Hemispherical Optical Dome for Underwater Communication

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ABSTRACT

For many years, acoustic systems have been used as the primary method for underwater communication; however, the data transfer rate of such systems is low because sound propagates slowly through water. A higher throughput can be achieved using visible light to transmit data underwater. The first issue with this approach is that there is generally a large loss of the light signal due to scattering and absorption in water, even though there is an optimal wavelength for transmission in the blue or green wavelengths of the visible spectrum. The second issue is that a simple communication system, consisting only of a highly directional source/transmitter and small optical detector/receiver, has a very narrow field of view. The goal of this project is to improve an optical, underwater communication system by increasing the effective field of view of the receiving optics.

To this end, we make two changes to the simple system: (1) An optical dome was added near the receiver. An array of lenses is placed radially on the surface of the dome, reminiscent of the compound eye of an insect. The lenses make the source and detector planes conjugate, and each lens adds a new region of the source plane to the instrument's total field of view. (2) The receiver was expanded to include multiple photodiodes. With these two changes, the receiver has much more tolerance to misalignments (in position and angle) of the transmitter.

Two versions of the optical dome (with 6" and 8" diameters) were designed using PTC's Creo CAD software and modeled using Synopsys' CODE V optical design software. A series of these transparent hemispherical domes, with both design diameters, were manufactured using a 5-axis mill. The prototype was then retrofitted with lenses and compared with the computer-generated model to demonstrate the effectiveness of this solution. This work shows that the dome design improves the optical field of view of the underwater communication system considerably. Furthermore, with the experimental test results, a geometric optimization model was derived providing insights to the design performance limits.

Keywords: Underwater optical communication, hemispherical dome

1. INTRODUCTION

Existing acoustic underwater communication systems use a legacy technology that provides low data transmission rates for medium-range communication. The data rate is generally limited to around tens of megabits per second for a kilometer transmission range while less than a megabit per second for transmission ranges up to 100 km. Additionally, the speed of acoustic waves in the ocean is approximately 1.5 km/s; this leads to signal latency between the transmitter and receiver, making real-time response and synchronization problematic. This limitation is mostly due to attenuation and surface-induced pulse expansion [1], [2]. In short, this technology cannot satisfy emerging applications that require high data rates (~tens of megabits per second) and sending real-time video and imaging of subsurface ecology and marine biology to the surface receiver over distances longer than 1 km. The need for high-speed-throughput underwater observation and monitoring systems has created a considerable interest in advancing the technology for underwater optical wireless communication and sensor networks. With this motivation, NASA is pursuing technologies that could enable autonomous underwater drones, to study Earth's oceans and those on icy moons like Jupiter's Europa, transmitting a large volume of image and video data to a receiver at the surface via optical wireless communications. In particular, there has been a surge of interest in developing underwater optical communications using blue-green sources and detectors [3], [4], [5], [6], [7], [8]. The advantage of the 'blue-green optical window' is a relatively low attenuation of electromagnetic radiation in this wavelength band underwater. Figure 1 shows the absorption and scattering coefficients for pure sea water; these coefficients also increase for murkier water due to higher levels of hydrosols.

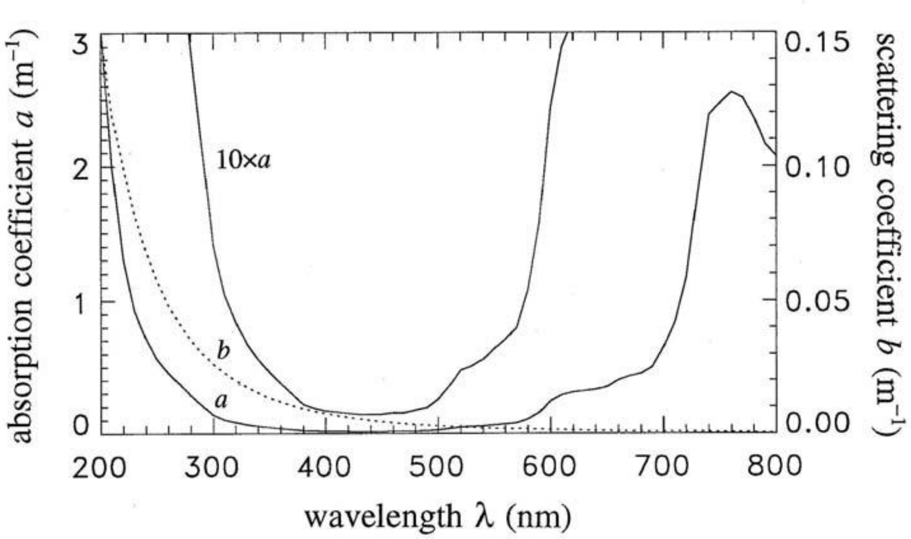

Figure 1, Absorption (solid line) and scattering (dotted line) coefficients for pure sea water, from Smith & Baker (1981) [9].

2. METHODS

2.1 Optimal wavelength for underwater communication

A simple underwater optical communication system consists of a highly directional source/transmitter and a small optical detector/receiver with a very narrow field of view. To assess the performance of a unidirectional wireless system, a low-cost, benchtop testbed, using a water tank, lens, photodiode detector, and LEDs, was designed (Figure 2). The electronics for signal transmission at the transmitter and the receiver was implemented using Arduino boards. In this configuration, all components, including the transmitter- LED, collector- lens, and receiver- photodiode, were placed outside the water tank. The thickness of the water tank Plexiglass was neglected, as both transmitter and receiver are placed close to the tank wall. The main objective of this experiment was to determine the optimal wavelength for underwater communication for a line-of-sight communication link.

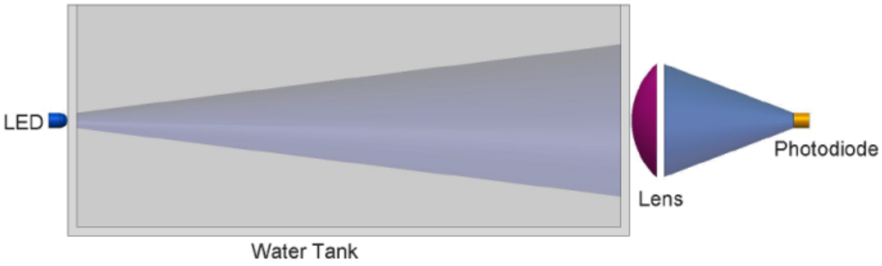

Figure 2, Diagram of bench top underwater optical communication test bed

A set of programs was developed to modulate a digital signal from a LED transmitter and demodulate it once it is received by a photodiode detector. In a series of experiments, a variety of colored LEDs, representing wavelengths in red, orange, yellow, green, and blue, were used to transmit a codded signal through the water tank. The photodiode, placed at the focal length of the converging lens, received the transmitted signal; the Arduino board decoded it and the result was displayed on a laptop. Figure 3 shows the benchtop setup.

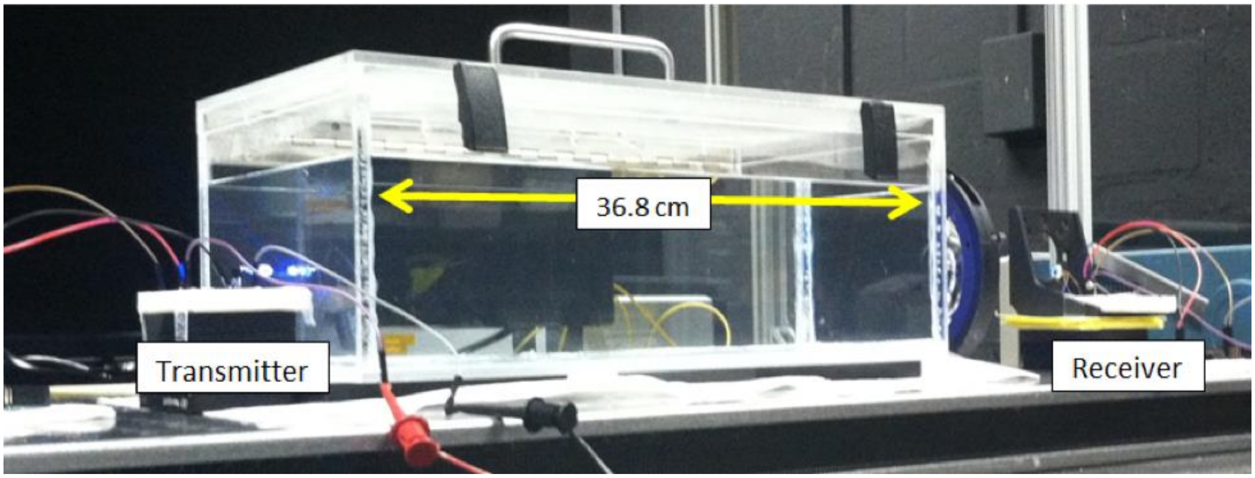

Figure 3, Bench top low-cost underwater optical communication system. The LED transmitter, collecting lens, and photodiode receiver are placed outside the water tank.

The photodiode used in this setup has a wavelength-dependent responsivity. To take this into account, the voltage (V) was converted into incident light power (P) using the following equation.

$$P = \frac{V}{R_{load} * \Re}$$

where R_{load} is the load resistance used in the circuit and $\Re$ is the responsivity of the photodiode. As expected, the power from blue and green LEDs were the highest detected by the photodiode (Figure 4).

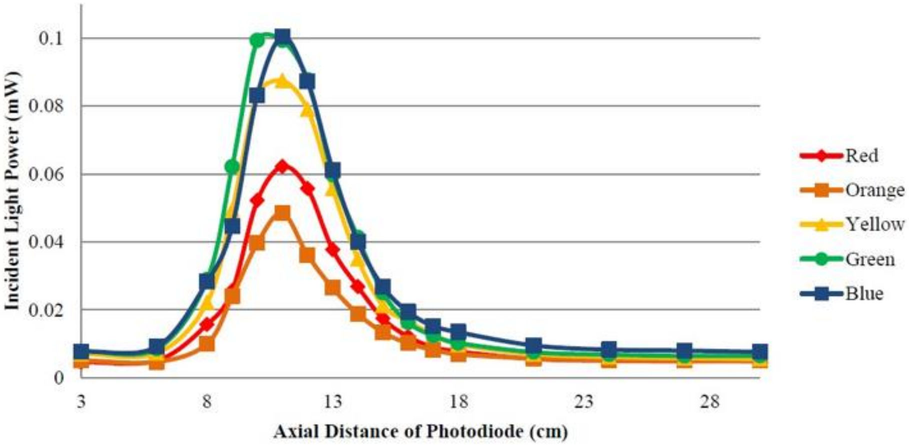

Figure 4, Power of incident light detected by photodiode from various LEDs

2.2 Optical dome design and manufacturing

An omnidirectional underwater optical communication system requires a wide field of view when either the transmitter or the receiver is moving. To remedy the narrow field of view of a unidirectional system, we designed, developed, and tested an optical hemispherical dome. The dome incorporates multiple focusing lenses and houses an array of photodiodes at the focal plane of the lens and center of the sphere. This design achieves a wider optical field-of-view for the underwater communication system (Figure 5).

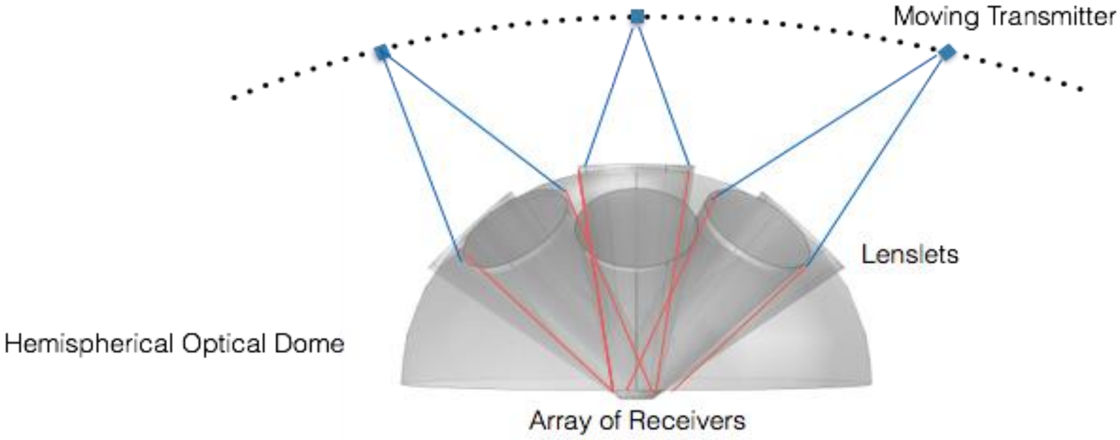

Figure 5, Hemispherical Optical Dome (HOD) for underwater optical communication.

For this work, Synopsys' CODE V optical design software was employed to design the lens configuration and their placement on the hemispherical dome. The dome was retrofitted with a series of lenses positioned with a radial symmetry. In this configuration, the optimized parameters of each lens were found to be a focal length of 75 mm and a clear aperture of 50.8 mm. The optical model was also used to optimize the LED position in the focal plane with respect to the dome at a distance of 300 mm (Figure 6). A merit function based on the RMS beam spot size was used to optimize the position of each of 6 lenses on the surface of the dome (Figure 7). The dome structure was designed using PTC's Creo CAD software and then a prototype was built with a 6-inch diameter transparent camera dome. The holes were cut in the camera dome using a 5-axis mill cut holes and were retrofitted with 2-inch diameter lenses (Figure 8). At the focal plane of the lenses, multiple photodiodes were used to increase the portion of the field of view from which transmitted light from the LED sources can be detected.

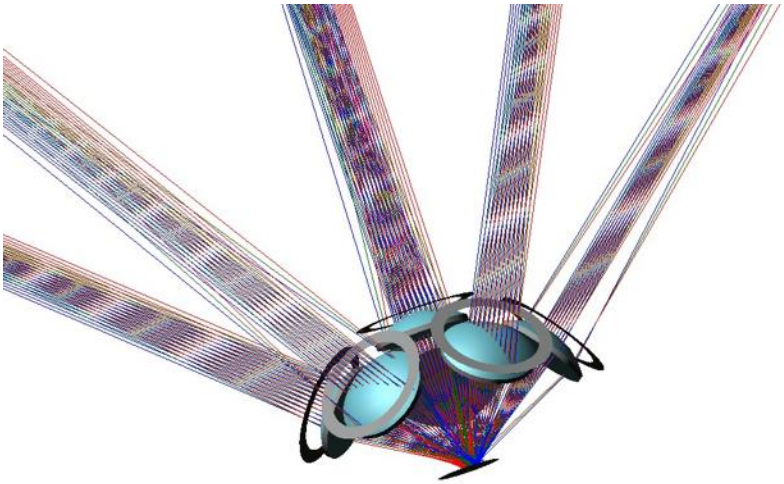

Figure 6, CODE V optical model of dome and lenses plus photodiode configuration at the center of the base of the dome.

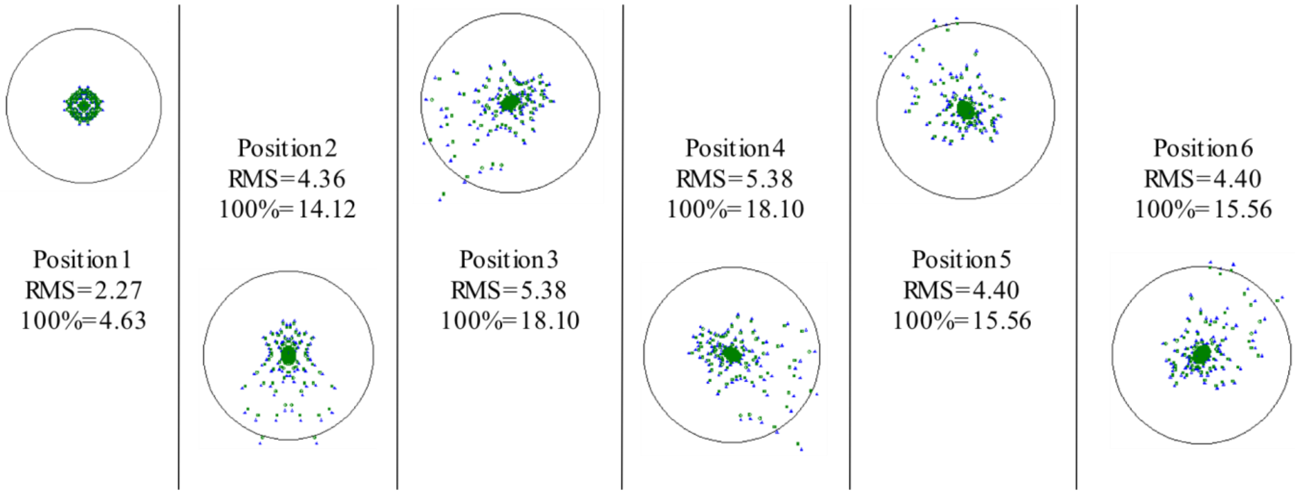

Figure 7, CODE V optical analysis of beam spot for each of the six lens positions on the dome.

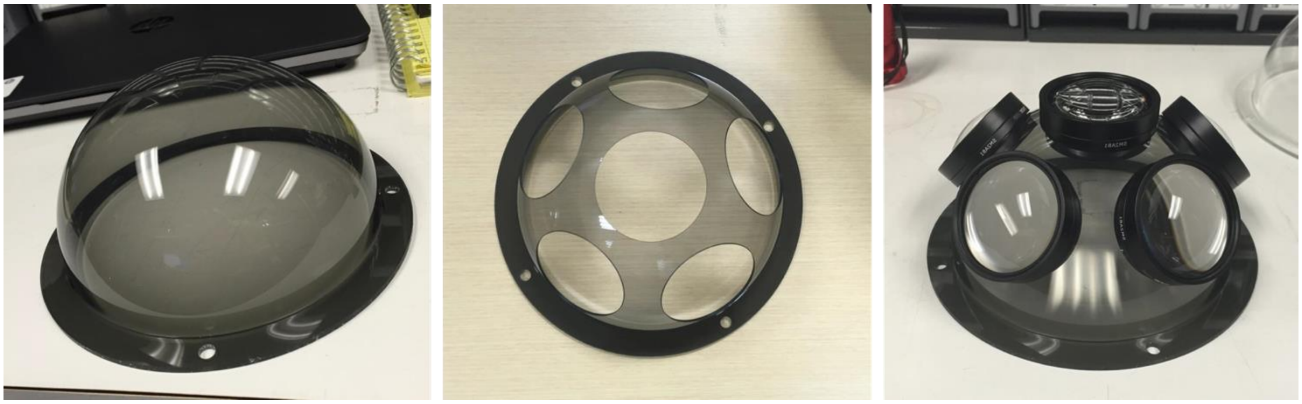

Figure 8, Manufacturing of the optical dome. Left: 6" diameter security camera dome; Center: dome cut on 5-axis mill; Right: retrofitted dome with lenses.

A series of tests were conducted to assess the performance of the optical dome submerged in a water tank. For this purpose, a hemispherical rim was patterned on the benchtop breadboard so that a LED transmitter moved in uniform steps along the rim (Figure 9). In this configuration, the photodiode detector was placed at the center of the rim attached to the Arduino circuitry. A sample coded signal was uploaded to the LED and transmitted to the receiver while its position was tracked along the rim. The signal received by the photodiode was decoded and displayed by a second laptop. This process was repeated by introducing the converging lenses into the line of sight between the transmitter and detector. Subsequently, the number of photodiodes was increased to three, representing an array of photodiodes. On the final test, the constructed optical dome, retrofitted with the converging lenses, was placed over the photodiode detectors while the LED moved along the rim 180 degrees, from one side to another (Figure 10).

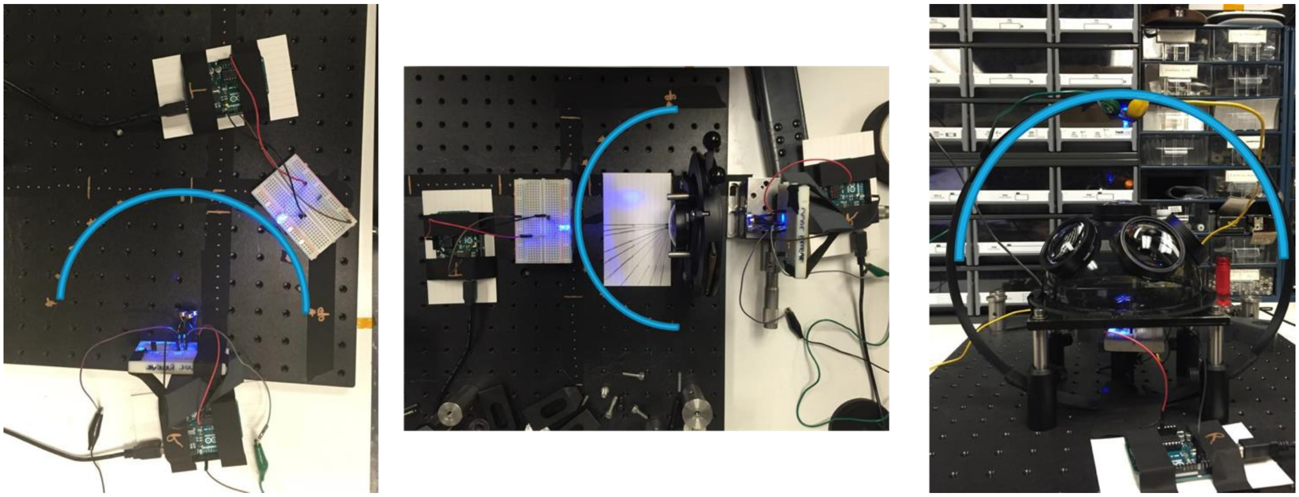

Figure 9, Measuring field of view. Left: 3 photodiodes, no lenses; Center: 3 photodiodes with 1 lens; Right: Hemispherical dome.

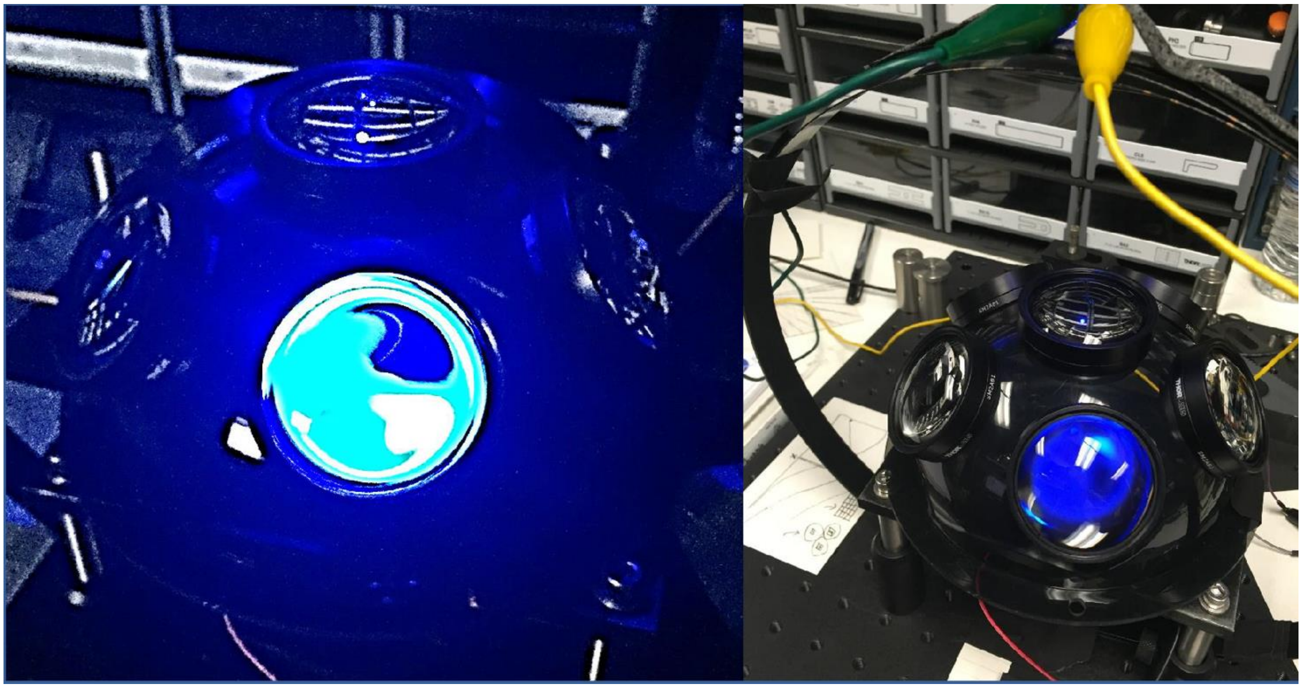

Figure 5, Hemispherical dome is being tested.

3. RESULTS

The underwater optical communication considered in this study follows a general model of line-of-sight communication, assuming a straight and unobstructed path of communication between the transmitter and receiver. The power of the optical signal at the receiver is obtained by multiplying the transmitter power, telescope gain, and losses:

$$P_{R\_LOS} = P_T \eta_T \eta_R \exp\left(\frac{-C(\lambda)d}{\cos(\theta)}\right)\left(\frac{A_{\mathrm{Re}c}\cos(\theta)}{2\pi d^2\left(1-\cos(\theta_0)\right)}\right)$$

where

$$C(\lambda) = a(\lambda) + b(\lambda)$$

is the extinction coefficient of the aquatic medium and has contributions from absorption (α) and scattering (β) coefficients. P_T is the average transmitted optical power, η_T is the optical efficiency of the transmitter, η_R is the optical efficiency of the receiver, d is perpendicular distance between transmitter and receiver, θ is the angle between the perpendicular to the receiver plane and transmitter–receiver trajectory, θ_0 is the beam divergence angle, and A_{Rec} is the receiver aperture area [10].

Figure 11 shows the power recorded at the receiver (photodiode) under different scenarios. As expected, a single photodiode with lens has a narrow field of view. However, increasing the number of photodiode to 3 and number of lenses while moving the transmitter (LED) allows a wider field of view (red line).

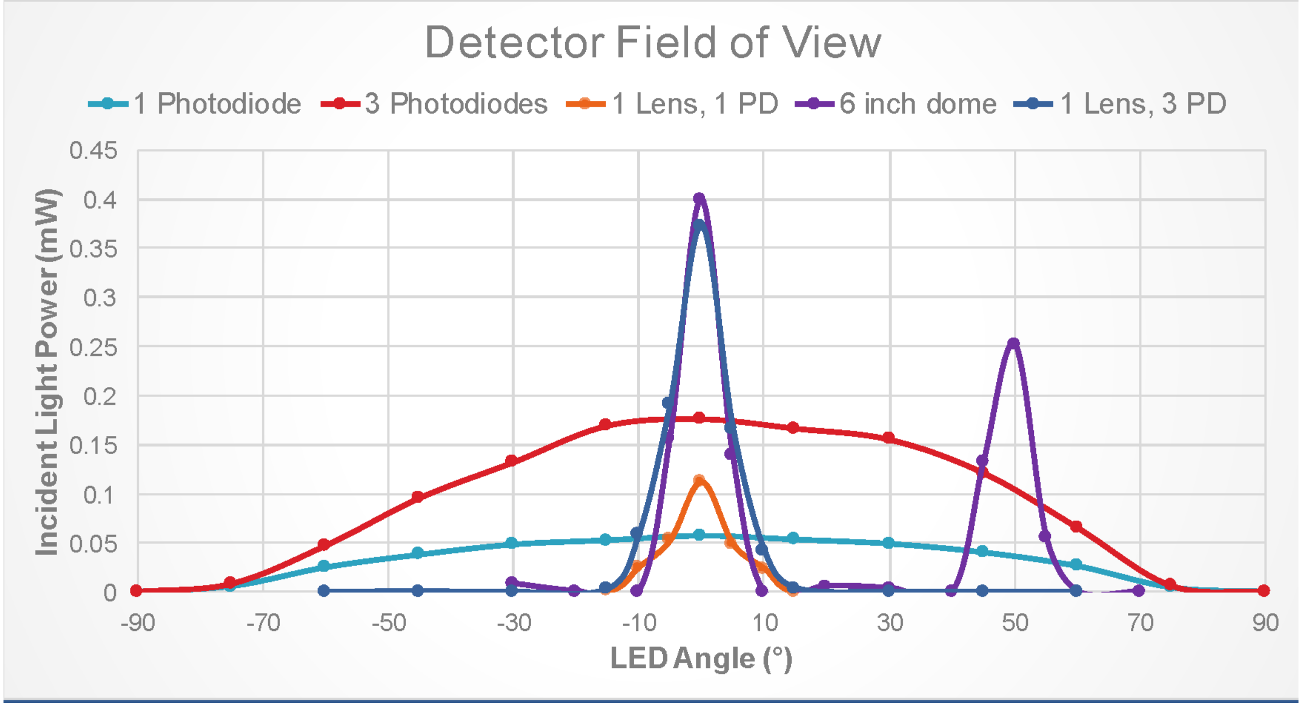

Figure 6, Field of view of 5 different detector systems. The LED source is moved from -90 degrees to +90 degrees to access the performance of the field-of-view of dome.

4. CONCLUSIONS

An optical dome for underwater optical wireless communication was designed and tested, that contains 6 lenses for collecting light from a moving transmitter and 3 photodiodes positioned at the focal plane of the lenses for detection. In this design, we achieved an increased power at the detector while widening the field of view. This is important since the dome allows the photodiodes to detect the light when the source is located off of the optical axis. The performance of the system could be improved by increasing the number of lenses on the dome and replacing the individual photodiodes with a planar array of photodiodes. This work shows the dome design improves the optical field of view of the underwater communication system considerably.

5. ACKNOWLEDGEMENTS

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