Time-of-flight measurements for LiDAR

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1. Introduction

The Time of Flight (ToF) measurement technique is a pivotal method in distance sensing and imaging, leveraging the speed of light to determine distances with high precision. This technique underpins critical applications in fields ranging from autonomous vehicle navigation (via LiDAR systems) to 3D imaging and medical diagnostics. Central to the accuracy of ToF measurements is the utilization of laser light, whose properties—coherence, and intensity—are essential for precise distance calculations.
This report focuses on the examination of ToF measurements using laser light, incorporating detailed characterizations of both the laser source and the Multi-Pixel Photon Counter (MPPC). The laser characterization aims to outline the operational parameters critical for ToF applications, while the MPPC characterization evaluates the detector's efficiency and sensitivity in photon detection.

2. Theoretical Framework

2.1 Laser Characterization

Lasers, due to their coherence, monochromatic nature, and high intensity, are ideal for ToF systems. Characterizing the laser involves understanding its frequency, beam temperature, and power. These parameters are critical as they affect the laser's ability to precisely measure distances in ToF applications.

2.2 Multi-Pixel Photon Counter (MPPC) Characterization

MPPCs detect single photons with high efficiency, making them valuable in ToF measurement for their sensitivity and accuracy. Characterization of MPPCs focuses on quantum efficiency, noise rates, and photon detection efficiency. These metrics are vital for evaluating an MPPC's performance in ToF systems.

2.3 Time of Flight(ToF) Measurement Principles

Time of Flight (ToF) measurements rely on the calculation of the time it takes for a light pulse to travel to an object and back to the sensor. The distance is determined by $d = \frac{c \cdot t}{2}$, where d signifies the distance, c denotes the speed of light, and t represents the time interval observed. Key factors influencing ToF accuracy include the speed of light in different media, reflectivity of the target object, and environmental variables.

3. Methods and Results

3.1 Laser Characterization

The bias value is a specific current setting chosen to optimize the laser's performance for a particular application. It is typically set above the threshold current but within a range that avoids the non-linearities and thermal issues associated with higher currents. The selection of an appropriate bias value is crucial for ensuring stable laser operation, maximizing efficiency, and maintaining the integrity of the laser over time. The first thing is to find the bias value for laser setting in constant temperature, frequency, and only various in current supply, which range from 0 to 500 mA, with comparatively reasonable test distribution. And based on the test result, the bias current I found is 67 mA.

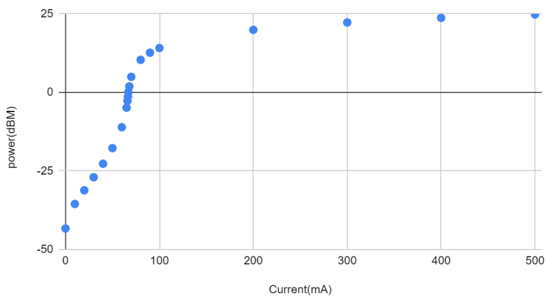

Figure 1: power(dBM) changing with Current(mA)

Next, I learned to figure out the relationship between the temperature supply and the wavelength. Since The wavelength of light emitted by a laser diode is fundamentally linked to the bandgap energy of the semiconductor material from which it is made. As temperature changes, so does the material's bandgap energy, leading to a shift in the emitted wavelength. The value of temperature varies between 20 and 35, and excluding individual parts with errors, it can be seen that the wavelength grows with temperature.

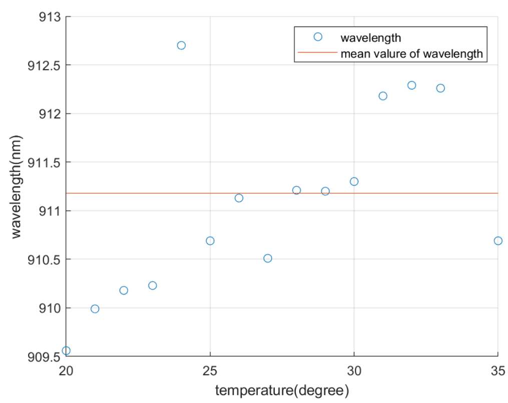

Figure 2: wavelength(nm) changing with temperature($^{\circ}C$)

After working on the continuous wave, the experiment moves on to work with the pulsed wave laser, since it is preferred in ToF applications primarily due to their ability to provide high temporal resolution, enabling precise measurement of the time interval between the emission and return of a light pulse.
Firstly, test starts with measuring the power various with frequency with the pulse width equal to $10ns$, and the temperature set to $25°C$. Due to the special property, through the simple multimeter only the average power could be measured, but it is not hard to see that as frequency increases, the power goes up.

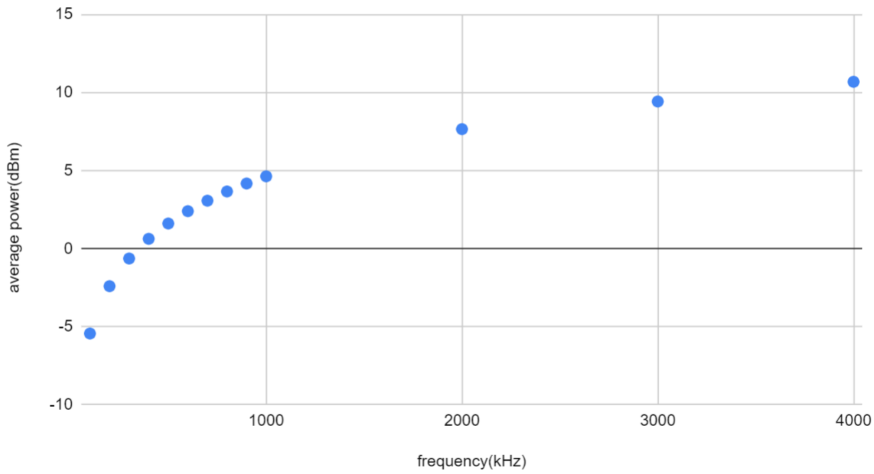

Figure 3: average power(dBm) versus frequency(kHz)

After this, to understand how the characteristic parameter will influence laser performance in ToF application, the pulse width and frequency are varied sequentially. In order to ensure that the final value would be within the safe range of the device, when measuring the peak value with the instrument, an optional reducer was added to reduce the input value by 20 dBm. From figure 4 and 5, not hard to see that decreasing the pulse width results in higher peak power, as the same amount of energy is concentrated over a shorter time period. And, unlike the direct impact pulse width has on peak power, the frequency of a pulsed laser primarily affects the average power and the duty cycle but not the peak power of individual pulses directly. Increasing or decreasing the frequency changes how often pulses are emitted but does not inherently alter the energy content of individual pulses unless the laser's pumping mechanism or energy storage capacity is affected. Thus, for a given pulse energy and width, the peak power of each pulse remains constant regardless of changes in frequency.

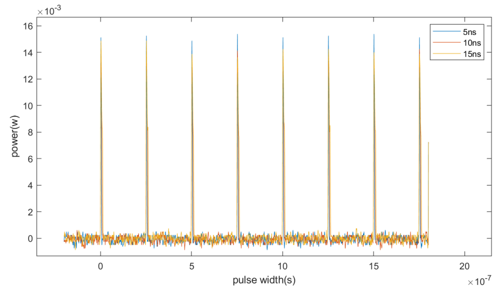

Figure 4: various in pulse width

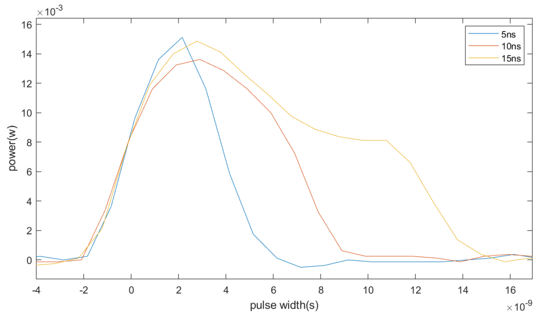

Figure 5: one pulse

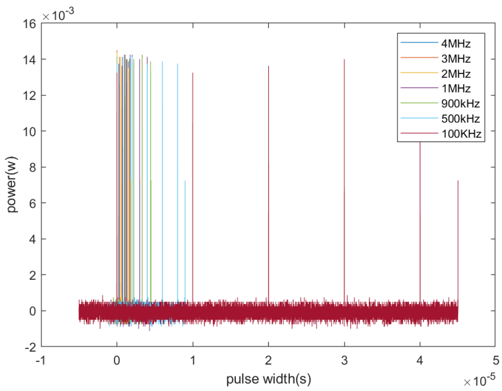

Figure 6: various in frequency

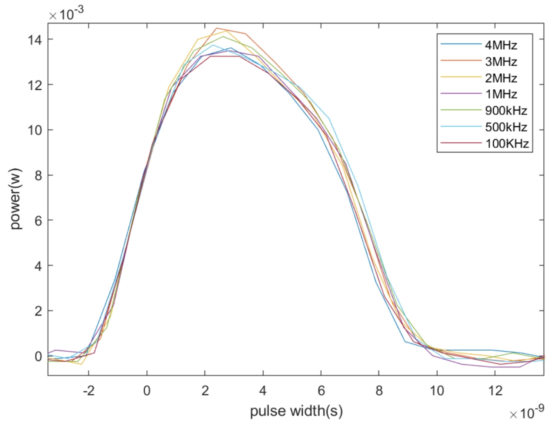

Figure 7: one pulse

3.2 Multi-Pixel Photon Counter (MPPC) Characterization

The characterization procedure commenced with the laser pulse width set to 10 nanoseconds and the power supply voltage established at 45 volts. Utilizing a straightforward connection configuration, both the emitted laser beam and the light detected by the MPPC were concurrently displayed on a single graph. This arrangement prominently revealed a time delay between the emission of the laser light and its subsequent detection by the MPPC. Leveraging this configuration, a straightforward methodology was employed to measure the time of flight, facilitating the precise determination of this critical parameter.

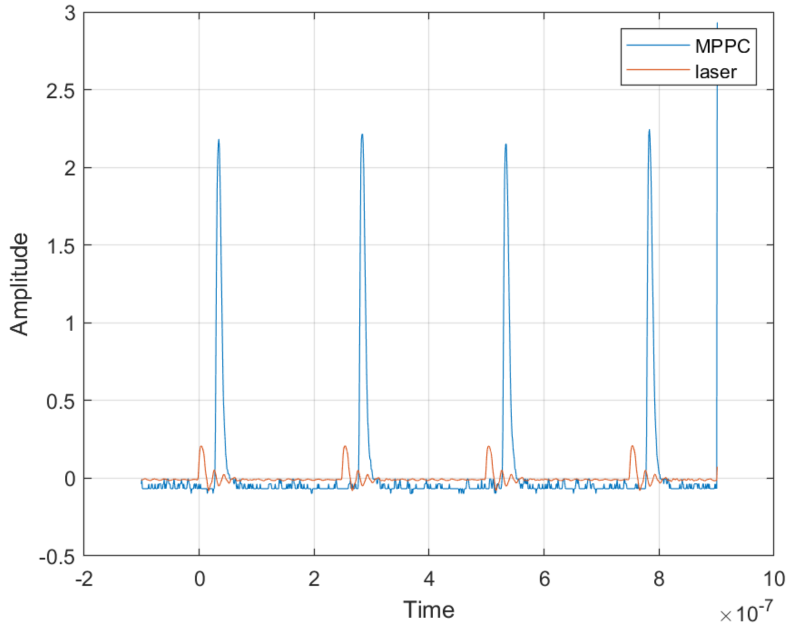

Figure 8: signal amplitude of MPPC and laser beam

The power supply voltage to a MPPC significantly influences the amplitude of the signal it receives and generates upon detecting photons. This effect is primarily due to the relationship between the supplied voltage, overvoltage, and the MPPC's operational characteristics, including gain and photon detection efficiency. Applying a higher power supply voltage, and consequently a higher overvoltage, increases the MPPC's gain, which results in a larger output signal for each photon detected because more charge carriers contribute to the signal. Essentially, the signal amplitude observed on an oscilloscope or other measurement devices will be higher.

From figure 9, obviously the amplitude goes up when the voltages increases, but falls down after the voltage reach 52V. I would prefer this is the effect of saturation semiconductor. At very high overvoltages, the MPPC can enter a regime where the avalanche multiplication process becomes saturated. In this state, the device may not be able to proportionally increase the gain for additional incoming photons because the semiconductor's charge carriers are already maximally excited.

Table 1 provides a systematic documentation of the variations in the input voltage supplied to the MPPC and its corresponding test values, as measured by a multimeter, for both continuous wave and pulse wave configurations while maintaining consistency in all other experimental parameters. The objective of this examination is to ascertain the optimal bias voltage for the MPPC within the specific setup and environmental conditions. The analysis unequivocally indicates that the bias voltage for the MPPC, conducive to optimal performance in this experimental framework, is discerned to be in the range of 2.71 to 2.81 volts.

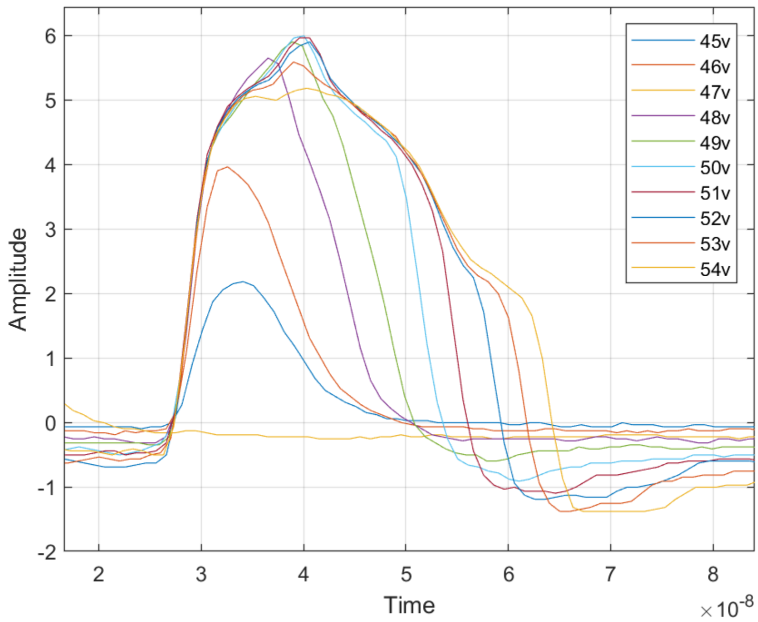

Figure 9: MPPC signal plot with different power supply

Table 1: Frequency = 1MHz, Peak current = 0.6A, Width = 10ns

Input Voltage(v)	Continuous Wave(dBm)	Pulse wave(dBm)
2.51	3.46	-10.23
2.61	2.27	-10.17
2.71	0.93	-10.56
2.81	-0.64	-10.96
2.91	-2.08	-11.53

3.3 Time of Flight(ToF) Measurement

3.3.1 Original Setup

In the initial phase of the experiment, the setup was comprised solely of the laser emitter for light generation, the target object to serve as the reflector of the light, and the MPPC to detect the reflected light. Within this configuration, the time of flight was distinctly observable (Figure 10 and 11). Employing the relevant equation $d = \frac{c \cdot t}{2}$, the distance between the target object and the laser emitter can be accurately calculated, demonstrating the efficacy of the setup in facilitating precise distance measurements through time of flight analysis.

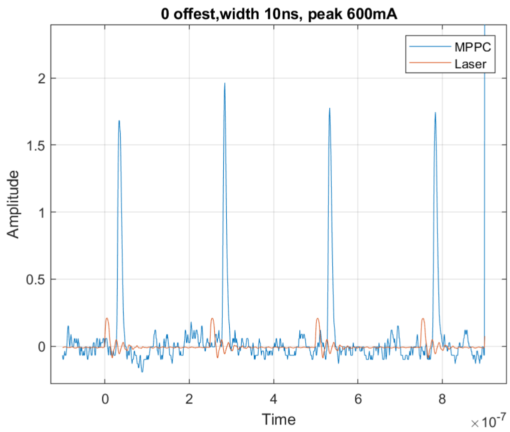

Figure 10: MPPC versus laser

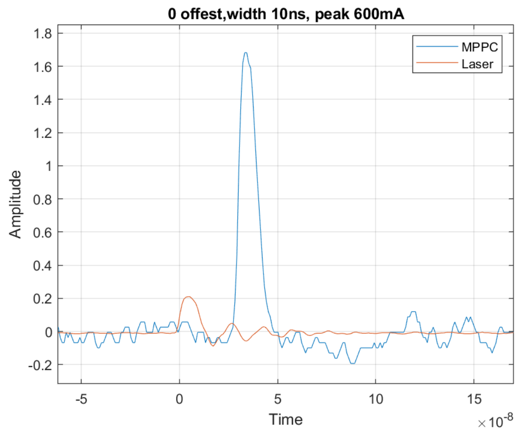

Figure 11: zoom in one reflection

Figure 12 illustrates the discrepancy between the calculated distances and the distances configured in the experimental setup. It is evident from the data presented that the variance between these two sets of distances remains minimal, indicating a high degree of accuracy in the distance measurement process.
Figure 13 depicts the outcomes of measurements for distances exceeding 86cm. In this instance, the graphical representation reveals significant challenges. The data captured by MPPC exhibits a pronounced level of noise, complicating the identification of genuine pulse signals. This degradation in data quality can be attributed to the increased loss of energy as the distance between the target object and the MPPC expands, with a consequential dispersion of energy into the surrounding space, rather than being efficiently reflected back to the MPPC.

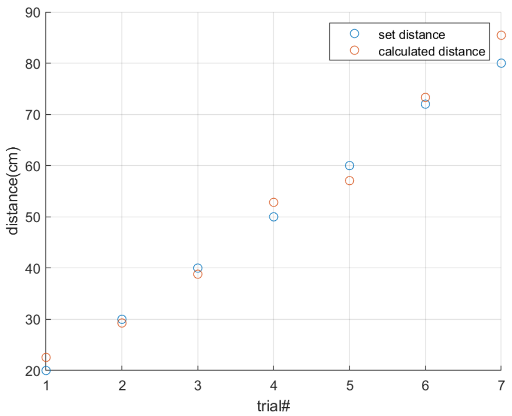

Figure 12: scatter plot of real distance and calculated distance

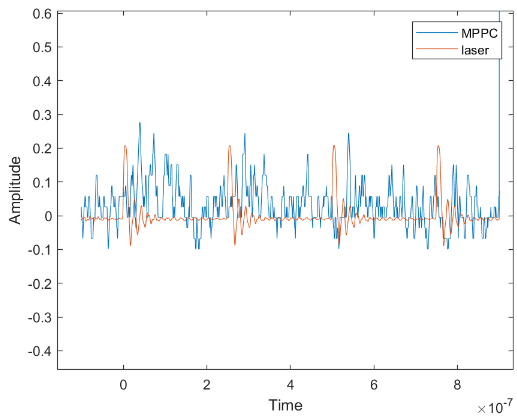

Figure 13: The distance longer than 86cm

3.3.2 Final Setup

In this part, the procedure commences with the laser beam being directed into a beam splitter cube, engineered to transmit 50% of the incident light while reflecting the remaining 50% into open space. The transmitted portion of the beam proceeds to illuminate a target object, which absorbs a fraction of the light and reflects the remainder back towards the beam splitter. Upon return, the beam splitter again divides the light, with a portion being transmitted through and another portion being redirected towards the Multi-Pixel Photon Counter (MPPC). A wavelength-specific filter is incorporated in front of the MPPC to mitigate the effects of out-of-range wavelengths, ensuring that only relevant light signals are detected, thereby enhancing the accuracy and reliability of the measurement. The equipment is set up as below, Figure 14.

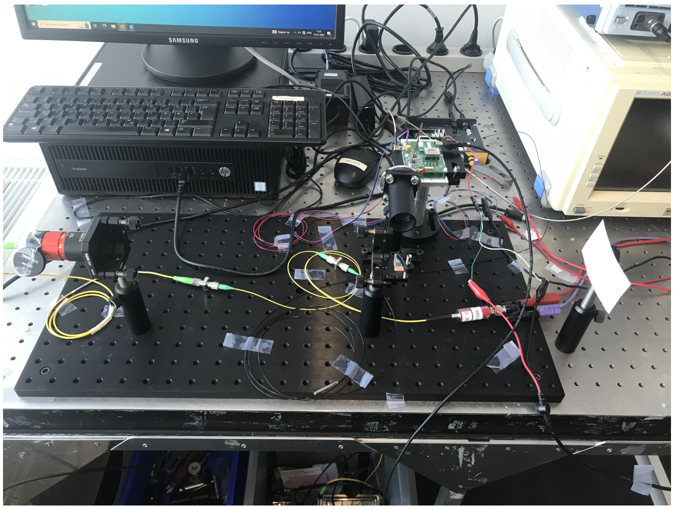

Figure 14: set of ToF measurement

Upon configuring the input voltage of MPPC to 2.51V, a series of time interval measurements were conducted, with the corresponding distances calculated and presented in Figure 15. Statistical analysis of these calculated distances reveals that they tend to be consistently less than the distances predetermined in the experimental setup. This discrepancy can be attributed to a deviation from the previous experimental configurations, wherein the distances between the emitter, the target object, and the receiver were meticulously maintained to be equivalent. The alteration in setup likely resulted in a reduced time interval than anticipated, subsequently leading to the derivation of diminished calculated distances.

Figure 16 is the plot of MPPC versus Laser, given the distance between the object and the laser emitter equals to 55 cm, not hard to see there is a time difference between the emitter and receiver.

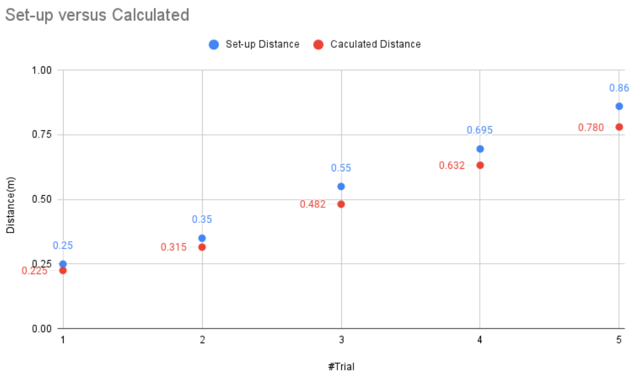

Figure 15: Voltage = 2.51v

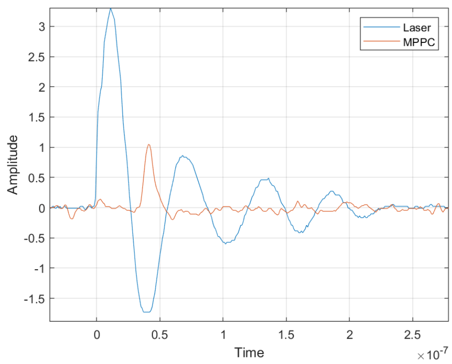

Figure 16: distance = 55cm

In Figure 17, the separation between the object and the laser emitter is consistently maintained at 55cm, with variations applied exclusively to the input voltage of MPPC. It is readily observable that an increase in voltage corresponds to a diminution in signal amplitude. Furthermore, figure 18 reveals the value devoid of any object-reflected signals, in other words, only the value natural light from empty space. The resultant amplitude, derived from subtracting the signal without object reflection(Figure 18) from that with reflection(Figure 17), approximates to zero. This observation aligns with findings presented in Table 1, where the bias voltage for the MPPC within this experimental setup is identified to be in the vicinity of 2.71V, underscoring the critical voltage threshold for optimal MPPC performance.

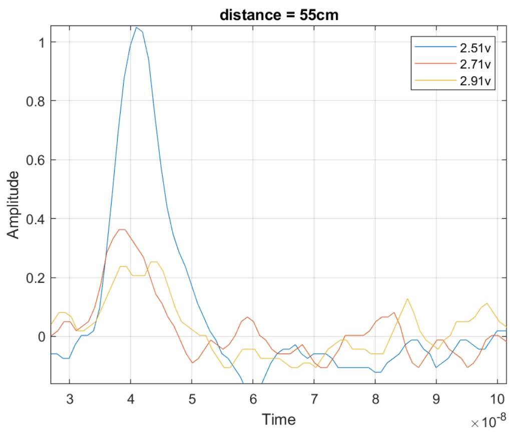

Figure 17: same distance(55cm) different input voltage

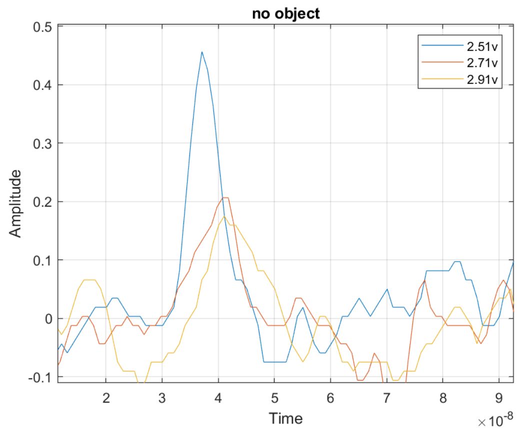

Figure 18: no object reflection

4. Conclusion

In conclusion, this report has systematically explored the intricacies of Time of Flight (ToF) measurements utilizing a laser emitter and a Multi-Pixel Photon Counter (MPPC) within a controlled experimental setup. Through meticulous calibration and testing, key operational parameters such as pulse width, input voltage, and the impact of varying distances on signal integrity have been thoroughly examined.

Throughout the experimental process, it is acknowledged that certain errors may have arisen due to human involvement in the operation of the equipment, potentially impacting the precision and uniqueness of the data obtained. Despite these considerations, it is important to note that the data garnered and subsequently calculated remained within acceptable margins of accuracy. Given this context, the experiment can be deemed successful in its overall execution and outcomes.