGURE 21: DIAGRAM FOR REVERSE BIAS CIRCUIT WITH PHOTODIODE (THORLABS)

Waterproof Housing

The waterproof housing for the photodiodes was designed and constructed by Paul Lavoie from the Center of Coastal and Ocean Mapping. These housings were made from a clear cylinder of acrylic with a bore through the center where the photodiode can fit. There is a watertight wire crimp attached to the rear of the housing where the cable from the photodiode protrudes. Figure 22 shows the waterproof housing with the photodiode inside along with the laser beam incident on the diode. It also demonstrates the method used to mount this housing to the 80x20 rig to be used in the Wave and Tow Tank.
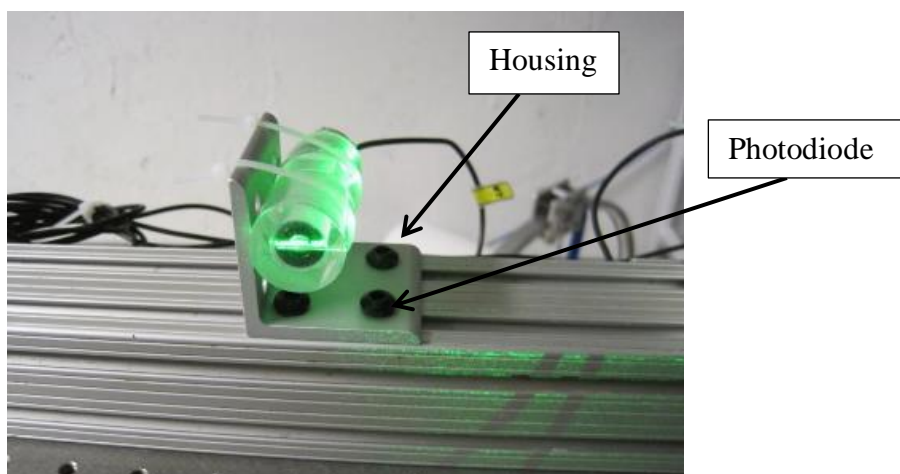
FIGURE 22: DIODE HOUSING

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System Design

The laser detection system is designed to be installed in Portsmouth Harbor and span the gap between Kittery Point, Maine, and Salamander Point, New Hampshire. Support structures on either side of the harbor will hold the lasers, and photo-detectors frames. Figure 23 simply depicts the basic layout of the system. As a proof of concept, a scaled model (1:60 length-wise) was mounted along the Chase Ocean Engineering Wave and Tow Tank. The rig used 80X20 aluminum structure to hold it rigid against the wall of the pool. Figure 24 shows an example of the construction of the support rig that held the laser transmitter and photo-detectors rigidly in place. The rig used a C-shaped mount to hold the structure firmly against the side of the Tow Tank. The crosshatching provides flexibility on the mounting locations for the photo-detectors and lasers to be mounted to the frame. Figure 24 shows an example of the structure mounted to the side of the Tow Tank and submerged in the water. The photo detectors will be held in a square 5x3 array for a total of 15 diodes.

Low Tide in Portsmouth

20 ft

2000 ft
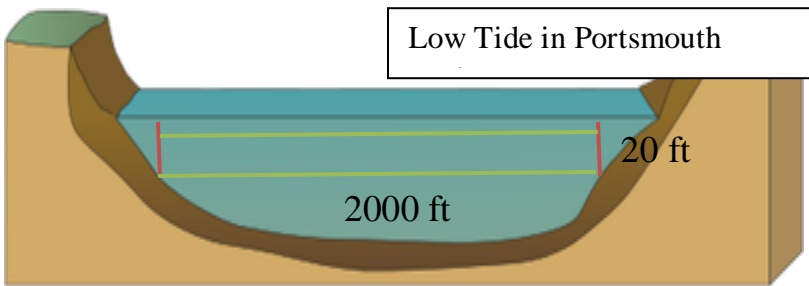
FIGURE 23: SIMPLE DIAGRAM OF LASER GATE (INTEGRATION AND APPLICATION NETWORK)

FIGURE 24: EXAMPLE OF 80X20 RIG IN SOLIDWORKS
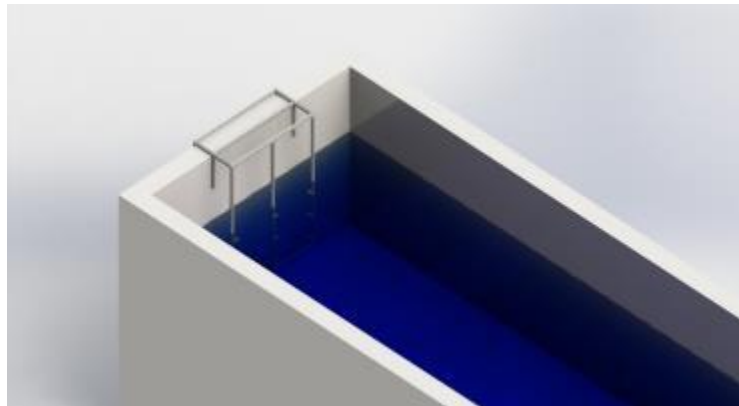
FIGURE 25: RIG MOUNTED ON SIDE OF TOW TANK

A similar rig was mounted on the opposite wall of the pool that stabilized the laser and its laser line generator housing. By using this method, a laser-line generator oriented such that it produces a horizontal line will illuminate up to five photo detectors at a time. The laser can also be swept up and down on a vertical arc such that the single laser can be used to cover the entire array in the span of several seconds. Such a sweeping motion can be achieved using a 5 volt DC Brushless motor to turn a gearbox. The gearbox would contain a worm gear driven by the motor that will in turn drive that shaft that will rotate the laser on its vertical arc. Although the

sweep option was not used proof-of-concept model, this option but should be considered in future steps that are beyond the scope of this study.

The system was rigged and constructed for testing in the Chase Ocean Engineering Wave and Tow Tank. Figure 26 provides a diagram of the final design of the scale Harbor Security System that will be tested. Although the diagram is not to scale, all system components and their orientation in the Wave and Tow Tank are presented.
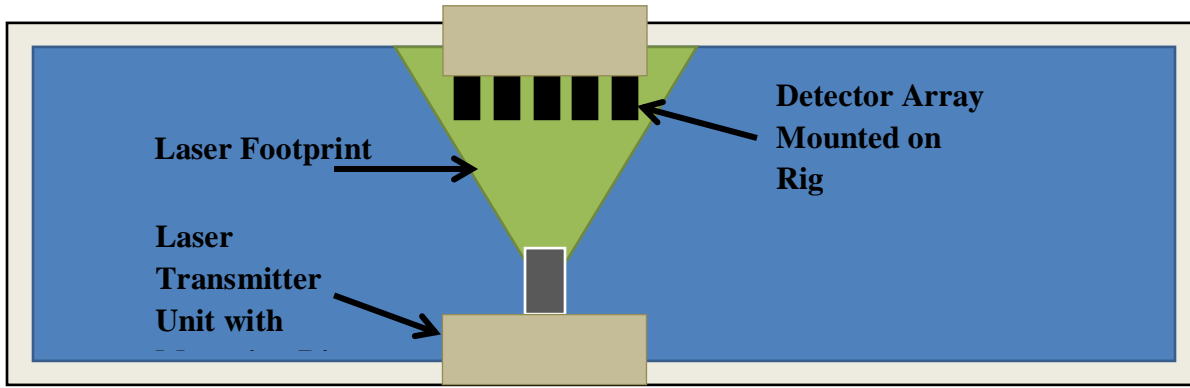
FIGURE 26: SCALED HARBOR SECURITY SYSTEM IN WAVE AND TOW TANK (TOP DOWN VIEW)

3) Harbor Security Detection Algorithm

Detection System Objectives

Full-Scale Harbor Security objectives: Portsmouth Harbor

1. Detect commercial ships and submarines either entering or leaving Portsmouth harbor.
2. Calculate the approximate speed, size, and relative threat of the traffic.
3. Be able to work in varying levels of water level (tides), turbidity (Ebb and Flood tides), and in all seasons of the year.

Scaled Harbor Security objectives: Tidal Tank & Ocean Wave and Tow tank

1. Detect a mock ship when moved in and out of the harbor passed the detection system.
2. Characterize the speed, size, time of the detected ship and define if the ship poses a threat.
3. Validate the system's performance by conducting tests with varying levels of disturbance to the detection system, i.e. rippling water and adding diffuse materials.

Detection System Interface

Hardware

Hardware Overview
A PD1A photo detector is used to measure the power intensity of the transmitter unit of the harbor security system. The PD1A photo detector is connected through a reverse bias circuit to an Arduino Mega 2560 using a SMA male pin with a female thread (relatively uncommon), a bread board (prototyping board), and jumper wires. The Arduino Mega 2560 is connected to a 9v power supply and to the computer using a power cable and a USB A-B connector respectively.

Hardware Components
The list of hardware components are listed below:

- PD1A Photo Diode
  - SMA male pin w/ female thread to SMA male pin w /female thread
  - Capacitor 0.1µF & resistor 1 kΩ (For Reverse Bias)
  - Bread Board (Prototyping Board)
  - Jumper wires (100 or more)
- Arduino Mega 2560
  - 9v power cord
  - USB A (computer) to B (Arduino) connector
- Computer

Hardware Descriptions
The PD1A photo diode was selected for its high responsivity in the wavelength of the transmitter unit laser.

The Arduino mega 2560 was selected because it has the most analog inputs of the Arduino boards (16 analog inputs) and is the cheapest type of microcontroller for the application ($30).

Software

Software Overview
The software package used for the detection algorithm is MATLAB R2014a operated on a windows 7 computer. The software is licensed by UNH and the windows 7 operating system is provided on a personal laptop.

Software Components
The list of software components are listed below:

Windows 7

- MATLAB R2014a (latest version and licensed through UNH)
- Arduino Software (Open source)

Linux (Alternate Arduino computer interface)

- Linus Command Terminal (Open Source)
- Arduino Software (Open Source)

Software Descriptions
An alternate software package to Windows 7 that is commonly implemented with Arduinos boards is the linux command terminal. The advantage of linux command terminal is that it is an open source. This means that access to the program is provided to the public at no additional charge. The main disadvantage of open source programs is the time it takes to learn and program. At the University of New Hampshire there is a license for a computational computer program known as MATLAB. Arduino and MATLAB have teamed together to make an additional free download that allows MATLAB to work seamlessly with Arduinos. MATLABs coding structure allows for easy manipulation of the raw data from the detector unit of the harbor security system. If our project did not have access to MATLAB licenses then it would be advantageous to use all open source programs, but it would increase time spent coding the detection algorithm.

Detection Algorithm

Overall Structure

The detection algorithm is based on the MATLAB Arduino communication. The detection algorithm is coded for MATLAB R2014a with Arduino package. The main concepts of the algorithm are broken down into the following sequence; calibration, detection, data collection. (Figure 27):

- Calibrating the array.
- Checking and capturing detections.
- Saving and displaying the characteristics onto the computer.

-
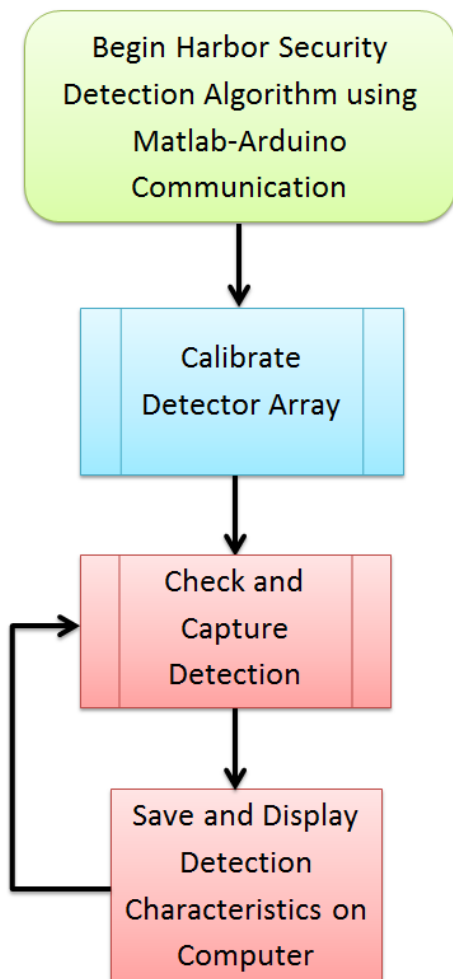
FIGURE 27 - DETECTION ALGORITHM STRUCTURE

Calibrating the Detector Array

Calibrating the detector array is an important process that must occur frequently for a detector system. To keep values up to date the calibration procedure should be run every hour to account for changes in ambient light due to environmental conditions(sun position, weather,ect.) The process of calibrating the detector array is detailed in figure 28. The calibration process has been coded as a reusable MATLAB function. For the experiments conducted at the University of New Hampshire, the detector array only needs to be calibrated once per test run. The MATLAB code will be stopped between each test. In Portsmouth harbor, it would be advantageous for the detector to calibrate based on the weather, tides, and time of day such that the ambient light measured by the detectors is up to date. The information for all those characteristics can be autonomously extracted from the National Oceanic and Atmospheric Administration online resources. The sub process for calibrating the detector array is shown in Figure 28.
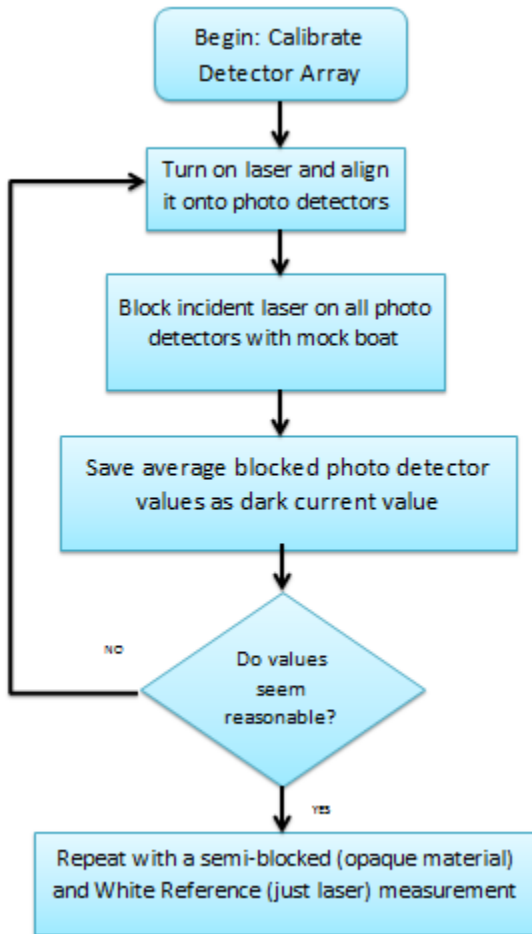
FIGURE 28 - CALIBRATE DETECTOR ARRAY SUBPROCESS

Check and Capture Detection

Once the detector is calibrated the detection algorithm will begin checking for detections. If all photo detectors in a row are blocked systematically then a detection will be made. The speed of extracting measurement data using MATLAB is about 1 microsecond for each piece of data extracted from the analog inputs of the Arduino microcontroller. The overall time for a loop of the MATLAB code ends up being around two-tenths of a second. The MATLAB Arduino interface checks the photo-detectors at a rate of 5 Hz.

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If either one of the end photo-detector is blocked (voltage value goes below 110% of the dark current calibrated voltage), then the rest of the photo detectors in that row are systematically checked. The array of the photo-detectors must be blocked systematically (blocked one by one) in order to continue the count down the row of photo detectors. If the next photo detector in the sequence is not blocked for 30 seconds, then the system resets itself. Once the last photo-detector in the row is no longer blocked, the detection log is stored and saved as a text file. An outline of the sub process is shown in Figure 29.
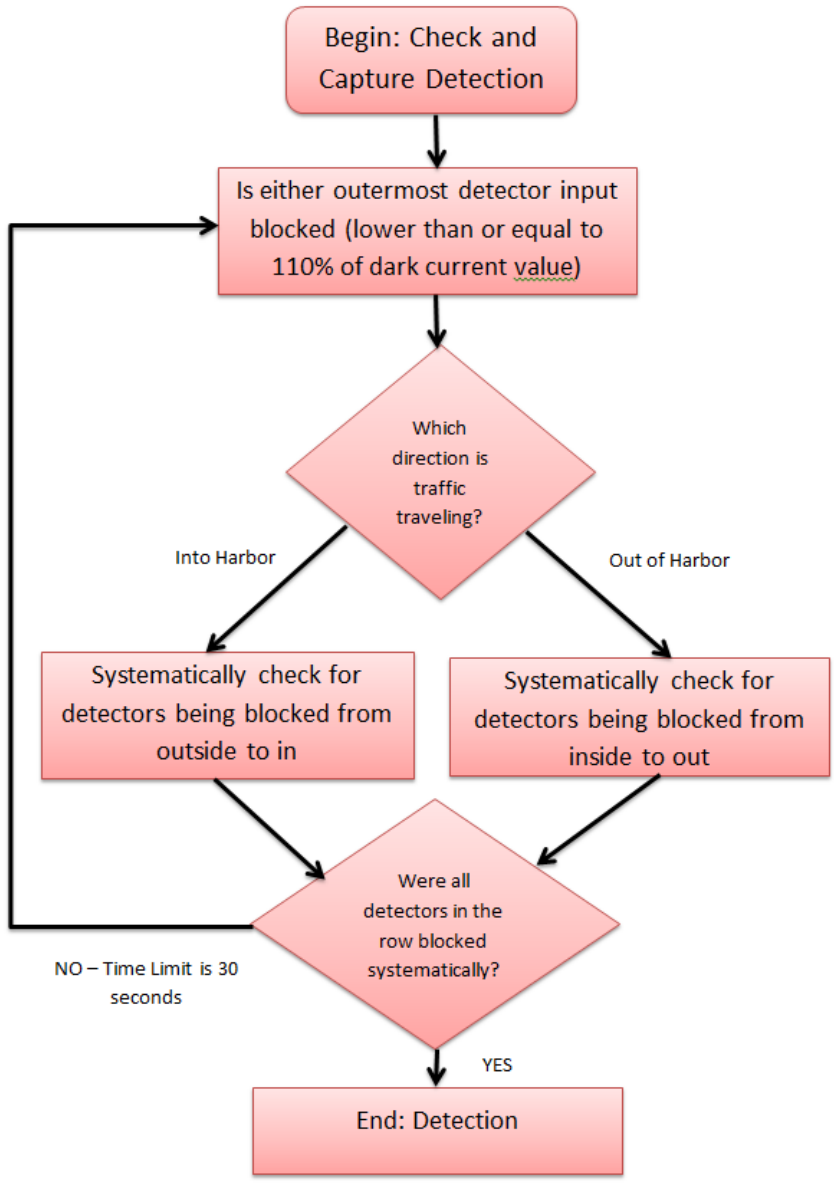
FIGURE 29 - CHECK AND CAPTURE SUB PROCESS

Saving the Characteristics

Once a detection is made all the times between photo-detectors being blocked are used to calculate average velocities and estimates of size of the vessel. All of the characteristics determined from the system are written to a text file (figure 29.)

4) Detection System Experiments

Optical Bench Test

The detection array, transmitter unit, computer interface, and detection algorithm were tested on the optical bench at the Center for Coastal and Ocean Mapping laser laboratory. The details of the testing procedures and results are outlined in Appendix A. Initial tests were conducted to ensure that all photodiodes would output the same voltage readings for a constant incident 532nm laser beam. All diodes were found to be the same and readings can be easily compared.

From another experiment the minimum irradiance required to produce a measurable voltage output from the photodiodes was found to be $0.42\mu W/cm^2$. This value was important for calculating the maximum distance between transmitter unit and detector array.

The dependence of photodiode output on temperature was also characterized (see Appendix A.) It was found that the output decreases linearly as the temperature of the diode increases. The dependence was characterized with a linear trend and the voltage output can be found as with equation 2.

$$V_{corrected}\,(T) = Vo(T) + (Vo(20) - Vo(T)) \qquad \text{Equation 2}$$

Flume Sediment Transport Tank Test

Goals

This experiment tested the laser detection system in an underwater environment. The experiments were conducted in the Flume Sediment Transport Tank located in the Chase Ocean Engineering Laboratory. Results from the experiment will support the assumption that all the system components identified in the previous sections work well together and detect objects in an underwater environment. Positive results from this experiment will allow movement to testing in the Ocean Wave and Tow tank located in the Chase Ocean Engineering High Bay. It is expected that the laser detection system is capable of tracking detections along with the relative size and velocity of the passing traffic. The accuracy of the derived data is in direct correlation to the validity of a true detection of the harbor security system and the detection algorithm.

Setup

The test is to be conducted in the flume sediment transport tank. The tank was filled to water level of height of 16 cm Due to the size of the tank it may be more useful to use only three photodiodes on the detector rig. Figure 30 shows two options for setting up the experiment: 1) laser shining through the clear walls from outside of the tank; 2) laser in the tank pointing length-wise towards the detectors. The laser should be mounted at the same height as the photodiodes on top of 80X20 aluminum bars. The two pieces can then be oriented as shown in Figure 30. For the experiment option 1 was selected. The next step is to ensure that the laser is aimed such that the swath created by the laser line generator is coincident on the photo detector surface of each diode. The alignment should be done by hand and follow UNH laser operator regulations (e.g., eye protection should be

used while visually checking that the laser in on the center of the photo detector). Once the alignment was complete, the photodiodes were connected to the reverse bias circuit powered with 5 volts. Each diode has its own individual circuit to connect to. Finally, each circuit can be connected to the Arduino and connected to the computer with the detection algorithm. The Arduino was powered by a 9 V wall charger to be able to produce the voltage necessary for the reverse bias circuit.
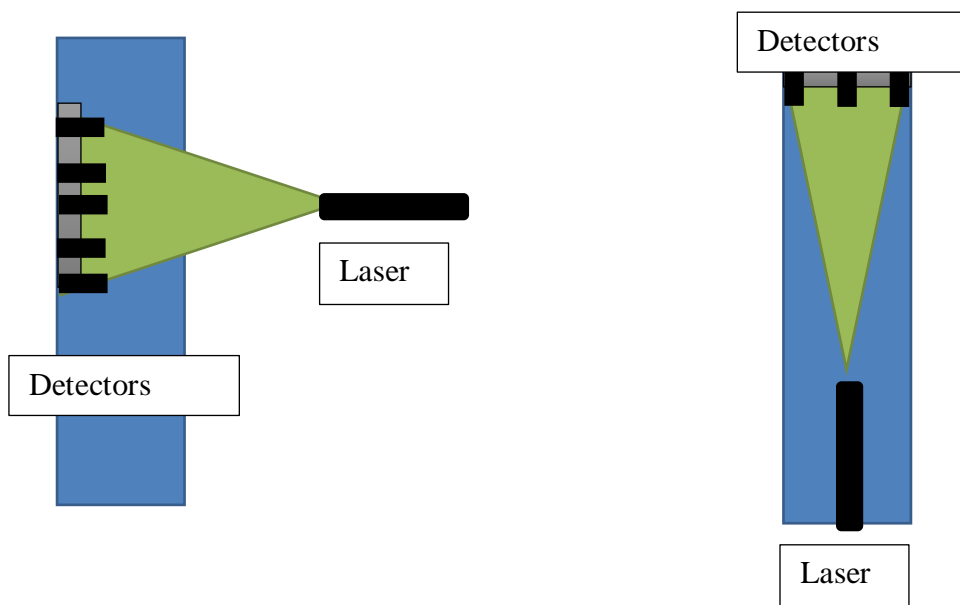
Option 1   Option 2

FIGURE 30 – FLUME TANK EXPERIMENTAL
SETUP

Procedure

Once the setup, is complete with the laser aligned on the photodiode array the system is ready for data collection. To simulate vessels, plastic or wood objects were used in the flume tank. These small toys approximate vessels seen in harbors on a 1:60 scale. The scaled ships were pulled through the detection system at a variety of speeds that simulate typical cruising speeds of boats in Portsmouth harbor (3-10kts). The experiments also tested the limits of maximum velocity detection of the system.

All experiments were initially conducted with the overhead lights of the high bay turned on. With the system in optical alignment, the laser and Arduino were turned on, and a connection between the data collection computer and the Arduino was established. Then, the Arduino program takes a dark current measurement with the laser light fully blocked from the photodiodes and a white reference measurement with the laser shining full power on the diodes. After this the system is calibrated, the experiment can be conducted.

The experiments included two boats of differing lengths: 1) a long boat (28 cm in length) to simulate a large barge or tanker passing into the harbor and will be large enough to block up to three photodetectors at once; and 2) a small vessel to simulate a small-class submarine (9 cm) and. For each experiment, the vessels were pulled through the system at ten different speeds between the ranges defined below for slow, medium, and fast (speeds indicated in Table 4). The method of moving the objects is by hand and can only approximate specific speeds after careful training. Therefore, it is beneficial to move the objects at constant speeds close the slow, medium, and fast scaled velocities. The speeds will be timed by hand using a measuring tape and stop watch. Two points 50 cm apart on the wall of the tank were identified as reference hat are. The reference velocity was calculated by dividing the 50 cm distance by the time visually measured using a stop watch. The goal is to have several measurements near each of the slow through fast speeds.

Vessel Length (cm)	Slow Speed	Med Speed	Fast Speed

| 9 | 3 cm/s | 15cm/s | 30 cm/s |
| 28 | 5 cm/s | 15 cm/s | 35 cm/s |

TABLE 4:

Test within this experiment were repeated with the vessels moving in both directions past the detector array (i.e. left to right and right to left) in order to ensure that the detection algorithm will produce accurate results for traffic without a direction bias. Some of the tests were conducted in turbid water conditions (higher diffuse attenuation coefficient values). To run the turbid water case the vessel was passed through the system while the water was being splashed and churned up by hand. This simulated rough water conditions. To simulate additional attenuation several acrylic plates that represent water attenuation were placed in front of the laser transmitter while the test was conducted.

Results

To evaluate the detection algorithm actual velocity vs. calculated velocity plots and actual length vs. calculated length plots were used. These plots compare the actual speed and vessel size to the values reported by the security system. The ideal velocity vs. velocity plot would produce the line with a slope of 1, where the detection algorithm is reporting the same velocity as manually measured velocity.
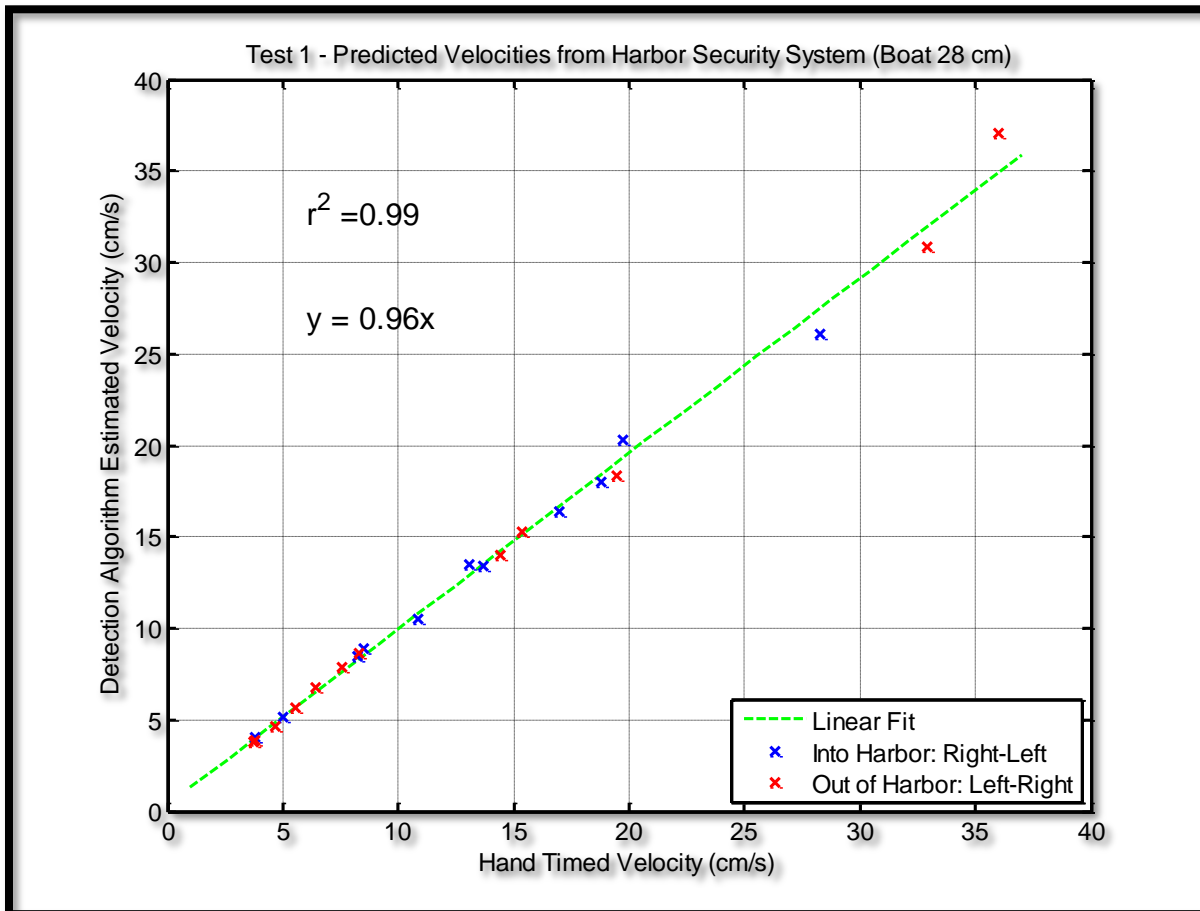
FIGURE 31 - TEST 1 VELOCITY

The first experiment involved passing the 28 cm vessel through the detection system from both sides at a number of varying speeds. The data is presented in Figure 31 with the hand timed actual velocity on the x axis and the detection algorithms estimation of velocity on the y axis.

The data was fit with a trend line with an r^2 value of 0.99. It can be seen that as velocity increases the accuracy of the estimated velocity declines somewhat. The velocity measurements begin to deviate from the trend line. Error is calculated as the difference of the slop from a 1:1 ratio. Table 5 presents the parameters of the fit line

TABLE 5

r^2	slope	y-intercept	Error in Velocity Estimate
.99	.96	.36	4%
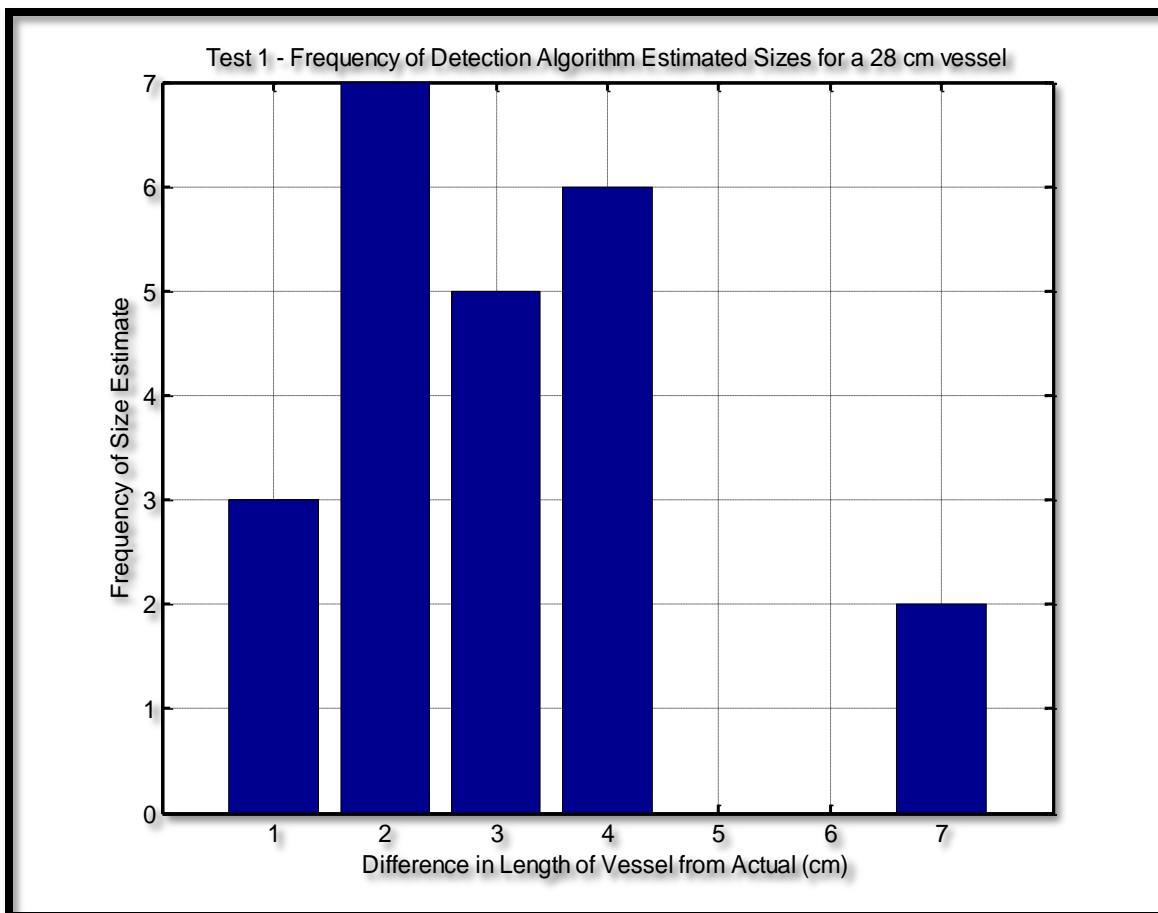
FIGURE-32-TEST1-LENGTH

The relative size of the vessel can also be estimated using the estimated velocity and blocked photo detector times. Figure-32 shows frequency with which the detection algorithm estimates vessel lengths that differ from the actual lengths on a centimeter scale (Actual − Estimated). As the plot indicates, the detection system consistently underestimates (difference is positive) the length of the vessel between 1 and 4 cm less that its

actual length. As the detection algorithm quite accurately calculates velocity, it is possible that the timer used to calculate length is less than the actual time of blocking.

The approximate error of the 28 cm length measurement = (Avg Difference/Total Length)=10% Error.
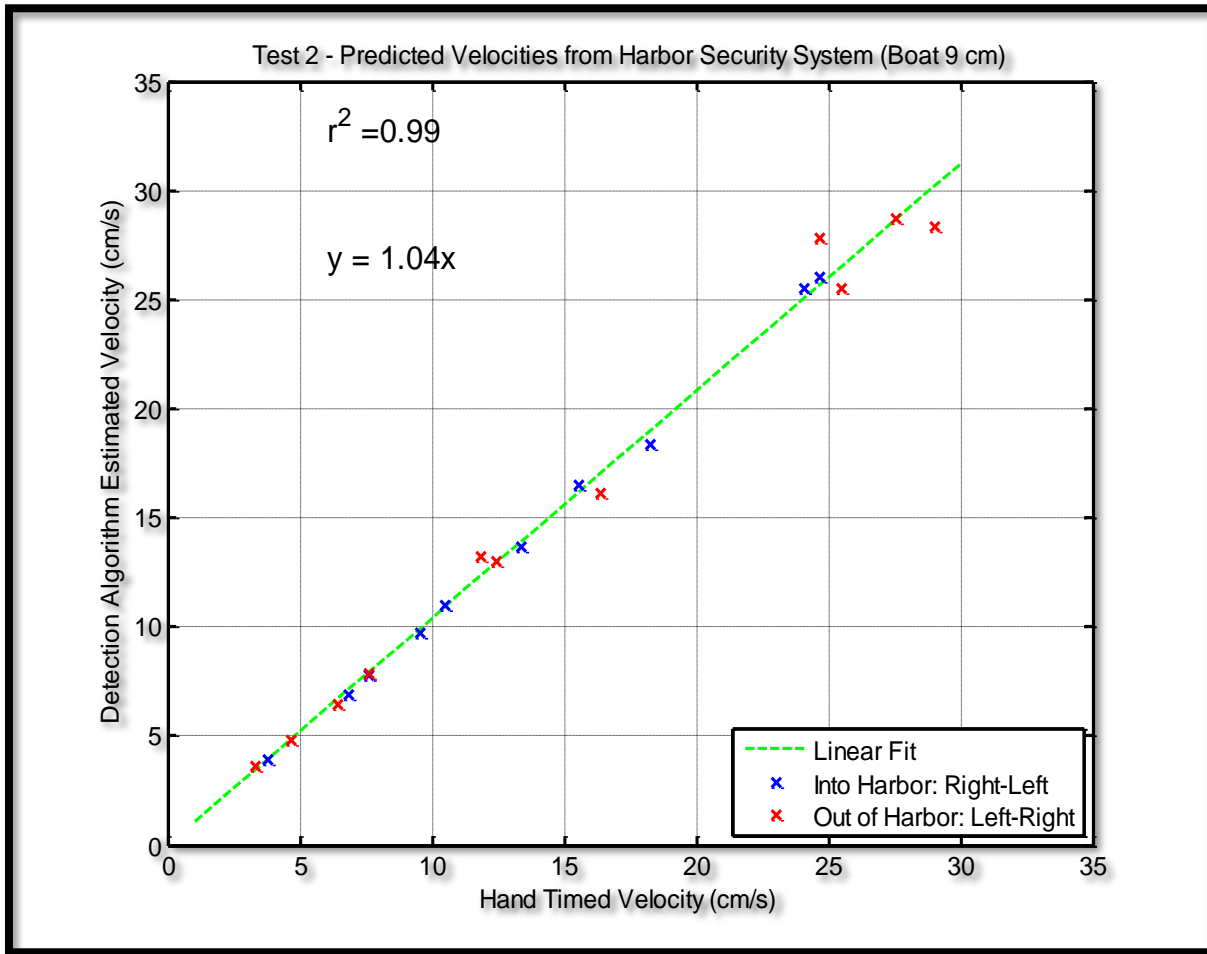
FIGURE 33 - TEST 2 VELOCITY RESULTS

The second test involved using a 9cm vessel, once again moving in both directions through the system ranging in speed from 3 to 30 cm/s. The data is presented in Figure 33 with the hand timed actual velocity on the x axis and the detection algorithms estimation on the y axis. The linear regression of the data shows a trend line with a slope of 1.04 and the r^2 value is once again close to 1. These factors indicate that the detection algorithm is performing its task with a high degree of accuracy. The parameters for the fit line are presented in the table below.

r^2	slope	y-intercept	Error in Velocity Estimate
.99	1.04	.022	1%

TABLE 6

FIGURE 34 - TEST 2 LENGTH

Figure 34shows the variance in estimation of the length of the vessel as a frequency of the difference between actual length and estimated length (Actual − Estimated). It can be seen that the detection algorithm can detect the actual size but often underestimates the true size. Once again due to low error in the velocity measurement there is likely an error in the timer used to calculate the length (velocity * time blocked.

The approximate error of the 9 cm length measurement =(Avg Difference/Total Length)=16% Error.

Discussion
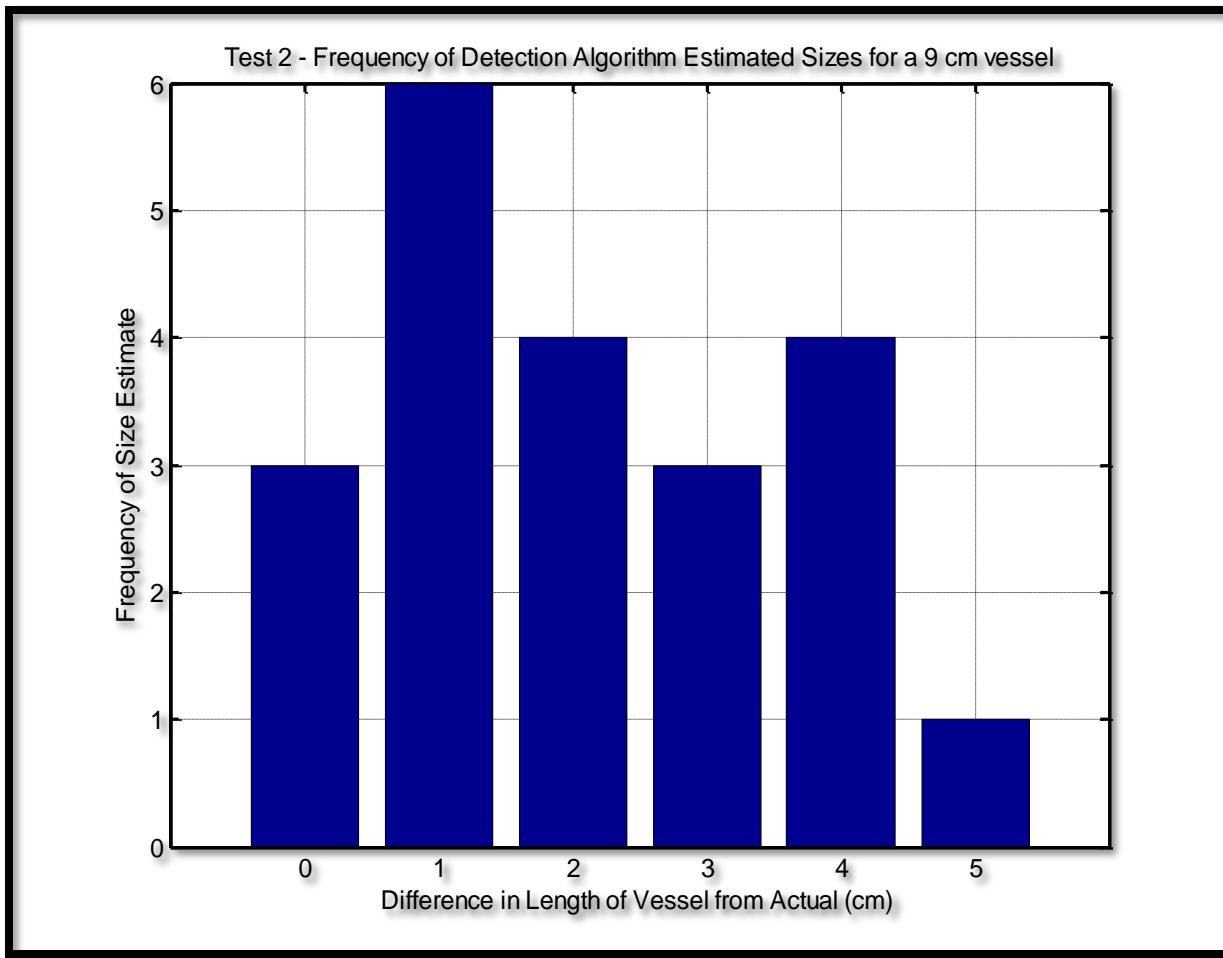
From these results it is clear that the detection system and algorithm are capable of detecting and accurately calculating the velocity of a vessel passing through the detection system. The data fit with less than 1% difference from the expected values.

There was however significant discrepancies in the estimation of the vessels length as produced by the algorithm. Up to 16% error was calculated for the 9 cm vessel case. This error could be due to the fact that the algorithm uses a timer to count the time in seconds that a detector is blocked, but that timer is nested in a MATLAB function. It is possible that the small amount of time required to exit a function and then enter a function and start the timer creates lower times that detectors are blocked. The lower blocked time is averaged

into the size estimate and brings the overall size estimate down consistently. In order to obtain more accurate estimate sizes a revision will need to be made to the detection algorithm.

Ocean Wave and Tow Tank Test

Goals

The purpose of the Ocean Wave and Tow Tank experiment is to move larger vessels through the harbor security system at varying speeds. The system should be able to record the speed and size of passing vessels at a high degree of accuracy. Setup of the experiment will mimic that from the Flume Tank Test. The advantage of ocean wave and tow tank is that the tow carousel can be used to move ships through the security detection system at precise speeds. In this test there is no error due to inaccuracies of the actual velocity.
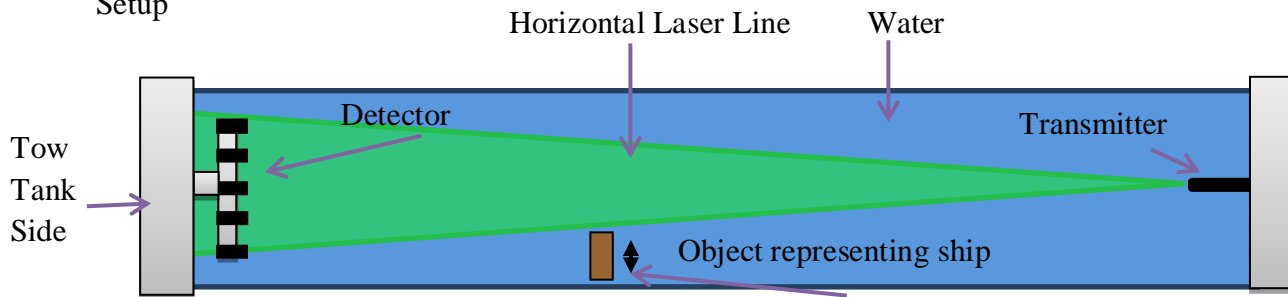
Setup

FIGURE 35 - TOW TANK EXPERIMENTAL SETUP

Procedure

The detector array with five photo detectors will be mounted to the sidewall of the Wave and Tow Tank such that the detectors are .5 m below the surface. Then the system will be connected to the Arduino and MATLAB as in the Flume Tank Test. The laser transmitter will be mounted in the clear side window of the tank directly across from the detector array. The system should then be aligned such that the laser beam is incident on all photo detectors.

Table 7 gives the range of speeds that two vessels (a short 30.5 cm and long 181 cm vessel) will be pulled at. The tow carriage will support a mock submarine (length of 80X20) .5 m below the surface. Then the carriage will be run through the system ten times in each direction at speeds varying between the slow and fast velocities.

Vessel Length (cm)	Slow Speed (cm/s)	Med Speed (cm/s)	Fast Speed (cm/s)
30.5	5	100	200
181	5	25	50

TABLE 7 - OCEAN WAVE AND TOW TANK EXPERIMENT

Results
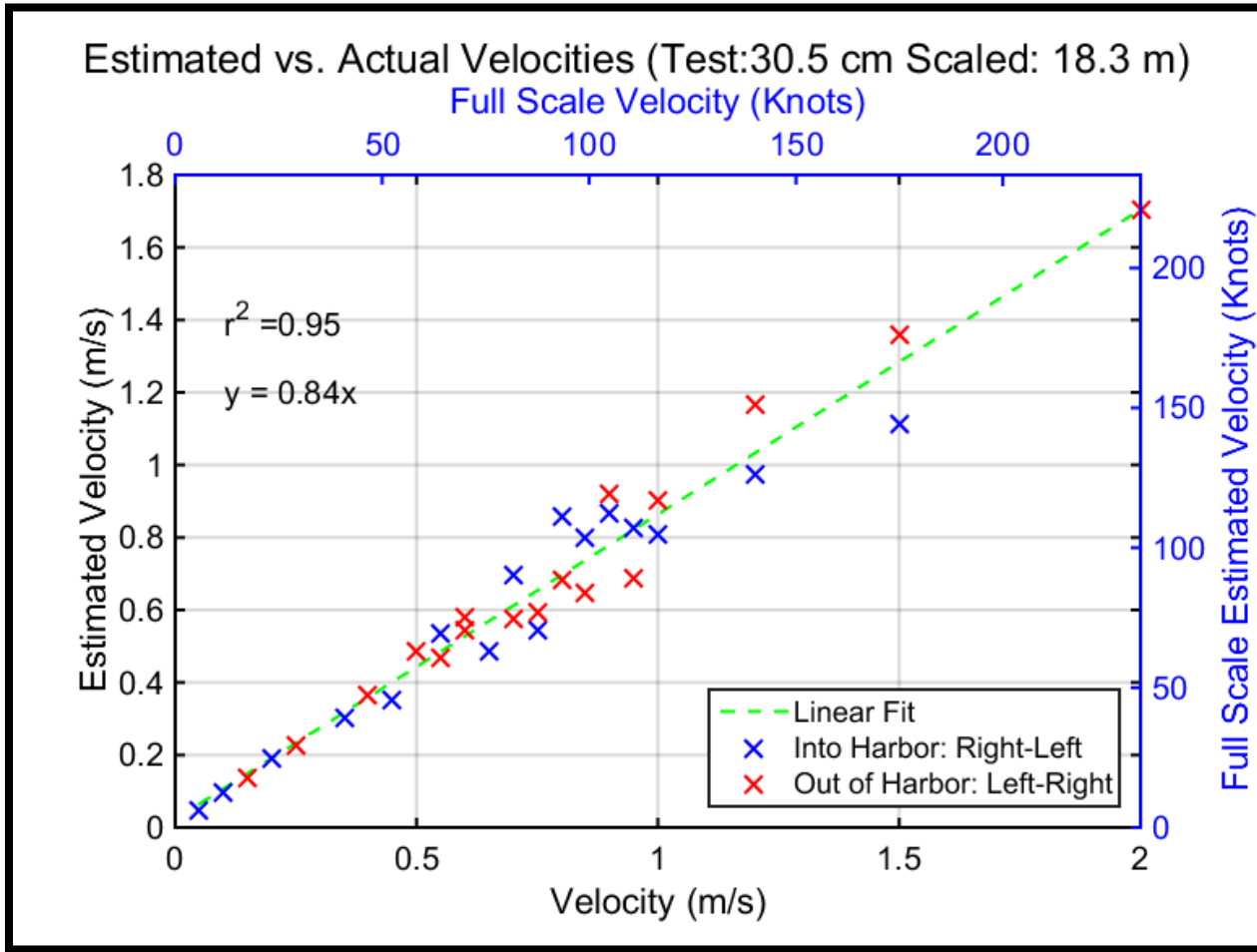
FIGURE 36: TOW TANK TEST 1 VELOCITY RESULTS

The first experiment in the Tow Tank was to pull a 30.5 cm object through the system over the range of velocities. Figure 36 shows the velocity plot with the actual carriage velocity on the x axis and the resulting detection system estimation velocity on the y axis.

The data was fit with a trend line with an r^2 value of .95. It can be seen that as velocity increases the accuracy of the estimated velocity declines somewhat. The velocity measurements begin to deviate from the trend line. Table 8 presents the parameters of the fit line.

r^2	slope	y-intercept	Error in Velocity Estimate
.95	.84	.4	4%

TABLE 8

FIGURE 37: TEST 1 SIZE ERROR

Figure 37 shows the variance in estimation of the length of the vessel as a frequency of the difference between actual length and estimated length (Actual – Estimated). It can be seen that the detection algorithm can detect the actual size but often underestimates the true size. Once again due to low error in the velocity measurement there is likely an error in the timer used to calculate the length (velocity * time blocked).

The approximate error of the 30.5 cm length measurement =(Avg Difference/Total Length)=17% Error.
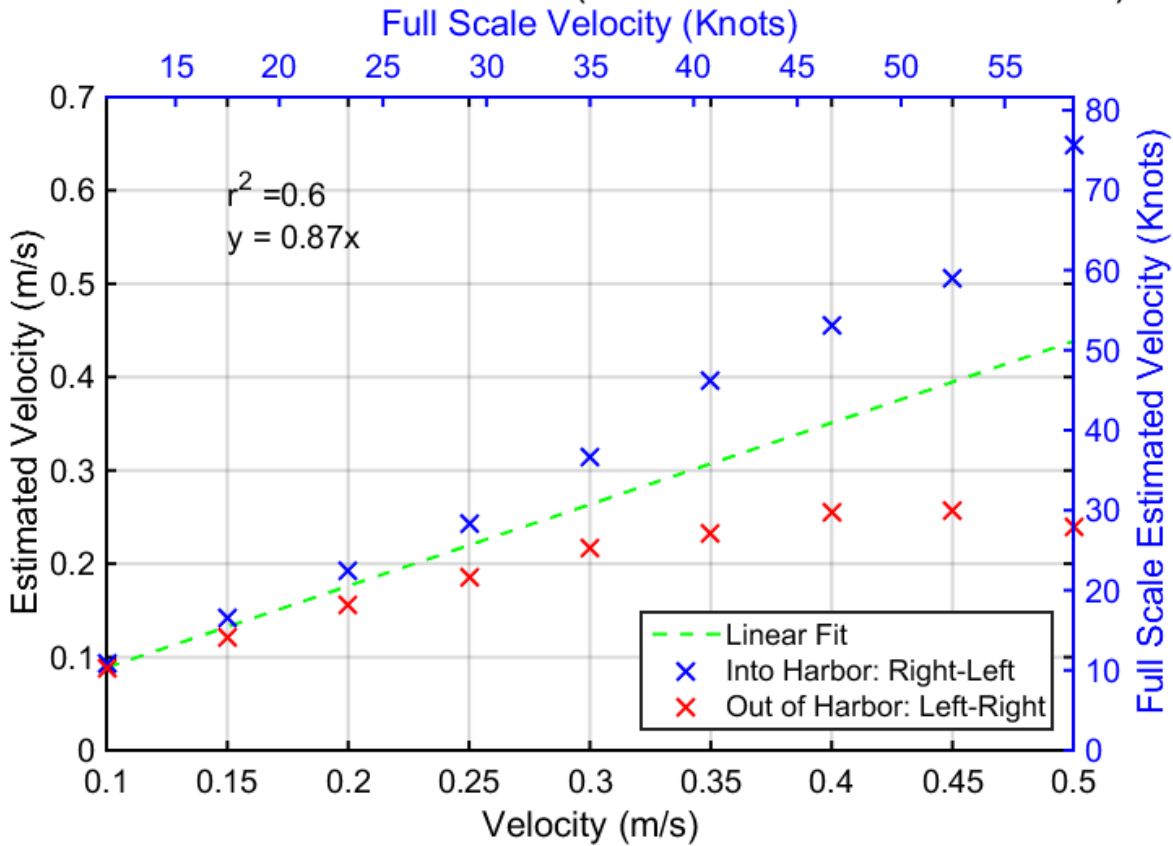
FIGURE 38: TOW TANK TEST 2 VELOCITY RESULTS

The second experiment in the Tow Tank used a 1.81 meter object at a range of slightly slower velocities. Figure 38 shows the velocity plot with the actual carriage velocity on the x axis and the resulting detection system estimation velocity on the y axis.

The data was fit with a trend line with an r^2 value of .6. It can be seen that as velocity increases the accuracy of the estimated velocity declines considerably. The velocity measurements begin to deviate from the trend line. Table 9 presents the parameters of the fit line. There is a much larger error in the velocity measurement.

r^2	slope	y-intercept	Error in Velocity Estimate
.6	.87	.2	9%

TABLE 9

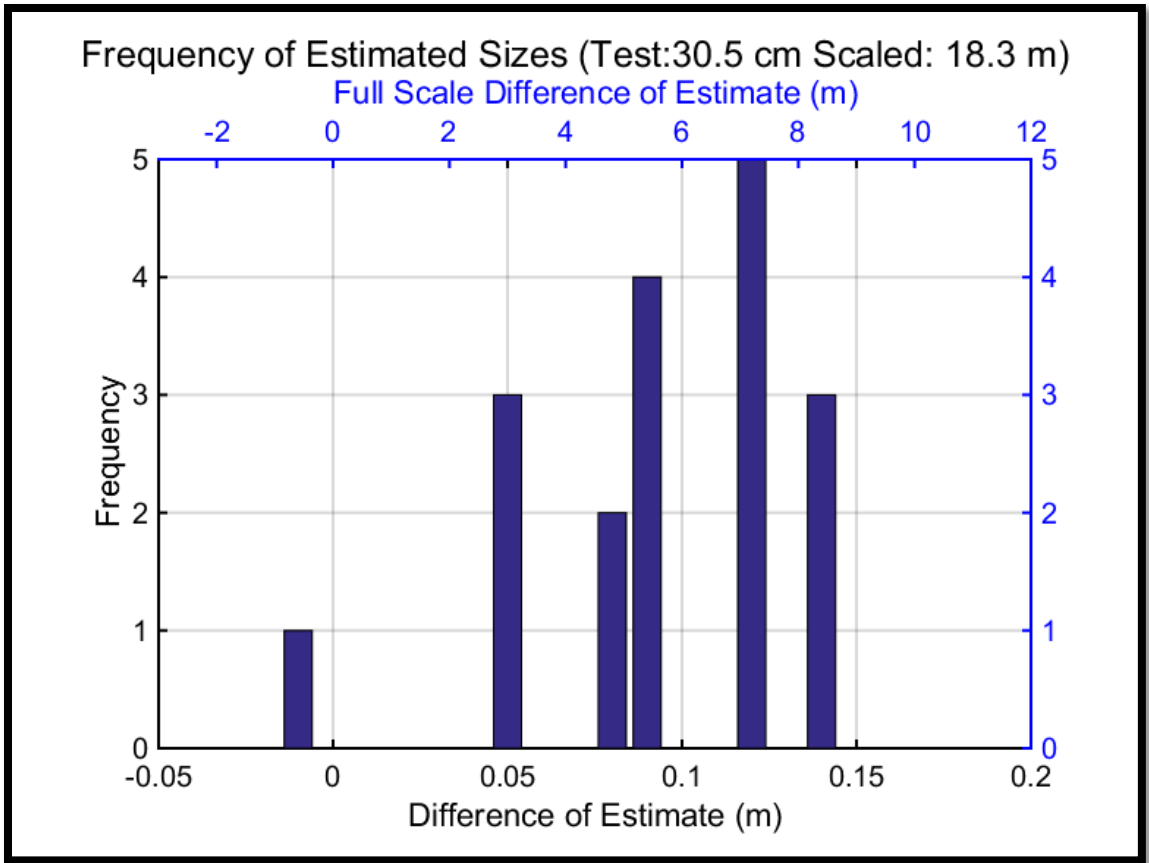FIGURE 39: TOW TANK TEST 2 SIZE ERRORS

Figure 39 shows the variance in estimation of the length of the vessel as a frequency of the difference between actual length and estimated length (Actual – Estimated). It can be seen that the detection algorithm can detect the actual size but often underestimates the true size. Once again due to low error in the velocity measurement there is likely an error in the timer used to calculate the length (velocity * time blocked).

The approximate error of the 1.81 m length measurement =(Avg Difference/Total Length)=20% Error.
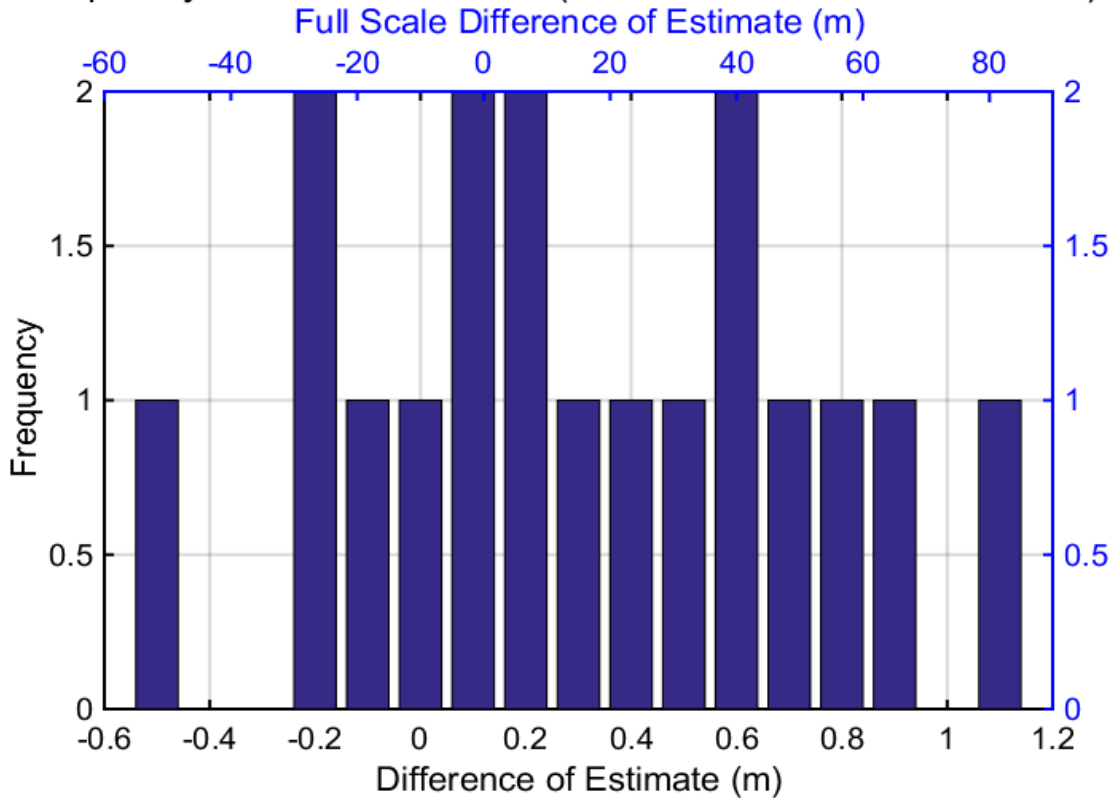
Discussion

The detection algorithm functioned well during the Tow Tank tests and was able to detect a passage in all cases. The velocity and length estimations lost some accuracy compared to the Flume Tank results. The error increased from around 1% to nearly 9% in the velocity estimations. The length estimations in this test typically underestimated the full length of the mock vessel with errors up to 20%. This error is likely due to the decrease in accuracy of the velocity estimation at the actual velocity increases. This value is used to calculate the size and compounds on the error of length estimates.

5) Conclusion Harbor Security

The harbor security system provides a proof of concept for a laser gate detection system that is able to surface and subsurface vessels (e.g., detect cargo ships and submarines passing) passing through a harbor. Portsmouth Harbor was selected as a model site in order to use realistic values that describe the possible conditions that the system may encounter. Details on conclusions derived from the study with respect to the scales and parameters are provided below.

Change in Scaled Width of Detector Unit

The proposed width of the Portsmouth harbor detector unit is ~ 30.5 meters (100 ft). The proposed depth is from the MLLW to 6 m below. The detector unit width is based on the length of the target length of the boat to be measured as 1:7 of 213 meters (700 feet). After computing results and using the time lag of the detector system, it is apparent that the width of the detection system can be greatly reduced.

Based on the results of the experiments, the smallest time difference measured between the first and last detector is 0.15 seconds. If the fastest desired speed to be measured by harbor system in Portsmouth harbor is 25 knots (typical open water cruising speed of a cargo ship), then the width of the detector system can be reduced to 1.9 m. This uses the results from the tow tank measurement that the shortest time between the first and last detector measured is 0.15 seconds. If measurements of faster speeds are desired than the detector system can be scaled appropriately. The equation assumes that there is an array of 5 photo-detectors spaced equally. It also assumes using an Arduino and MATLAB communication with the MATLAB code for the detection algorithm developed in this project.

$$Width\ Detector\ System\ (m)$$
$$= Desired\ Measured\ Speed\ \left(\frac{m}{s}\right)$$
$$* Detector\ System\ fastest\ time\ measurement\ between\ first\ and\ last\ detector(s)$$

$$Width\ (m) = Desired\ Measured\ Speed\ \left(\frac{m}{s}\right) * .1488\ (s)$$

Concluding Statements

The harbor security system using a pulsed green laser of 532 nm that can cross 100 m of Portsmouth harbor can be detected by a photo diode and also be considered by NEPA as eye safe. A detection algorithm can be developed in many different types of software based on the budget to make vessel detection and collect useful information on the traffic entering or exiting the harbor. The detection algorithm can be tested and revised to increase accuracy and precision in detecting useful parameters such as velocity (m/s, knots) and size (m). The detection algorithm can be linked to NOAA real time data on tides, storm events, and time of year to provide confidence in the detections, and change parameters to laser detection system accordingly. One example would be sweeping the laser into the tidal zone as the tide rises and falls. The laser motion would change based on the NOAA tidal predictions.

The laser alignment of photo detectors and laser will be a challenging obstacle to overcome. The most convenient solution would be to mount the laser on a rotating platform that sweeps the laser vertically through the water column. This eliminates the need to fix the laser on specific photo detectors.

Resulting Conceptual Design

In order to eliminate blind spots there could be an extra transmitter and detector unit on opposing sides. Two lasers would sweep on opposite sides. The two lasers could be different wavelengths so as to not interfere with each other. It is proposed to use a laser at 532 nm and a second laser at 450 nm. This conceptual design is shown in Figure 40. See Table 10 for symbolic labels
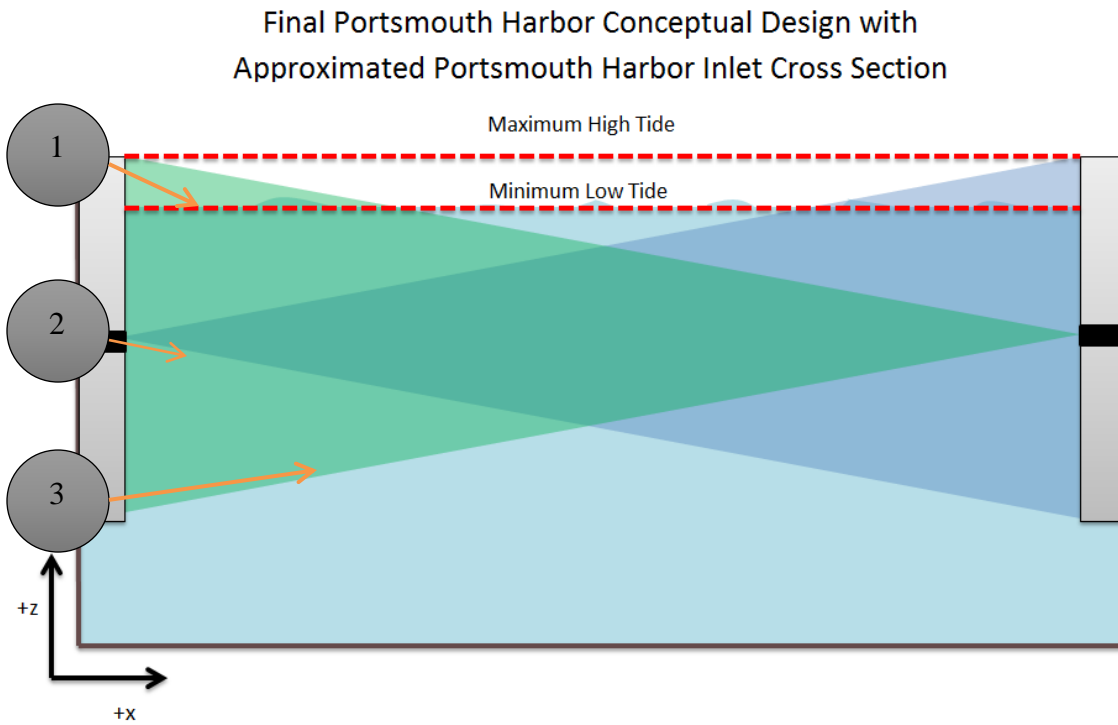

FIGURE 40: EXAMPLE OF BI-CHROMATIC SYSTEM

Number	Name	Diagram Picture	Function
1	Detector Unit (Detector Array)		Detector Unit is a two dimensional array of photo detectors to convert incident laser power to a voltage and transfer to a computer and ultimately a detection algorithm.
2	Transmitter Unit (Laser)		Transmitter Unit is the laser that creates and transmits the light that crosses the gap to the photo detectors. The Transmitter Unit is on a motorized platform that allows the laser to sweep vertically
3	Laser Swathe		Laser Swathe is the representation of the horizontal laser line swept through varying angles. It represents the entire range of motion of the laser vertically.

TABLE 10

Future Considerations for Harbor Security System

- Fully design a detector unit and transmitter unit to operate in Portsmouth harbor. The two dimensionality of the detector array will need to be determined as well as the appropriate sizes. Based on the testing in this project the width of the detector array was calculated to be about 1.9 meters.
    - o Transmitter Unit must meet NEPA eye specifications contained in Environmental considerations
    - o Detector Unit can be composed of many detectors and needs to be at least 1.91 meters wide for same photo detectors and algorithm used in this project
    - o Test the speed at which the laser must rotate so that photo detectors can pick up signal. Develop detection algorithm that can work with rotating motorized laser system. For a two dimensional detector array.
    - o Vertical size of detector unit should be at least 6 m.
    - o Waterproof the motor and platform to rotate laser.
- Evaluate detector and transmitter unit in terms of security, I.E. How easy is it to get by detector system?
    - o Possible ways to negotiate harbor security threats:
        - ▪ Develop detection algorithm to alert when a boat is stopped in security system area.
        - ▪ Regulate the area around the system as no loitering; if a ship stops in the area it will be searched.
        - ▪ Add a LIDAR (light detecting and ranging system) to the security system to check where the boat is in relation to the transmitter unit.
        - ▪ Add Buoys in middle with their own laser systems that interact with land mounted transmitter and detector units.

- Conduct full ecological study with contracted professionals for all environmental impacts. These include the implications of submerging lasers, and detector units permanently, as well as marine life safety.
- Proceed with experiments in Portsmouth harbor.

Next Steps in Application of harbor security to different applications

- Apply processes, components, ideas, and test results to future laser gate systems. These include a intertidal laser gate system for swimmers, recreational crafts, ROVs, AUVs, and ASVs. An example of this setup is shown below for both a green and blue laser.
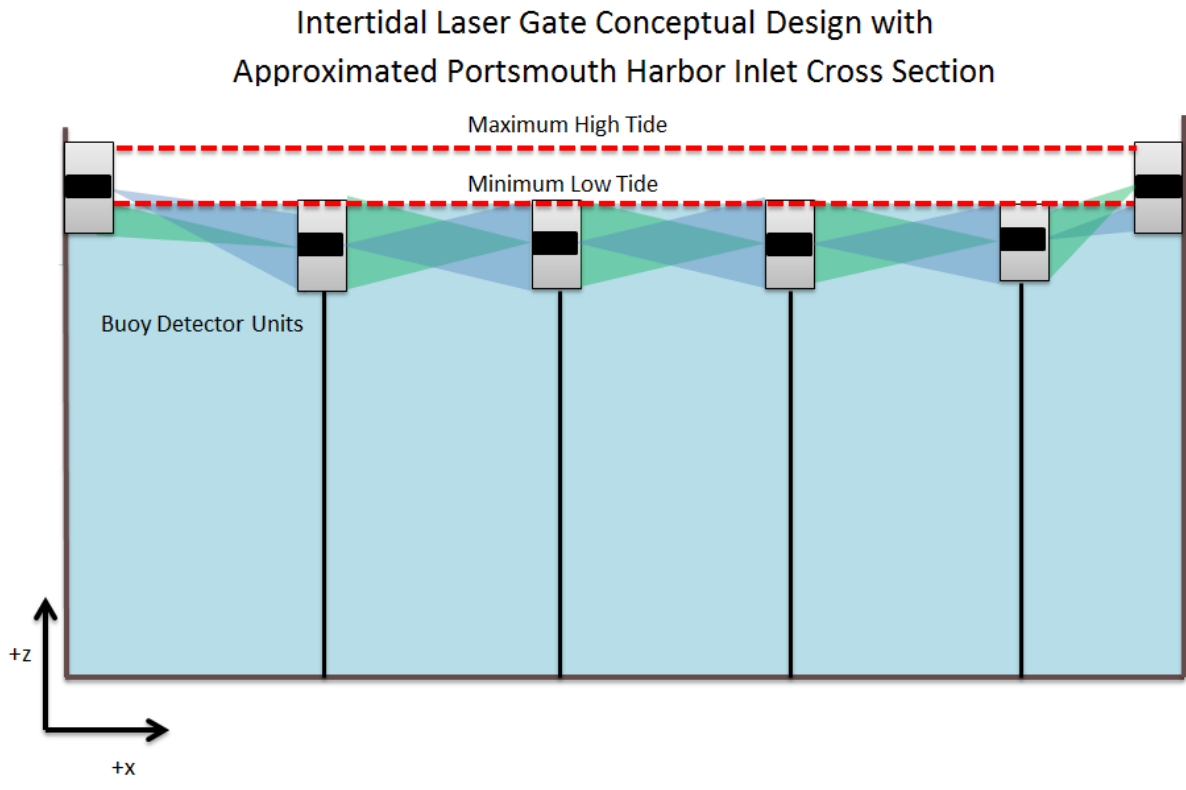

FIGURE 41: EXAMPLE OF INTERTIDAL LASER SECURITY GATE AT LOW TIDE

Intertidal Laser Gate Conceptual Design with
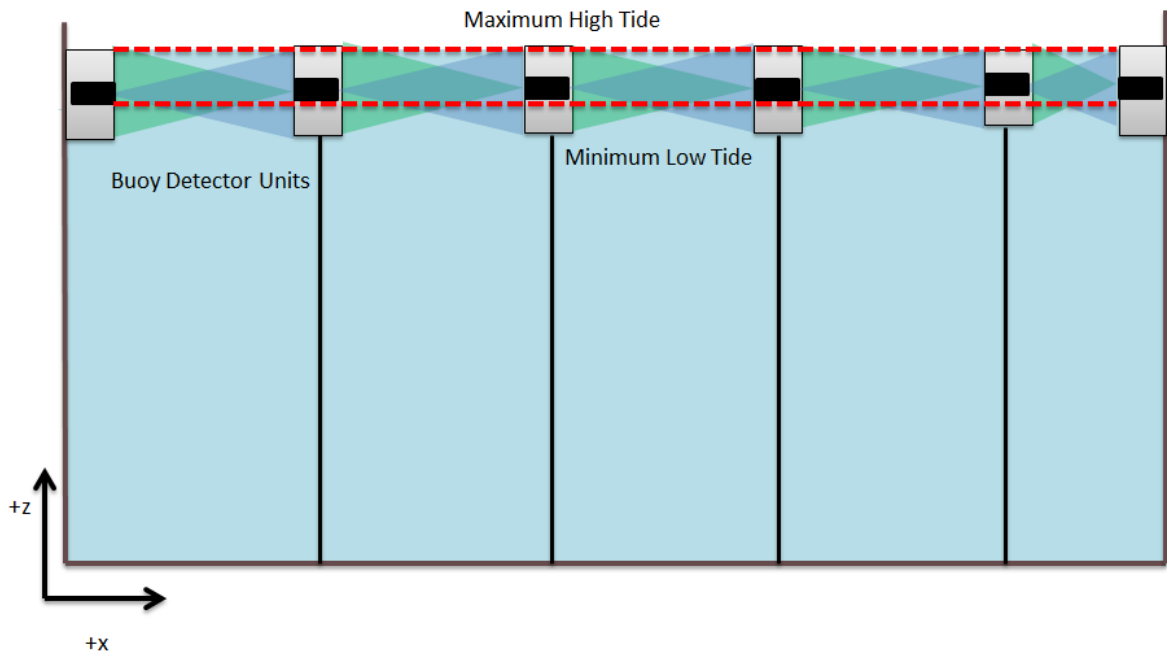Approximated Portsmouth Harbor Inlet Cross Section

FIGURE 42: EXAMPLE OF INTERTIDAL LASER SECURITY GATE AT HIGH TIDE

- In order to develop buoy detector units significant work would need to go into stabilizing unit in order to align transmitter and detector unit.
- Test laser cross talk to operate lasers of different wavelengths.
- Test the Brewster angle of the transmitter unit and possible escaping of laser from surface of water.

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Appendix

Lab Bench Experiments

9/26/14 - Calculate the minimum power density of a PD1A photodiode.

Objective:

- Logarithmically decrease the incident power on the photodiode to find the voltage sensitivity
- Find the minimum power density required to trigger a response

input power	distance	Optical Density	Voltage Output (mV)
4.2 mW/cm^2	150 Cm	0	527
		1	443
		3	290
		4	214
		5	130
		6	46
Min power reading mW/cm^2			
0.0000042			

10/31/14 - Testing photodiode in underwater housing with 9m SMA cable and adapter (one dimensional)

Objective:

- Test photodiode in air with 9m cable and adapter in scenario that it will be in underwater. Record Voltage detected. In a one dimensional case.
- Test filter paper (Roscolux Gaslight Green 532 nm).
- Record Voltage output as a function of angle of laser beam.

Setup:

Clamped into laser lab table.
Photo Diode clamp uses 80-20. Laser clamp uses Edmund optics clamps.

11/12/14 - Photo Diode Calibration with constant halogen light source.

Objective:

- To make sure all photo diode measure same mean voltage given the same light source

Setup:

- PL-900 Fiber-Lite light source connected to a fiber optics cable to air
- PD1A photo diode at a distance of 17.5 cm (6.9") away from output of light source
- PD1A is connected to Tektronix Oscilloscope
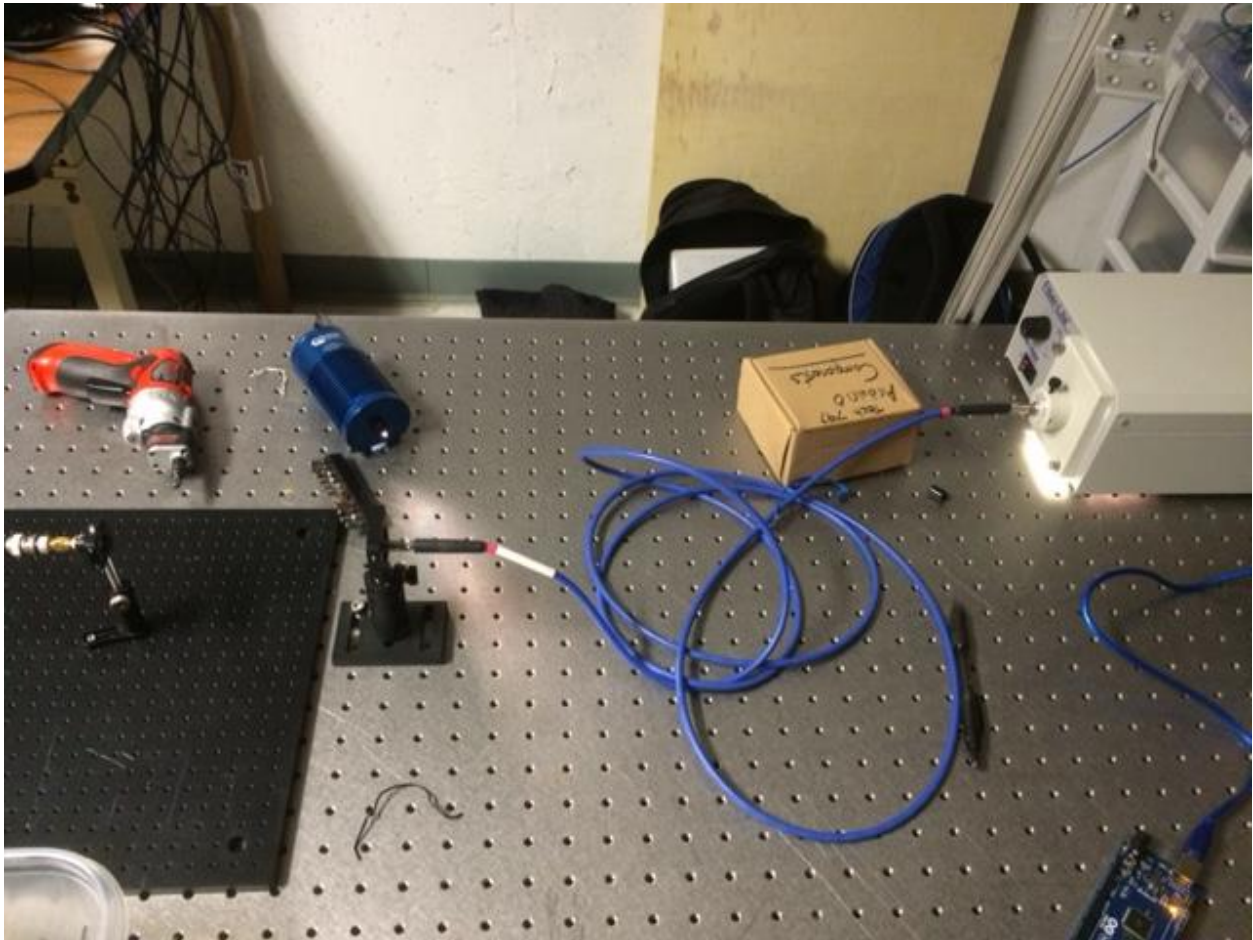- Voltage output from Oscilloscope is the mean averaged value

Notes:

Lights were turned off to conduct test
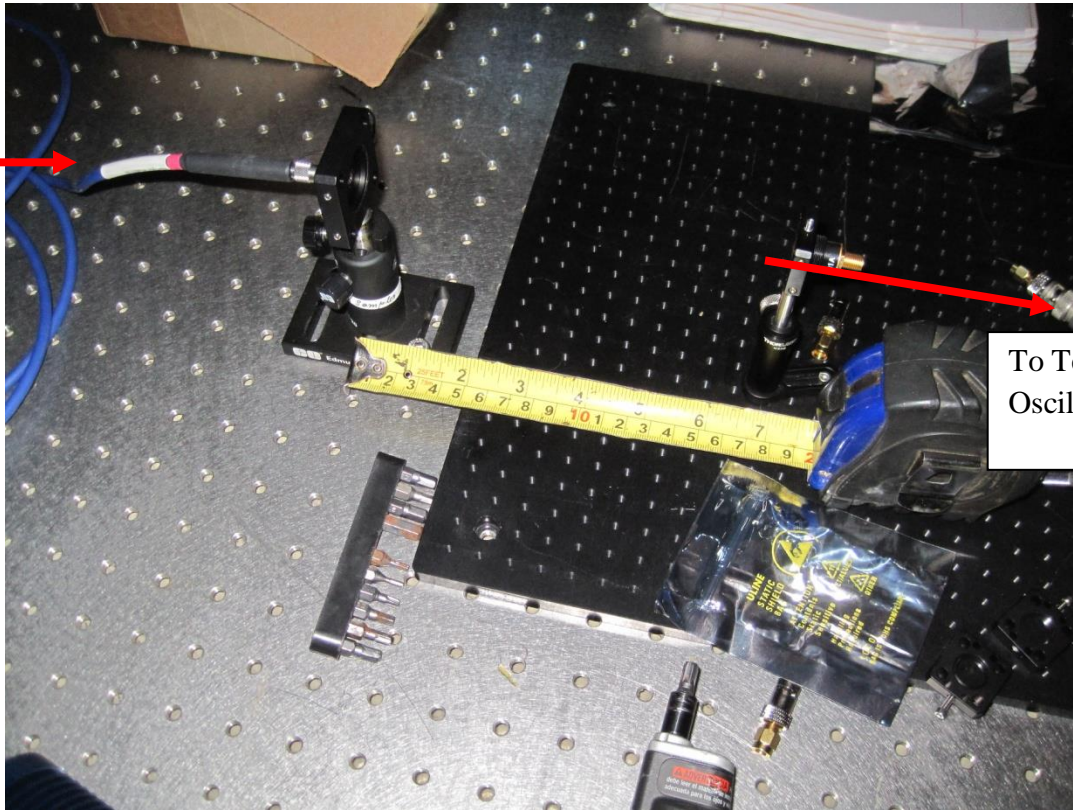
Results:

Photo Diode Number	Mean Voltage (mv)
Hs 1	292
Hs2	298
Hs3	298
ROV1	296
ROV2	291
ROV3	292
ROV4	296
ROV5	294
ROV6	298
ROV7	300
ROV8	297
ROV9	298
ROV10	294
ROV11	299

ROV12	298
ROV13	298
ROV14	298
ROV15	298
ROV16	299
ROV17	296
ROV18	299
ROV19	298
ROV20	299
ROV21	300
ROV22	299
ROV23	299
ROV24	300
ROV25	299
ROV26	300
ROV27	294/287/310
ROV28	300
ROV29	301
ROV30	300
ROV31	298
ROV32	297
ROV33	299
ROV34	298
ROV35	297
ROV36	300

Results:

Test 1

Distance (cm)	Voltage (mv)	Noise
94	390	50 mv
100	400	
150	543	
200	549	

12/5/14 - Calculate the response of the photodiodes to the generated laser line using arduino mega

Objective:

- In air measure the Ardunio mapped output of the photodiodes to a laser line as a function of position along the line at a distance of 20" from the output of the laserline generator.
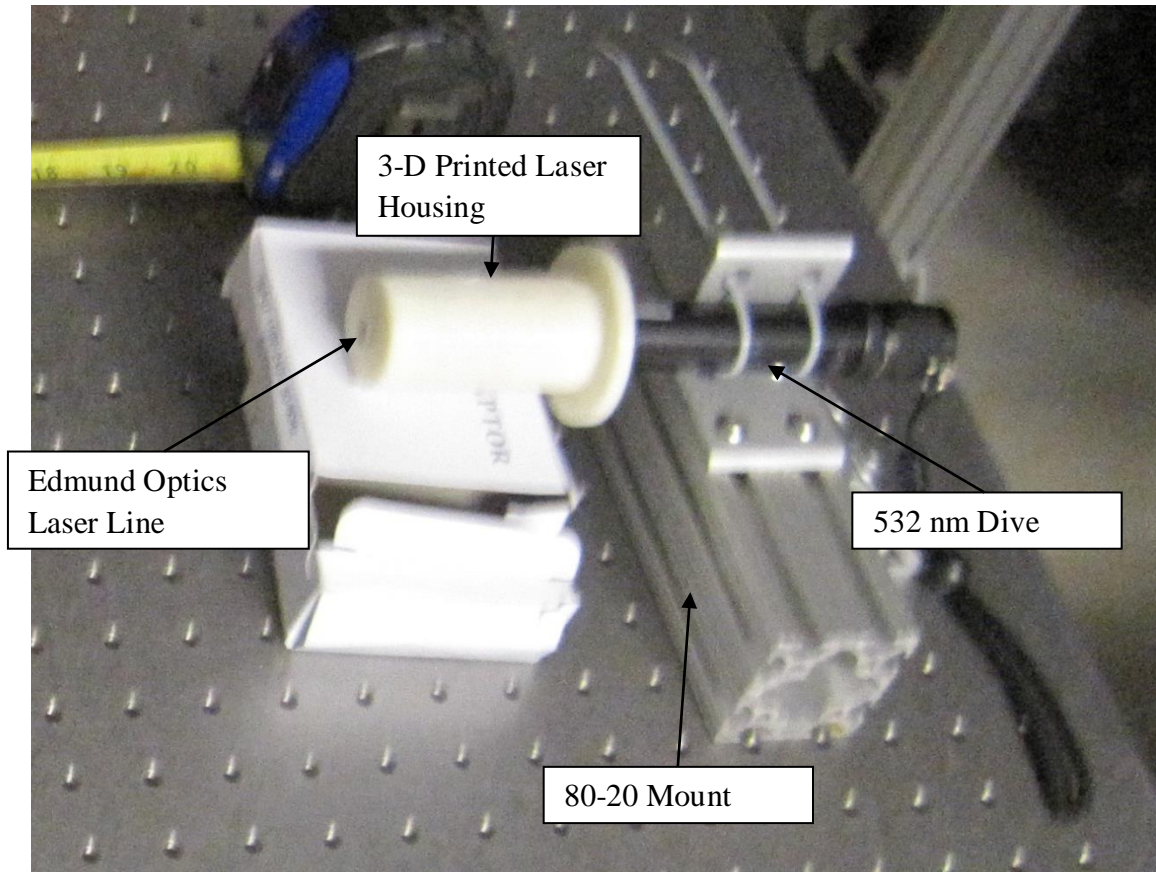
Setup:

Transmitter Unit:

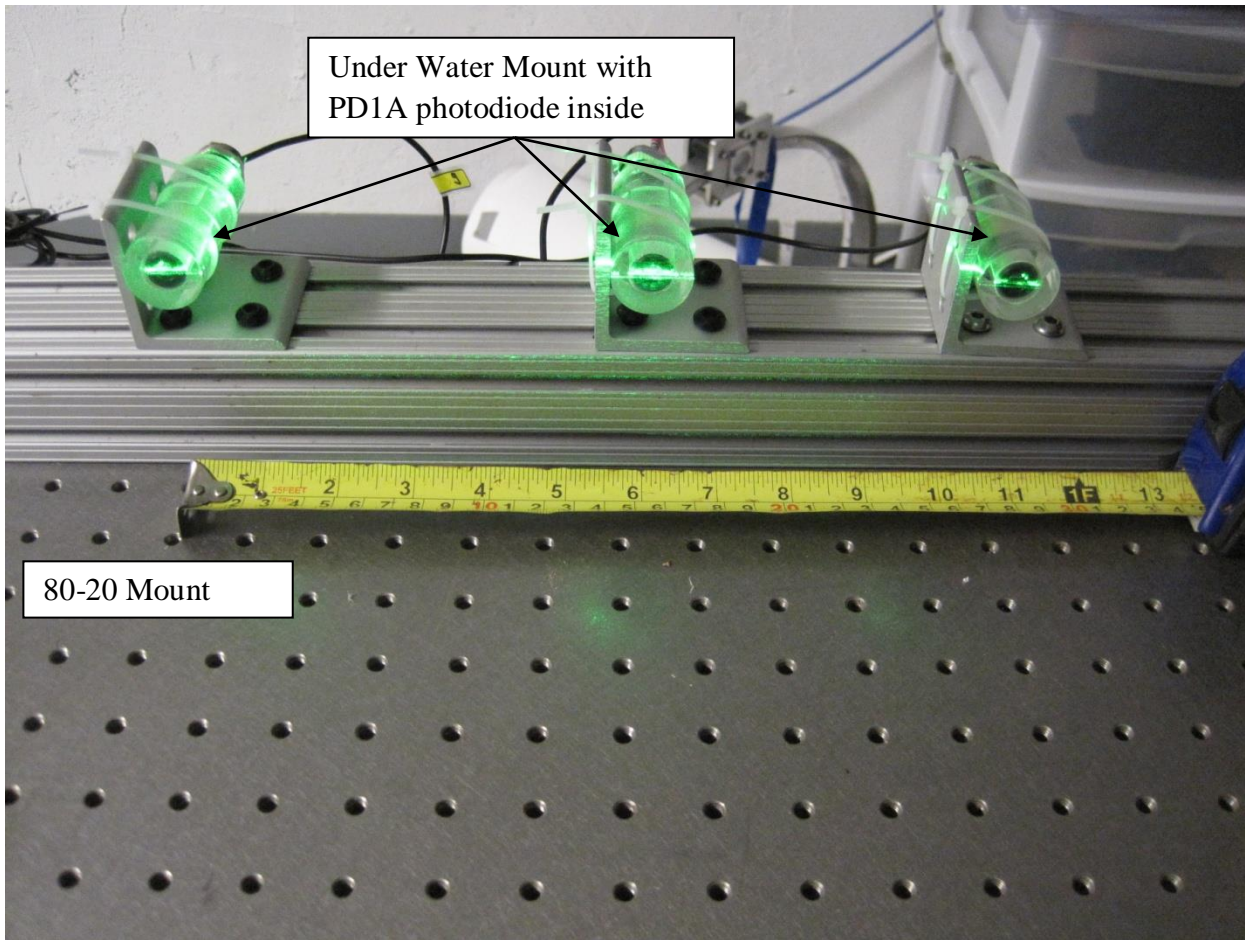FIGURE 43 - TRANSMITTER UNIT FOR 2-D AIR TEST

Detector Array:

FIGURE 44 - DETECTOR ARRAY FOR 2-D IN AIR TEST
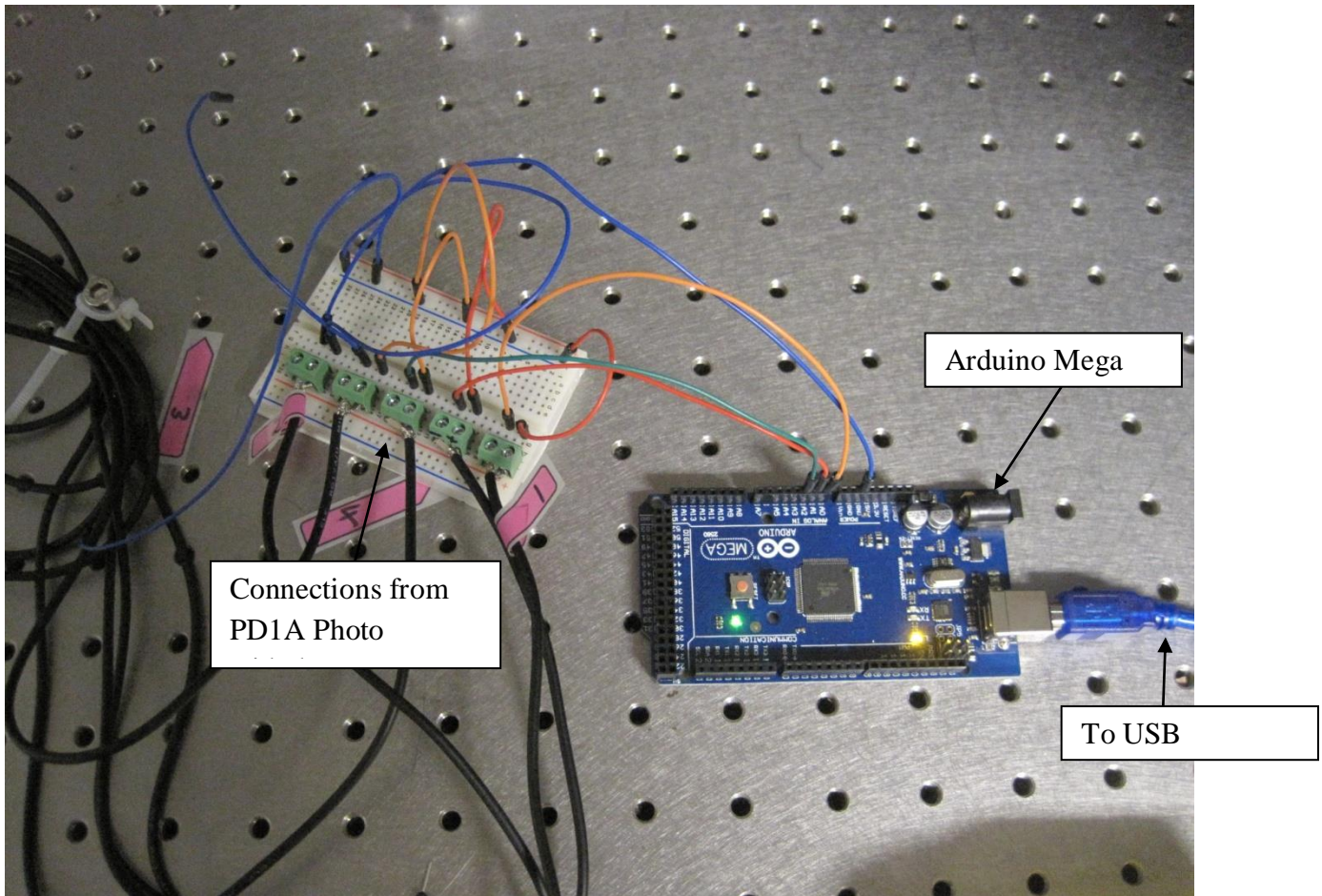
Photodiode to Computer Connection:

FIGURE 45 - INTERFACE BETWEEN PHOTO DIODES AND COMPUTER

Computer Interface:

```
int a0;
int al;
int a2;
int count=0;
int i=1;
void setup()
{
  Serial.begin(9600);
  Serial.println("CLEARDATA");
  Serial.println("LABEL,Time, A0,A1,A2,A3,A4,Degrees");
}
void loop()
{
  a0=analogRead(A0);
  al=analogRead(Al);
  a2=analogRead(A2);

  Serial.print("DATA,TIME,");
  Serial.print(a0);
  Serial.print(",");
  Serial.print(al);
  Serial.print(",");
  Serial.print(a2);
  Serial.println("\n");
  delay(100);
  count++;
 if (count == 30) // take  data points
  {
    count=0;
     Serial.println("ROW,SET,2");
     }
    i=i+1;
}
void fin(){
Serial.end();
}
```

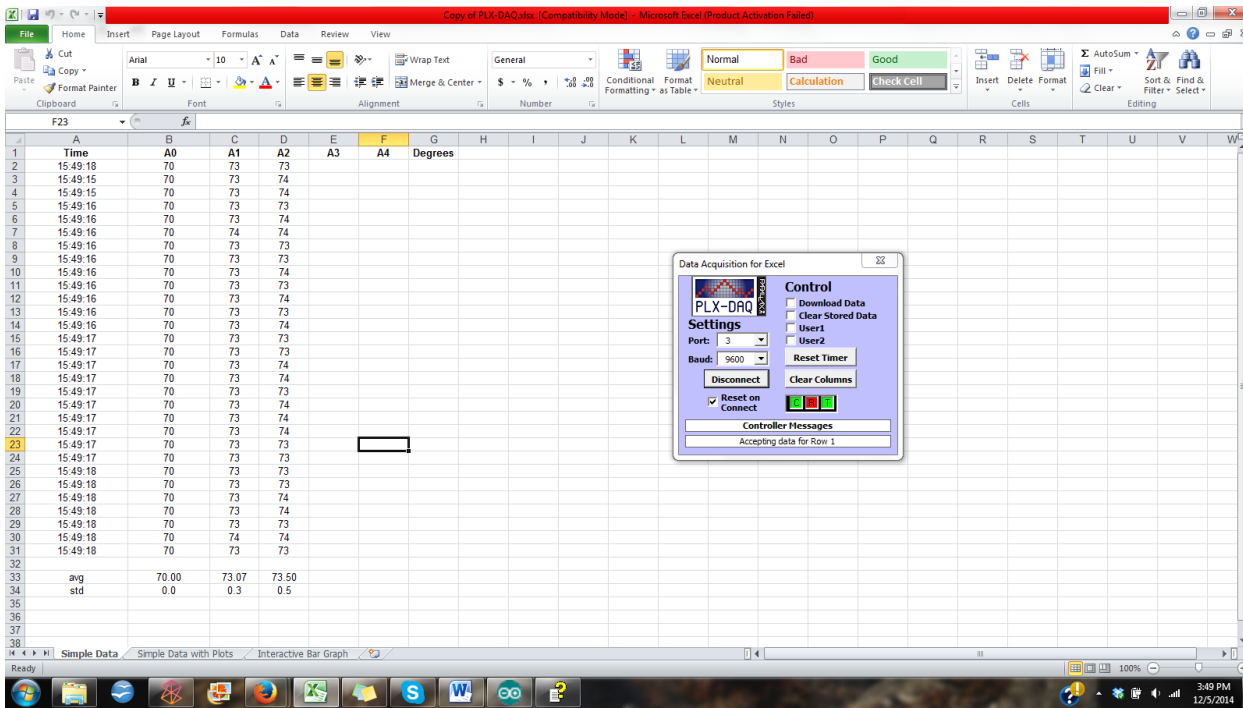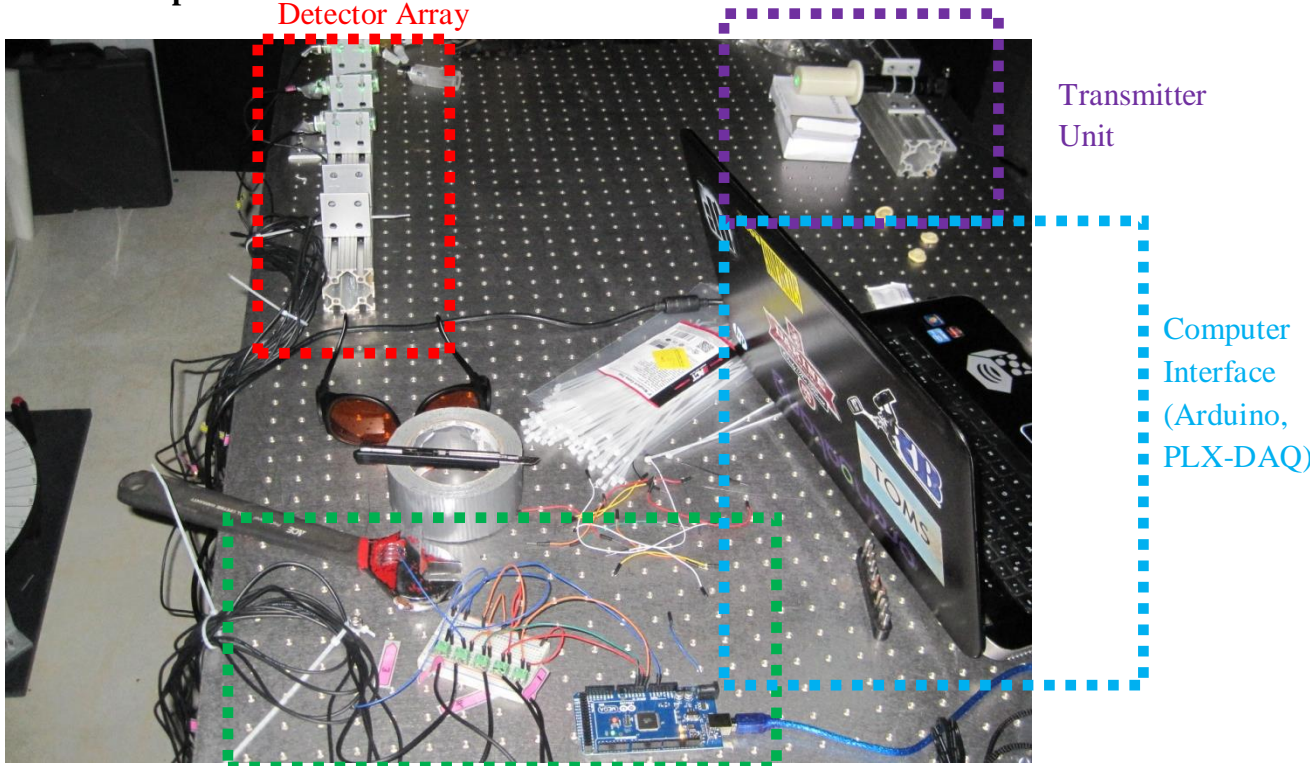FIGURE 46 - ARDUINO COMPUTER CODE TO COLLECT DATA

FIGURE 47 - PLX-DAQ USED WITH ARDUINO TO COLLECT DATA IN REAL TIME

Download PLX-DAQ here: http://www.parallax.com/downloads/plx-daq

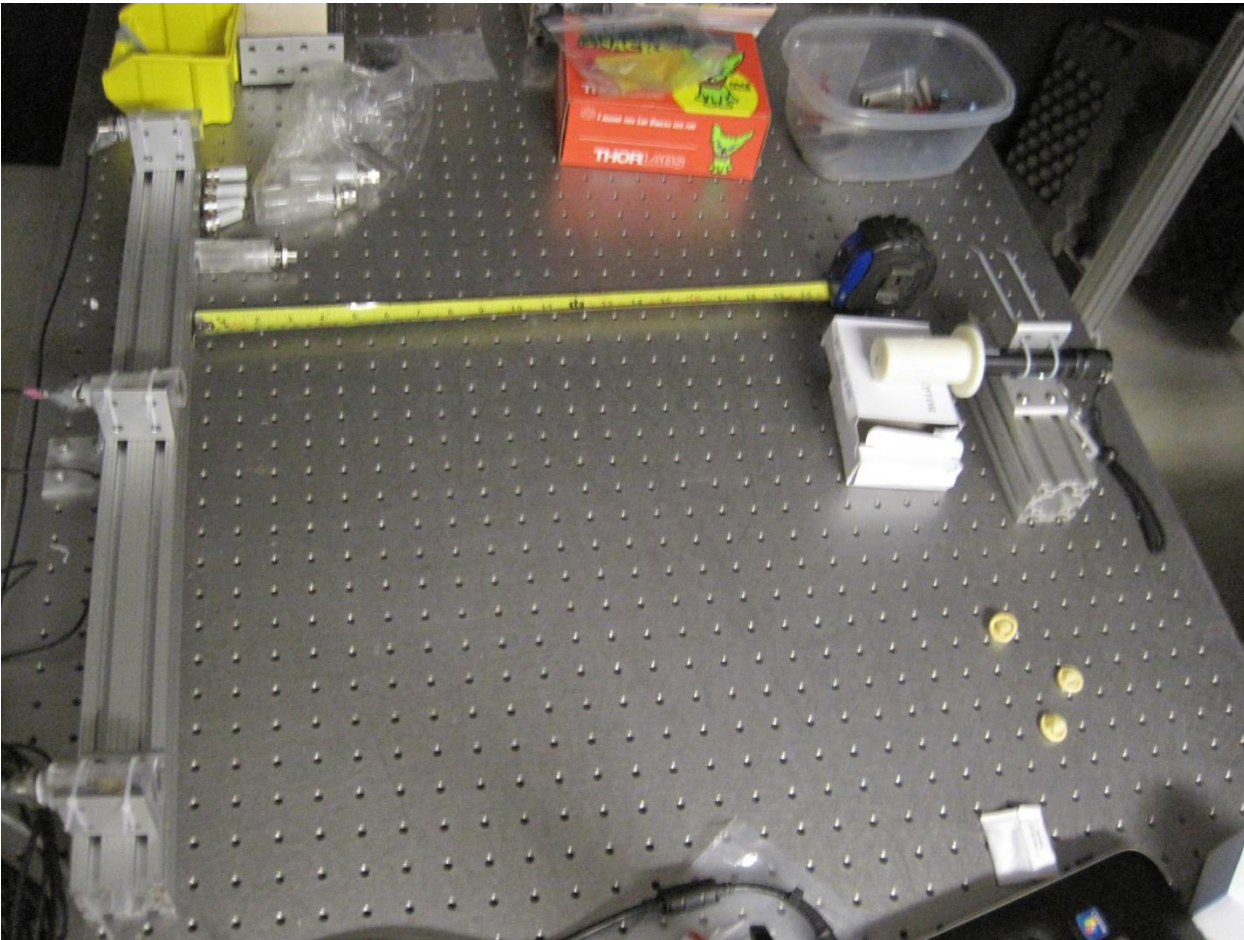**Overall Setup:**

Method:

All Tests

FIGURE 48 - OVERALL SETUP SHOWING DISTANCE FROM TRANSMITTER UNIT TO DETECTOR ARRAY

All tests were conducted 20" from the output of the laser line generator to the photo detector array. All measurements were conducted with the overhead lights off.
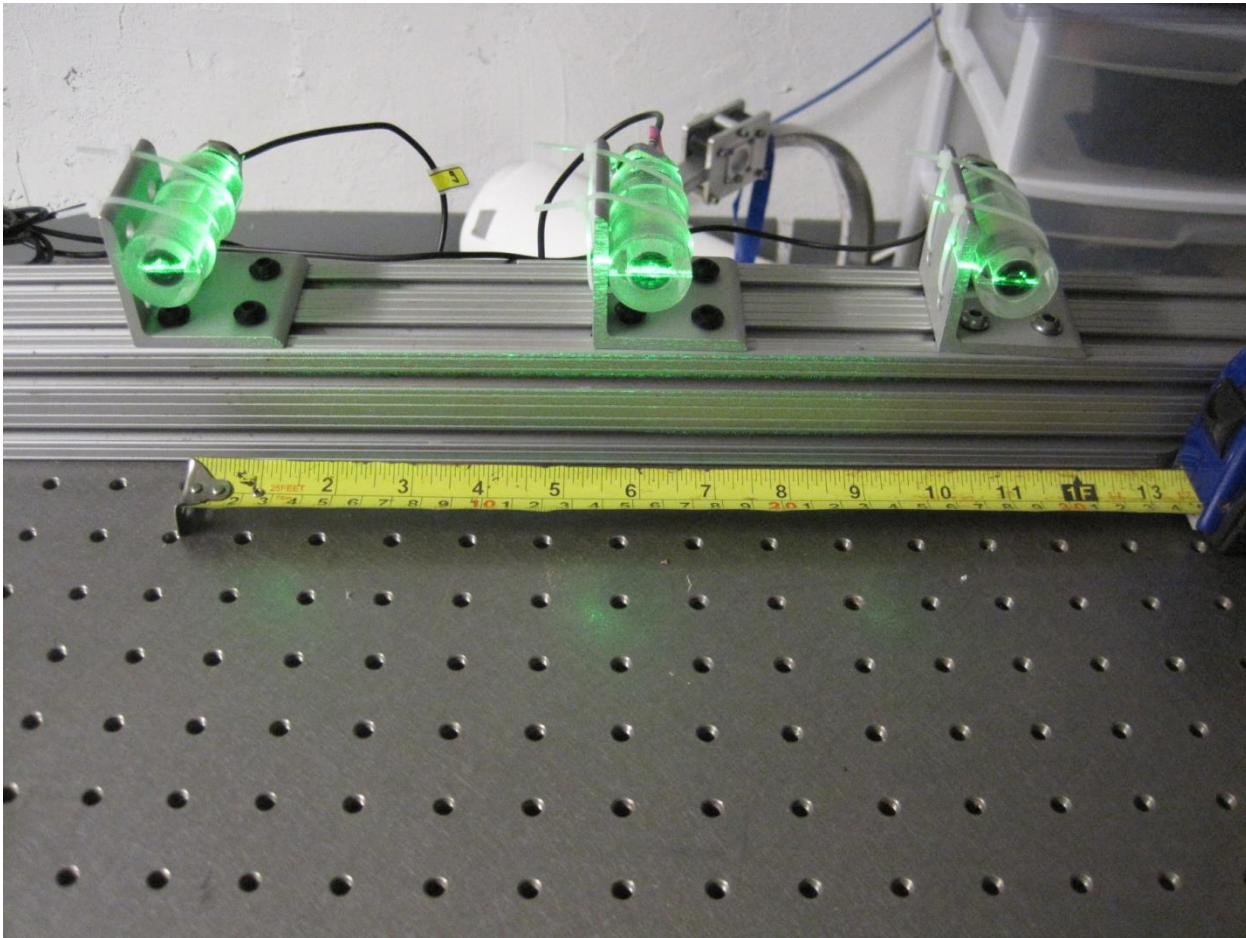
Test 1

FIGURE 49 - PHOTO DETECTOR IN SIGHT OF LASER LINE GENERATOR FOR TEST 1. 1 DETECTOR IS IN MIDDLE AND THE OTHER TWO ARE AT OPPOSITE ENDS

The reference measurement for positions along the photo detector array is that the left side of the beam at 20" away from transmitter unit. The middle detector was placed in alignment with the placement of the laser.

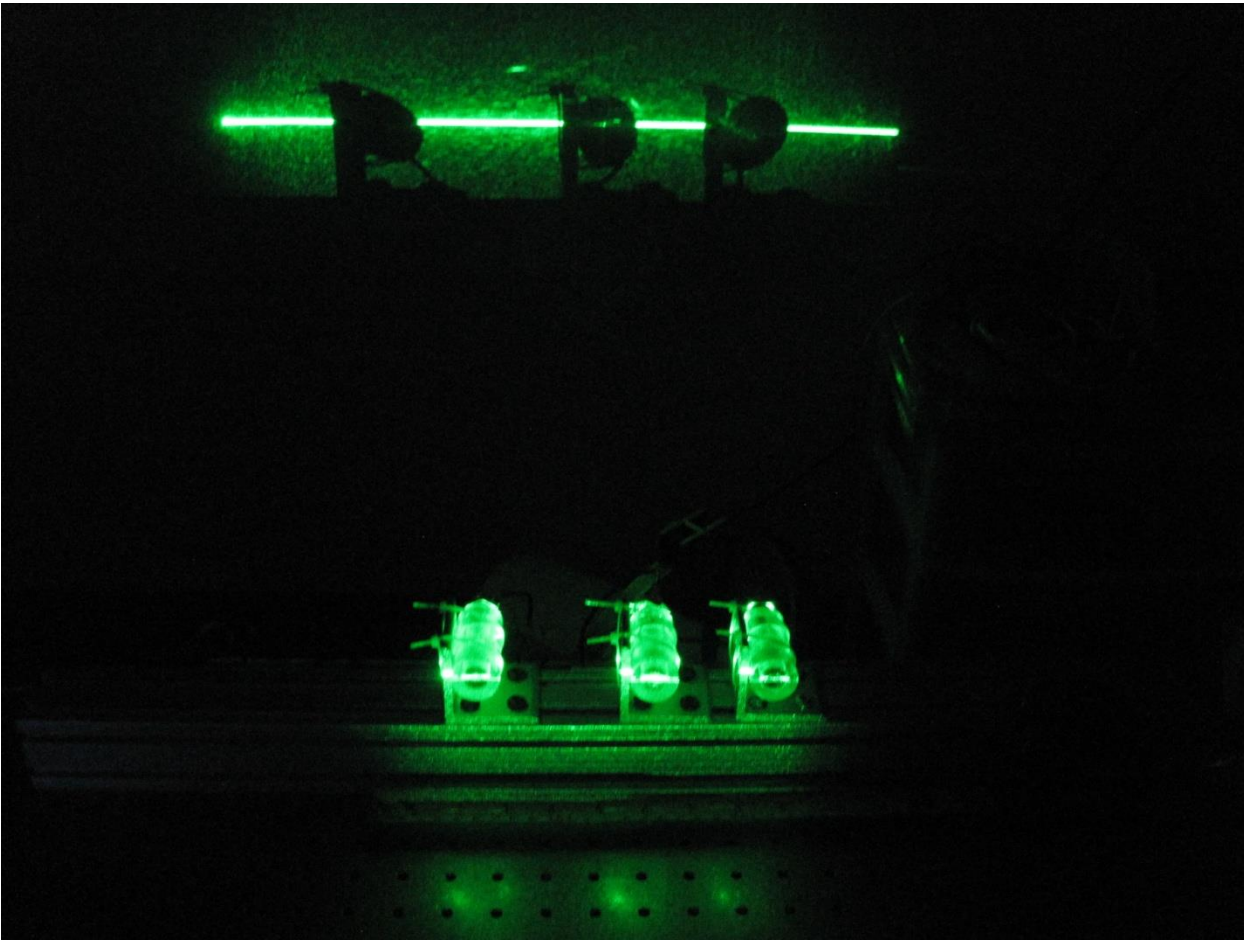| 12/5/2014	Test 1		
	PD 1 (A0)	PD 2 (A1)	PD 3 (A2)
Dark Average (3 second)	19	20	22.7
Laser Line Average (3 Seconds)	70	74	79
inchs Distance	0	6	10.5

Test 2

FIGURE 50 - THE PHOTO DETECTOR ARRAY WITH INCIDENT LASER LINE GENERATED AND SHADOW ON WALL BEHIND. TTHE OUTMOST DETECTORS WERE MOVED IN 2" EACH FROM TEST 1.

	Test 2		
Dark Average (3 second)	20	21.1	23.8
Laser Line Average (3 Seconds)	72	73.6	72
inchs Distance	2	6	8.5

Test 3

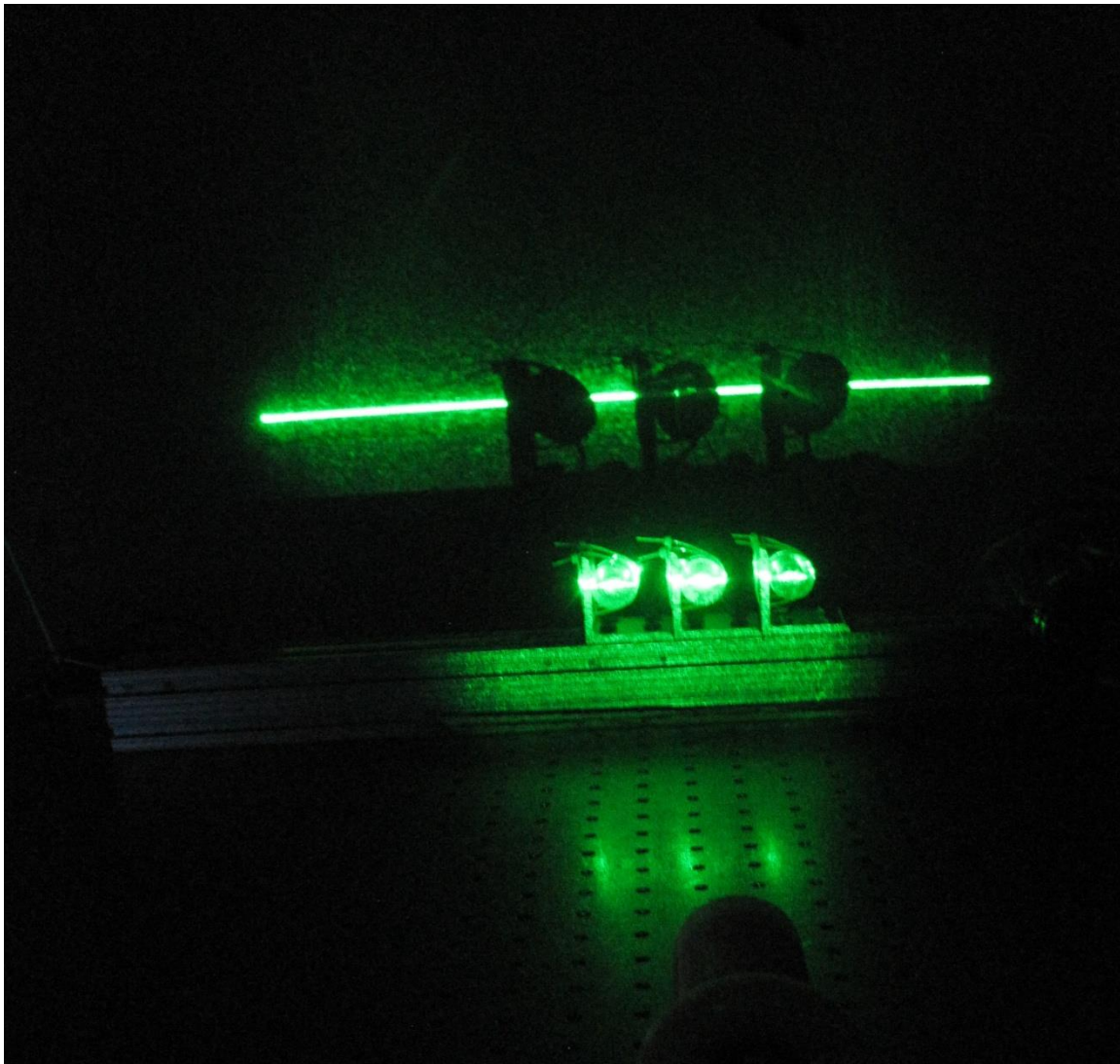FIGURE 51 - THE PHOTO DETECTOR ARRAY WITH INCIDENT LASER LINE GENERATED AND SHADOW ON WALL BEHIND. TTHE OUTMOST DETECTORS WERE MOVED IN AS FAR AS POSSIBLE AND CENTERED ON LASER LINE GENERATOR.

Dark Average (3 second)	20.1	21.1	22.4
Laser Line Average (3 Seconds)	72	73	71
inchs Distance	4	6	8

Condensed Results:

12/5/2014	Test 1

	PD 1 (A0)	PD 2 (A1)	PD 3 (A2)
Dark Average (3 second)	19	20	22.7
Laser Line Average (3 Seconds)	70	74	79
Distance from reference (inches)	0	6	10.5
	Test 2		
Dark Average (3 second)	20	21.1	23.8
Laser Line Average (3 Seconds)	72	73.6	72
Distance from reference (inches)	2	6	8.5
	Test 3		
Dark Average (3 second)	20.1	21.1	22.4
Laser Line Average (3 Seconds)	72	73	71
Distance from reference (inches)	4	6	8

Discussion:

The laser line generator produces responses in the photo detectors about 30% than just the beam alone. The measurements of the incident power from the laser line generator over 20" are large enough that when propagated over the distance of the proposed test in the ocean wave and tow tank the photo detector will be able to detect the incident power of the laser beam. The specifications of the edmund optics laser line generators are designed to attenuate the signal 20%. In the experiment the results show a 30% attenuation across the laser line. This could be due to imperfect alignment, both at the laser line generator end, or the detector array end. The percent change from farthest point of laser line to center in the 1024 bit response is about 5% for photodiode HS-1. For Hs-3 the percent change is about 7% with the high powered measurement on the outside. This could be due to imperfect alignment issues and reflections of the housing.

Conclusion:

The 532 nm Z-bolt laser and Edmund optics laser line generator are sufficient to conduct tests in the Ocean Wave and Tow tank.

Notes:
The laser pulses sometimes between high power and low power. This could be due to recent stress to the laser that cracked the front lens, and rendered it no longer water proof. The laser line was not perfectly aligned, there could be more tests to quantify this. The cables Firat ordered work very well. The next step is to JB weld the laser into the 3-D printed housing, rendering it a relatively permanent water tight housing. An important step is to secure the laser line generator inside so it does not rotate.

Abstract:

Silicone photodiodes measure incoming relative irradiance in numerous environments. In this experiment silicon photodiodes were used to interpret the relative irradiance emitted from a laser at a set distance away.

The sensitivity and temperature dependence of the photo diode must be known to accurately interpret the power of the incident laser beam. In this experiment a 532 nm laser with variable power output was used to find the sensitivity of the Thorlabs PD1A photodiode. The laser was also used in conjunction with a temperature controlled water bath to determine the dependence of quantum efficiency on the temperature of the diode. Finally a method of correcting the voltage output for changes in temperature was created to allow for accurate measurements outside of STP conditions.

Introduction:

The calibration of the Thorlabs photodiode will allow the voltage output from the diode to be converted into a meaningful value that describes the power of the light shining on the photodetector. The PD1A is a silicone photodiode with working range in the visible light spectrum (300-1000nm), with a housing and circuit. Connecting the PD1A to a load resistance allows the voltage output of the system to be measured. Once the photodiode is calibrated, the voltage output can be converted into a corresponding value that represents the wattage of the incoming light.

The value of this incident power measurement is important for several ongoing projects including the Harbor Security project and a Light Guided AUV System.

The Harbor security project is Matt Birkebak and Tim Brown's senior tech 797 project. The problem is as follows; Commercial, Military, and Submarine traffic through Portsmouth harbor (New Hampshire, USA) must be constantly tracked and recorded for identification of rogue vessels entering the harbor and provide information to aid in harbor maintenance and upkeep. The method examined in a proof of concept design is to monitor traffic through Portsmouth Harbor via a laser gate. The laser gate incorporates pulsed 532 nm lasers as the transmitter unit and arrays of photo detectors as the detector array. The idea of the project is an extrapolation of recent work in Lidar (Light Detecting and ranging). Lidar is a method of shining a laser down onto a surface and measuring the time it takes for the laser to reflect. The time it takes the light to travel can be used to calculate distances away from laser to surface or in ocean mapping depths. Through many well documented experiments the best wavelength for water column penetration is 532 nm. In the Harbor Security Project the laser gate will be able to detect a passing ship when the ship blocks the pulsed laser from reaching the photo detector. The photo below shows a water test of the proof of concept with the transmitter unit and the detector unit.

PHOTO 1: UNH OCEAN WAVE AND TOW TANK. 1 DIMENSIONAL TEST OF DETECTOR UNIT AND TRANSMITTER UNIT IN WATER.

The detector array uses a Thorlabs PD1A silicone photodiode. The photodetectors are connected to the analog inputs of an arduino and fed through a USB into a computer. The sensitivity of the photodiode in terms of (V/W) is highly desirable for the project because the sensitivity of the photodiode is used to quantify the incoming power of the laser. This can be especially useful when there is excess debris in the water column and the laser is scattered to a point where it may resemble being blocked. The connection between output voltage and incoming laser power is important. In addition, silicon photodiodes are known to change quantum efficiency due to temperature changes. Temperature changes in Portsmouth harbor can be due to seasons, time of day, or industrial/boat heat waste. The temperature dependence of the PD1A photodiode must be known to have a more accurate ability to quantify output voltage to incident laser power.

This work is also important for a system designed to guide an automated underwater vehicle to its docking station. The vehicle will have a spherical array of photodetectors on its front. It will use a light source mounted on docking rig to aid in guiding the vessel. The system must be able to determine which photodiodes are detecting a source bright enough to be the docking light. The project is being conducted by PHd student Firat Eren and in the project he will be using the same PD1A photodiodes, connectors, and housings. The calibration of the photodiodes to a laser input as well as the temperature dependence will help Firat decrease error in detecting location of the AUV under water based on actual incident power of incoming irradiance.

The goals of this experiment are to quantify laser power on the PD1A photodiode by developing a calibration curve of a PD1A photodiode at 20 ˚C, and a correction for output voltage at temperatures between 20-70 ˚C.

Background and Analysis:

Laser

There were two lasers used to calibrate the Thorlabs photodiode; a Continuum ND:YAG pulsed laser, and a Z-Bolt SCUBA underwater dive laser. Both lasers operate at 532 nm (green color). This wavelength is known to be best suited for underwater situations. In water the green and blue wavelengths transmit more due to waters light absorption properties.

The Continuum laser is a pulsed beam laser with variable power output. The light is created by exciting energy though a crystal ND:YAG rod. The energy released is then reflected between two parallel mirrors until the light passes through a small opening in one mirror. All light leaving the laser housing is nearly on a parallel path and is at a wavelength of 532nm (green light). This laser is stated to have a maximum power output of 12mW. The range used in this experiment is 1mW to 9 mW.

The Z-Bolt SCUBA underwater laser is a waterproof laser pointer. This laser has a small laser diode that produces light at 532nm. There is a lens in front of the diode that helps to focus the light beam and prevent the beam from expanding. This laser is known to have a 4mW power output.

Photodetector Sensitivity Calculations

In this experiment the photodetector, a Thorlabs PD1A Silicone photodiode, was calibrated. Photodiodes can convert light into a current that can be measured. The incident photons excite electrons in the silicone of the photodetector, and these electrons in turn begin to flow and produce current. The voltage output of a photodiode is dependent on several factors including the incident light power, the quantum efficiency of the silicone diode, the temperature of the silicone, and the construction of the associated electrical circuit. The following figure shows the electrical diagram for the Thor Labs PD1A Photodiode. The current produced by the photo detector flows through the circuit and the load resistor is used to measure a voltage output that corresponds to the amount of light that is measured.
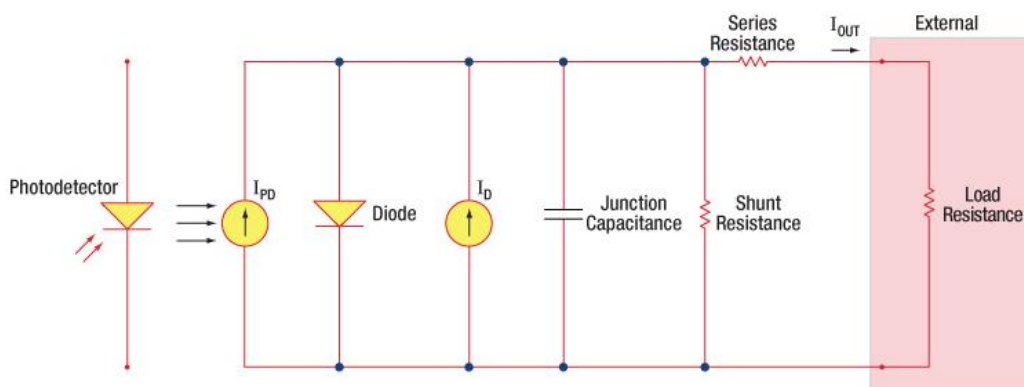

FIGURE 52: ELECTRICAL MODEL OF PHOTODIODE CIRCUIT

The sensitivity of the photodiode describes the change in voltage output for a change in the incident power of the light. Often this value is dependent on the wavelength of the light being measured. Equation 1 provides a method to calculate the voltage output of the photodiode.

$$V_o = P \times \Re(\lambda) \times R_l$$

<div align="center">EQUATION 1</div>

Where P is the incident power in Watts, $\Re(\lambda)$ is the responsivity of the diode at the given wavelength in units of amps/Watts, and R_l is the resistive load placed on the circuit in ohms(Ω), that provides the voltage drop for the measurement.

The Thorlabs PD1A used in this experiment contains an FDS 100 diode, which has a predefined curve for responsivity from the manufacturer provided in figure 2. The responsivity relates amperage produced by the photodetector to the power in watts of the light source. All tests are intended to be done with a green laser at 532 nm therefore the specific value of responsivity can be found from Figure 53: Thorlabs Responsivity Curve.
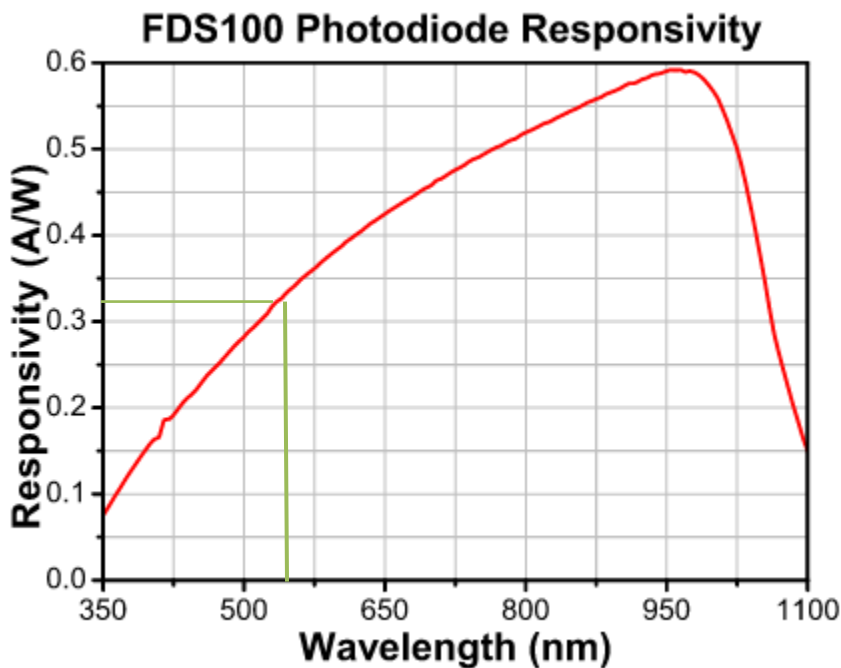
FIGURE 53: THORLABS RESPONSIVITY CURVE (WWW.THORLABS.COM)

It is known that to find the sensitivity the a relationship between voltage output and power input must be established. Equation 1 can be arranged to find a relationship between voltage output and power input.

$$\frac{V_o}{P} = \Re(\lambda) \times R_l$$

<div align="center">EQUATION 2</div>

Where, $\frac{V_o}{P} = sensitivity\ (\frac{Volts}{Watt})$

From the manufacturers plot it is known that responsivity is .32 A/W at a wavelength of 532 nm.

Also knowing that the load resistance of the Tectronix Oscilloscope to be used is 50Ω, the sensitivity can be calculated.

Using the relationship in equation 2, the resulting sensitivity of the system should be 16 V/W.

Thermal Calculations

The responsivity curve for this silicone diode is valid only for a specific temperature, 20 ˚C. For STP (20 ˚C,101.3kPa) the analytical sensitivity was found to be 16V/W. It is known that as the temperature of the photodiode varies the optical properties of silicone change and that for any specific wavelength (λ) the responsivity will change (3. Quantum Efficiency). Typically, blue and green wavelengths responsivity decreases with increasing temperature, while red and yellow wavelengths are the opposite.

This change in responsivity is proportional to the change in quantum efficiency. Quantum efficiency is defined as a percentage of the total incident light that a photodiode converts to measured current. Equation 3 gives the relationship for quantum efficiency

$$\%QE = \frac{\#\ photons\ converted}{\#total\ photons}$$

EQUATION 3

The quantum efficiency relates the amount of photons that trigger current flow from the photodiode to the total number of photons that contact the diode surface. For the PD1A photodiode the quantum efficiency is stated to be 75%. The quantum efficiency can also be calculated from the responsivity at a specific wavelength as shown in equation 4

$$\%QE = \frac{1.24\times10^5\times\Re_\lambda}{\lambda} \implies \Delta\Re_\lambda = \frac{\lambda*\Delta QE}{1.24\times10^5}$$

EQUATION 4

For a typical silicon diode as used in the Thorlabs PD1A the quantum efficiency change per degree Celsius is a function of the wavelength (1. Photodiode Technology). Figure 3 shows this relationship. For room temperature the quantum efficiency is assumed to be 75%. From this plot it can be found that for laser light at 532 nm the quantum efficiency would change by .08% per degree. Using equation 4, the corresponding change in responsivity per degree Celsius is .0256(A/W). Using equation 1 with a resistance of 50Ω and value of 4mW for the laser power (the power of the laser pointer to be used) the theoretical change in voltage output per degree Celsius is -5mV.

The goal of the experiment is to measure the change in voltage output of the PD1A photo detector from temperatures ranging from 20 ˚C (Standard Ocean Water in Portsmouth Harbor) to 70 ˚C. This temperature range is large enough to develop a functional curve of the dependence of voltage output to temperature. The range of ocean water is only about 15 ˚C~30 ˚C. The temperature dependence of the photo detector can be then used to establish a voltage correction equation that can be used to calculate the actual incoming power. The actual incoming power values can then be used to aid in the avoidance of false detections in the harbor security system.
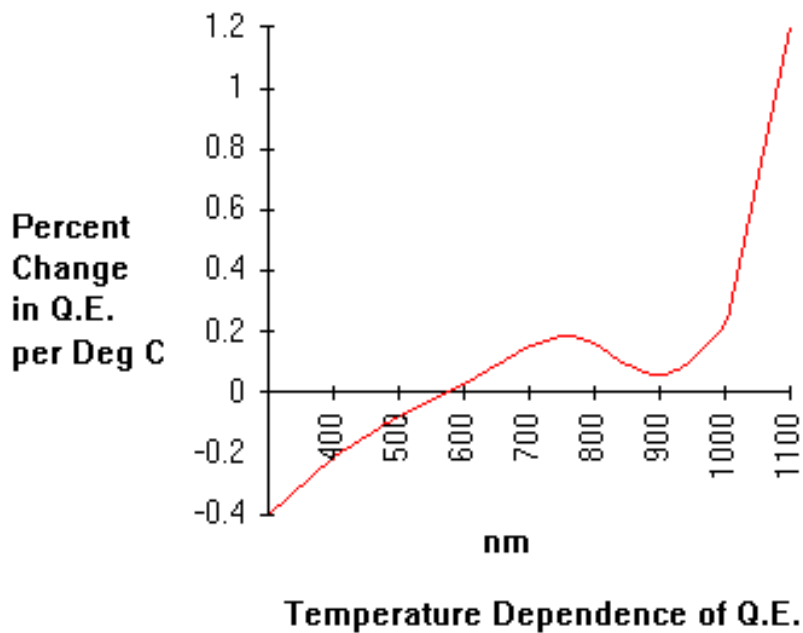
Temperature Dependence of Q.E.

FIGURE 54: TEMPERATURE EFFECT ON QE VS WAVELENGTH (3. QUANTUM EFFICIENCY)

Sensitivity Experimental Setup

The sensitivity calibration required the use of the ND:YAG Continnum Minilite 532nm laser. The power output as a function of the variable dial was calculated via an Ophir power sensor. The results pf the calibration of the the ND:YAG Continnum Minilite 532nm laser are shown in the results. The laser beam was aimed at the Thorlabs PD1A Silicone Photodiode with the use of a fiber optic cable. The distance from output of fiber optics cable to the photodiode is 10 cm because it is the focal length of the fiber optics cable. Figure 4 shows the configuration for this part of the experiment. The laser was allowed to warm up for 5 minutes before use. The laser was pulsed at 1Hz at the photodiode at 4 different settings of the dial corresponding to different power outputs. Figure 5 shows the dial on the laser that allows the power output to be controlled. On each setting of the laser 9 different responses were captured on a Tectronix Td1200 Oscilloscope. The oscilloscope was set with a load resistance of 50Ω and sampled at 10kHz. The waveforms collected at each power level were averaged to produce a mean voltage output associated with the incident power.
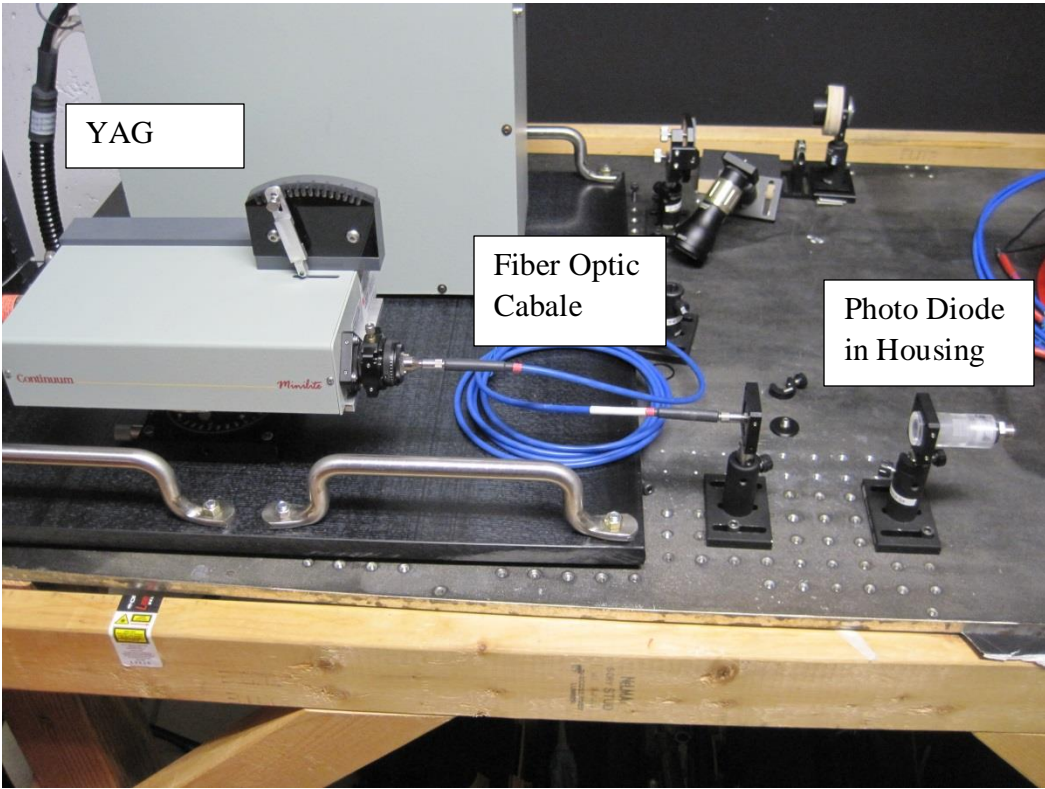
FIGURE 55: SENSITIVITY EXPERIMENT SETUP
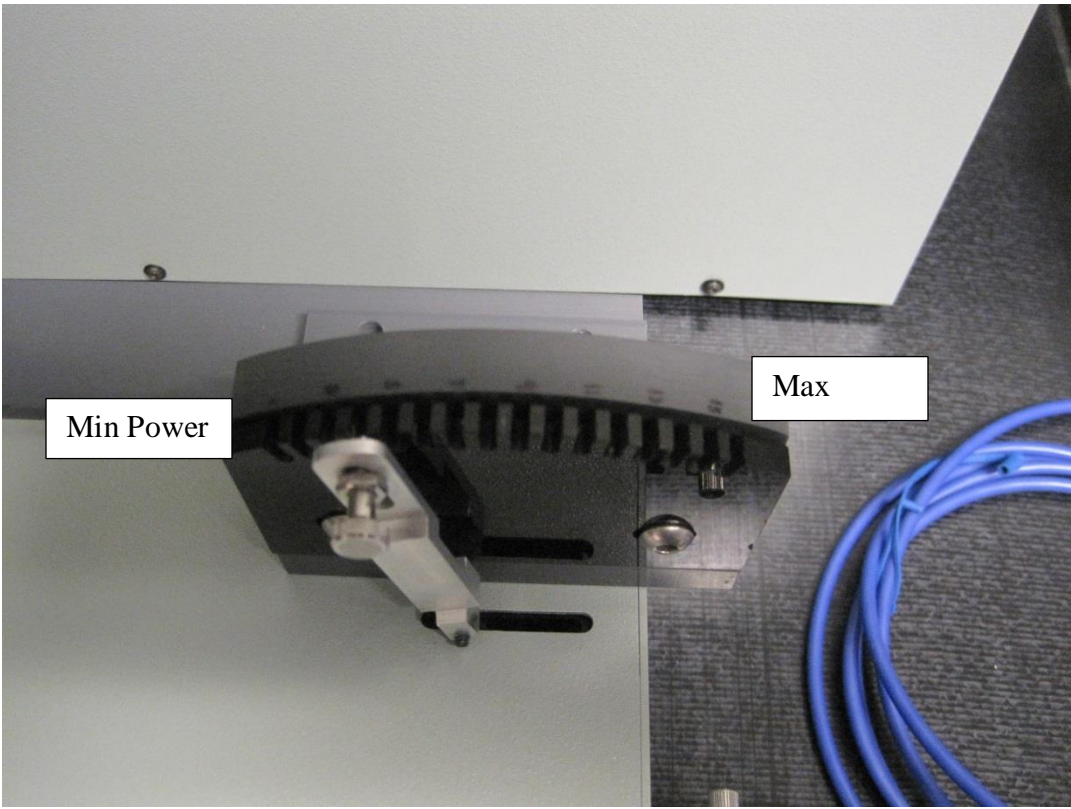
FIGURE 56: POWER DIAL

Thermal Experimental Setup

The thermal properties of the PD1A were also measured. The first step was to calculate the thermal time constant of the photodiode and its water proof housing. To do this a k-type thermocouple and amplifier were used. The tip of the thermocouple was threaded into the waterproof housing and pressed against the silicone diode. The amplifier connecting the thermocouple to the oscilloscope allowed for 1mV being equal to a .1 ˚C change. The waterproof housing system was dropped into a NESLAB RTE water bath held at 70˚C once it had reached air steady state temperature. The output of the thermocouple was monitored with a NI PXI 5142 Oscilloscope until the system reached steady state inside the 70 ˚C water bath.

The water proof housing and connection needed to be designed and constructed to be water proof. The water proof housings are made from acrylic. The properties of acrylic are such that most of the incident light passes through without scattering. A cylindrical piece of acrylic was drilled down the middle and threaded on one end. On the top of the acrylic cylinder a circular piece of acrylic was glued in place. On the bottom a water tight connection was used to seal the cable interface. Teflon tape was used between the threads of the housing and the metal connections. The concept and construction of the waterproof housing was done by Paul Lavoie, the machinist in the Jere Chase Ocean Engineering building. A photo can be seen in the Appendix.

To collect data of voltage output over changing temperature the PD1A and waterproof housing were placed in the RTE water bath. A small laser pointer with constant power output known to be 4mW was shined from above the water onto the silicone diode. Figure 6 shows the setup of this test.
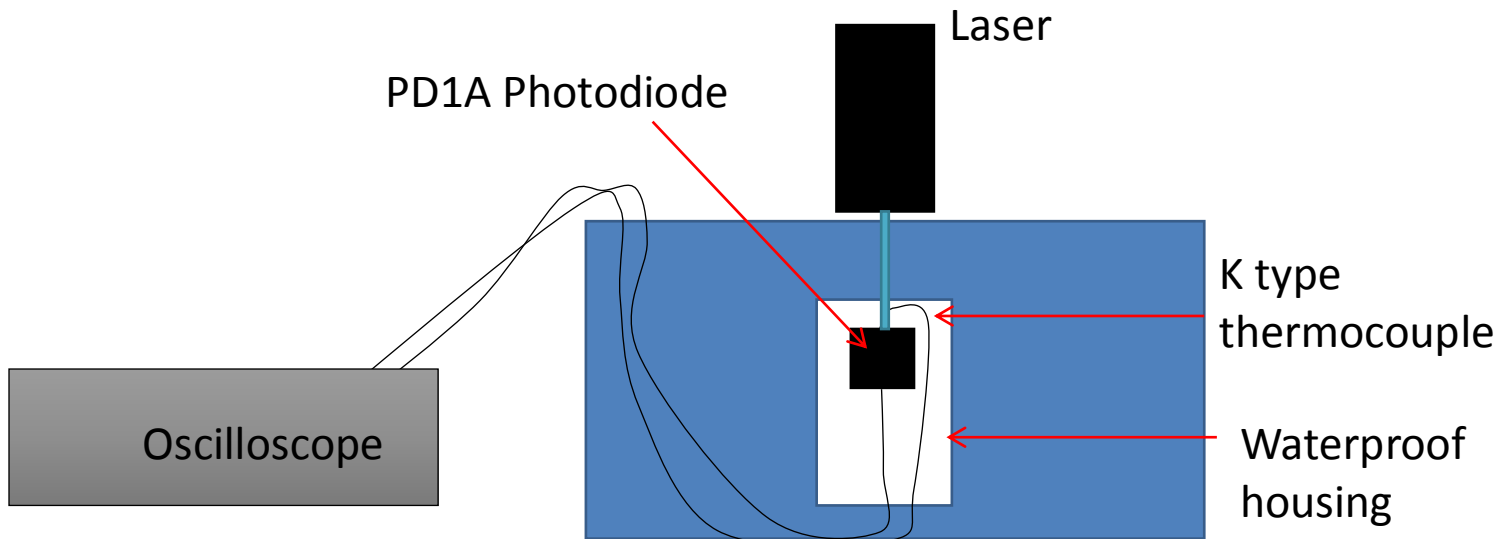

FIGURE 57: POWER OUTPUT FROM THE OPHIR POWER SENSOR

The laser provided constant incident light while the temperature of the water was increased from 20˚C to 70˚C in increments of 10 degrees. At each temperature the system was allowed to come to thermal steady state before the voltage output of the photodiode was measured. ANI PXI 5142 Oscilloscope was used with a 50Ω load resistance. The averaging function was used when collecting the voltage output data. Figure 7 shows an example of how the system was configured.
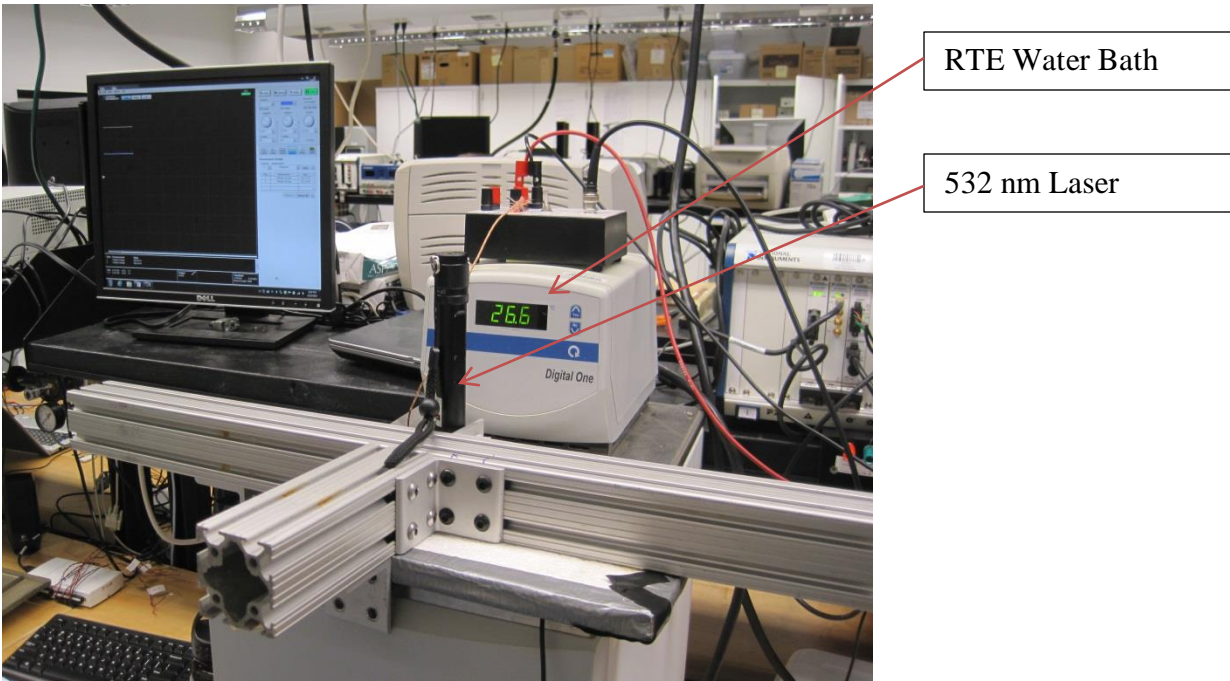
FIGURE 58: RTE WATER BATH

Results and Discussion:

Laser Power Calibration

The first step in the calibration process is to measure the power output of the ND YAG Continnum Laser. Plot 7 shows the power response as collected from the Ophir PD-300 laser power sensor. This sensor gave provides the laser power output in Watts. Beyond a dial setting of 11 it appears that the laser power sensor was saturated and measurments could not be taken. For this reason only measurments at or below a setting of 11 were used for the experiment. The laser was pulsed for 5 minutes at 1Hz while the sensor collected power measurments. The power over the collection period was then averaged to determine the power outpur for a given value on the dial.
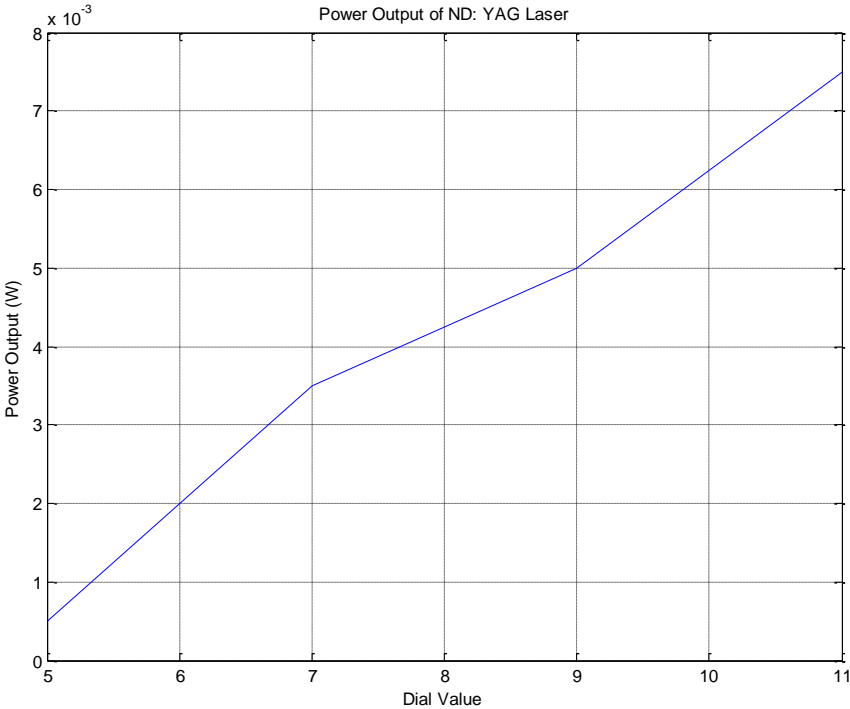
FIGURE 59: POWER OUTPUT FROM THE OPHIR POWER SENSOR

Sensitivity of PD1A Photodiode

Photodiode Voltage Output vs. Incedent Power
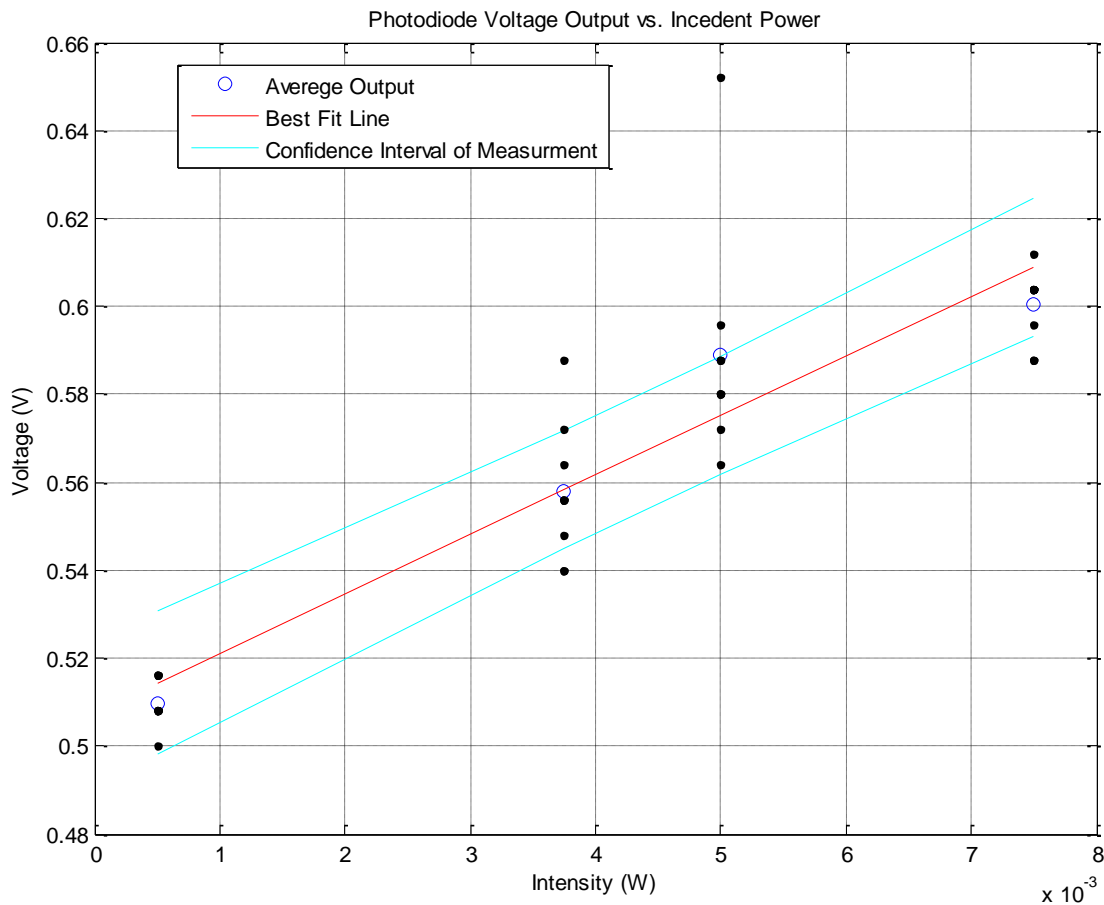
FIGURE 60: SENSITIVITY OF PHOTODIODE

The next test involved aiming the laser directly at the photodiode at a distance of 10cm due to the focal length of the fiber optics cable used(See figure 4). At each dial setting with a known power output, nine data points were collected and averaged. Figure 10 shows an example waveform of a laser pulse. The maximum value was used for the voltage output value. For these averaged values shown in Figure 9 a least squares fit was run on the data to produce a best fit line. The slope of this line represents the sensitivity of the laser in V/W and was found to be 13.53 V/W. The experimental value for sensitivity was found to be close to the analytical value with error of 15%. The blue lines in figure 9 represent the interval of confidence for the trend line; some data points are not in this interval and can be assumed to be outliers.
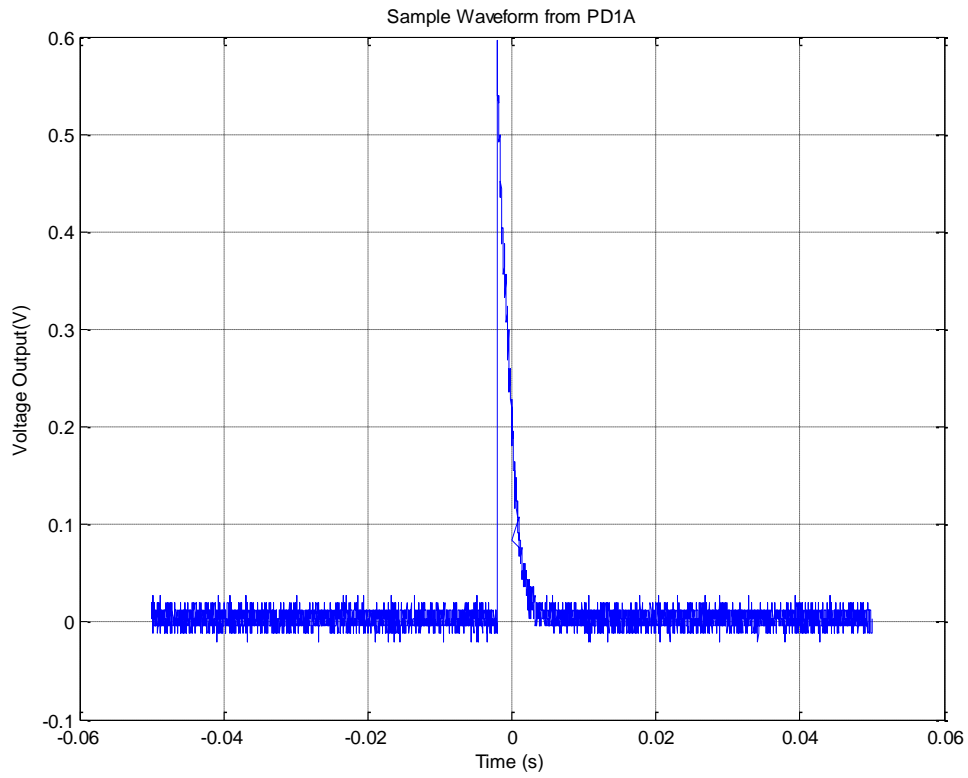
FIGURE 61: SAMPLE WAVEFORM

The results of the sensitivity calibration are presented in the table below.

	Sensitivity V/W
Analytical	16
Experimental	13.53
Error	15.625%

Thermal Time Constant
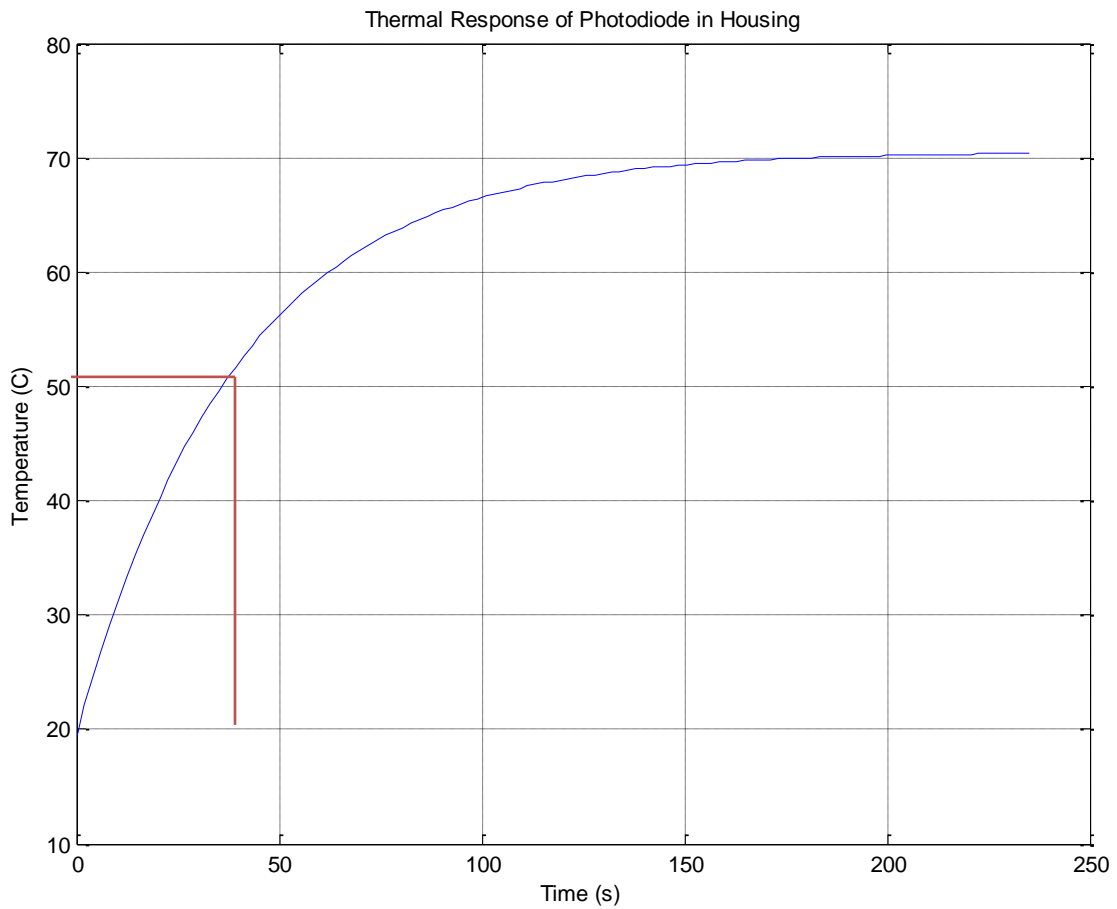
FIGURE 62: THERMAL TIME CONSTANT

To determine how long the photodiode and housing required to reach a specific temperature the thermal time constant was experimentally calculated. A k-type thermocouple was used to measure the temperature of the silicone diode. The system was allowed to come to steady state before then being dropped into 70 degree water. The voltage output of the thermocouple was recorded over time and was then converted to temperature as shown in figure 4 above. The thermal time constant was calculated to be 39 seconds, as shown in figure 11.

Time Constant	Time to Reach Steady State(4*T)	Mass of system	Sensitivity of Thermocouple
39 seconds	156 seconds	184 grams	10 mv/deg C

Thermal Temperature Dependence
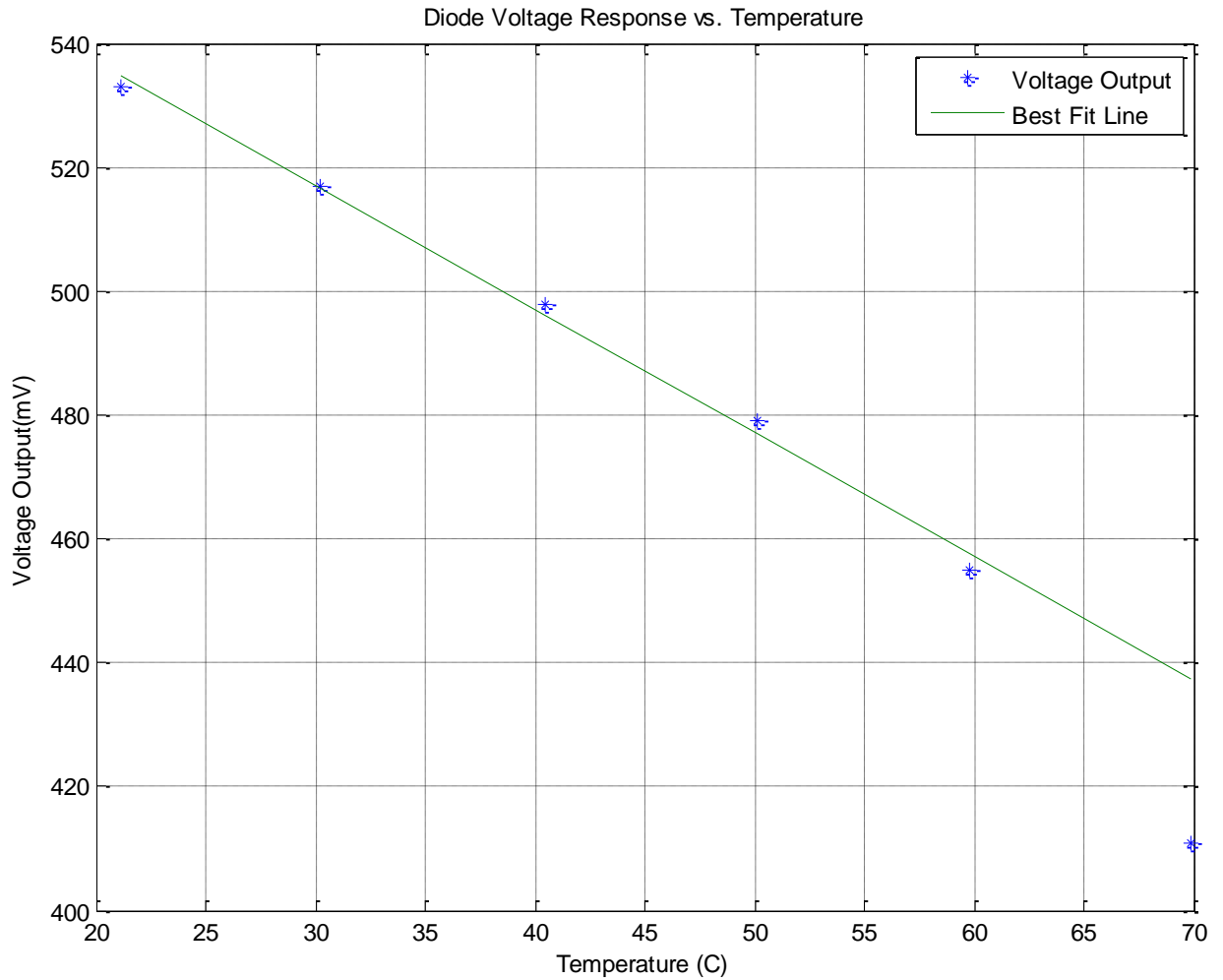
FIGURE 63: THERMAL DEPENDENCE

Data was collected from the photodiode at range of temperatures from 20 to 70 ˚C. For each measurement the system was allowed to come to equilibrium determined by the thermal time constant. A constant 532 nm laser power was incident on the photodiode. Figure 12 shows the data with the best fit line, it was noted that at the 70 ˚C measurement there was a build of steam in the water bath that significantly affected the amount of light reaching the photodiode. For this reason this data point was ignored when calculating the best fit line. It was found that the spectral sensitivity to temperature was -2mV/˚C. The equation for the fit line is a follows in mV.

$$Vo(T) = -2 * T + 576$$

EQUATION 5

	Voltage dependence	Responsivity	% Error

	(mV/C)	Dependence (A/(W*C))	
Analytical	-5	.02	60%
Measured	-2	.01	

Using this data and the fit line, data at any temperature that is not STP can be corrected back to standard temperature. The equation used to make this correction is as follows

$$V_{corrected}(T) = Vo(T) + (Vo(20) - Vo(T))$$

EQUATION 6

Where, Voltage (mV) and Temperature (Celsius)

With this equation the voltage output is corrected for temperature, and using the calculated sensitivity of 13.5mV/mW the incident power on the photodiode can be calculated.

Conclusion:

The actual incoming power from a 532 nm laser on a PD1A photodiode can be calculated at STP using a sensitivity of 13.5 V/W as well as a dynamic range of temperatures from 20 ˚C to 70 ˚C by correcting output voltage of the PD!A photodiode using Equation 6.

It was found that analytically with an increase in incoming power at 532 nm the voltage output of the diode will increase proportionally at 16V/W. The actual sensitivity measured was 13.5 V/W. The error between analytical and measured is reasonable because each individual PD1A photodiode will have a slightly different sensitivity.

If the waterproof housing is allowed to sit in the water bath for 3 minutes, the outside temperature of the water is the same as the temperature of the photodiode.

 It was found that analytically the temperature dependence of a silicon photodiode is -5 mV/deg (C). The actual measured temperature dependence of the PD1A photodiode was -2 mV/deg (C). The error between analytical and measured is reasonable because the analytical data was taken from a silicon photodiode curve independent of the PD1A. From the temperature dependence values a voltage correction equation was developed to correct in real time to be able to quantify the actual incoming laser power.

The next steps in terms of the Harbor Security project and Firats project is to add a thermocouple that measures the surrounding temperature of the detector array. Then to add the equation and temperature for voltage correction into the arduino code that interacts with the photodetectors.

Poster:

Arduino Sketch Collect Data

The following code is used to print out detector information to the serial port. Matlab was used for the final algorithm because a text file cannot be created and two arduinos cannot be used either without using linux command module and a beagle bone.

```
double distance_pd = 5;

int photocellPin = 0; // the cell and 10K pulldown are connected to a0
int photocellPin1 = 1;
int photocellPin2 = 2;
int photocellPin3 = 3;
int photocellPin4 = 4;

int detection = 0;

int dark0 = 0;
int dark1 = 0;
int dark2 = 0;
int dark3 = 0;
int dark4 = 0;

int i = 0;

int tick0 = 0;
int tick1 = 0;
int tick2 = 0;
int tick3 = 0;
int tick4 = 0;

int d0_1 = 0;
int d1_2 = 0;
int d2_3 = 0;
int d3_4 = 0;

double v0_1 = 0;
double v1_2 = 0;
double v2_3 = 0;
double v3_4 = 0;
double v_avg = 0;
```

```
int size0_1 = 0;

double time_step = 0; // 100 ms

int block0 = 0;
int block1 = 0;
int block2 = 0;
int block3 = 0;
int block4 = 0;

double block0_1 = 0;
double block1_2 = 0;
double block2_3 = 0;
double block3_4 = 0;

int switch0 = 0;
int switch1 = 0;
int switch2 = 0;
int switch3 = 0;
int switch4 = 0;

int exposed0 = 0;
int exposed1 = 0;
int exposed2 = 0;
int exposed3 = 0;
int exposed4 = 0;

int count_in  = 0;
int count_out = 0;
int counter = 0;

int reset0_1 = 0;
int reset1_2 = 0;
int reset2_3 = 0;
int reset3_4 = 0;

int det_reset1 = 0;
int det_reset2 = 0;
int det_reset3 = 0;
int det_reset4 = 0;
```

```
int exposed = 30;
int c_num   = 30;

int t_step = 20;
int num_2_avg = 10;
int read0; // the analog reading from the sensor divider
int read1; // the analog reading from the sensor divider
int read2; // the analog reading from the sensor divider
int read3; // the analog reading from the sensor divider
int read4; // the analog reading from the sensor divider
int readPrev; // the analog reading from the sensor divider

void setup(void) {
  Serial.begin(9600);   // We'll send debugging information via the Serial monitor so if you can
read it   without using a led
  Serial.println("CLEARDATA");
  Serial.println("Label,Time,1,2,3,4,5");
  Serial.print("Dark Calibration Keep Laser off, Turn Lights off");
  Serial.print("\r\n");
  delay(1000);
  Serial.print("Taking Dark Calibration");
  Serial.print("\r\n");
  delay(1000);
  dark0=analogRead(photocellPin);
  dark1=analogRead(photocellPin1);
  dark2=analogRead(photocellPin2);
  dark3=analogRead(photocellPin3);
  dark4=analogRead(photocellPin4);

  dark0=dark0+dark0*.5;
  dark1=dark1+dark1*.5;
  dark2=dark2+dark2*.5;
  dark3=dark3+dark3*.5;
  dark4=dark4+dark4*.5;
  delay(3000);
}
void loop(void) {

  read0 = analogRead(photocellPin);
```

```
       read1 = analogRead(photocellPin1);
       read2 = analogRead(photocellPin2);
       read3 = analogRead(photocellPin3);
       read4 = analogRead(photocellPin4);
// Establish Traffic In or Out


// Traffic


// Zeroth Detector
// Photo Detector Has Just been Blocked
       if(read0 < dark0 && switch0 == 0)
        {switch0 =  1;
         block0 = 1;
         block0_1 = 1;
         reset0_1 = 0;}


// Photo Detector is Blocked
       if(read0 < dark0 && switch0 == 1)
        {block0 = block0+1;}


// Photo Detector Has Just been Exposed
       if(read0 > dark0 && switch0 == 1)
        {switch0 = 0;
         exposed0 = 1;}


// Photo Detector is Exposed
       if(read0 > dark0 && switch0 == 0)
        {
          exposed0  = exposed0+1;
        }
// Count Between First Block and Second Block
       if(reset0_1 == 0)
        {
         block0_1 = block0_1+1;
        }
//////////////////////////////////////////////////////////
// First Detector
// Photo Detector Has Just been Blocked
       if(read1 < dark1 && switch1 == 0)
        {switch1 =  1;
```

```
    block1 = 1;
    reset0_1 = 1;
    block1_2 = 1;
    reset1_2 = 0;}


// Photo Detector is Blocked
   if(read1 < dark1 && switch1 == 1)
    {block1 = block1+1;}


// Photo Detector Has Just been Exposed
   if(read1 > dark1 && switch1 == 1)
    {switch1 = 0;
     exposed1 = 1;
     det_reset1 = 0;}


// Photo Detector is Exposed
   if(read1 > dark1 && switch1 == 0)
    {
      exposed1  = exposed1+1;
    }


// Determine Detection between zero and first detector
   if(switch1 == 1 && det_reset1 == 0)
    {
    if(switch0 == 1 || exposed0 < 40)
    {d0_1 = 1;
     v0_1 = distance_pd/(block0_1*(time_step/1000));
     det_reset1 = 1;
    }
    }


//Expire Detection between zero and first detector
   if(d0_1 == 1)
    {
    if(switch1 == 0 && exposed1 > 50)
    {d0_1 = 0;}
    }
// Count Between First Block and Second Block
   if(reset1_2 == 0)
    {
```

```
   block1_2 = block1_2+1;
   }
/////////////////////////////////////////////////////////////////////////////////////
// Second Detector
// Photo Detector Has Just been Blocked
   if(read2 < dark2 && switch2 == 0)
   {switch2 =  1;
    block2 = 1;
    reset1_2 = 1;
    block2_3 = 1;
    reset2_3 = 0;}


// Photo Detector is Blocked
   if(read2 < dark2 && switch2 == 1)
   {block2 = block2+1;}


// Photo Detector Has Just been Exposed
   if(read2 > dark2 && switch2 == 1)
   {switch2 = 0;
    exposed2 = 1;
    det_reset2 = 0;}


// Photo Detector is Exposed
   if(read2 > dark2 && switch2 == 0)
   {
     exposed2  = exposed2+1;
   }


// Determine Detection between zero and first detector
   if(switch2 == 1 && det_reset2 == 0)
   {
   if(switch1 == 1 || exposed1 < 40)
   {
   if(d0_1 ==1)
   {
   d1_2 = 1;
   v1_2 = distance_pd/(block1_2*(time_step/1000));
   det_reset2 = 1;
   }
   }
```

```
    }

//Expire Detection between zero and first detector
    if(d1_2 == 1)
    {
      if(switch2 == 0 && exposed2 > 50)
      {d1_2 = 0;}
    }
// Count Between First Block and Second Block
    if(reset2_3 == 0)
    {
      block2_3 = block2_3+1;
    }
/////////////////////////////////////////////////////////////////////////////////////
// Third Detector
// Photo Detector Has Just been Blocked
    if(read3 < dark3 && switch3 == 0)
    {switch3 =  1;
      block3 = 1;
      reset2_3 = 1;
      block3_4 = 1;
      reset3_4 = 0;}

// Photo Detector is Blocked
    if(read3 < dark3 && switch3 == 1)
    {block3 = block3+1;}

// Photo Detector Has Just been Exposed
    if(read3 > dark3 && switch3 == 1)
    {switch3 = 0;
      exposed3 = 1;
      det_reset3 = 0;}

// Photo Detector is Exposed
    if(read3 > dark3 && switch3 == 0)
    {
      exposed3  = exposed3+1;
    }

// Determine Detection between zero and first detector
```

```
    if(switch3 == 1 && det_reset3 == 0)
     {
     if(switch2 == 1 || exposed2 < 40)
      {
       if(d1_2 == 1)
        {
        d2_3 = 1;
        v2_3 = distance_pd/(block2_3*(time_step/1000));
        det_reset3 = 1;
        }
      }
      }

//Expire Detection between zero and first detector
    if(d2_3 == 1)
     {
      if(switch3 == 0 && exposed3 > 50)
       {d2_3 = 0;}
     }
// Count Between First Block and Second Block
    if(reset3_4 == 0)
     {
       block3_4 = block3_4+1;
     }
//////////////////////////////////////////////////////////////////////////////////
// Fourth Detector
// Photo Detector Has Just been Blocked
    if(read4 < dark4 && switch4 == 0)
     {switch4 =  1;
      block4 = 1;
      reset3_4 = 1;}

// Photo Detector is Blocked
    if(read4 < dark4 && switch4 == 1)
     {block4 = block4+1;}

// Photo Detector Has Just been Exposed
    if(read4 > dark4 && switch4 == 1)
     {switch4 = 0;
      exposed4 = 1;
```

```
    det_reset4 = 0;}


// Photo Detector is Exposed
   if(read4 > dark4 && switch4 == 0)
   {
     exposed4  = exposed4+1;
    }


// Determine Detection between zero and first detector
   if(switch4 == 1 && det_reset4 == 0)
    {
    if(switch3 == 1 || exposed3 < 40)
    {
     if(d2_3 == 1)
     {
     d3_4 = 1;
     v3_4 = distance_pd/(block2_3*(time_step/1000));
     det_reset4 = 1;
     detection = detection+1;
     v_avg = (v0_1+v1_2+v2_3+v3_4)/4;
     d0_1 = 0;
     d1_2 = 0;
     d2_3 = 0;
     d3_4 = 0;
     }
    }
    }

//Expire Detection between zero and first detector
   if(d3_4 == 1)
   {
    if(switch3 == 0 && exposed3 > 50)
    {d3_4 = 0;}
   }
delay(time_step);


   Serial.print(read0);
   Serial.print(",");
   Serial.print(dark0);
```

```
Serial.print(",");
Serial.print(switch0);
Serial.print(",");
Serial.print(block0);
Serial.print(",");
Serial.print(exposed0);
Serial.print(",   ");
Serial.print(read1);
Serial.print(",");
Serial.print(dark1);
Serial.print(",");
Serial.print(switch1);
Serial.print(",");
Serial.print(block1);
Serial.print(",");
Serial.print(exposed1);
Serial.print(",   ");
Serial.print(read2);
Serial.print(",");
Serial.print(dark2);
Serial.print(",");
Serial.print(switch2);
Serial.print(",");
Serial.print(block2);
Serial.print(",");
Serial.print(exposed2);
Serial.print(",   ");
Serial.print(read3);
Serial.print(",");
Serial.print(dark3);
Serial.print(",");
Serial.print(switch3);
Serial.print(",");
Serial.print(block3);
Serial.print(",");
Serial.print(exposed3);
Serial.print(",   ");
Serial.print(read4);
Serial.print(",");
Serial.print(dark4);
```

```
Serial.print(",");
Serial.print(switch4);
Serial.print(",");
Serial.print(block4);
Serial.print(",");
Serial.print(exposed4);
Serial.print(",   ");
Serial.print(block0_1);
Serial.print(",");
Serial.print(d0_1);
Serial.print(",");
Serial.print(v0_1);
Serial.print(",");
Serial.print(reset0_1);
Serial.print(",");
Serial.print(det_reset1);
Serial.print(",   ");
Serial.print(block1_2);
Serial.print(",");
Serial.print(d1_2);
Serial.print(",");
Serial.print(v1_2);
Serial.print(",");
Serial.print(reset1_2);
Serial.print(",");
Serial.print(det_reset2);
Serial.print(",   ");
Serial.print(block2_3);
Serial.print(",");
Serial.print(d2_3);
Serial.print(",");
Serial.print(v2_3);
Serial.print(",");
Serial.print(reset2_3);
Serial.print(",");
Serial.print(det_reset3);
Serial.print(",   ");
Serial.print(block3_4);
Serial.print(",");
Serial.print(d3_4);
```

```
Serial.print(",");
Serial.print(v3_4);
Serial.print(",");
Serial.print(reset3_4);
Serial.print(",");
Serial.print(det_reset4);
Serial.print(" ");
Serial.print(detection);
Serial.print(" ");
Serial.print(v_avg);
Serial.print("\r\n");
}
```

Matlab Collect Data:

This published file is the matlab code used to interact with the PD1A photo detectors. It is used to make detections and calculate velocities and sizes. The function Arduino is from a matlab arduino support package. The rest of the functions were created for this project.

Contents
- [Arduino with Matlab](#)
- [Given Variables](#)
- [Read in Arduino](#)

Called Functions
- [arduino](#)
- [check_detection](#)
- [dark_calibration](#)
- [traffic_in_out2](#)

Arduino with Matlab

Tim Brown & Matt Birkebak

```
clear; clc;
```

Given Variables

```
traffic_in = 0;
```

```
traffic_out = 0;

loop = 0;

detection = 0;
```

Read in Arduino

```
a = arduino('COM7');



[dark,turbid,bright] = dark_calibration(a);



dark = dark+dark*.05;



while loop == 0;



[in,out] = traffic_in_out2(a,dark);

ts = 1;



if in == 1

    in_out = 0;

    [ detection ] = check_detection( a,in_out,ts,dark,detection );

end



if out == 1

    in_out = 1;
```

```
    [ detection ] = check_detection( a,in_out,ts,dark,detection );

end




in = 0; out = 0;

end
```

```
Error using Detection_Algorithm (line 12)

No Arduino hardware is found on port COM7. If using an official Arduino board, make
sure it is plugged in. Otherwise, please specify both port and board type. For more
information, see the arduino function reference page.
```

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Contents

- [Constructor](#)
- [Destructor](#)
- [Public methods](#)
- [Private methods](#)
- [Public methods for arduino libraries implementing LibraryBase](#)
- [A simple resource manager for clients of the Arduino object](#)

```
classdef (Sealed) arduino < arduinoio.internal.BaseClass & matlab.mixin.CustomDisplay

The Rest of the Arduino function can be found at http://www.mathworks.com/hardware-
support/arduino-matlab.html
```

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```
clear

function [ detection ] = check_detection( a,in_out,t_start,dark,detection )
```

```matlab
%check_detection Systematically Check Detection

%   Check for detection by going through each photo detector systematically

%   if in_out is 0 then boat is going in. If in_out is 1 then boat is going

%   out.

pd_num = [0,1,2,3,4];

loop = 0;

block = zeros(1,5);

block(1,1) = 1


c = zeros(1,5);  % counter

c_2 = zeros(1,5);  % counter

tb = zeros(1,5); % time_blocked

ts = zeros(1,5); % Start_Time

ts1 = tic;


time_between = zeros(1,5);


if in_out == 1

    pd_num = fliplr(pd_num);

    dark   = fliplr(dark);

end
```

```matlab
while loop == 0



    v(1,1) = readVoltage(a,pd_num(1,1));

    v(1,2) = readVoltage(a,pd_num(1,2));

    v(1,3) = readVoltage(a,pd_num(1,3));

    v(1,4) = readVoltage(a,pd_num(1,4));

    v(1,5) = readVoltage(a,pd_num(1,5));



% First Detector Time Blocked

if (c(1,1) == 0) && (v(1,1) > dark(1,1))

    tb(1,1) = toc(ts1)

    c(1,1)  = 1;

end



% Second Detector Blocked

if v(1,2) < dark(1,2) && c_2(1,2) == 0

    block(1,2) = 1

    time_between(1,1) = toc(ts1)

    ts2 = tic;

    c_2(1,2) = 1;

end
```

```matlab
% Second Detector Time Blocked

if (c(1,2) == 0) && (v(1,2) > dark(1,2)) && block(1,2) == 1

    tb(1,2) = toc(ts2)

    c(1,2)  = 1;

end



% Third Detector Blocked

if v(1,3) < dark(1,3) && block(1,2) == 1 && c_2(1,3) == 0

    block(1,3) = 1

    time_between(1,2) = toc(ts2)

    ts3 = tic;

    c_2(1,3) = 1;

end



% Third Detector Time Blocked

if (c(1,3) == 0) && (v(1,3) > dark(1,3)) && block(1,3) == 1

    tb(1,3) = toc(ts3)

    c(1,3)  = 1;

end



% Fourth Detector Blocked

if v(1,4) < dark(1,4) && block(1,3) == 1 && c_2(1,4) == 0
```

```matlab
    block(1,4) = 1

    time_between(1,3) = toc(ts3)

    ts4 = tic;

    c_2(1,4) = 1;

end


% Fourth Detector Time Blocked

if (c(1,4) == 0) && (v(1,4) > dark(1,4)) && block(1,4) == 1

    tb(1,4) = toc(ts4)

    c(1,4)  = 1;

end


% Final Detector Blocked

if v(1,5) < dark(1,5) && block(1,4) == 1 && c_2(1,5) == 0

    block(1,5) = 1;

    time_between(1,4) = toc(ts4)

    time_between(1,5) = toc(ts1)

    ts5 = tic;

    c_2(1,5) = 1;

    detection = detection+1

    while loop == 0

        v(1,1) = readVoltage(a,pd_num(1,1));
```

```matlab
v(1,2) = readVoltage(a,pd_num(1,2));

v(1,3) = readVoltage(a,pd_num(1,3));

v(1,4) = readVoltage(a,pd_num(1,4));

v(1,5) = readVoltage(a,pd_num(1,5));

% Fifth Detector Time Blocked

if (c(1,1) == 0) && (v(1,1) > dark(1,1))

    tb(1,1) = toc(ts1)

    c(1,1)  = 1;

end



if (c(1,2) == 0) && (v(1,2) > dark(1,2)) && block(1,2) == 1

    tb(1,2) = toc(ts2)

    c(1,2)  = 1;

end



if (c(1,3) == 0) && (v(1,3) > dark(1,3)) && block(1,3) == 1

    tb(1,3) = toc(ts3)

    c(1,3)  = 1;

end



if (c(1,4) == 0) && (v(1,4) > dark(1,4)) && block(1,4) == 1

    tb(1,4) = toc(ts4)
```

```matlab
            c(1,4)  = 1;

        end




        if (c(1,5) == 0) && (v(1,5) > dark(1,5)) && block(1,5) == 1

            tb(1,5) = toc(ts5)

            c(1,5)  = 1;

            break;

        end

    end




    [vel,size] = speed_size(tb,time_between,20*.75); %20 inches = 50.8 cm

    Save_txt_easy( detection,tb,time_between,vel,size )

    return;

end




end
```

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Contents

```matlab
function [ dark,turbid,bright ] = dark_calibration( a )

%Dark_Calibration Collect dark, semi blocked, and not blocked calibration

%for harbor security system
```

101

```matlab
%   Collect measurements for dark calibration, turbid measurements, and

%   bright measurements to make better detections.

num_avg = 20;

num_pd = 5;



dark_raw = zeros(num_avg,num_pd);

dark = zeros(1,num_pd);



turbid_raw = zeros(num_avg,num_pd);

turbid = zeros(1,num_pd);



bright_raw = zeros(num_avg,num_pd);

bright = zeros(1,num_pd);
```

Dark Calibration

```matlab
input('Click Enter to Start Dark Calibration')

for i = 1:num_avg;

    dark_raw(i,1) = readVoltage(a,0);

    dark_raw(i,2) = readVoltage(a,1);

    dark_raw(i,3) = readVoltage(a,2);

    dark_raw(i,4) = readVoltage(a,3);

    dark_raw(i,5) = readVoltage(a,4);

end
```

```matlab
dark(1,1) = mean(dark_raw(:,1));

dark(1,2) = mean(dark_raw(:,2));

dark(1,3) = mean(dark_raw(:,3));

dark(1,4) = mean(dark_raw(:,4));

dark(1,5) = mean(dark_raw(:,5));


% %% Turbid Calibration

% input('Click Enter to Start Turbid Calibration')

% for i = 1:num_avg;

%     turbid_raw(i,1) = readVoltage(a,0);

%     turbid_raw(i,2) = readVoltage(a,1);

%     turbid_raw(i,3) = readVoltage(a,2);

%     turbid_raw(i,4) = readVoltage(a,3);

%     turbid_raw(i,5) = readVoltage(a,4);

% end

% turbid(1,1) = mean(turbid_raw(:,1));

% turbid(1,2) = mean(turbid_raw(:,2));

% turbid(1,3) = mean(turbid_raw(:,3));

% turbid(1,4) = mean(turbid_raw(:,4));

% turbid(1,5) = mean(turbid_raw(:,5));

%

% %% Bright Calibration
```

```
% input('Click Enter to Start Bright Calibration')

% for i = 1:num_avg;

%     bright_raw(i,1) = readVoltage(a,0);

%     bright_raw(i,2) = readVoltage(a,1);

%     bright_raw(i,3) = readVoltage(a,2);

%     bright_raw(i,4) = readVoltage(a,3);

%     bright_raw(i,5) = readVoltage(a,4);

% end

% bright(1,1) = mean(bright_raw(:,1));

% bright(1,2) = mean(bright_raw(:,2));

% bright(1,3) = mean(bright_raw(:,3));

% bright(1,4) = mean(bright_raw(:,4));

% bright(1,5) = mean(bright_raw(:,5));

end
```

```
function [ traffic_in,traffic_out ] = traffic_in_out2( a,dark )

%traffic_in_out Loops reading edge values until an edge value is read

%    Continously loops until it measures a detection on either end of the

%    arduino

traffic_in =0;

traffic_out = 0;
```

```matlab
while (traffic_in == 0 || traffic_out == 0)

    v1 = readVoltage(a,0);

    v5 = readVoltage(a,4);


    if v1 <= dark(1,1)

        traffic_in = 1;

        return;

    end


    if v5 <= dark(1,5)

        traffic_out = 1;

        return;

    end

end


end
```

Analyze Data

```matlab
% Example of how to Analyze Data. Test 3 of Tow Tank. It requires the printed text files to be in
the same folder. An example text file is at below.
clear; clc; close all
tests = 35;

num_rl =  [3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33];
vel_rl = [.2 .1 .35 .45 .05 .55 .65 .7 .75 .8 .85 .9 .95 1 1.2 1.5];
num_lr =  [2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34];
vel_lr = [.6 .25 .15 .4 .5 .55 .6 .7 .75 .8 .85 .9 .95 1 1.2 1.5 2];

plot_data( num_rl,vel_rl,num_lr,vel_lr,tests );
```

```matlab
function plot_data( num_rl,vel_hand_rl,num_lr,vel_hand_lr,tests )

%UNTITLED6 Summary of this function goes here
%   Detailed explanation goes here

% Test 3
items = 13;
```

```
A = zeros(items,tests);

for i = 1:tests
    file_name = ['detection_',num2str(i),'.txt'];
    A(:,i) = importdata(file_name);
end
```

Error using plot_data (line 8)
Not enough input arguments.

Right to Left

```
vel_rl  = A(12,num_rl); %m/s
size_b_rl = A(13,num_rl);
size_b_rl = round(size_b_rl*100)/100;
diff_srl = .30-size_b_rl;

k = 1;
for i = min(diff_srl):.01:max(diff_srl)
    freq_rl(k) = sum(diff_srl == i);
    k = k+1;
end
std_rl = min(diff_srl):.01:max(diff_srl);
```

Left to Right

```
vel_lr  = A(12,num_lr); %cm/s
size_b_lr = A(13,num_lr);
size_b_lr = round(size_b_lr*100)/100;
diff_slr = .30-size_b_lr;

k = 1;
for i = min(diff_slr):.01:max(diff_slr)
    freq_lr(k) = sum(diff_slr == i);
    k = k+1;
end


std_lr = min(diff_slr):.01:max(diff_slr);
```

Both

```
vel_tot = [vel_lr vel_rl];
size_tot = [size_b_rl size_b_lr];
diff_tot = [.30-size_tot];
k = 1;
for i = min(diff_tot):.01:max(diff_tot)
    freq_tot(k) = sum(diff_tot == i);
```

```
        k = k+1;
    end


    std_tot = min(diff_tot):.01:max(diff_tot);
    avg_size = mean([size_b_rl size_b_lr]);
```

Linear Fit

```
x = [vel_hand_rl vel_hand_lr];
y = [vel_rl vel_lr];
P = [.8407 .0231];
rsq = .95;
xfit = linspace(min(x),max(x),100);
yfit = polyval(P,xfit);
```

Plot

```
set(0,'defaultlinelinewidth',1.5)
set(0,'defaultLineMarkerSize',10)
set(0,'defaultAxesFontSize',15)
set(0,'defaultAxesLineWidth',1.5)
figure(1)
hold on
plot(xfit,yfit,'--g',vel_hand_rl,vel_rl,'xb',vel_hand_lr,vel_lr,'xr')
plot(xfit,yfit,'--g',vel_hand_rl,vel_rl,'xb',vel_hand_lr,vel_lr,'xr')
grid;box on; xlabel('Velocity (m/s)');
ylabel('Estimated Velocity (m/s)')
legend('Linear Fit','Into Harbor: Right-Left','Out of Harbor: Left-Right',...
    'location','southeast')
string1 = ['r^2 =' num2str(rsq)];
string2 = ['y = ' num2str(.84) 'x'];
text(.1,1.4,string1,'fontsize',15)
text(.1,1.2,string2,'fontsize',15)
ax1 = gca;
set(ax1,'XColor','k','YColor','k');
ax1_pos = get(ax1,'Position');
xlim_r = get(ax1,'XLim');
ylim_r = get(ax1,'YLim');
ylim_b = ylim_r.*1.94384449*60;
xlim_b = xlim_r.*1.94384449*60;
ax2 = axes('Position',ax1_pos,...
    'XAxisLocation','top',...
    'YAxisLocation','right',...
    'Color','none','XColor', 'b','YColor', 'b',...
    'XLim',xlim_b,'YLim',ylim_b);
xlabel('Full Scale Velocity (Knots)')
ylabel('Full Scale Estimated Velocity (Knots)')
suptitle('Estimated vs. Actual Velocities (Test:30.5 cm Scaled: 18.3 m)')
hold off

figure(2)
```
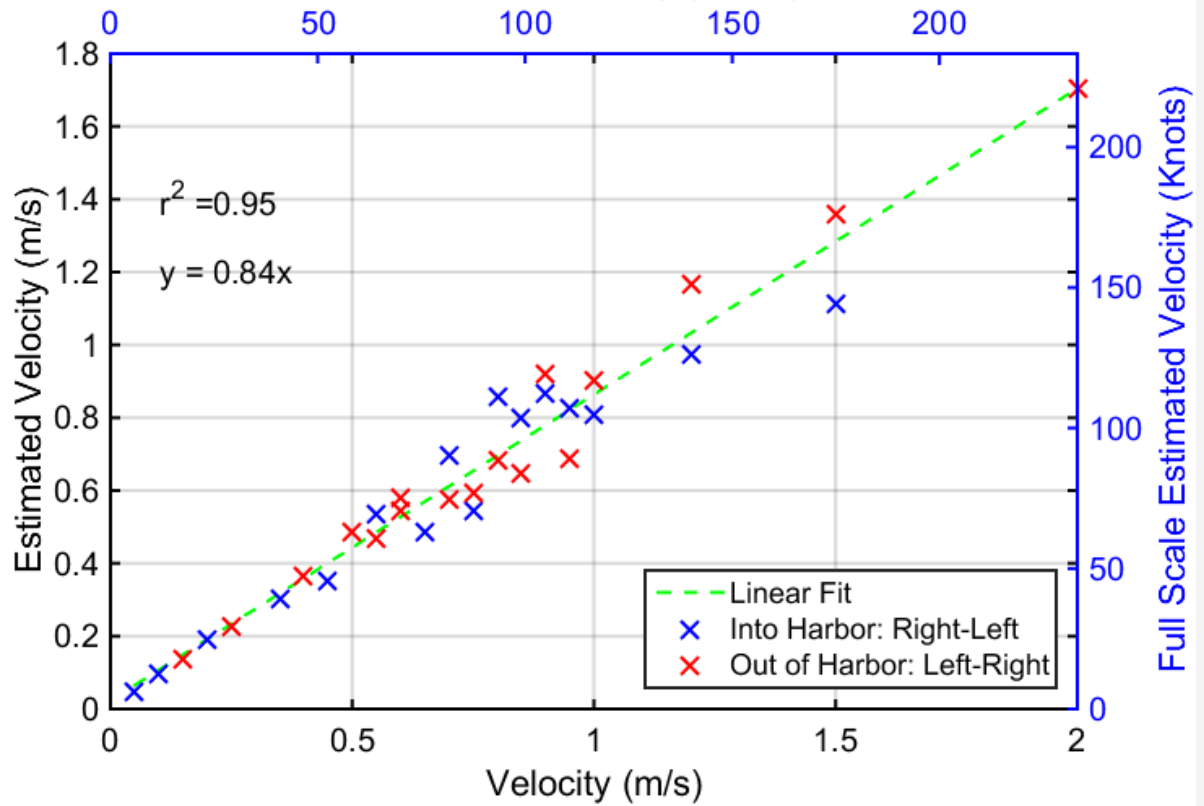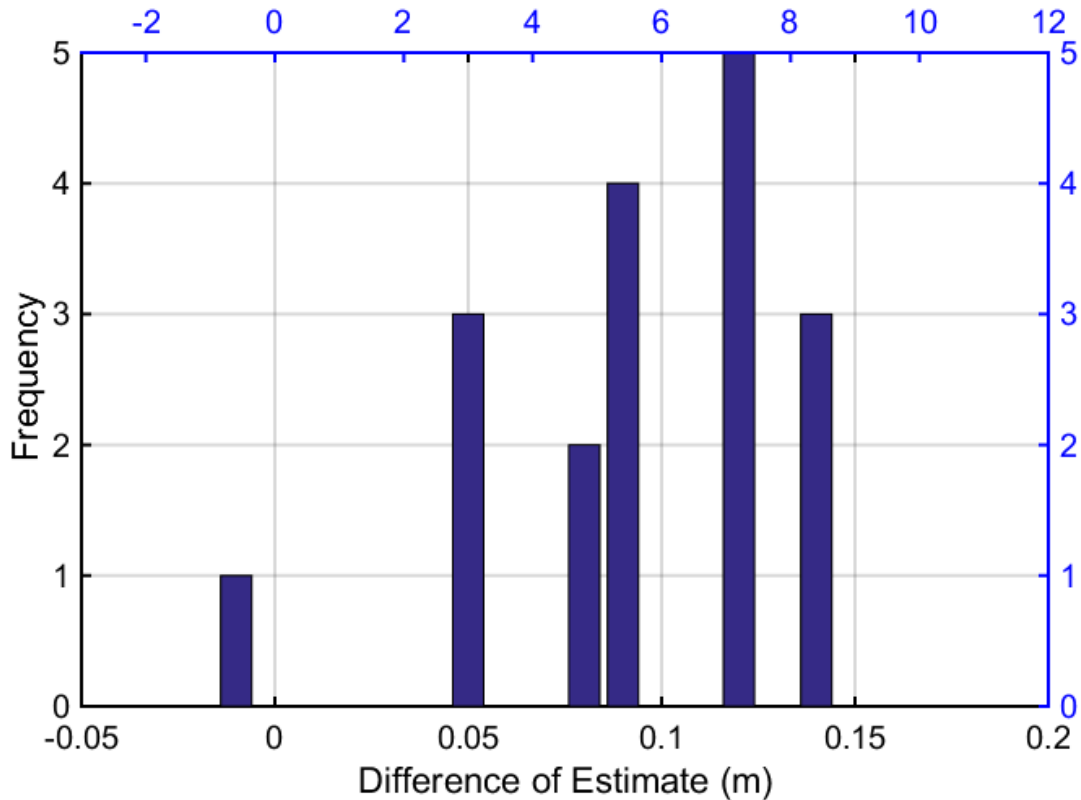
```matlab
hold on
bar(std_tot,freq_tot)
bar(std_tot,freq_tot)
grid;box on; xlabel('Difference of Estimate (m)');
ylabel('Frequency')
% string2 = ['Average =' num2str(ceil(avg_size)) ' (m)'];
% text(27.1,27,string2,'fontsize',15)
ax1 = gca;
set(ax1,'XColor','k','YColor','k');
ax1_pos = get(ax1,'Position');
xlim_r = get(ax1,'XLim');
ylim_r = get(ax1,'YLim');
ylim_b = ylim_r;
xlim_b = xlim_r*60;
ax2 = axes('Position',ax1_pos,...
    'XAxisLocation','top',...
    'YAxisLocation','right',...
    'Color','none','XColor', 'b','YColor', 'b',...
    'XLim',xlim_b,'YLim',ylim_b);
xlabel('Full Scale Difference of Estimate (m)')
suptitle('Frequency of Estimated Sizes (Test:30.5 cm Scaled: 18.3 m)')
hold off


end
```

Estimated vs. Actual Velocities (Test:30.5 cm Scaled: 18.3 m)

Frequency of Estimated Sizes (Test:30.5 cm Scaled: 18.3 m)

Example of a Resultant Text File from Algorithm

Detection_2.txt:

Guide:

Detection: 2.000000
Time Blocked (s): 0.561184, 0.411102, 0.265038, 0.371942, 0.500466,
Green is Time between Blocks (s); Red is total time : 0.287492, 0.146230, 0.000171, 0.000025, 0.438226
Estimated Velocity (m/s): 0.579610
Estimated Size (m): 0.224389

Actual:
2.000000
0.561184, 0.411102, 0.265038, 0.371942, 0.500466,
0.287492, 0.146230, 0.000171, 0.000025, 0.438226

0.579610
0.224389