

# Experimental validation of an undersea free space laser network simulator in high turbidities

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## ABSTRACT

Mobile, high throughput mid-range data communications and robust real-time data networking in the subsea environment that can accommodate high bandwidth sensors such as optical imagers have a potentially high impact as enabling technologies for a variety of future subsea operations in the areas of distributed sensing and real-time wireless feedback and control of unmanned undersea vehicles. Although much work has been done recently in the field of undersea optical free space communications and networking, to date there has yet to be an implementation of a complete multi-node undersea wireless optical data communications network. The deployment and testing of optical wireless network equipment in the undersea environment is expensive and time-consuming, and there is a clear need for a network simulation framework that will allow researchers to explore higher level networking concepts and the effects of operational and environmental factors on network performance.

This paper describes a network simulation approach that uses an accurate time dependent Monte Carlo channel model to simulate the networking physical layer, which can be used in conjunction with higher network layer protocols to simulate larger scale network performance and to help determine hardware requirements for overall network system design in a variety of undersea channel conditions.

## 1. INTRODUCTION

High bit rate data links (on the order of several million bits per second) with low bit error rates are required for real-time transmission of audio, video, and imagery which can be useful in a variety of applications such as environmental monitoring, commercial subsea operations, and inspection and surveillance operations. Modern terrestrial wireless communication systems such as WIFI or cellular phone networks employ radio frequency (RF) to transmit data, and while RF works very well in air, the severe attenuation of RF in water makes it impractical to use for most underwater wireless communication needs [1]. Although acoustic waves are able to travel great distances underwater, the low carrier frequencies used in the acoustic spectrum (typically between 10Hz and 1MHz) combined with the relatively slow propagation speeds of acoustic waves underwater result in low bandwidth, high latency, and low data rates [2]. Recent advances in semiconductor laser technologies have made underwater optical wireless communication a feasible alternative to acoustic and RF carriers of data. In this paper, we present a physical layer simulator for free space undersea optical wireless data links

Our ultimate goal is to interface the physical layer simulator with a higher level network simulator (such as OpNet or ns-2) in order to help design optimal routing protocols, multiple access, modulation and error correction schemes, and per-node power management for delay-tolerant networks (DTN) and mobile ad-hoc networks. The purpose of the experiments described in this paper are to validate the accuracy of our physical layer simulator in predicting bit error rates (BER) for a variety of pulse repetition rates and water turbidities. Our main performance metric is the 95% confidence level bit error rate (95% CL BER), which differs from a raw bit error rate in that a raw bit error rate is only useful in describing the BER for a particular data set, while a 95% CL BER can be said to predict the BER ceiling (with 95% accuracy) for all possible data sets utilizing the same environmental parameters. Maximum acceptable BER ceilings vary depending on the application, with real-time voice data requiring  $10^{-2}$ , while TCP file downloading requires a BER ceiling on the order of  $10^{-6}$ . Modern cellular telephone data networks such as LTE employ additional protocols that allow data transmissions with a BER ceiling of  $10^{-4}$ . [3]

### 1.1 Paper Organization

In section 2, we describe our physical layer simulation framework. In section 3, we describe our experimental setup used to validate the simulation framework. Section 4 shows results from both experiments and simulations, and section 5 details conclusions, discussion, and future work.

## 2. NETWORK SIMULATOR

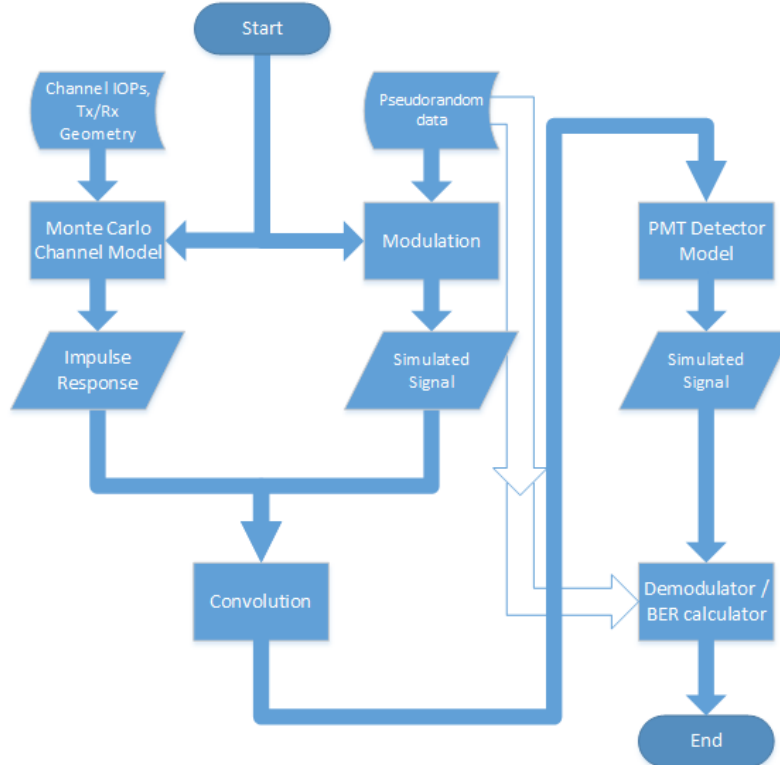


Figure 1: Physical layer simulator

Our physical layer simulator (as shown in the flowchart in Figure 1), is written in Matlab and consists of 4 main execution blocks: The modulator, the channel model, the detector model, and the demodulator.

### 2.1 Modulator

In this set of experiments, we used 16-slot pulse-position-modulation (PPM-16) as our modulation scheme. This allowed us to more easily isolate and analyze individual pulses, in order to compare against the experimental data. For future system design, we can easily replace the modem blocks (with OOK, for example, to maximize throughput in low-noise scenarios). The PPM-16 modulator block takes as input a bitstream (in this case we used a predefined pseudorandom bitstream), peak laser power, laser power variance, sampling interval and pulse repetition rate. The output is a 1-dimensional array representing the simulated signal in terms of optical power.

### 2.2 Channel Model

This block takes as input the beam attenuation coefficient ( $c$ ), the absorption coefficient ( $a$ ), the scattering phase function, the position and orientation of the source and receiver in 3D space, the beam divergence, the receiver half-angle, radius, and acceptance shape. The model then simulates photon bundles traveling from the source through the medium, and outputs an impulse response based on the number of simulated photon bundles that reached the receiver. The channel model, developed by Metron, Inc., is a one-way variation of the model described in [4], and used by Vuorenkoski et. al. in [5] to demonstrate the depolarization effect of multi-path scattering on optical signals traveling through the undersea channel. An initial unit energy is evenly distributed among many photon bundles, each of which then travels a predetermined distance (calculated from the position and orientation parameters of the transmitter and receivers). Each photon bundle travels an average distance of  $1/b$  (where  $b$  is the scattering coefficient) before encountering a scattering event, after which the direction of the photon bundle is changed randomly so that, on average, the distribution of scattering

angles conforms to the distribution described by scattering phase function parameter. This is repeated for each photon bundle until passing through the 2D plane represented by the receiver, and the total energy passing into the receiver is obtained by summing the individual energy contributions of photons that hit the detector window.

$$E_{rcv}^{scat} = \frac{R_{panel} A_{rcv}}{2\pi} \cdot \frac{E_{bundle}}{2\pi R^2} \int_0^{2\pi} W(\theta, \phi) d\phi \quad (1)$$

Equation (1) describes the two-way model, where  $E_{rcv}^{scat}$  is the scattered energy at the receiver,  $R_{panel}$  is the panel reflectivity (note that in our one-way model scenario, there is no panel; the photons instead are simulated traveling directly from the source to the receiver),  $A_{rcv}$  is the receiver acceptance area,  $E_{bundle}$  is the energy contained in a photon bundle,  $R$  is the distance between transmitter and receiver, and  $W$  is the acceptance function of the receiver (for more details please see [4]).

Jaruwatanadilok described a similar model in [6], although our approach in this study assumes negligible noise contribution from solar downwelling irradiance. Our experimental setup used narrow bandpass filters and minimal ambient light to eliminate this noise source from our experimental data (see section 3), and instead focuses on system noise introduced on the signal by the laser source (section 2.1) and the detector (section 2.3).

The channel model solves the time-dependent radiative transfer equation by performing Monte Carlo simulations to create a time-dependent impulse response for the channel. It is flexible in that it allows us to specify position and orientation of a receiver in relation to a transmitter, and it also allows us to specify the position and orientation of a second receiver (placed behind [relative to the position and orientation of] the transmitter, which allows us to model the backscatter impulse response. This is important in determining under what circumstances (if any) it would be possible to use full-duplex and/or half-duplex communications at the same wavelength. By combining the two impulse responses we can also model scenarios in which non line of sight (NLOS) communications would be possible.

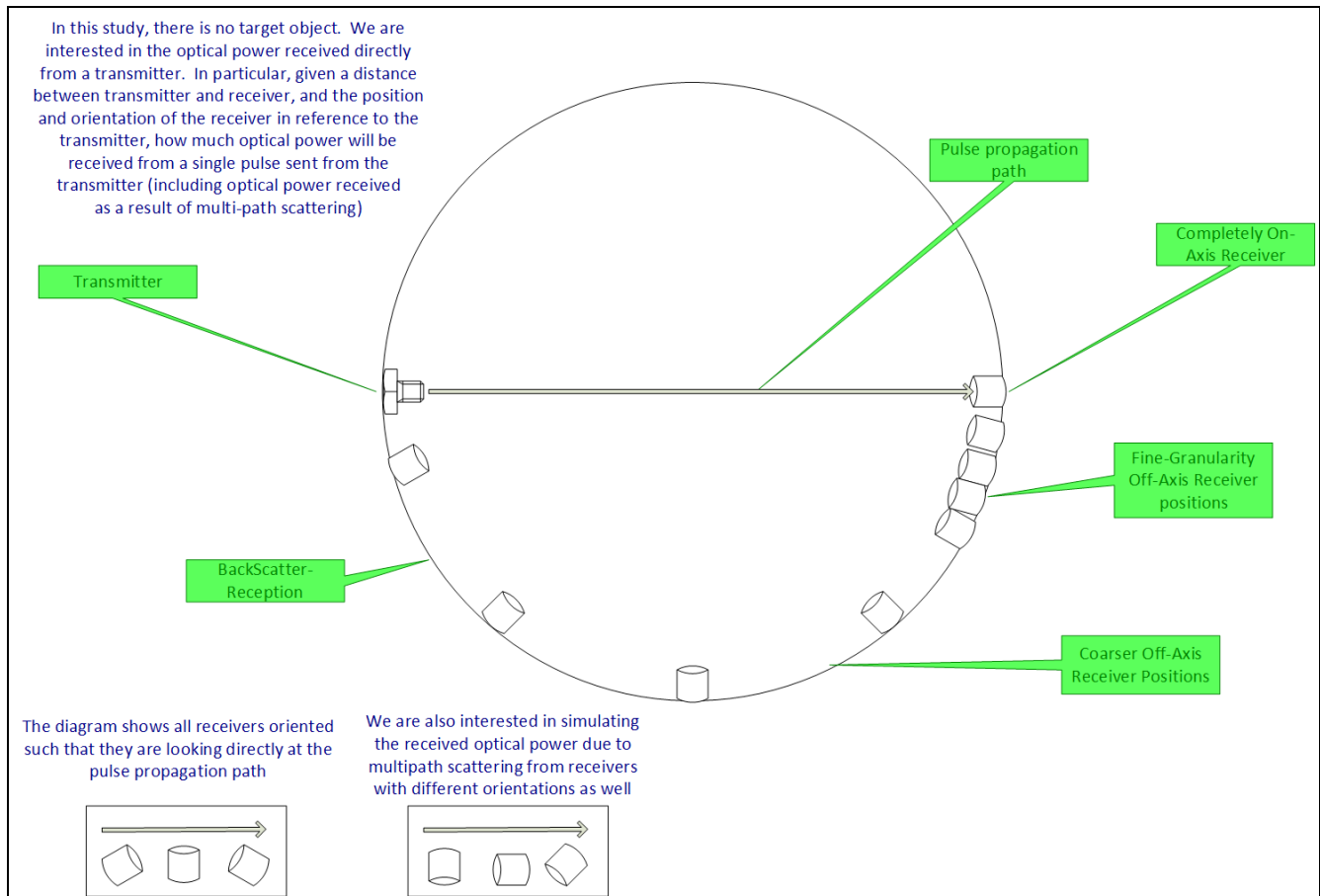


Illustration 1: Design diagram for the one-way Monte Carlo channel model code

### 2.3 Photomultiplier Tube (PMT) Detector Model

This block takes as input a simulated signal, the source laser wavelength, the quantum efficiency of the detector, and the current gain applied to the PMT photocathode. The output is a noisy simulated signal. PMT detectors being so-called shot noise limited devices, we ignore thermal and dark current noise and focus on predicting the shot noise introduced on the signal by the PMT. We approximate this shot noise by modeling the photomultiplier output  $X(t)$  as a non-stationary compound Poisson process,

$$X(t) = \sum_{k=1}^{N(t)} G_k h(t - S_k) \quad (2)$$

where  $N(t)$  is the number of photons striking the photocathode up to time  $t$ ,  $S_k$  is the arrival time of the  $k^{\text{th}}$  photon,  $G_k$  is the random amplifier gain, and  $h$  is the electrical impulse response of the detector. A more in-depth derivation and analysis of the accuracy of this detector model in predicting per-sample noise on a simulated signal is documented in [7].

### 2.4 Demodulator

The demodulator block takes the noisy simulated signal as input, demodulates and compares against the predefined pseudorandom bitstream, and calculates the 95% CL BER. In this iteration of the simulation framework, the demodulator and the BER calculator are included in the same block, to allow us to more efficiently record pulses for later analysis and comparison against experimental data. In future iterations of the framework, the BER calculator will be separate from the demodulator block.

## 3. EXPERIMENTAL SETUP

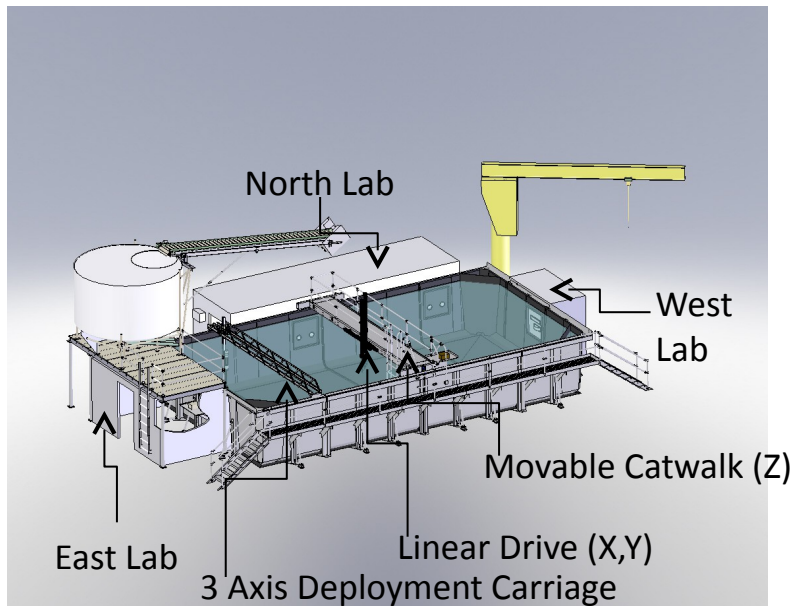
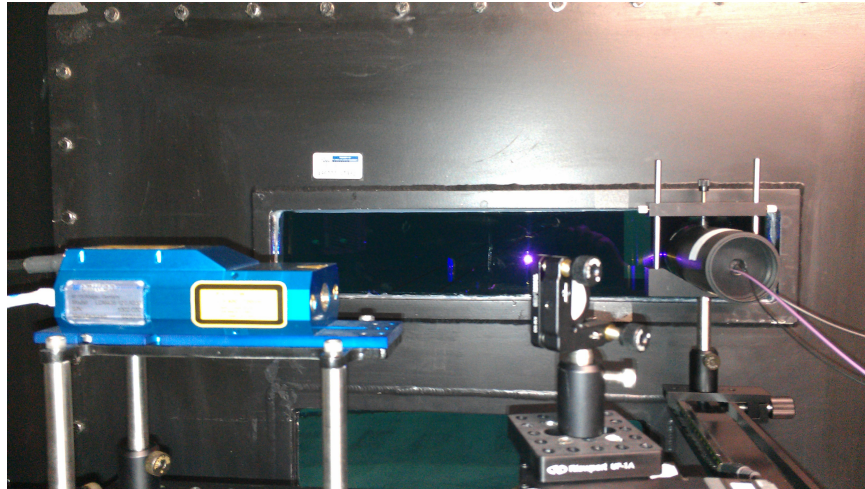


Figure 2: 12.5x7.5x2.5 m tank used for experimental data acquisition

In this set of experiments, we used a 12.5x7.5x2.5 meter saltwater tank located at the Harbor Branch Oceanographic Institute in Fort Pierce, Florida (see Figure 2). The turbidity of the water was controlled using ISO 12103-1 A1 Ultrafine Arizona Test Dust. The beam attenuation and absorption coefficients were measured using a Wet Labs AC-9 in-situ spectrophotometer. We placed a 405nm Omicron A350 laser source in the west lab, and a Hamamatsu R9880U-210 Photomultiplier Tube (PMT) detector in the east lab (12.5m apart). The laser was placed so that the beam was perpendicular to the viewport, and directed through the viewport by use of Thorlabs mirrors (see Image 1). The PMT was fitted with a 405nm narrow (3nm at full width half maximum) bandpass filter and a focusing lens that expanded the effective radius of the PMT to 5 centimeters and a 20 degree field of view. The mean output power of the laser was

measured using a Nova Ophir II power meter, and found to be 10.4 mW at 6.3% duty cycle.



*Image 1: Experimental setup, west lab. Note that the PMT pictured here is the same model (Hamamatsu R9880U-210) as the PMT in the east lab used to collect the data used in these experiments.*

The lasers were driven using an Agilent 81130A high-speed pulse generator. A predefined bitstring of length 65488 (the internal memory limit of the Agilent) representing a PPM-16 modulated pseudorandom bitstream (along with a trailer for synchronization) was loaded into the internal memory and signaling was set to non-return-to-zero (NRZ). The detector outputs were attached to a National Instruments PXI 5154 high-speed 8-bit digitizer (though the dynamic range was effectively 7 bits since we were unable to set the digitizer offset to take advantage of the entire 8-bit range), set to record at 1 Gbps with a vertical range of  $\pm 0.01$  V.

Using the Arizona test dust, we ran several turbidity cycles. During each cycle, we set the Agilent pulse frequency to 100MHz, 200MHz, 250MHz, and recorded 100 million samples. The gain voltage applied to the PMT was varied so that the mean voltage output of the detector remained close to 5mV (using 50 $\Omega$  terminations, this corresponds to 100nA mean current through the detector, the limit for these particular PMTs).

#### 4. RESULTS

We ran the simulator as described in section 2 using the parameters measured in our experiments and described in section 3. For each simulated turbidity cycle, we simulated transmission of 10 million samples at the data rates described in section 3 (we used 10 million samples instead of 100 million due to the computational complexity of the simulation). Comparing the simulated results to the experimental results (see figure 3 and table 1), we see very good alignment across all turbidities for the 100MHz (25Mbps effective data rate), 200 MHz (50Mbps effective data rate), and 250MHz (62.5Mbps effective data rate) cases. Note that in the 100MHz,  $c=0.95$  case, both the simulated and experimental results contained 0 bit errors. The difference in 95% CL BER ceiling is due to the fact that we simulated 10 million samples rather than the 100 million used in the experiments.

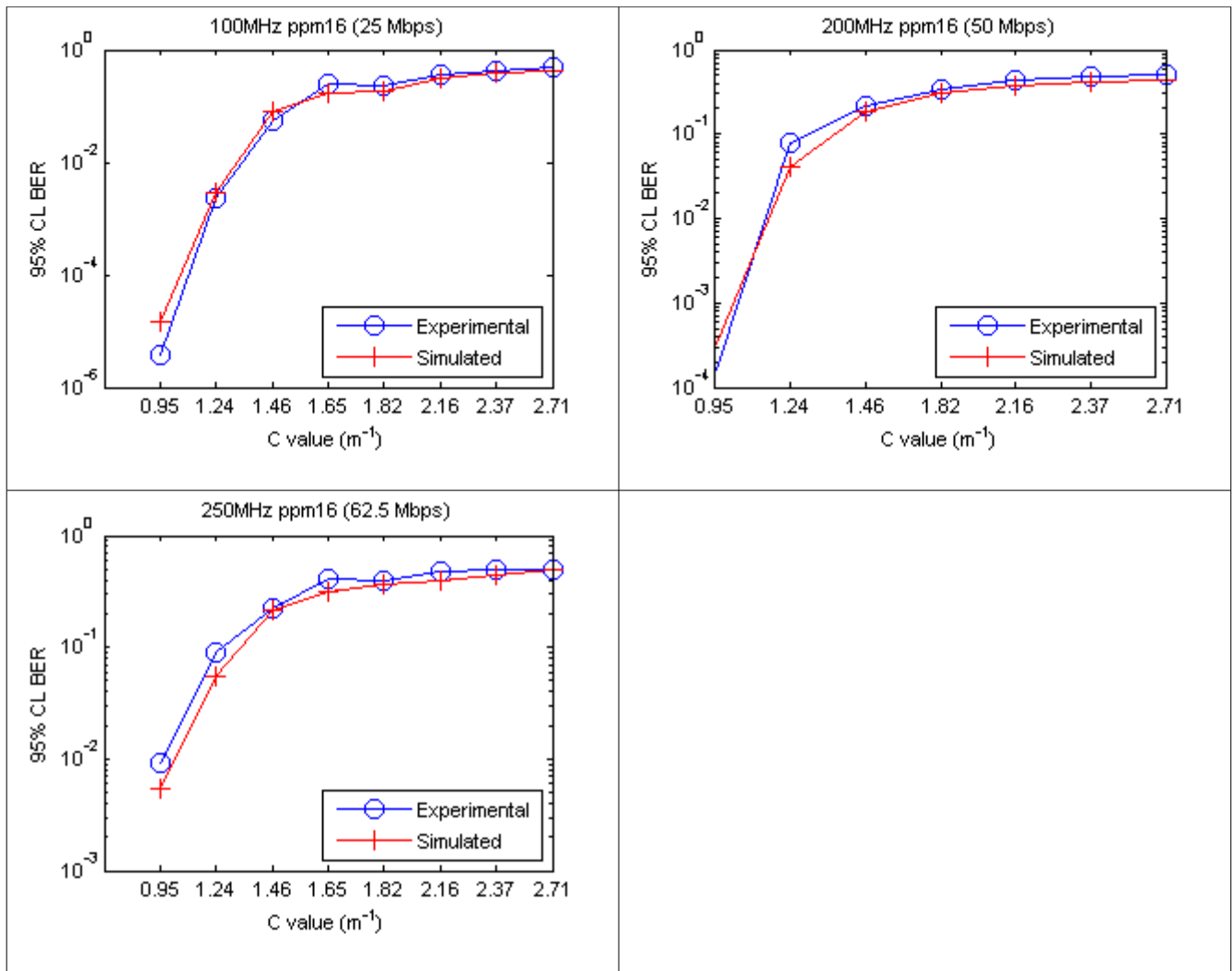


Figure 3 Experimental and simulated results for various turbidities and pulse repetition rates

Pulse repetition rate	C = 0.95	C = 1.24	C = 1.46	C = 1.65	C = 1.82	C = 2.16	C = 2.37	C = 2.71
100 MHz	Exp: 1.5e-6 Sim: 1.5e-5	Exp: 2.3e-3 Sim: 2.9e-3	Exp: 5.3e-2 Sim: 7.9e-2	Exp: 2.4e-1 Sim: 1.7e-1	Exp: 2.4e-1 Sim: 1.8e-1	Exp: 3.7e-1 Sim: 3.2e-1	Exp: 4.3e-1 Sim: 3.8e-1	Exp: 4.9e-1 Sim: 4.2e-1
200 MHz	Exp: 1.5e-4 Sim: 3.1e-4	Exp: 7.9e-2 Sim: 4.1e-2	Exp: 2.1e-1 Sim: 1.9e-1	Exp: - Sim: -	Exp: 3.4e-1 Sim: 3.0e-1	Exp: 4.5e-1 Sim: 3.7e-1	Exp: 4.8e-1 Sim: 4.2e-1	Exp: 5.0e-1 Sim: 4.3e-1
250 MHz	Exp: 9.3e-3 Sim: 5.4e-3	Exp: 8.9e-2 Sim: 5.5e-2	Exp: 2.2e-1 Sim: 2.2e-1	Exp: 4.1e-1 Sim: 3.1e-1	Exp: 3.9e-1 Sim: 3.7e-1	Exp: 4.7e-1 Sim: 3.9e-1	Exp: 5.0e-1 Sim: 4.4e-1	Exp: 5.0e-1 Sim: 5.0e-1
PMT Gain Voltage	500.75 V	622.5 V	707.75 V	707.75 V	807.75 V	915 V	987.5 V	987.5 V

Table 1: Data used to generate the charts in Figure 3

During demodulation, we recorded sample windows corresponding to pulses which were correctly demodulated. These were then averaged to arrive at the mean pulses shown in figures 4(a) – 4(f). In comparing these mean pulses, we see good alignment between experimental and simulated pulses, with full width half maximum (FWHM) values matching up well.

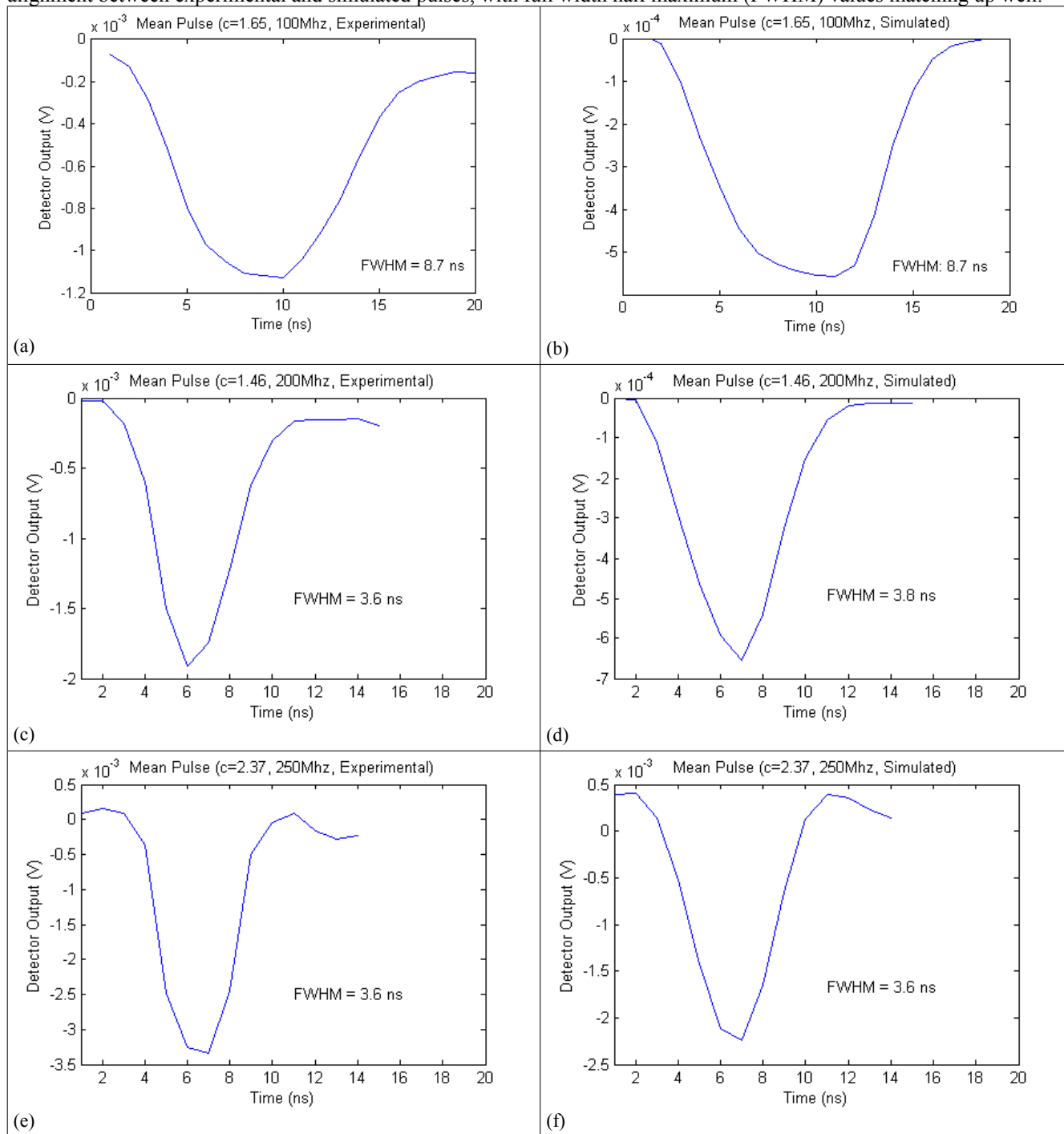


Figure 4: (a)-(f) Successful (correctly demodulated) mean pulses for a selection of turbidities and pulse repetition rates.

## 5. CONCLUSIONS, DISCUSSION, AND FUTURE WORK

Our physical layer simulator is shown to be an accurate predictor of observed experimental results, with simulated 95% CL BER ceilings within half an order of magnitude in most cases, and all within one order of magnitude. As stated in section 4, more work is needed on modeling the laser source, particularly with respect to the shape of the pulses and the per-pulse

variance. Additionally, using symbol error rate (SER) rather than bit error rate (BER) might provide a better performance metric for comparing PPM-16 results, since a single symbol error can result in anywhere from 1 to 4 bit errors. The demodulator block had no awareness of the pulse stretching effects of the channel and the detector response, but we can see from the mean pulse figures (figures 4(a) - 4(f)), after traveling through the channel, there is a noticeable stretching as a result of multipath scattering in the channel and the detector rise and transit times. At low data rates (longer pulse durations) this may not have a noticeable affect on the signal, but at higher data rates, needs to be taken into account in both simulations and demodulation hardware components in real-world systems. Ouyang et. al. [8] demonstrated the feasibility of using the two-way version of our channel model to simulate non line of site (NLOS) imaging using information-bearing multiple scattered photons. We hope to use a similar approach in future work to demonstrate conditions under which NLOS communication channels can be achieved.

Now that our physical layer simulator has been verified for on-axis 12.5m distance one-way communication, we will compare it against more test data to ensure the accuracy of the model in more potential real-world scenarios. Of particular interest is off-axis cases, as this will allow us to more accurately define pointing requirements for Tx/Rx for a given set of IOPs. We also plan to use the model to define system requirements for  $10^{-4}$  BER ceiling transmission rates, which we can use to design a set of in-tank and at-sea experiments to verify the validity of these requirements. Additionally, we will integrate the physical layer model with network simulation software to perform higher layer network protocol analysis and system design parameters for a working real-world system.

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