CHALMERS
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Investigation of Digitalization in Laser Rangefinder Receiver

How to Use Digital Signal Processing and Pulse Detection to Improve Performance in the Laser Rangefinder Receiver

Master's thesis in Communication Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
www.chalmers.se

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Master's Thesis 2022
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Typeset in LaTeX
Printed by TeknologTryck
Gothenburg, Sweden 2022

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Abstract

Digitization provides many opportunities for a wide range of applications since it can generate more flexible and stable solutions compared to analog solutions. It also allows using other tools than the ones available for analog solutions. The purpose of this master's thesis was therefore to investigate how the performance of an analog laser rangefinder receiver can be improved by digitalizing the receiver and using digital techniques on the laser rangefinder's received echo signal. This included investigating the detection sensitivity, as well as, the possibility to separate false alarms and true optical echo pulses in the received signal. Separating the two would provide a possibility for increased bias voltage in the Avalanche Photodiode (APD), used for detection in the laser rangefinder. An increase in bias voltage would also improve the sensitivity of the laser rangefinder.

The investigation was done by simulations in MATLAB. The simulations consisted of constructing a laser rangefinder's received echo signal, applying digital signal processing to it and using digital pulse detection. It was also investigated if some other analog solutions in the laser rangefinder can be replaced by digital techniques in a digital solution. The Central Processing Unit (CPU) time for the investigated digital methods was also measured.

The result demonstrated that a digital laser rangefinder receiver would be superior to an analog receiver under the circumstances of the thesis. The detection statistics were much improved and the detection sensitivity of the optical pulse amplitude was increased by 10.57 dB. The digital solution also managed to separate false alarms and true optical pulses to a certain extent. Thereby making it possible to increase the bias voltage in the APD.

Keywords: Laser Rangefinder, Digital Signal Processing, Digital Pulse Detection, Filtering, Avalanche Photo Diode, Denoising, Denoise Received Echo Signal, Digitalization

Acknowledgements

I would like to express my gratitude to everyone that helped and supported me while writing my master's thesis. I would like to thank my supervisor at Saab AB, Stefan Horrdin, for developing and proposing a thesis project molded for my interests and skills. Throughout the process, he has helped me and provided me with all the support and information I have needed. He has also supported my ideas and pushed me toward developing my solutions. I would also like to thank my examiner at Chalmers, Vessen Vassilev, for supporting my work and giving me feedback and new ideas to excel the thesis further. Lastly, I would like to thank all my friends at Chalmers for always giving me a laugh and a good time during the study breaks, as well as for always supporting me in my studies during the past five years.

Josefine Åberg, Gothenburg, June 2022

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

ADC	Analog to Digital Converter
APD	Avalanche Photodiode
CPU	Central Processing Unit
DSP	Digital Signal Processing
EMD	Empirical Mode Decomposition
IMF	Intrinsic Mode Functions
LiDAR	Light Detection And Ranging
SNR	Signal to Noise Ratio
TVG	Time Varying Gain

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1
Introduction

This is a master's thesis in communication engineering at Chalmers University of Technology. The thesis was carried out in collaboration with Saab AB*. In general, the thesis was to investigate how the performance of an analog laser rangefinder receiver can be improved by digitalizing the receiver and using digital techniques on the received signal.

To digitalize the receiver, an Analog to Digital Converter (ADC) can be used to convert the received electrical signal to a digital signal. The signal can then be processed in software instead of in analog hardware. Digital signal processing and pulse detection in software are more flexible and have much higher repeatability than analog signal processing. Also, working in software provides more opportunities, e.g. by using software it is possible to use mathematical and statistical tools, as well as implement programming [1], [2].

1.1 Background

The general principle of the laser rangefinder is that the transmitter is sending out laser pulses and in the receiver, the pulses that have been reflected of objects are received. The received signal is called the echo signal. The receiver is using an Avalanche Photodiode (APD) to detect and transform the optical echo signal into an electrical signal [3]. The signal is then put through an analog detection circuit with an amplitude threshold. If the signal is above the threshold the system signs for a detection [4].

By increasing the APD's bias voltage, the APD's sensitivity and thereby the laser rangefinder's sensitivity can be increased. When the bias voltage is increased, it causes more spontaneous avalanching in the APD [5]. This in return increases false alarms in the laser rangefinder. This problem limits the performance of the analog detection circuit and increasing the bias voltage is therefore not possible for the analog solution [4].

If the laser rangefinder receiver were to be digitalized, digital signal processing and pulse detection can be used on the received signal [1]. This would allow to separate true optical pulses and false alarms depending on their pulse characteristics.

*At the end of May 2022, Saab AB will no longer have a department for laser solutions. The laser department and their solutions will convert to Lumibird Photonics Sweden AB.

If this is possible, the bias voltage can then be increased and thereby also the laser rangefinder's sensitivity [4].

As mentioned in Chapter 1, digital signal processing offers more opportunities compared to analog signal processing. Therefore, there are many digital signal processing techniques that can be explored to improve the performance of the laser rangefinder, e.g. it might be possible to reduce noise in the signal and increase the Signal to Noise Ratio (SNR) [3]. Digital pulse detection also allows a more complex pulse detection method [6]. It would also be possible to use correlation between multiple signals to detect a moving object far away and also approximate its velocity [3]. There are also some other analog solutions in the laser rangefinder that can be digitalized. One example is the Time Variable Gain (TVG). The TVG is used to have a dynamically increasing gain over time for one pulse. This ensures that reflections from small particles close to the laser rangefinder are not amplified and do not generate a detection [4].

1.2 Related Research

When doing a research review on digitalization of laser rangefinders and digital techniques for received echo signals not much was found. There are a few interesting Chinese reports (based on their headlines and abstracts), but unfortunately due to the language barrier, they can not be read and used as research for this thesis. There is some research on the denoising of laser, Light Detection And Ranging (LiDAR) and radar signals, which in some aspects are similar to a laser rangefinder's signals. There is little research on how to simulate laser rangefinder's received echo signals.

1.3 Purpose

The aim of the master's thesis was to investigate if and how digital techniques can be used to separate false alarms from the true optical pulses in the laser rangefinder's received echo signal. If it is possible, investigate how much the bias voltage can be increased. Also, investigate how digital techniques can increase the detection sensitivity of the laser rangefinder. Lastly, explore how digital techniques can improve and replace the analog TVG filter in the laser rangefinder receiver.

1.3.1 Scope and Limitations

- The thesis only takes into consideration the laser rangefinder Saab AB is developing and makes assumptions and tailors solutions based on it.
- Since no real data have been sampled the project only uses simulated signals created in MATLAB. Therefore the project does not consider the extra work that would be needed for real-world sampled data.
- The project only focuses on the laser rangefinder receiver and not the transmitter.

- The project does not consider the laser rangefinder's range resolution or range ambiguity.

1.3.2 Specification of Issue Under Investigation

A specification of what was being investigated is presented as issues and each issue is aimed to be answered in the thesis. Each issue can also be viewed as a sub-goal in the main project.

- Can digital techniques separate true optical pulses from false alarms?
- Is it possible to increase the bias voltage of the APD in a digital solution?
- Can digital techniques increase the detection sensitivity of the laser rangefinder?
- How much Computer Processing Unit (CPU) time will the digital methods use?
- Is there a digital solution that can replace the analog TVG?
- Can correlation between signals enable better detection performance?

1.4 Societal, Ethical and Ecological Aspects

Technical products and the work of engineers can have a high impact on society, the environment and people [7]. Therefore when starting a project it is important to consider the societal, ethical and ecological aspects related to the project.

The general purpose of this thesis was to investigate if digital techniques can be used to improve the performance of a laser rangefinder. The investigation was mainly performed in software and some parts were explored in a laboratory environment with already existing equipment and products. The thesis, therefore, had little to no effect on the environment since the project did not produce any material waste nor did need any products to be imported or purchased. The methods used in the thesis are not to be considered as dangerous and do not expose anyone to risk, therefore the execution of the project was not an issue of societal or ethical measures.

The result of the thesis might lead to further investigation of digitalization in the laser rangefinder receiver and further investigation of how digital techniques can benefit the laser rangefinder receiver. This in return might lead to the implementation of the solution in real practice and thereby replacing the analog receiver with a digital one. The societal, ethical and ecological aspects of that can not be derived since it is too far in the future and not directly linked to this thesis.

The thesis was done together with the defense company Saab AB, which develops defense products, therefore the result from this project might be used in projects and products intended for military purposes. There are split opinions about the defense industry and there are both pros and cons to it. Military conflicts are usually not profitable from a societal, ethical or ecological standpoint and military conflicts are to be avoided at all costs. On the other hand, there is a necessity of being able to defend country borders, people and democracy. Also, Saab AB do not export their products everywhere. There are strict laws considering the export of military products. This is to ensure that military products do not fall into the wrong hands.

1.5 Thesis Outline

This master's thesis consists of 8 chapters. Chapter 1 gives an introduction to the problem being investigated and provides relevant background information. It also presents the purpose of the thesis, as well as specifies issues and limitations. Further in the chapter, a review of related research is presented. An analysis of the societal, ethical and ecological aspects is presented, as well as the thesis outline.

The next chapter, Chapter 2, consists of the theory and information to understand the problem modeling, methods and results. The chapter provides information on semiconductor fundamentals, the laser rangefinder principle and laser rangefinder signals, as well as common signal processing and pulse detection techniques.

Chapter 3 provides information from a practical signal study. The signals from the laser rangefinder are described and analyzed.

In Chapter 4 the methods used in the thesis are presented. The chapter covers methods used in the literature study, how the practical signal study was performed and how the signal simulation and signal processing were done. The design of the pulse detection method is presented, as well as how the results were validated. How each issue was investigated is also described.

In Chapter 5 the simulations are presented. The simulations are a large part of the investigation for this thesis and are the foundation of what later is presented in Chapter 6.

Chapter 6 presents all of the results. Most of what is presented in Chapter 6 can be evaluated from Chapter 5, but Chapter 6 highlights the outcome of the simulations in Chapter 5 and presents the results clearly.

In the next chapter, Chapter 7, the results are analyzed and a discussion regarding the results is given. The results are put into context and validated.

Finally, Chapter 8, gives a summary and presents the final conclusions of the thesis.

2
Theory

In this chapter the relevant theory to understand the problem and interpret the methods and solutions is presented. First, the laser rangefinder principle is presented to understand how it works and what components and functions it needs. To understand one of the driving factors of digitalization of the laser rangefinder for this thesis, semiconductor fundamentals and APDs are described. This information will also provide insight on the problem modeling, especially the noise modeling. Further, the topic of digitization is introduced, as well as some issues it induces. Then, digital signal processing and pulse detection techniques are described. Some specific signal processing methods particular for laser rangefinder's signals and other similar signals are presented, as well as relevant research within the area. Lastly, laser rangefinder signal characteristics and signal segments are described.

2.1 Laser Rangefinder Principle and Characteristics

The principle for laser rangefinders has already been slightly introduced in Section 1.1, but in this section, a more detailed explanation will be given. Some laser rangefinder characteristics will be introduced as well.

Laser rangefinders are used to monitor or measure distances or object lengths and are used in many areas such as construction, military, surveillance, automotive vehicles, sports, industrial production processes and also in home applications. With the wide range of applications, there are several different kinds of laser rangefinders with different sensitivity and range. Though, the principle for a laser rangefinder is the same [8]. Figure 2.1 views a simplified block diagram of a typical laser rangefinder principle.

The laser rangefinder has one transmitter and one receiver. In the transmitter, a laser pulse is generated [9]. The laser rangefinder modeled in this thesis needs to be sensitive and useful for long distances, so the optical transmit pulse is a square pulse with 10 - 20 ns in pulse width and has high pulse power [4]. The pulse is transmitted and travels through the air. When the pulse hits a target, the pulse is reflected off the object and travels back to the laser rangefinder receiver. When arriving at the receiver, the received echo signal is first focused by an optical lens. The received optical echo signal is then pointed to some kind of photodiode that transforms the optical signal into an electrical signal [8], in this case, an APD is used. The received pulse is different in shape and also much weaker than the transmitted optical pulse.

The received pulses are varying in amplitude, while the pulse width remains at 10 - 20 ns. The received pulse shape is usually a mix of a square pulse and a Gaussian pulse [4]. Then the signal goes through some kind of detection method. There are both analog and digital solutions. The detection and range calculations are usually done by threshold pulse detection and time-stamping circuits or algorithms. For a digital solution, the signal from the APD goes through an ADC and then through processing and detection algorithms [10]. In the analog solution, the signal goes through a detection circuit instead [8].

The analog detection circuit for the laser rangefinder modeled in this thesis is measuring if pulses exceed an amplitude threshold of 40 mV. This circuit is required to detect 50 % of the optical pulses and about 0.1 % of all detections are false alarms at the amplitude threshold level of 40 mV [4]. False alarms are when the noise currents exceed the threshold value of the detection method and falsely signals for detection. By measuring the time interval from emitting the pulse to receiving the pulse, the distance can be calculated and the target can be located. The detection results are then sent to a user interface [3].

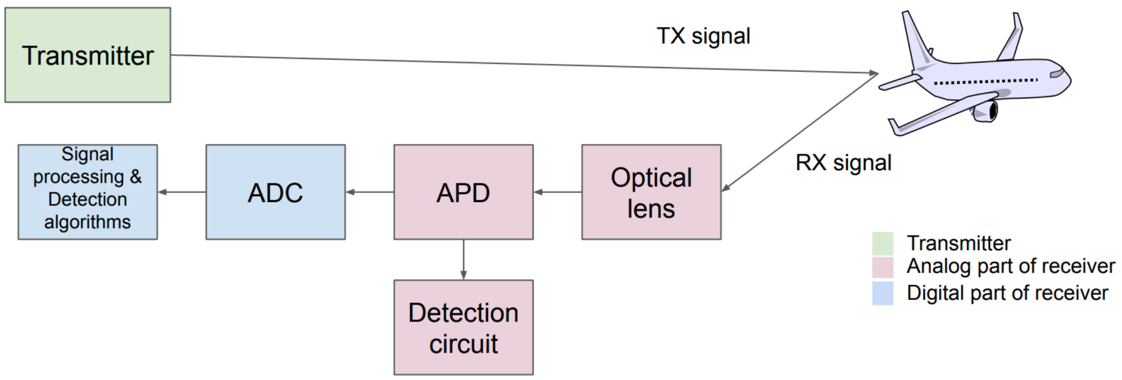

Figure 2.1: Simplified block diagram of the laser rangefinder principle.

2.1.1 Time Varying Gain Function and Backscatter

Backscatter is defined as a diffuse reflection of waves, particles and signals, which is reflected back to the source [11]. The diffuse reflection is due to scattering and is the opposite of a specular reflection. For laser rangefinders, backscatter is not wanted. Even though it is true optical pulses, these echos are usually from detecting small particles close to the laser rangefinder. Immediately after being sent from the transmitter, the signal is high in power and when hitting a target like a small particle in the adjacent air, the signal is scattered and some of the scattered signal is reflected back to the laser rangefinder receiver. Since the signal was large when hitting the small particle and the distance is small, the echo signal can generate a detection. This phenomenon is inevitable and therefore the receiver needs to be able to handle the backscatter so the receiver does not give detections for it [11], [4]. In an analog solution, this can be handled by a TVG filter in the receiver circuit. The TVG filter is an amplifier where the gain is varying over time. The function is timed and used to reduce the first detections of every laser pulse, as well as to amplify the rest of the signal [4]. The principle of the analog TVG filter over time is presented in Figure 2.2. In the figure, the four signal variations demonstrate the variation of the TVG filter over the time of four measurements (four laser shots). In the figure the shape of the function is ideal (non-fluctuating) and the amplitude, as well as the frequency, are not true to reality. In reality, the function is not as stable and is fluctuating more due to variations in the electronics.

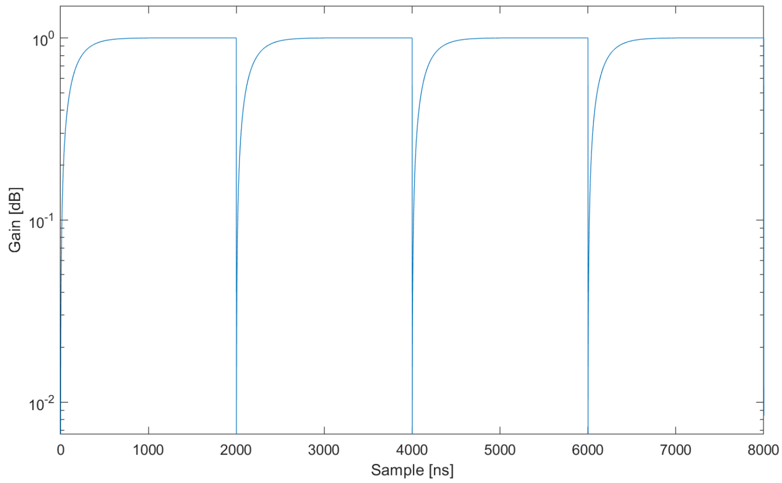

Figure 2.2: Ideal example of an analog TVG filter over four measurements. Amplitude and frequency are not true to reality, it is only to illustrate the principle.

2.2 Semiconductor Fundamentals

In this section, the basics of semiconductors are presented. Semiconductors are highly used in electronics and are important components in modern circuits [12]. An APD is a type of semiconductor used in the laser rangefinder, as presented in Section 2.1. To be able to understand its characteristics and function, as well as the origin of the problems and limitations of the analog laser rangefinder receiver, the basics of semiconductors need to be understood.

A semiconductor is a crystalline solid intermediate in electrical conductivity between a conductor and an isolator. This creates a material that is not an isolator nor a conductor. A crystalline solid is a material where the internal structure is arranged in a regular pattern. In this type of structure, the electrons with the most energy are moving like free particles in the material. The free-moving electrons leave an absence of a negative charged particle in the valence band of the atom, this is called a hole and in the absence of an electron is seen as a positive charged free particle. The current in a semiconductor is defined by the moving electrons in the conductor band and the holes in the valence band. Thereby, the more free electrons and holes there are in the semiconductor, the more current it can carry [13]. A band diagram showing the conductor and valance band with its electrons and holes is illustrated in Figure 2.3.

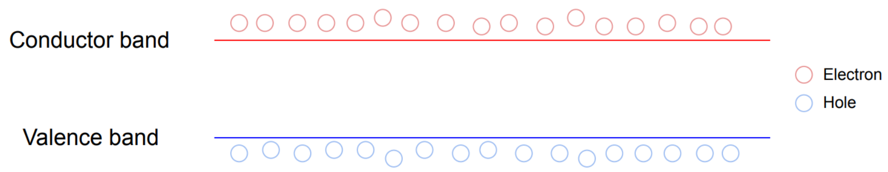

Figure 2.3: Band diagram for a typical semiconductor, the figure also illustrates the principle placement of electrons and holes.

The space between the two bands is called the band gap or energy gap. This gap represents the potential needed to rip an electron from the valance band to the conductor band. If the band gap is large, the material is an insulator and if it is small, the material is a conductor [13]. In Figure 2.4 a few band diagrams for different semiconductors are viewed. The green line in the middle of the band gap is the Fermi potential. This line defines if the electrons belong to the conductor band or if it belongs to the valance band. Therefore the Fermi potential can be defined as the energy an electron needs to be exited and move like a free particle [12].

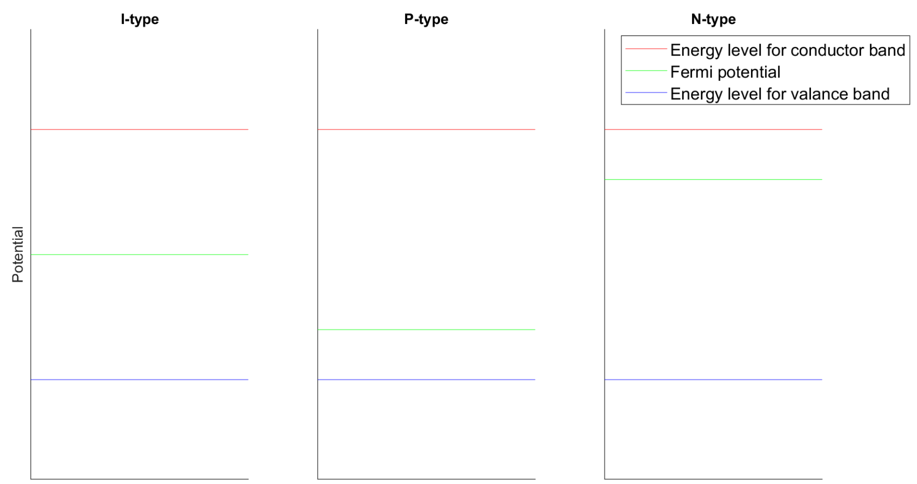

Figure 2.4: Band diagrams for semiconductors of i-, n- and p-type.

Free electrons and holes increase or decrease by generation and recombination. To have generation, energy needs to be added. The energy excites the electrons in the valance band and lifts them to the conductor band. Like so, a pair of one free electron and one hole have been generated. By recombination, energy is instead emitted from the electron and the electron then falls down from the conductor band to the valance band and is therefore filling the empty position, that is the hole [13].

In an ideal semiconductor in steady-state, where no generation or recombination is happening and there is constant temperature, the concentration of electrons and holes are the same. The charge carrier density and Fermi potential are therefore constant. By doping the semiconductor the charge carrier density is affected and the

Fermi potential shifts. This is done by inducing impurities into the semiconductor. Often elements from the same period and the nearby groups in the periodic table are used [12]. To explain this, silicon and phosphorus can be used as an example. Silicon is a semiconductor with 4 valance electrons. The doping element phosphorus has 5 valance electrons and can thereby almost fit into the silicon crystal structure, resulting in an extra free electron in the conductor band for every doping atom. Since phosphorus offers an extra electron to the structure it is called a donor to silicon. If aluminum would be used instead of phosphorus, this would result in an extra hole in the valence band since aluminum instead has 3 valence electrons. Aluminum is called an acceptor to silicon [14].

A semiconductor that is not doped is called intrinsic and is i-type. A doped semiconductor is extrinsic and if doped with a material with an extra valence electron, a donor like phosphorus, the semiconductor is called n-type. When doped with a material with one valence electron less, an acceptor like aluminum, the semiconductor is called p-type [13]. The band diagrams for an i-type, p-type and n-type semiconductor can be seen in Figure 2.4.

The charge density and Fermi potential are not just affected by the doping, but also the temperature. In an i-type semiconductor, the Fermi potential is decreased when the temperature increases and free electrons and holes are generated accordingly. In a p-type material, the Fermi potential is decreased towards the valance band with increasing temperature and vice versa for n-type, where the Fermi potential is increased towards the conductor band with increasing temperature. The charge carrier density is therefore affected by both the doping and temperature [12].

2.2.1 PN-Junctions

A PN-junction is created where a p-type semiconductor and n-type semiconductor are in contact. This is the main part of a diode [5]. As explained in Section 2.2, the doping creates free electrons and holes in the semiconductor, in a PN-junction, this produces a concentration gradient between the p- and n-type. The gradient creates diffusion currents between the p- and n-type, i.e a flow of electrons from n- to p-side and a flow of holes in the opposite direction [15]. Before the gradient reaches zero, an electric field has stopped the charges from flowing over to the other side. This electric field emerges from the depletion region, which is the region closest to the junction. The junction has no free charges since the holes and electrons have moved to the other side due to the diffusion currents. Left in the area are positive donors ions and negative acceptor ions, which give uprise to an electric field that oppose the diffusion currents. When the electric field is large enough to stop the diffusion currents completely the junction is in an equilibrium state [5]. The electric field could also be expressed as a potential, this potential is often called the built-in potential or potential barrier [15].

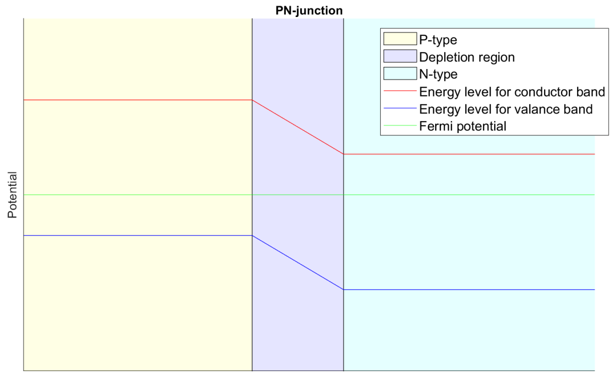

Figure 2.5: Band diagram for a typical PN-junction.

By applying an external voltage, called bias voltage, over the PN-junction different phenoms happens. If there is a forward bias over the junction, which is when a positive voltage is connected to the p-side and negative to the n-side, the electric field in the depletion region is decreased. This lowers the potential barrier and allows for a current to flow through it. Therefore, for a current to flow through the junction, the applied external voltage needs to be larger than the potential barrier [15]. If there is a reverse bias, which is when a negative voltage is connected to the p-side and positive to the n-side, the depletion region is widened and the electric field is increased. This increases the potential barrier. For a reverse-biased PN-junction, a negligible current is flowing through the depletion region and instead, the PN-junction starts behaving like a capacitor. As the reversed voltage is increased so is the width of the depletion region and the capacitance is then decreased. The PN-junction is therefore a voltage-dependent capacitance [5]. In Figure 2.5 a band diagram of a PN-junction is shown.

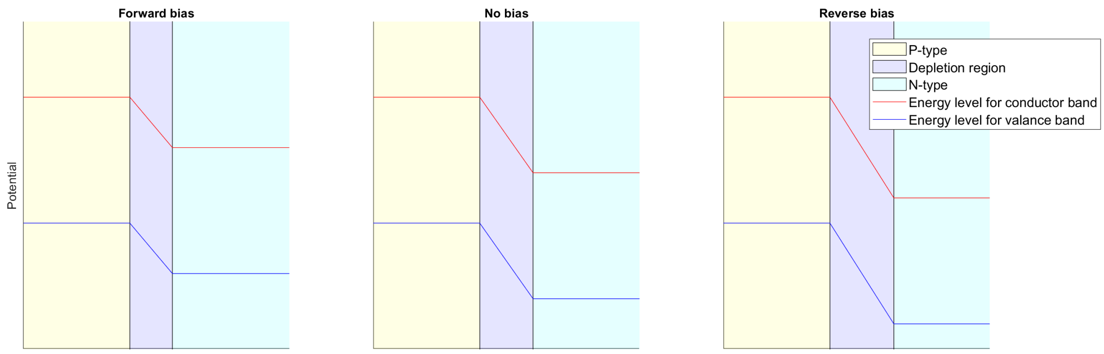

Figure 2.6: Band diagrams for three PN-junctions with different bias voltages; forward bias, no bias, reverse bias.

In Figure 2.6 band diagrams for a few PN-junction under different bias is demonstrated. It is clearly shown what happens to the junction due to forward and reverse bias [14].

For the reverse biased PN-junction, as the voltage increases, a breakdown eventually occurs and a large current flows through the depletion region. There are two types of effects that generate a breakdown, the Zener effect and the avalanche effect. As described previously in this section, the depletion region is containing ions that have lost an electron or hole and have no free charges. Though, when a large electric field is applied to the area, it can tear the covalent bonds in the ions and therefore create more free charges. The new free electrons are accelerated by the electric field and swept to the n-side of the junction, this is the Zener effect. To be able to have a large enough electric field for this to be possible, with reasonable voltages, a narrow depletion region is required. This is done with high doping levels on both sides of the junction [5].

For the avalanche effect, the small current (leakage current) coming into the depletion region is accelerated by the electric field and can sometimes collide with the ions. This can break the ions' covalent bonds and separate electrons from the ions. The electrons can in turn accelerate into another ion and free more electrons. This is called impact ionization and can result in an exponential effect i.e. an avalanche effect and generate a large current resulting in a breakdown. This is called avalanche multiplication [5]. The avalanche breakdown happens for smaller electric fields than for Zener breakdowns and can therefore have lower doping levels in the PN-junction [14]. Figure 2.7 views the IV characteristics for a PN-junction. The figure illustrates how the current depends on the voltage.

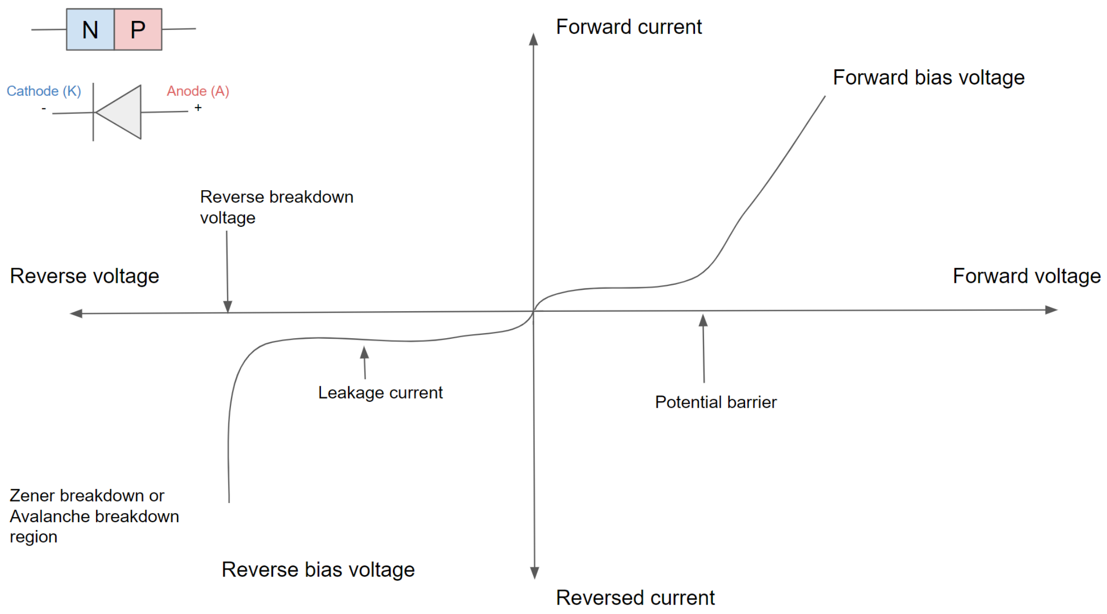

Figure 2.7: The IV-characteristics for a PN-junction. The leakage current is the same thing as dark noise current for an APD.

2.3 Avalanche Photodiode

In the laser rangefinder for this project, an APD is used for detecting the received echo signal. An APD is a kind of photodiode, but with internal gain. A photodiode is a diode that converts light to an electric current and is working during reversed bias. When the diode is exposed to light, energy is added to the semiconductor and generation happens, as described in Section 2.2. In an APD the generated electrons will be accelerated due to the high electric field in the depletion region and an avalanche effect will happen, as described in Section 2.2.1. Thereby, when light with high enough energy hits the APD, a large output current will come from the APD [16]. As described, an APD operates under reverse bias. As the reverse bias voltage is increased, the sensitivity of the APD is increased since light with less energy can generate an avalanche. Therefore to be able to detect low energy optical signals the reverse bias needs to be high. Though, since higher reverse bias voltage also generates more noise in the APD, this level is also limited by the noise [17]. In Figure 2.8 the relationship between the APD gain and reverse bias is illustrated.

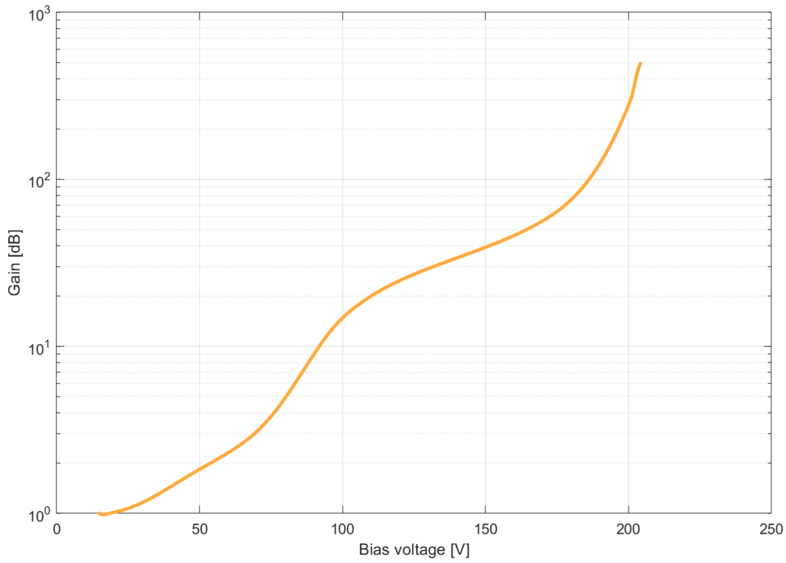

Figure 2.8: The gain as a function of bias voltage for an APD.

2.3.1 Avalanche Photodiode Noise

It is not just the optical pulses that are affecting the APD, temperature fluctuations, leakage currents and other quantum effects are also affecting it. These are effects in the PN-junction. The effects are generating currents without no particular optical pulse coming onto the APD, therefore the currents are considered as noise. This noise can affect the result and the electric output signal severely, especially in APDs since the avalanche effect amplifies some of the noise currents. A part of the noise currents generated in the PN-junction without any optical signal coming onto the APD is called dark current (this is what is called leakage current in a generic diode). The dark current is a random process by random generation of electrons and holes within the depletion region due to the phenomenons previously mentioned in Section 2.2 [18]. This noise is of Gaussian distribution even though it contains elements of Poisson's distribution, from some of the quantum effects [19].

In Figure 2.9 the histograms form the shape of the distributions for a Poisson and Gaussian distribution. The distributions have the same standard deviation and mean value.

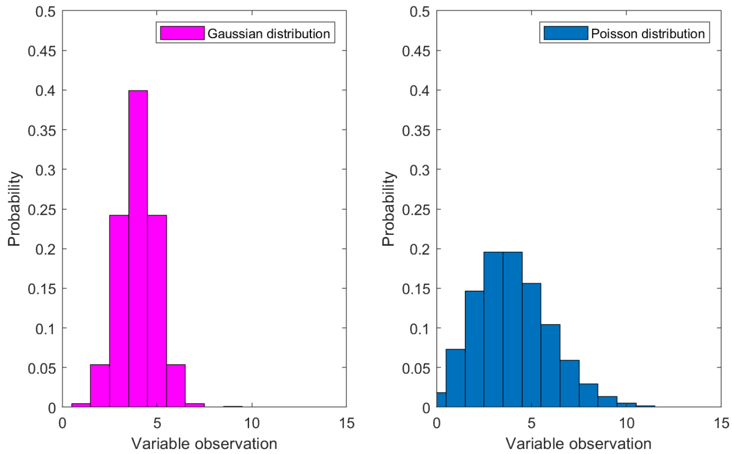

Figure 2.9: Gaussian and Poisson probability distribution functions.

Further, when increasing the reversed bias, the APD's strong internal electric field across the depletion region is also increased. This will cause the tunneling effect to happen more often and dark currents are usually negligible compared to that generated by the tunneling [18]. The tunneling effect is a quantum effect and simplified, it is charged particles moving from one side of the depletion region to the other without sufficient energy to pass. In research and books, some include the tunneling effect in the dark current and some do not, since the tunneling also happens in the absence of light like the other factors included in the dark noise. The noise due to the tunneling effect can also vary in size, but in APDs the tunneling effect can trigger the avalanche effect and therefore generate very large noise currents. An avalanche in the diode can either be caused by noise, usually due to tunneling, or an actual received echo pulse. It is impossible to separate the avalanches from just this fact and additional information or statistics on multiple measurements is needed [20]. The noise generated by the tunneling effect is called shot noise and is of Poisson distribution [21].

If the shot noise is included in the dark current the total noise distribution is approximated to Gaussian, though it contains elements of Poisson distribution. However, if the shot noise is not included in the dark current and is therefore assumed to be large, the total noise must include the dark current (Gaussian distributed) and shot noise (Poisson distributed) [18], [19].

As described in Section 2.3, the sensitivity of the APD is increased when the reverse bias voltage is increased, but as it is increased the amount of shot noise is increased as well. Since the APD is more sensible i.e. avalanching happens more easily and assuming the tunneling and dark current are constant, these effects will more often cause an avalanche [21].

2.4 Digitalization and Digitization of Signals

Digitalization is the term for enabling or improving processes by using digital technologies and digitized data [22]. Digitalization is a part of the digital transformation triangle, from bottom to top including; digitization, digitalization and digital transformations [23]. Digitization is the process of creating a digital representation of a physical object, like transforming an electrical signal in a circuit into a digital signal in a computer. Digitalization is, therefore, the use of digitization technologies in systems and processes. Digital transformation is the term for how digitalization implies changes in the society, business and other contexts connected to the digitalized product [22].

Investigating a digital laser rangefinder receiver is by the digital transformation triangle theory, a part of the digitalization and is utilizing digitization. In the laser rangefinder receiver, this means that the received echo signal is digitized. This enables handling the signal in a computer by using programming. This gives the opportunity to use mathematical and statistical tools, as well as typical digital signal processing techniques. Compared to analog solutions, digital solutions are usually more precise and consistent [2].

To be able to convert an electrical signal to a digital signal an ADC is needed. An ADC converts the signal by sampling and is often performed in two steps; discretization and quantization [24]. The sampling is an essential step in digitization since if it is not performed correctly, the signal can be reconstructed wrong and not be a true representation of the electrical signal. To avoid this phenomenon, called aliasing, the Nyquist–Shannon sampling theorem is often used [1].

2.4.1 Possible Problems with Digitization

As explained in Section 2.4, digitalization is really useful in many ways and can often improve products and systems, but there are some issues and potential problems related to digitization. In this subsection, only a limited few will be discussed.

As described in Section 2.1, laser pulses are very narrow and therefore, to avoid aliasing, the sampling needs to be high. This in return requires a good quality ADC, in particular, a high-speed converter [24]. When the sampling frequency is high, there is relatively much data streaming to the CPU at a high speed. This requires buffers, CPUs and data communications that can handle the amount of data and can process it quickly enough [2], so when the data has finished processing and is sent to be viewed in the laser rangefinder's user-interface it is still relevant. Designing a data system for the laser rangefinder receiver is not in the scope of this master's thesis, but it is necessary to investigate that the digital algorithms are not too process-heavy for a reasonable data system. Therefore estimation of CPU time for the algorithms is relevant.

As mentioned in Section 2.4, the sampling performed by the ADC is important, but another essential notice about digitization is the errors and noise introduced by the ADC. The accuracy of the ADC is affected by thermal noise, quantization errors, offset errors, gain errors and linearity errors. The errors can introduce timing and amplitude errors [25]. This noise is usually called process noise and is varying depending on the ADC, but can be reduced by filtering and calibration techniques [26].

2.5 Digital Signal Processing

Digital Signal Processing (DSP) provides useful tools for analyzing, modeling and manipulating signals. DSP is used in many areas and has in the past decades had a major impact on the development of signal systems, electronics, telecommunications, information technology systems, etc. DSP has improved the efficiency, reliability, repeatability, storage and representation of signals. DSP has also made it possible to extract information from noisy signals, recognize patterns in signals, forecast signals and improve signal enhancement and signal classification and pulse detection [26].

The foundation of DSP is signal classification. Signals can have different characteristics and properties, These can be used to classify signals. The classification can be used to detect pulses or signal segments in the signal [26]. Some examples of characteristics are amplitude, frequency, pulse width, phase, time or frequency domain, symmetric or asymmetric, deterministic or non-deterministic, even or odd, periodic or aperiodic, energy or power signal, real or imaginary, causal vs. anticausal vs. non-causal, etc [1].

2.5.1 Common Signal Processing and Denoising Methods

Convolution and the use of filters are the most common tools in DSP. Convolution is the mathematical operation to combine signals in the time domain. Simplified, the result is a new signal that is a combination of the signals in shape and value. Signals can be transformed to be expressed in the frequency domain and then multiplication is used instead of convolution, to represent the same operation.

Filters are usually used to remove some unwanted components in a signal. This is usually done by convolving a filter's impulse response with a signal. The most simple filters are high-pass, low-pass, band-pass and stop-band filters. High-pass filters let high-frequency components in the signal pass and low-pass filters pass low-frequency components. Band-pass filters pass a particular frequency band, while the stop-band filters stop a particular frequency band. For all of the filters mentioned, certain cut-off frequencies need to be specified [1]. Another tool often used is windowing. A signal window is often a time interval where outside of the interval the signal is set to zero. The interval itself is usually symmetric but can be any shape. Windowing can be described as a kind of filter but in the time domain [26].

DSP is frequently used to denoise signals. There are several ways to do this and different methods and filters are useful for different kinds of signals, depending on what segments and components the signal contains. If the noise in the signal is relatively stable, constant filters can be used. If the noise is highly varying, channel equalization can be used. This is often used for “noise canceling” headphones [26].

2.5.2 Digital Signal Processing Methods for Laser Rangefinder Signals and Other Similar Signals

There is not much research on specific techniques for denoising laser rangefinder signals, but there is some research on digital signal processing methods used for denoising LiDAR signals. The method of moving average, Wavelet threshold denoising method and Empirical Mode Decomposition (EMD) method are presented in [27] and are used on received LiDAR signals.

The Moving Average method is a highly used digital signal processing technique since it is simple and easily applied to multiple signals. The filter uses a number of samples in the input signal to produce each sample in the output signal, thereby averaging short terms variations in the signal. The moving average filter is often the most optimal for reducing random noise while still retaining a sharp step response, which makes this filter one of the most favorable to use in time domain encoded signals [27].

The Wavelet threshold denoising method is built on the principle of the multiresolution analysis, which consists of dividing the raw data into approximation and detail coefficients. The Wavelet transform is often used for this signal analysis method in the time-frequency domain. For the Wavelet threshold denoising method, a threshold is selected and the components of the Wavelet transform of the noisy signal are processed in order to improve the SNR [27].

The Empirical Mode Decomposition (EMD) method is a method for analyzing signals from nonlinear and non-stationary processes. The adaptive method can decompose any complicated signal. In the process of EMD, the signal is decomposed into small functions, called Intrinsic Mode Functions (IMF). When all the decomposed small functions are added together the result is the same original signal. The IMFs need to fulfill specific conditions. By removing some specific IMFs with high-frequency components, the noise can be removed from the signal [27].

In source [3], a digital signal processing method for a laser rangefinder was presented. For a laser rangefinder, multi-pulse correlation is suggested as a useful method. Multi-pulse correlation is the correlation of a number of pulse frames. Usually, the received echo signal contains much noise. While the optical echo pulses are periodic and correlative, the noise is stochastic and not correlative. The pulse correlation would therefore enhance the optical pulse but not the noise and therefore improve the SNR and the detection ability of the laser rangefinder. Before the multi-pulse correlation, a moving average filter was used for smoothing and denoising the signal [3].

2.6 Digital Pulse Detection Methods

Pulse detection is necessary to be able to analyze the pulses and separate true optical pulses from false alarm pulses. A stable detection method can also improve the detection sensitivity in the system. Signal classification is often used in detection methods, pattern recognition and other decision-making systems. Some signal classifications characteristics are mentioned in Section 2.5.

The first step in a pulse detection method is usually to find the signal baseline. The more baseline variations there are in the signal, the more difficult it is to define the pulses. Variations in the baseline can be caused by temperature variations, aging and pattern noise in the electronics. If the variations are not compensated, they can reduce the accuracy of the pulse detection [28], therefore it is crucial to have a stable baseline. This can be achieved with techniques that can track and compensate for unwanted signal variations, as well as suppress pattern noise. There are digital baseline stabilizers that can track slow baseline changes, that are caused by aging in electronics and temperature variations. The electronics, especially the ADC, can cause pattern noise. This noise can be the limiting noise in a system if not compensated [6]. Noise and interference can contribute to rapid changes in the signal and trigger false alarms. These rapid variations in the signal can be reduced by a filter [6], [28].

When the signal has a stable baseline, the next step is to detect the pulses. A trigger can be used to detect the start and end of the pulse. The start of the pulse can be defined by the first sample that is equal to or above a certain amplitude threshold and the end pulse can be defined as the sample when the amplitude is equal to or lower than the baseline level or amplitude threshold [28]. This is usually how a constant amplitude threshold works, but there are also adaptive thresholds. Adaptive thresholds are useful when the wanted detection pulses are varying in size. An adaptive threshold can e.g. use the pulse's peak value and the threshold will then be a constant fraction of the peak for each peak [6].

After the amplitude threshold, the pulses are usually analyzed. Often used metrics are peak value, pulse width and peak timestamp. The peak value is the maximum value on the pulse, the pulse width is the number of samples over the amplitude threshold and the peak timestamp is the sample where the pulse peak is. These pulse metrics are the most basic tools for analyzing detected pulses. By using these metrics, the pulses can be sorted based on their differentiating metric values [6].

When detecting pulses in a signal with noise, the main problem is determining if the observation is only noise or if it contains a pulse. In an automated pulse detection system, there will always be a risk of false alarms, as well as the risk of missing true pulses [26]. Therefore a trade-off between false alarms and missing true pulses is necessary. This trade-off needs to be decided depending on what is acceptable for the system and what the system's task is [6].

A detection window defines a period in time when pulses are accepted. The detection window has a fixed length and can need a triggering event. This is very similar to the windowing explained in Section 2.5.1. For applications like LiDAR, a detection window is useful. The detection window can be triggered for each laser pulse and timed to match the distance of a wanted detection. This can also help keep track and chronological order of the detections [6].

Another method of detecting pulses is to use correlation. In a detection method, an ideal true pulse can be correlated with the received signal. If the output of the correlation is high, the particular signal segment of the received signal is most likely a true pulse [26].

Another way of detecting pulses could be the use of a deep machine learning. A network could be trained to recognize the wanted pulses and therefore detect the correct pulses. In source [29], a comparison of a threshold pulse detection method and a deep machine learning pulse detection method was done for a radar signal. The deep machine learning network performed much better for signals when the SNR was low [29].

2.7 Laser Rangefinder Signal Simulation and Signal Segments

In this thesis the laser rangefinder received signal is simulated in MATLAB, therefore this section will explore and describe the segments of the signal, as well as what affects the signal. Some research regarding the simulation of laser rangefinder signals and signals similar to them will also be covered. The signal that is simulated in MATLAB is supposed to be the output signal from the ADC in a digital laser rangefinder receiver. In modeling and simulation of signals, it is important to classify their characteristics, patterns and noise processes. Reliable modeling of signal segments, especially the noise, is necessary for accurate signal simulation [26].

In litterateur, reports and other research, there are a couple of methods used to simulate laser rangefinder signals and other types of similar signals e.g. LiDAR signals. One way is to simulate the whole process starting with the transmit signal. This is done in [30], where the transmit signal is generated as a Dirac delta function, which is representing the ideal pulse shape of a transmit pulse in a LiDAR. The transmit pulse is then convolved with the LiDAR's transfer function to simulate the true transmitted pulse. To simulate the pulse traveling in the environment and hitting a target, convolution with the target surface impulse response is done. Then backscatter, solar noise, propagation noise, dark current and noise in receiver electronics are added as additive white noise (Gaussian noise, with Gaussian distribution). Shot noise from the APD is added and then the signal is convolved with the receiver electronics' impulse response. The signal is then convolved with the ADC impulse response and noise from the ADC is added to obtain the output signal from the ADC [30].

In another resource [10], a laser rangefinder's echo signal was generated by using a half period of a cosine squared function and adding Gaussian noise. In the resource, the Gaussian function is stated as popular to use for simulating optical echo pulses, though the Gaussian function has some drawbacks. It is said to be computationally complex, as well as it does not take into consideration the asymmetry between the rise and fall times of the pulse, where the rising slope is usually steeper than the falling one, usually seen in laser rangefinders. Even though, the approach used in the article still was to use a symmetrical approximation since it simplifies the analysis [10].

In source [19], the received echo signal in a laser rangefinder is simulated like the output signal from the APD and is the superposition of the noise from the APD with the optical pulses detected by the APD [19].

In article [31], the noise that is affecting a received LiDAR signal is described. Most random errors are due to random fluctuations in the signal and are primarily shot noise from the APD and thermal noise in the electronics [31]. A similar method is also presented in [8], where shot noise is stated as the primary noise source in the signal [8].

3

Practical Signal Study

As mentioned throughout the report, the laser rangefinder signals was needed to be constructed for the simulations in MATLAB since no real data could be sampled. To get an overview and somewhat understand the signals of a laser rangefinder, an easy laboratory setup was done to view the signals from a laser rangefinder in an oscilloscope. In this section, the laboratory signal study is presented. The method of the study is presented in Section 4.2. In Figure 3.1 the oscilloscope view is shown. The figure is showing the signals when there is no detection. The pink trace is the input signal to the detection circuit in the laser rangefinder receiver, which will in a digital solution go into the ADC. The turquoise trace is the transmitted optical pulse. The green trace shows when the detection circuit detects a pulse larger than the amplitude threshold (40 mV). When there is a detection a negative square pulse is sent to signal for detection. As can be viewed in Figure 3.1 there is no green negative square pulse, therefore there is no pulse detected in the signal.

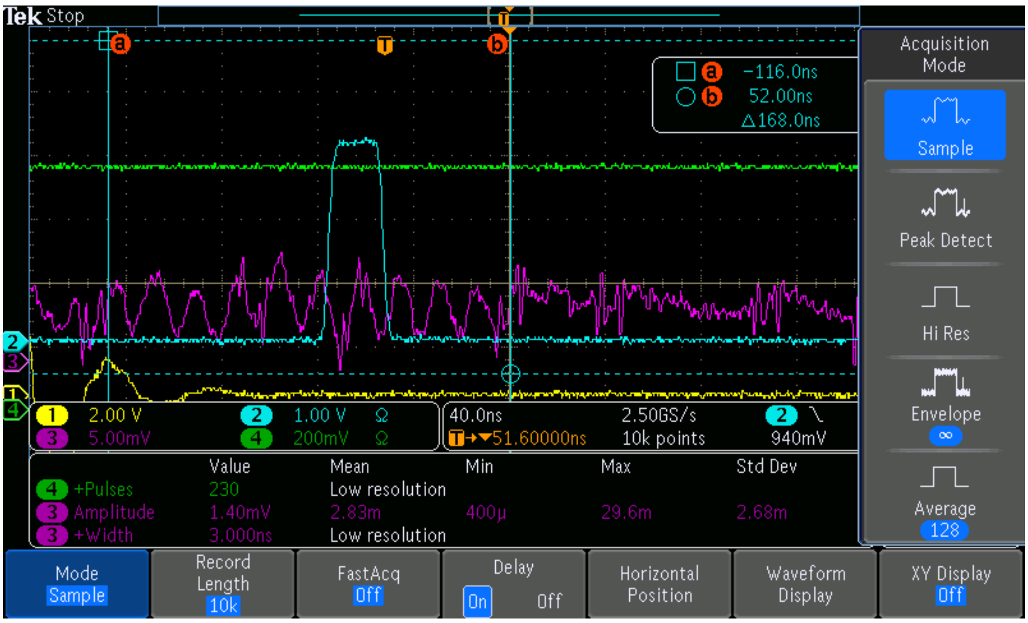

Figure 3.1: Oscilloscope view when there is no detection.

In Figure 3.2 the oscilloscope shows when a true optical pulse is detected. At first sight, the pink trace can be mistaken for noise only, but at the detection (during the green negative square), there is a peak in the pink trace. During the detected pulse, there is a slope in the pink trace, this is due to the detection circuit [4]. In

Figure 3.3 the oscilloscope shows when a shot noise pulse is detected and it is, therefore, a false alarm. It is a false alarm since there is no turquoise pulse (transmitted optical pulse), but a green negative pulse (detection pulse) is viewed. As can be seen in the pink trace during the detection the slope effect is repeated for this case as well.

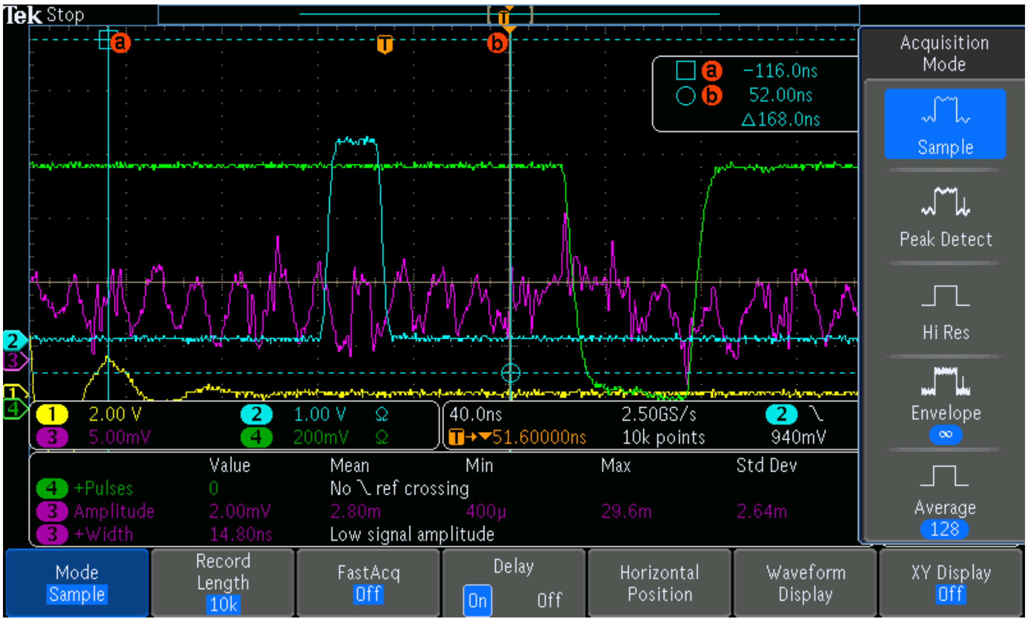

Figure 3.2: Oscilloscope view of a detection for an optical pulse.

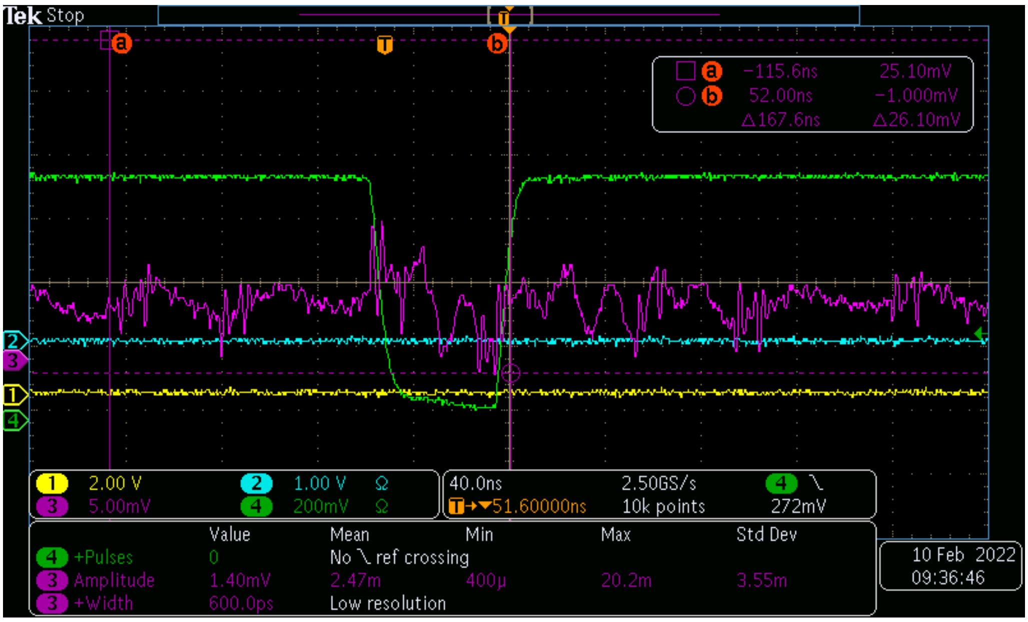

Figure 3.3: Oscilloscope view of a detection for a shot noise pulse, i.e. a false alarm.

In all figures, low-frequency periodic noise can be seen present in the pink trace and is probably due to noise in the electronics. There is also high-frequency noise present, this is probably Gaussian noise. The slope in the pink trace when there is a detection is always repeated and can be concluded to probably be due to the detection circuit. The pink trace is also lower in amplitude than it is in the actual detection circuit. In Figure 3.2, the pink trace is about 10 mV in amplitude, while in reality it must be 40 mV due to it being detected by the detection circuit. The pink trace is low in amplitude due to low sensitivity and poor soldering in the measuring probe [4]. The probe can also be the reason for some of the noise in the signal.

When studying the different pulses, the shot noise pulses usually have a pulse width of 1 - 7 ns. In the analog receiver with the current bias voltages, the shot noise pulses appear 16 times per second, which corresponds to a frequency of 16 Hz [4]. The optical pulses have a pulse width of 10 - 20 ns, as mentioned in Section 2.1. The amplitude of the pulses is difficult to study since the low-frequency noise is large and small pulses can not be spotted easily. The detected pulses are though above 40 mV since this is the threshold for the analog detection circuit. The Gaussian noise in the pink trace seems to have an RMS value of about 0.5 mV, which corresponds to about 2 mV in reality.

4
Methods

In this chapter, all methods used in the thesis are described. First the method used for the literature study is presented, then the practical signal study is described. Further, the signal construction, digital signal processing and pulse detection methods are explained, as well as how detection validation was made. Lastly, the methods for the different tasks and simulations are explained, as well as how validation was done for each simulation.

4.1 Literature Study

The literature study has been the foundation of the project. The purpose of the literature study was to provide basic knowledge of semiconductors, digital signal processing and pulse detection. Research on laser rangefinder's echo signals and noise was needed. Other similar signals especially those for applications using APDs were also researched. Research within the area of signal simulation, processing and detection was also included to study the field and gain ideas and knowledge.

Mostly academic books, journal articles and reports have been used as sources in the literature study. The resources were mostly found through Google Schoolar, Chalmers Library, IEEE, ResearchGate and Optics Express. The keywords used in the research were APD, digital signal processing, laser rangefinder, denoising, filtering, noise, reduction of false alarms, false alarms in laser rangefinder, false alarms in APD, noise in APD and digitization. Most research in the area of digital signal processing on laser rangefinder signals and other similar signals is not more than 15 years old, so all available found research was decided to be relevant and useful. Some sources in the area of fundamentals in semiconductors, microelectronics and common signal processing are older, but this is not an issue since fundamental information within the area has not changed over the years. For these kinds of sources, a trade-off between quality and age was made to find the most expedient information. Most sources are written by scientists from universities so the quality of all sources is seen as high.

4.2 Practical Signal Study

To be able to attain a clear understanding of the signals of a laser rangefinder and to make sure the simulated signal was as true to reality as possible, an easy laboratory setup was done to view the signals from a laser rangefinder in an oscilloscope. Note, these signals could not be sampled and used in the simulations. This study was only done to provide insight on the real signals. By doing this, the signal construction in MATLAB was more manageable since the signal values could be set according to the practical signal study. The study was performed by generating an optical transmit pulse by a pulse generator and an optical pulse generator. The optical pulse was then focused and aimed at the receiver circuit board, in particular the APD, to simulate an echo signal coming onto the APD. The signal from the APD was then sent to the oscilloscope and the detection circuit. The output from the detection circuit was also sent to the oscilloscope, as well as the transmitted optical pulse. By increasing and decreasing the optical transmit pulse's amplitude and pulse width and switching it on and off, both the optical signal, the false alarms and other noise could be viewed and studied in the oscilloscope. Measurements on pulse width, frequency and noise were done through the oscilloscope. The measurements and figures from the oscilloscope view and the observed signals can be seen in Chapter 3. The observed pulse characteristics were also later used when constructing and simulating the laser rangefinder's received echo signals.

4.3 Construction of Simulated Received Echo Signal

To be able to simulate relative true-to-reality detection statistics, the signal construction was crucial since no real sampled data was available. The theory and methods presented in Section 2.1, 2.3.1 and 2.7, as well as the signals that were studied in Chapter 3, were the main foundation for the signal construction. All simulations were made in MATLAB version R2020b.

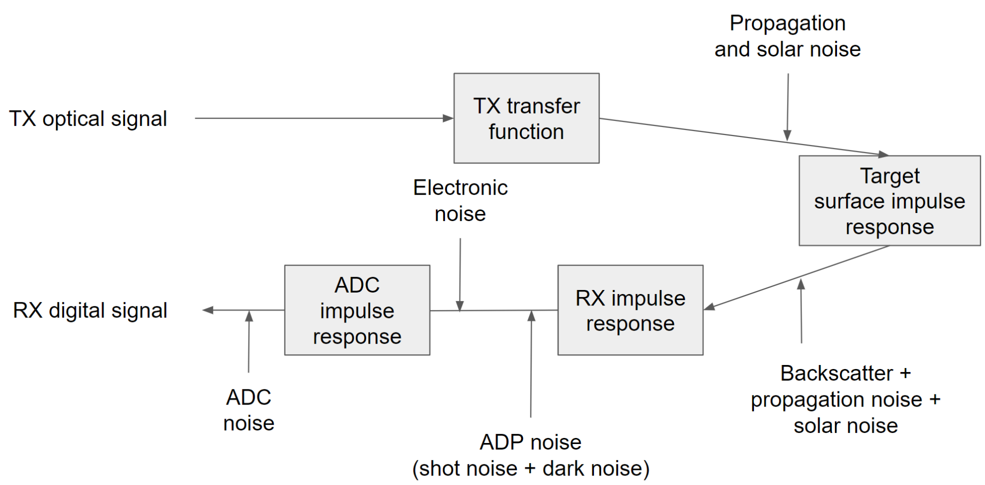

Figure 4.1: Simplified block diagram of an estimation of what affects the laser rangefinder signal throughout transmitting and receiving. The blocks represent convolution with the signal, while the arrows are addition to the signal.

The signal that was being constructed is supposed to represent the output signal of the ADC in a digital solution. In Section 2.7, one of the methods of simulating an echo signal is more complex than the others. The whole process is simulated, step by step, by convolving the transmit pulse with different impulse responses and all specific noise is added along the way. This method can together with what is known about the laser rangefinder and its signals be used to conclude what affects the signal from start to end. A block diagram of how this method could have been used in this thesis can be seen in Figure 4.1. Though this method would probably be specific and thorough, it can not be used unmodified since there is not enough knowledge of the signals and the components affecting the signal to perform it.

Proceeding from this method and removing or estimating the parts there is insufficient or no knowledge about, it is possible to use a method similar to the other methods presented in Section 2.7. For these methods, the received optical pulse is generated and then thermal noise, dark noise and shot noise are added. This seems to be a reasonable method and was decided to be used in the thesis together with the knowledge of the signal and its segments found in Section 2.1 and 2.3.1, as well as in Chapter 3.

For the simulated received echo signal the optical echo pulse was generated first. The optical pulse could be approximated and constructed by using the information presented in Section 2.1 and Chapter 3. As explained there, the optical pulse shape is a mix of a Gaussian pulse and a rectangular pulse. In MATLAB this pulse was generated by creating a Gaussian pulse and a rectangular pulse and adding them together in different ratios. If a more rectangular pulse is wanted a larger ratio of the rectangular pulse is added and vice versa. The amplitude span for the optical pulse could not be studied in Chapter 3 and was decided to be between 0 - 42 mV. It is known that the optical pulse amplitude can be larger than 40 mV since this was the threshold in the analog detection circuit used in the study in Chapter 3. The lower bound was assumed to be 0 but can probably vary depending on the sensitivity of the APD. The position of the optical pulse in the signal is randomized. If there are several optical pulses wanted in the signal, before putting the pulse in that randomized position, the position is checked so no other pulse already is positioned there. This is done since the pulses represent a generated current in the APD as explained in Section 2.3. The APD can not have several generated currents at the same time. In that case, the amplitude of the pulse would be greater, which would reflect more avalanching in the APD and the generation of a larger current instead.

The next step in the construction of the simulated signal was adding noise to the signal. The noise was deiced to be constructed of Gaussian noise and Poisson distributed shot noise pulses. The Gaussian noise is coming from the noise from the receiver electronics, dark noise and propagation noise as explained in Section 2.7. It is difficult to know how large the Gaussian noise should be since in a digital solution some of the receiver electronics would be removed while some electronics would be added, like an ADC. Therefore the Gaussian noise was decided to have an RMS value of 2 mV, the same as what was studied in Chapter 3. Gaussian noise can be generated by the MATLAB function *randn*. By scaling this generated noise by 3, the noise amplitude correlates to an RMS value of about 2 mV.

The shot noise pulses are coming from the APD as described in Section 2.3.1, the frequency of the pulses is dependent on the bias voltage. Their amplitude and pulse characteristics are somewhat known by the information presented in Chapter 3. Based on what is presented about shot noise in Section 2.3.1 and what is seen in Chapter 3, the shot noise pulses can be assumed to be the noise that most often generates false alarms. The shot noise pulses are Poisson distributed and can be generated by the function *poisspdf* in MATLAB. The position of the shot noise pulses is randomized in the same manner as the optical pulses and no pulses are added on top of each other. The shot noise pulses have a pulse width between 1 - 7 ns as described in Chapter 3. Just like for the optical pulse amplitude, the shot noise amplitude could not be studied. Therefore, it was assumed to be around, and slightly below the threshold for the analog detection circuit used in Chapter 3, that is 35 - 40 mV. The shot noise amplitude could probably be much lower than what was assumed, but this was decided to be unconsidered since if the digital solution can filter out shot noise pulses with large amplitude, shot noise pulses with small amplitude should not be an issue.

By using the three segments described in this section, a signal-generating function was coded. When calling this function several variables needs to be set and they affect the signal in different ways. The variables, what they mean, their values and how they affect the outgoing signal are explained in the bullet list below.

- Samples: The signal consists of X samples and 1 sample symbolizes 1 ns.
- Gaussian noise amplitude: This value amplifies the Gaussian noise in the signal. A value of 3 gives an RMS of 2 mV.
- Number of optical pulses: The signal has X number of optical pulses.
- Optical pulse width: Decides the pulse width of the optical pulses. This could be a constant value or a value span. If it is a span, the function randomizes the optical pulse width in between the span. The optical pulse width is usually between 10 - 20 ns, like described in Section 2.1 and Chapter 3.
- Optical pulse amplitude: Decides the amplitude of the optical pulses. This could be a constant value or a value span. The span follows the same randomizing process as previously described. The optical pulse amplitude is usually around 0 - 42 mV.
- Optical fullness: As explained in Section 2.1, the optical pulse shape is a mix of a Gaussian pulse and a rectangular pulse, the optical fullness decides the ratio of the mix. If put to 100 % the pulse is a true rectangular pulse and if put to 50 % the pulse is a 50/50 mix of a Gaussian pulse and a rectangular pulse. This could be a constant value or a value span. The span follows the same randomizing process as previously described. The fullness ratio was assumed to usually be around 60 - 80 % [4].
- Number of shot noise pulses: The signal has X number of shot noise pulses. The number of shot noise pulses represents the bias voltage. The number of shot noise pulses could be any number since the relationship between an

increase in bias voltage and shot noise pulses are different for different kinds of APD.

- Shot noise pulse width: Decides the pulse width of the shot noise pulses. This could be a constant value or a value span. The span follows the same randomizing process as previously described. As explained in Chapter 3, the shot noise pulse width is usually between 1 - 7 ns.
- Shot noise pulse amplitude: Decides the amplitude of the shot noise pulses. This could be a constant value or a value span. The span follows the same randomizing process as previously described. As explained previously in this section, the shot noise pulse amplitude is assumed to be between 35 - 40 mV.

The first graph in Figure 4.2 views the simulated signal constructed by the method described. In the second graph in the same figure, the different components of the signal are presented. This graph can be used for reference to know which part of the signal is what.

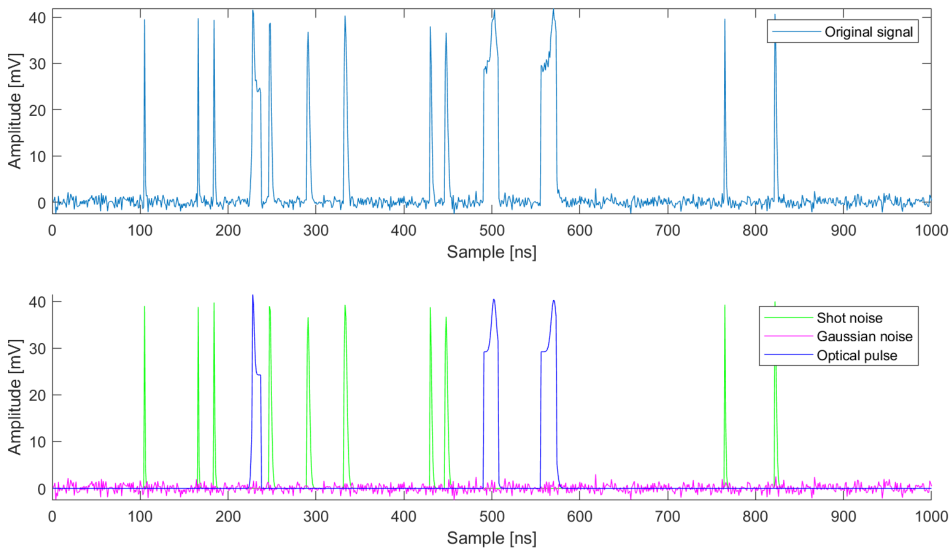

Figure 4.2: Simulated original signal and its different segments.

4.4 Digital Signal Processing and Investigation of Filters

As explained in Section 2.6, an essential factor for pulse detection is having a stable baseline and little to no rapid noise. Therefore, a denoising method was deiced to be applied to the simulated signal before pulse detection. In Section 2.5.1 and 2.5.2, a few different digital signal processing methods for laser rangefinder signals and other signals were presented. It was not clear which one of these methods that were the most beneficial, therefore a simple investigation of some of the filtering methods was done before deciding what filter to use in the simulations. The filters that were investigated were low-pass filter, band-pass filter and moving average filter. The low-pass and band-pass filters are common filters with specific cut-off frequencies as described in Section 2.5.1. The moving average filter is using the unweighted mean of the previous κ data-points, as presented in Section 2.5.2. In Table 4.1 the different filters and their characteristics are presented. The filter characteristics were decided by trial and error.

Table 4.1: The investigated filters and their characteristics.

Filter	**Low-pass**	**Band-pass**	**Moving average**
Cut of frequencies [Hz]	1000	10 - 500	-
κ	-	-	5

The other methods presented in Section 2.5.2, like the Empirical decomposition method, multi-pulse correlation method and Wavelet method are more process-heavy and complex than the chosen filters. Since another part of this thesis was to measure CPU time and too process-heavy methods could be a critical issue, they were not considered in the thesis.

The goal of the investigation was to see what filter was the most beneficial for the detection method. The purpose of a filter in this system was to reduce the Gaussian noise and reduce the shot noise pulses since it would give a stable baseline and be favorable for the detection method, but it was also important that the pulse shapes and pulse widths were not changed much from the filtering. This would make it even more difficult to separate the optical pulses from the shot noise pulses and thereby inhibit detection.

The investigation was done by generating a signal according to the method described in Section 4.3. Then filtering the signal with each of the three filters and retrieve three resulting signals. The detection method, which will be presented in Section 4.5, was performed on the signal to see if the detection statistics would differ between the filtered signals. This simulation was performed 100 times to attain resulting detection statics. The simulations from the investigation can be viewed in Appendix A. The low-pass filter seemed to be the most advantageous filter and was chosen to be used. The result of the signal filtering can be seen in the first graph in Figure 4.3, the second graph is presenting the original signal before signal filtering and the third is viewing its different segments.

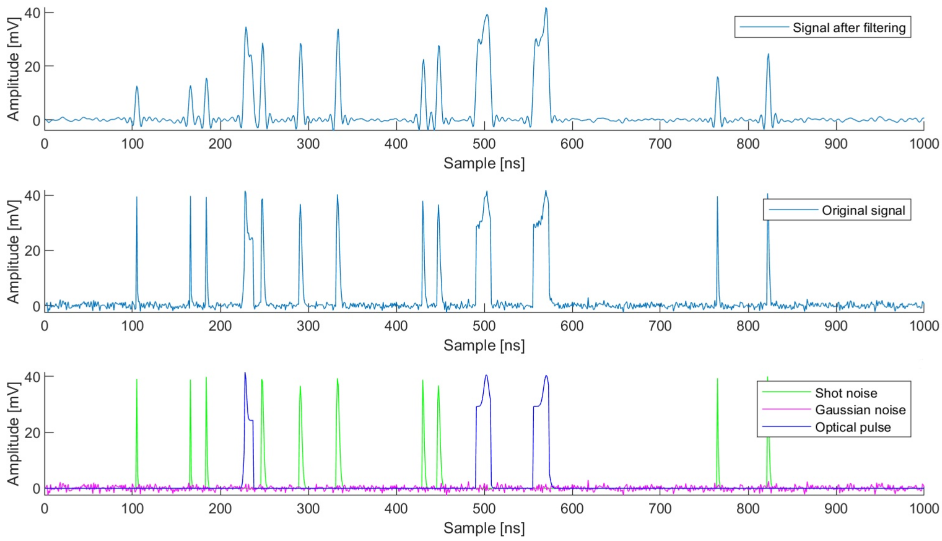

Figure 4.3: Signal after filtering, original signal and its different segments.

4.5 Detection Method and Validation

The detection method was central to separate optical pulses and shot noise pulses and therefore important for the thesis purpose. When designing the detection method, the foundation was the characteristics of the simulated signal described in Section 4.3 and the pulse detection methods explained in Section 2.6. The goal of the detection method was to detect only true optical pulses even when the difference between optical pulses and shot noise pulses is small. Since the pulses do not necessarily have a large difference in amplitude or pulse width, both of these differences are advantageous to use in a detection method. This also enables using the pulse's shape to differentiate them since it utilizes two dimensions.

In Section 2.6 a few different methods for pulse detection are presented. It was decided to use a method using thresholds. In the section, both constant and adaptive thresholds are described. Though an adaptive threshold might have been useful due to large variations in pulse amplitude and width, the thresholds are constant in this detection method.

After the signal filtering, the first step in the detection method is to detect peaks larger than an amplitude threshold. In this step, depending on the threshold value, optical pulses and shot noise pulses are detected in the signal. In some cases depending on the threshold value and how high the Gaussian noise is, some peaks from the Gaussian noise might be detected as well. The pulse start and end are defined as the first and last sample larger than or equal to the threshold as proposed in Section 2.6. The optimal amplitude threshold was found by trial and error. The result of this operation can be observed in the first graph in Figure 4.4. In the second graph, the original simulated signal is presented and in the third graph, the different signal segments are viewed.

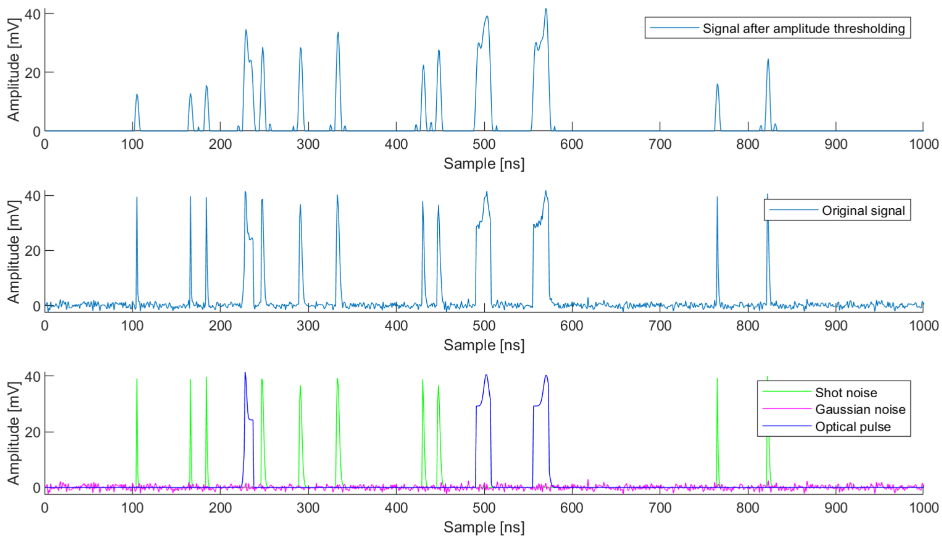

Figure 4.4: Signal after amplitude thresholding, original signal and its different segments.

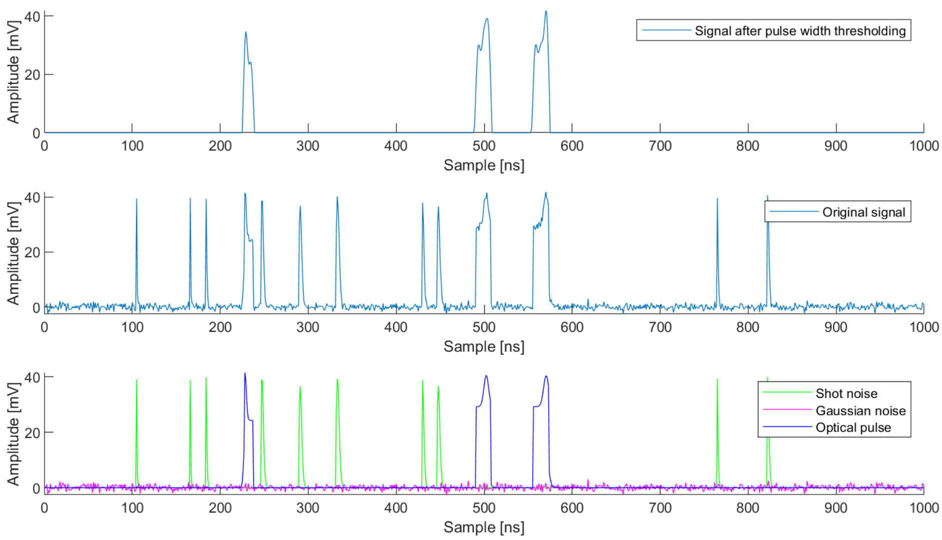

Figure 4.5: Signal after pulse width thresholding, original signal and its different segments.

The next step is to use a pulse width threshold on the peaks already detected. In this step, the goal is to only detect optical pulses. Because of the pulse shape of the pulses, the optical pulses usually have a larger pulse width at the base of the signal and also have a relatively constant pulse width before they get more narrow at the peak. Compared to the shot noise pulses that have almost as large pulse width at the base as the optical pulses, but get more narrow much faster towards the peak than the optical pulses. Therefore the optical pulses should most of the time have a larger pulse width at the amplitude threshold than the shot noise pulses. The optimal pulse width threshold was also found by trial and error. The first graph in Figure 4.5 shows what peaks the detection method finds larger than the pulse width threshold. After the pulse width threshold, the peaks that are left are measured to find the peak timestamp to find the position of the peak. These position indexes are then the result of the detection method, which then can be used to calculate the range to the target.

The performance validation of the detection method was done by using the detection method and really low thresholds on the signal segments for the optical pulses and shot noise pulses. By doing this the number of pulses and their position for the shot noise pulses and optical pulses respectively was received. This knowledge was used to compare the detections for the whole signal. If the detection matched the position for an optical pulse or a shot noise pulse, it was determined if it was a correct detection or a false alarm. If the detection did not match any of the positions for the optical or the shot noise pulses, it was determined to be a detection of a peak in the Gaussian noise. By keeping track of the amount of correct detection and false detection statistics could be calculated for several simulations. The detection statistics that were found to be useful were the percentage of detected optical pulses from all optical pulses, the percentage of detected shot noise pulses from all shot noise pulses and the number of detections in the Gaussian noise. The false alarm rate was calculated by adding the number of detected shot noise pulses and detections in the Gaussian noise, then dividing this by all detections (optical pulses, shot noise pulses and Gaussian noise).

An algorithm functioning like the analog detection circuit, that was used in the study in Chapter 3, was also coded. This algorithm gave detections for pulses that were above an amplitude threshold set to 40 mV. The performance validation explained previously in this section, was used on this analog method as well and this was then used for comparisons to know if the digital or analog method was working the best.

4.6 Sensitivity and False Alarm Trade-Off

The purpose of this thesis was to investigate if digital techniques could be used to separate optical pulses and false alarms. As seen in Section 4.5, it is clear that the digital signal filtering and pulse detection can separate optical pulses from false alarms, but as said in Section 2.6, often a trade-off between false alarms and missing true optical pulses needs to be found in these kinds of applications. Another goal was to investigate how the detection sensitivity could be increased by digital techniques, i.e. how small optical pulses can be detected. This section presents the method for investigating how much the signal and pulses can vary and still detect the optical pulses but not the noise, i.e. how much the sensitivity can increase (both by increased bias voltage and decreased minimum detection level for optical pulses) while still having a low false alarm rate. A few test cases were simulated to study this trade-off. The first step in the simulations was to construct a signal as described in Section 4.3, the signal was then filtered as described in Section 4.4. Then detection and validation were made as presented in Section 4.5. The test cases had varying signal values and were developed by trial and error to find signal values that represented some specific scenarios. The test cases are presented in Section 5.1. To retrieve stable and reliable results each test case was simulated 1000 times and detection statics for all cases were gathered. The detection statistics are also presented in Section 5.1.

While doing the simulations, the goal of the detection methods was to detect as many optical pulses as possible, as small optical pulses as possible and give as few false alarms as possible. As described in Section 2.1, the analog detection method detects 50 % of the optical pulses and 0.1 % of all detections are false alarms at the amplitude threshold level of 40 mV. Proceeding from these statistics, it was decided that these were the minimum detection limits. Thereby, detecting less than 50 % of optical pulses or more having more than 0.1 % of false alarms were considered as not acceptable detection statistics.

4.7 Digital Replacement for Analog TVG

One of the tasks in the scope of this thesis was to investigate digital solutions to replace the analog dynamical TVG explained in Section 2.1.1. As also mentioned in the section, the purpose of the TVG is to remove or reduce the amplitude of the backscatter so it does not generate any detections. For the digital replacement method, this was done by multiplying the signal with a function filter, like windowing described in Section 2.5.1 and 2.6. The functions investigated for this were a binary function, a linear function, an exponential function and an inverse exponential function. The functions filters can be viewed in Figure 4.6.

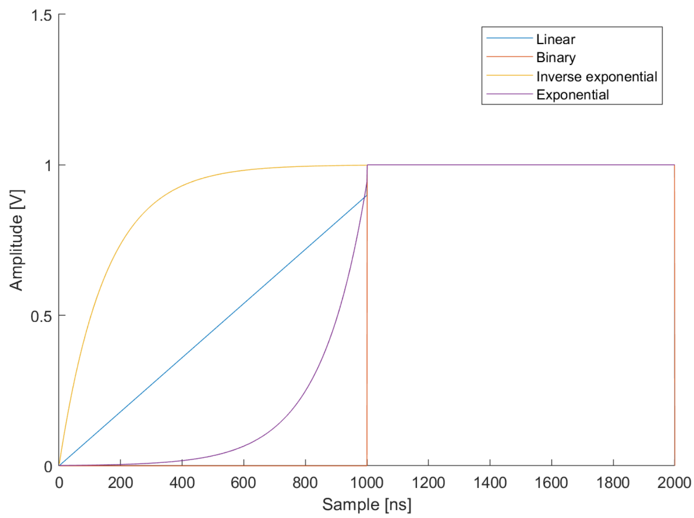

Figure 4.6: The four function filters investigated to replace the analog TVG.

The investigation was done by generating a signal with backscatter. This was done by generating many, large, linearly decreasing optical pulses in the first 1000 samples of the signal. The second 1000 samples of the signal were a standard representation of the rest of the received echo signal. Then each function filter was multiplied by the signal. Then the filtering and detection method, as described in Section 4.4 and 4.5, was applied to the resulting signal. As mentioned previously in this section, the goal was that there was no detection on the backscatter, i.e. the first 1000 samples of the signal. The simulation for this investigation is presented in Section 5.2.

4.8 Time Estimation

One of the tasks in the scope of this thesis was to estimate the CPU time for the digital methods. Since simulations are done in MATLAB, time estimations were also done in MATLAB. MATLAB has two useful functions; one that measures real-time and one that measures CPU time [32]. CPU time is the amount of time the CPU has spent processing instructions of a computer program, process or system. The function that calculates the CPU time, calculates the CPU time only used by MATLAB. Both time functions are not precise and if the code is too fast the function can not provide useful data since it sets the time measured to 0 [32], [33].

For the different digital methods that were being simulated, time was measured for each one. Time was measured for the signal filtering and detection method explained in Section 4.4 and 4.5, as well as for the operation of the TVG replacement explained in Section 4.7. For each operation, the time was measured for all simulations (either 1000 or 100) and among them the minimum, maximum, average time and mean time was calculated.

The times were taken on a computer with 1 CPU with 2 cores, 4 logical processors and a clock speed of 2.5 GHz. The results can be found in Section 6.3.

5

Simulations

In this chapter, all simulations are presented. The simulations are described and the outcome is presented. The results concluded from the simulations are explained in Chapter 6.

5.1 Sensitivity and False Alarm Trade-Off

In this section, different test cases are simulated to investigate the detection sensitivity, as well as the trade-off between detecting true optical pulses and false alarms, using both the analog and the digital detection method as explained in Section 4.5. In Table 5.1 the signal values and detection statistics for different test cases are presented. What the signal values and value names represent are explained in Section 4.3. In the section, the detection statistics are also explained.

The different test cases illustrate different scenarios and are further explained later in the text, but are briefly described here. Test case 1 is constructed to represent the current situation. Test case 2 - 4 are constructed to illustrate different cases where the values are pushing the limits of performance or limits of different signal and pulse sizes. To get clear results all pulse sizes are kept constant throughout simulations for test case 2 - 4. For test case 2 the optical pulses are the smallest they can be and the shot noise is very high, while still meeting the accepted detection statistics as explained in Section 4.6. In test case 3 the Gaussian noise is large, while the optical pulses and the shot noise are the same as for case 2. In test case 4 the optical pulses are like for test cases 2 and 3, while the shot noise is extremely high and larger than even observed. Test case 5 is constructed to represent a realistic case where the bias voltage in the APD is increased and the detection sensitivity for optical pulses is increased, compared to the case when using an analog receiver.

Table 5.1: Detection statistics and signal values for different test cases.

Test case	**1**	**2**	**3**	**4**	**5**
Samples [ns]	1000	1000	1000	1000	1000
Gaussian noise amplitude *	3	3	6	3	3
Number of optical pulses [#]	1	1	1	1	1
Optical pulse width [ns]	10 - 20	9	9	9	9 - 20
Optical pulse amplitude [mV]	40 - 42	3.5	3.5	3.5	3.5 - 42
Optical fullness [%]	60 - 80	60	60	60	60 - 80
Number of shot noise pulses [#]	1	15	15	15	15
Shot noise pulse width [ns]	1 - 7	7	7	9	1 - 8
Shot noise pulse amplitude [mV]	35 - 40	40	40	50	35 - 50
Pulse amplitude threshold for digital detection method [mV]	1.5	1.5	1.5	1.5	1.5
Pulse width threshold for digital detection method [ns]	9	9	9	9	9
Pulse amplitude threshold for analog detection method [mV]	40	40	40	40	40
Percentage of detected optical pulses using digital detection method [%]	99.9	64.6	49.8	62.1	99.1
Percentage of detected shot noise pulses using digital detection method [%]	0	0	5.46	1.5	0
Number of detections in Gaussian noise using digital detection method [#]	0	0	40	0	0
Percentage of false alarms of all detected pulses using digital detection method [%]	0	0	63.3	27.2	0
Percentage of detected optical pulses using analog detection method [%]	55.5	0	0	0	9.7
Percentage of detected shot noise pulses using analog detection method [%]	0.11	2.3	24.4	100	25.8
Number of detections in Gaussian noise using analog detection method [#]	0	0	0	0	0
Percentage of false alarms of all detected pulses using analog detection [%]	0.2	100	100	100	97.2

As described, test case 1 is constructed to reflect the current situation, therefore the pulses are varying and the shot noise pulses are simulated in size and amount as to when the current bias voltage is used. Note, this case is not an absolute true

*The Gaussian noise amplitude setting does not have a unit since the value only represents a scalar multiplication with the simulated noise in MATLAB, as explained in Section 4.3.

case. Even though the amount of shot noise pulses is set to the simulation program's minimum, this minimum is higher than reality, therefore the percentage of detected shot noise pulses is expected to be higher than reality. The shot noise pulse frequency in the simulated case is 1 MHz (the simulation program's minimum) and not 16 Hz as it is in reality based on the practical signal study in Chapter 3. In Figure 5.1 a typical signal in test case 1 is viewed. In the last lines of Table 5.1, the detection statistics are viewed. For the digital detection method, 99.9 % of all optical pulses are detected, while for the analog detection method 55.5 % of all optical pulses are detected. For the digital detection method, 0 % of all detection are false alarms, while it is 0.2 % for the analog detection method. The detection statistics for the analog method correlate with real practical measurements of the performance of the laser rangefinder [4], considering what is mentioned about the shot noise pulse frequency.

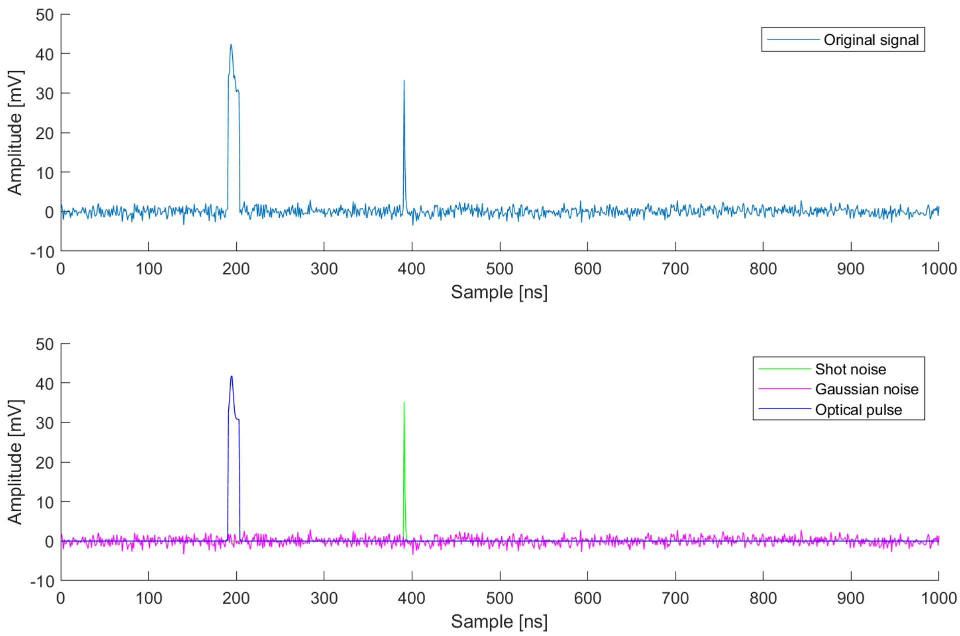

Figure 5.1: A typical signal in test case 1 and its different segments.

In test case 2 the number of shot noise pulses is increased to simulate an increase in bias voltage. Their width and amplitude are set to their observed maximum size while the optical pulses are set to a minimum in amplitude, pulse width and fullness while still meeting the minimum detection statistics for optical pulses for the digital method. This was to investigate how small the optical pulses could be, while the detection method still managed to meet the demands. The scenario reflects when the bias voltage is higher than in test case 1 and when the optical pulses are very small. The results in Table 5.1, view that 64.6 % of all optical pulses are detected and the false alarms are 0 % of all detection when using the digital detection method. The analog detection method is failing for this case since no optical pulses are detected and all detections are false alarms. If the analog amplitude threshold was to be lowered to the optical pulse amplitude for this case, there would be a 100 % detection of the shot noise pulses instead which is not wanted either. In Figure 5.2 a typical signal for test case 2 can be seen.

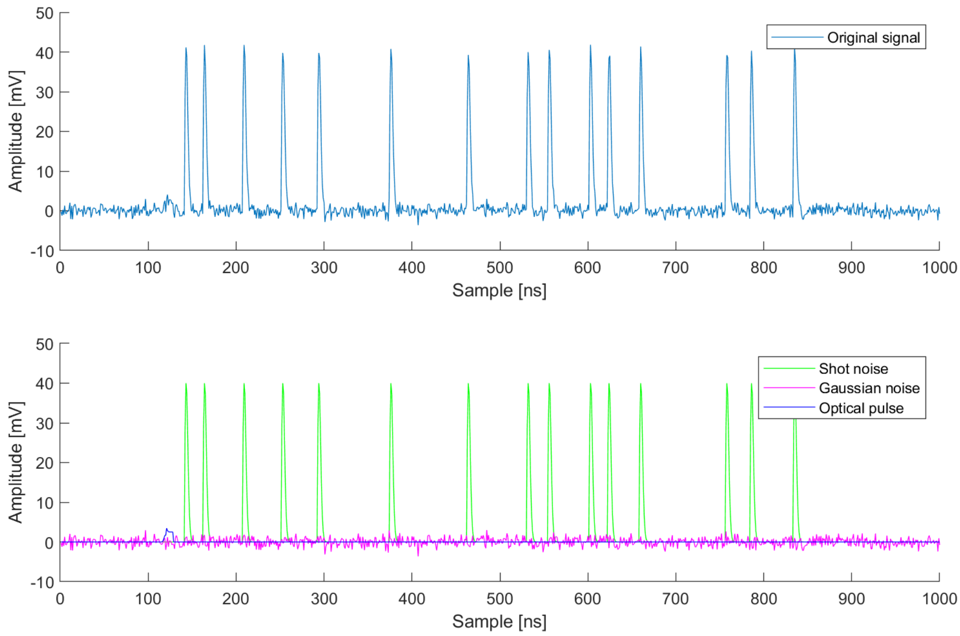

Figure 5.2: A typical signal in test case 2 and its different segments.

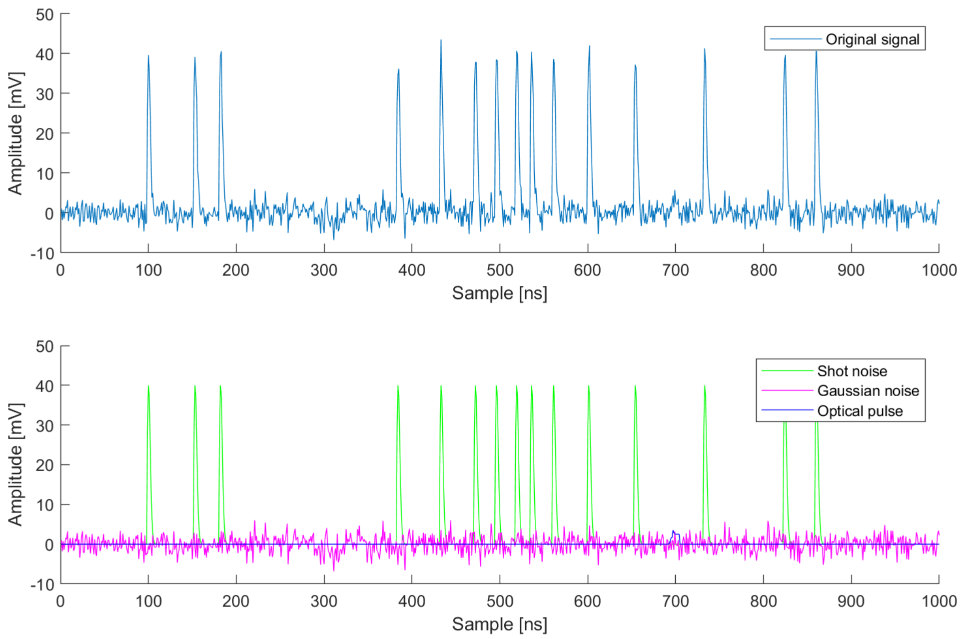

Figure 5.3: A typical signal in test case 3 and its different segments.

Test case 3 is much like test case 2, but the Gaussian noise is doubled in amplitude.

This is to see how robust the system is to Gaussian noise. As can be seen in Table 5.1, 49.8 % of all optical pulses are detected for the digital detection method, which is lower than for case 2. The number of false alarms is significantly increased, 63.3 % of all detection are false alarms. In this case, there is also some detections in the Gaussian noise, which is not observed for test case 1 or 2. Just like for case 2 the analog detection method is useless in this case. In Figure 5.3 a typical signal in this test case can be observed.

In test case 4 the optical pulses are as small as in case 2 and 3, while the shot noise pulses are many and even larger in amplitude and pulse width than before and ever observed. This case is only to test the limits of the detection method. As can be seen in Table 5.1, the percentage of detected shot noise pulses are increased compared to case 1 and 2 for the digital detection method. The percentage of false alarms was 27.2 % of all detected pulses, while 62.1 % of all optical pulses were detected. The analog method is useless for this test case as well. In Figure 5.4 a typical signal in this test case is shown.

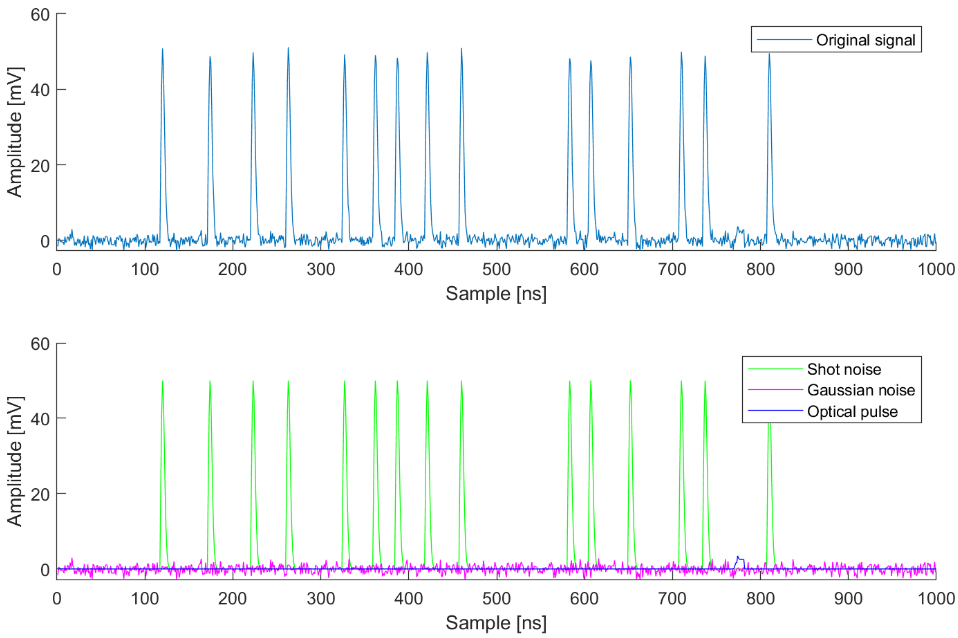

Figure 5.4: A typical signal in test case 4 and its different segments.

Test case 5 is constructed to represent a realistic scenario where all pulses are varying, like in test case 1. Compared to test case 1, this time the bias voltage is simulated to be increased and therefore the shot noise pulses are increased and larger in both amplitude and pulse width, while the optical pulses are like in test case 2, 3 and 4. When using the digital detection method 99.1 % of optical pulses are detected and there are 0 % of false alarms. The analog method detects 9.7 % of optical pulses and 97.2 % of all detected pulses are false alarms.

5.1.1 Failing Cases

In this section, some examples of when the digital detection method fails are presented. This can be used to evaluate if the method and threshold values are ideal and also see what issues need to be solved to increase the performance further. The detection method can fail in two ways, either miss to detect an optical pulse or detect noise, most often shot noise pulses.

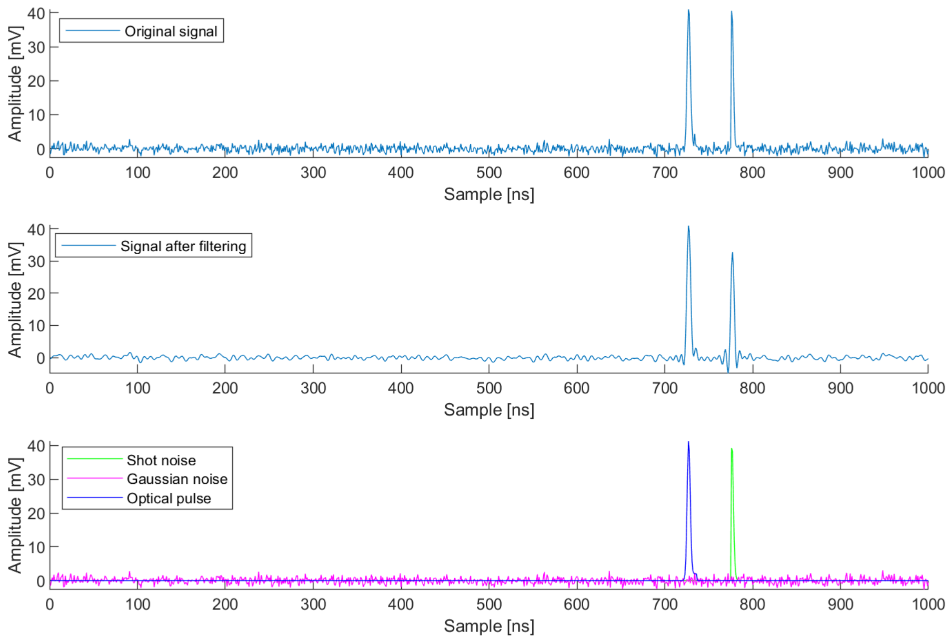

Figure 5.5: A signal when the detection method is failing to detect the optical pulse for case 1, the signal after filtering and its different segments.

In Figure 5.5 a signal where the method fails to detect an optical pulse for test case 1 is shown. By studying the figure, it seems like the Gaussian noise causes the optical pulse to be shorted, then the filtering enhances this and therefore the pulse is not detected. The detection method was performed once again on this signal but now with a lower pulse width threshold, equal to 7 ns (instead of 9 ns). For this case, the method did detect the optical pulse. A test with 100 signals was tested with the lowered pulse width threshold. For this case, 100 % of the optical pulses were detected, but 17.4 % of all detected pulses were false alarms.

In test case 2 the method fails to detect optical pulses because of the same reason as for test case 1. There are much fewer detections for optical pulses in test case 2 since the optical pulses are smaller in both amplitude and pulse width and are therefore easily affected by the Gaussian noise. A test with 100 signals for test case 2 was made, but where the amplitude threshold was lowered to 1 mV (instead of 1.5 mV). For this test, 88 % of the optical pulses were detected and 0 % of all detected pulses were false alarms.

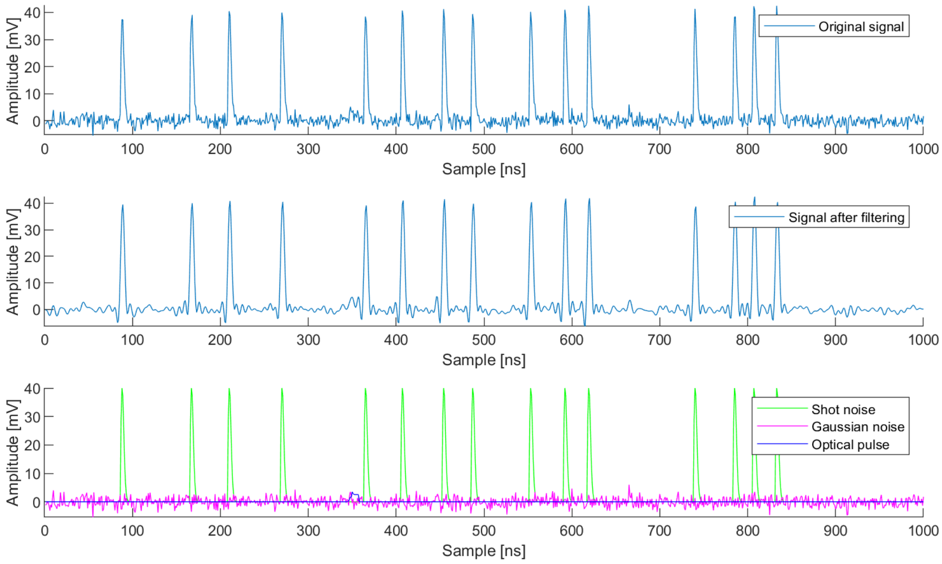

Figure 5.6: A signal when the detection method is failing to detect the optical pulse for case 3, the signal after filtering and its different segments.

In Figure 5.6 a signal where the method fails to detect the optical pulse for test case 3 is viewed. This signal is from test case 3, i.e. when the Gaussian noise is large. As for test case 1 and 2, the cause of failure is due to Gaussian noise. In this case, the Gaussian noise causes an irregularity in the middle of the optical pulse since the Gaussian noise happens to be a larger negative pulse in the same place as the optical pulse. The pulse is therefore not detected.

The detection method was performed once again on this signal but now with a lowered amplitude threshold, equal to 0.8 mV (instead of 1.5 mV). For this case, the method did detect the optical pulse, but now it gave detection for a pulse in the Gaussian noise as well. A test case with 100 signals was tested with the lowered amplitude threshold. For this case, 83 % of the optical pulses were detected and 24 % of all detected pulses were false alarms.

For all signals when the method fails in test case 3, it is due to the Gaussian noise affecting the signal in a way where either, as presented for test case 3, it splits the pulse in two below the amplitude threshold or affects the pulse so the pulse is shorted as illustrated for test case 1.

For test case 4 the missed optical pulses are due to the same problem as previously described. On the other hand, in this test case, the percentage of detected shot noise pulses is high. Therefore the threshold was altered to lower the percentage of detected shot noise pulses instead. A test where the amplitude threshold was increased to 2 mV (instead of 1.5 mV) was made. The percentage of detected optical pulses was lowered to 21 % and the percentage of detected shot noise pulses was decreased to 0.13 %. The false alarms were 8.7 % of all detected pulses. If the thresholds are kept like in Table 5.1 and the pulse width of the shot noise pulse was instead lowered to 8 ns (instead of 9 ns), 55 % of the optical pulses were detected. The shot noise pulse detection decreased to 0.06 % and the false alarms were 1.7 % of all detected pulses. The shot noise detections are high in test case 4 since the shot noise pulse width is larger than in the other cases. As for the cases where the method misses optical pulses due to the Gaussian noise shortening the pulse, this case is probably due to the opposite, where the Gaussian noise elongates the shot noise pulse instead. This can be seen in Figure 5.7.

For test case 5 optical pulses are missed due to the same reasons mentioned previously.

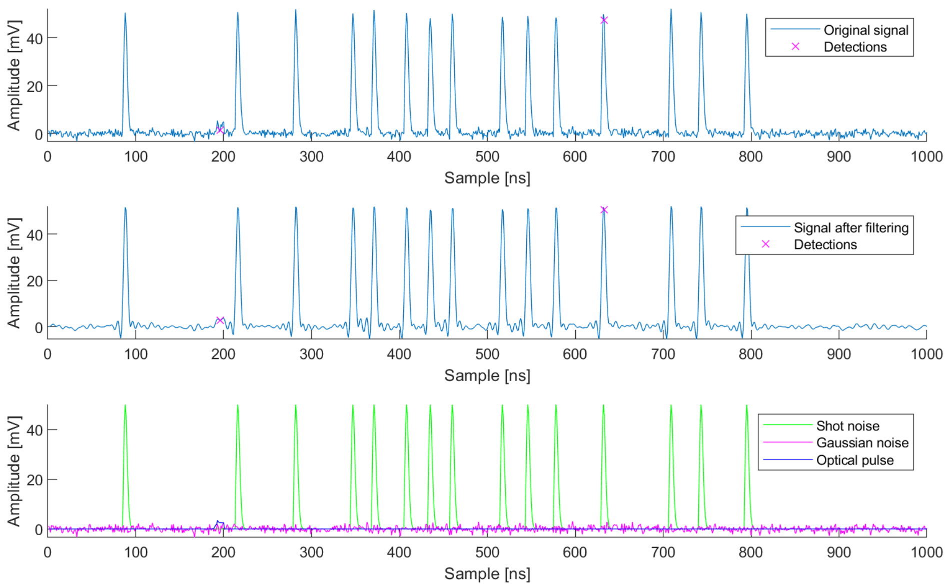

Figure 5.7: A signal when the detection method is failing (since a shot noise pulse is detected) for case 4, the signal after filtering and its different segments.

5.2 Digital Replacement for Analog TVG

In Section 2.1.1, the analog TVG filter is explained. In this section, the simulations for the digital replacement of the TVG are presented.

In Figure 5.8, 5.9, 5.10 and 5.11 the results of the digital TVG functions on a received signal with backscatter can be observed. There are 3 graphs in all figures. In the top graph, the result of the signal after the TVG function, signal processing and detection is viewed. In the second graph, the original received signal is shown and in the third graph, each signal component is illustrated. The optical pulses in the first 1000 samples represent the backscatter and the TVG function is to remove or reduce the amplitude of the backscatter so it does not generate any detections as described in Section 2.1.1 and 4.7.

In Figure 5.8 the result from when using the linear TVG function can be seen. As can be seen, there are many backscatter detections for this method.

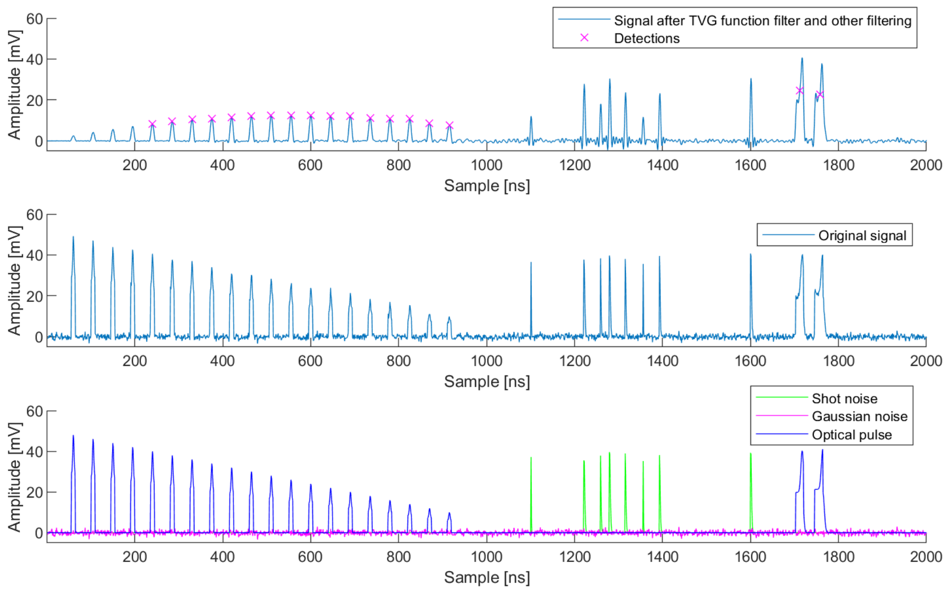

Figure 5.8: A signal after using the linear TVG function filter, the original signal and its different segments.

In Figure 5.9 the result from when using the binary TVG function is shown. As can be seen, there are no backscatter detections for this method.

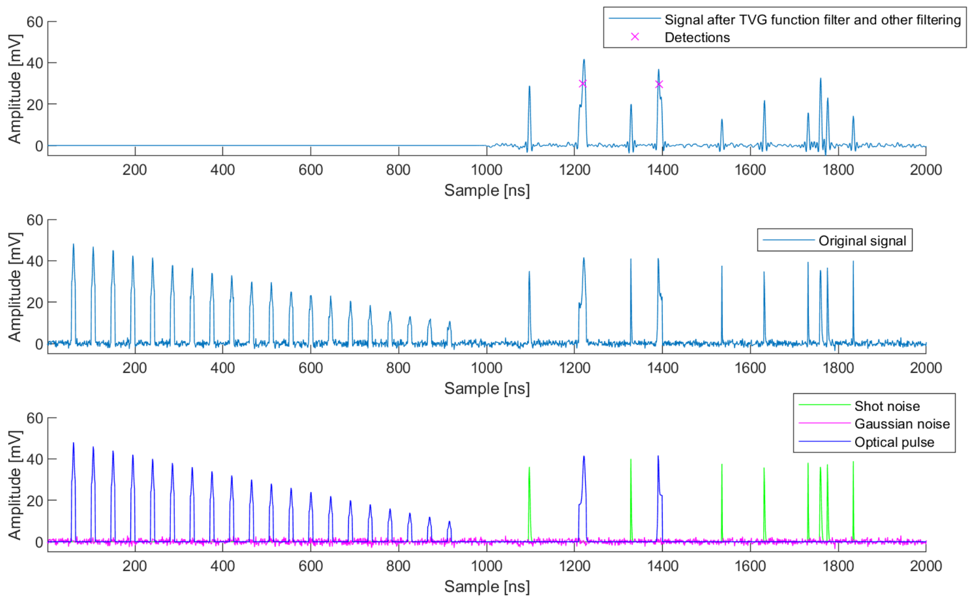

Figure 5.9: A signal after using the binary TVG function filter, the original signal and its different segments.

In Figure 5.10 the result from when using the inverse exponential TVG function is viewed. As can be seen, all backscatter pulses are detected for this method.

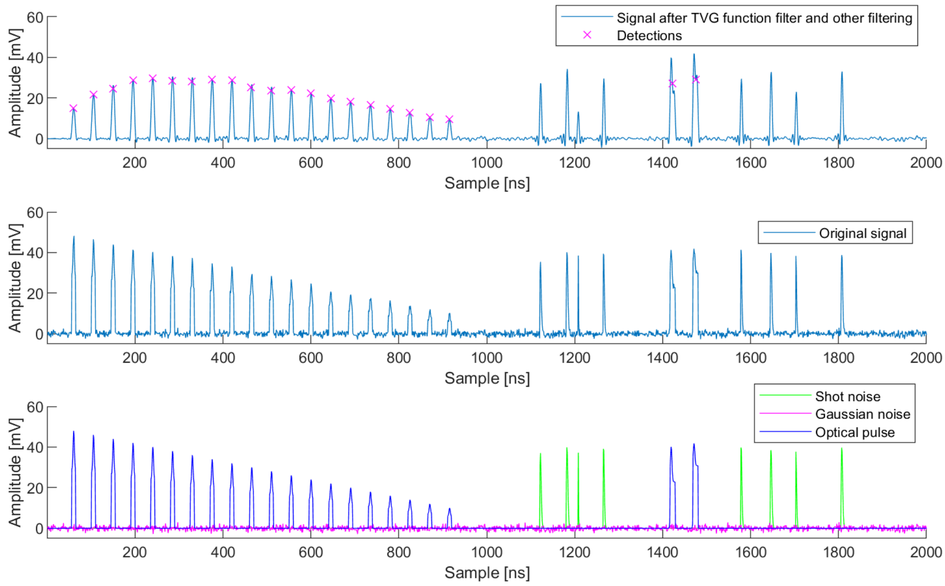

Figure 5.10: A signal after using the inverse exponential TVG function filter, the original signal and its different segments.

In Figure 5.11 the result from when using the exponential TVG function is presented. As can be seen, there are no backscatter detections for this method.

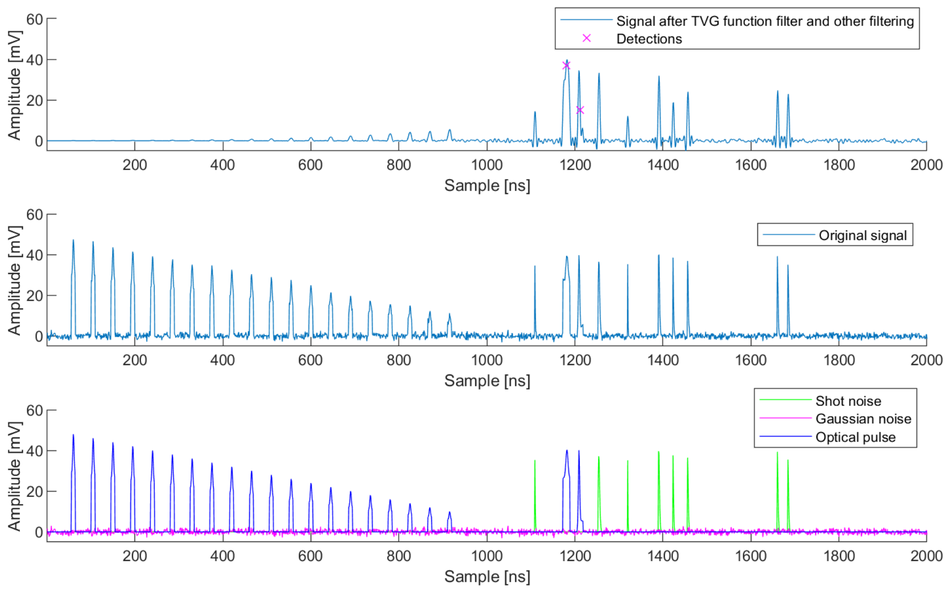

Figure 5.11: A signal after using the exponential TVG function filter, the original signal and its different segments.

6

Results

In this chapter, all results are presented. Most of the results are based on the simulations in Chapter 5. First, the results are evaluated from the simulations of the different test cases presented in Section 5.1 and 5.1.1. Then results from the simulation of the digital replacement for the TVG, found in Section 5.2, are evaluated. Lastly, the time estimations for all digital operations are presented.

6.1 Sensitivity and False Alarm Trade-Off

When evaluating the different simulations presented in Section 5.1 and 5.1.1, it is clear there is a trade-off between the detection sensitivity and false alarms. As presented, when decreasing the threshold in the detection method it might be possible to detect smaller optical pulses. On the other hand, more shot noise pulses will be detected as well and thereby increasing the false alarms. It is also clear that the detection method can separate optical pulses and false alarms to a certain extent and an increase in shot noise pulses frequency/bias voltage is, therefore, no problem as long as the shot noise pulses are small enough. Based on the detection statistics presented in Section 5.1 and 5.1.1, it seems like the thresholds are optimized for this particular method and situation. The smallest optical pulses that can be detected and still achieve acceptable detection statistics, have a pulse amplitude of 3.5 mV and are 9 ns in pulse width. This is an increase in detection sensitivity of the optical pulse amplitude with 36.5 mV compared to the analog detection method, which corresponds to 10.57 dB. The largest shot noise pulses can be 50 mV in pulse amplitude, 8 ns in pulse width and have a frequency of 15 MHz without over-stepping the acceptable detection statics.

In the simulations, the analog detection method was tested as well and it is clear that the analog method can not handle smaller optical pulses or more shot noise pulses under the circumstances of this thesis.

6.2 Digital Replacement for Analog TVG

Based on the simulations in Section 5.2, it is clear that a digital operation replacing the analog TVG filter is possible and is working well. According to the simulations, the binary and the exponential window functions were performing the best.

6.3 Time Estimation

In the tables in this section, the time and CPU time for different operations are presented.

6.3.1 Digital Signal Filtering and Detection Method

In Table 6.1, the times are presented for the different test case simulations presented in Section 5.1, while using digital signal filtering and pulse detection as described in Section 4.4 and 4.5. The time is only measured for the signal filtering and detection method, not for the creation of the signal or the calculation of the validation statistics.

Table 6.1: Time measures for the digital signal filtering and detection method for different test cases.

Test case	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Average time [ms]	0.56	0.61	0.62	0.66	0.6
Median time [ms]	0.35	0.53	0.58	0.59	0.55
Maximum time [ms]	11	43	17	19	10
Minimum time [ms]	0.32	0	0	0	0
Average CPU time [ms]	0.47	0.91	0.62	0.63	0.93
Median CPU time [ms]	0	0	0	0	0
Maximum CPU time [ms]	31	47	31	16	47
Minimum CPU time [ms]	0	0	0	0	0

6.3.2 Digital Replacement for Analog TVG

In Table 6.2 the times for the TVG operation described in Section 4.7 is presented. The time is only measured for the TVG operation, not for the creation of the signal, other signal processing, detection method, etc.

Table 6.2: Time measures for the TVG operation.

Average time [μs]	5.2
Median time [μs]	4.8
Maximum time [μs]	6.4
Minimum time [μs]	3.6
Average CPU time [μs]	6.3
Median CPU time [μs]	0
Maximum CPU time [μs]	0
Minimum CPU time [μs]	0

7
Discussion

Through the course of the thesis, several different decisions and assumptions have been made. The following chapter discusses their impact on the results and also how other alternatives could have made a difference. The results are also discussed and possible measures for problems, as well as optimization possibilities, are described.

7.1 Simulated Signal

As mentioned throughout the report, to achieve realistic results in the simulations, the signal simulation was important. If the simulated signal did not represent reality, the results would not either. When comparing the simulated signal with the signals viewed in Chapter 3, it can be difficult to see the similarity. As mentioned in Chapter 3, the low-frequency noise, as well as the slope in the detected pulses was assumed to be from the detection circuit and the bad measuring probe, which was removed in the simulated signal since they would not be used in a digital solution. It is most probable that the slope effect is from the detection circuit since it is repeated for every detected pulse and not the rest of the signal as said in Chapter 3. The low-frequency noise, on the other hand, is not necessarily from the detection circuit and could be from other electronics in the system, but it is most likely flicker noise caused by analog electronics. If this noise was from some other electronics and would still appear in a digital signal in a digital solution, this noise could be eliminated with a filter. The low-frequency noise would probably therefore not affect the results much since the noise has a different frequency than the rest of the signal. It would therefore be easily filtered out with a stop-band filter.

In a digital solution, the ADC would probably add some noise and other errors to the signal as mentioned in Section 2.4.1. Some of the noise would be thermal noise and be Gaussian distributed. The Gaussian noise is, as mentioned in Section 4.3, accounted for in the simulated signal. It is difficult to know if the noise level is agreeable to what it would be in reality since it would depend on the particular ADC. In the simulation for test case 3, viewed in Section 5.1, the system was tested for a higher noise level. Based on this result, the system is assumed to be robust enough for a slightly higher noise level. It is also possible to change the thresholds in the detection method to better fit this situation and perhaps get slightly lower sensitivity instead. The ADC would probably introduce other errors as well. Quantization errors, offset errors, gain errors and linearity errors would need to be considered and accounted for in a digital solution. It is though difficult to estimate their impact on the signal and is therefore difficult to simulate. Though as mentioned in Section 2.4.1, there are ways to minimize the noise and errors caused by the ADC (e.g. by calibration and filtering), but it is something that would need to be investigated further.

The simulations were made for a broad variety of signals and pulses. Though, it is not certain that the signal and pulses can vary as much as they do in the simulations. Even though a practical signal study was performed in the thesis, viewed in Chapter 3, this study was not extensive enough to specify the signal characteristics with certainty. Therefore a wide range of signals was used in the simulations. It is uncertain if some of the signals used in the simulation are useful or even reasonable, but they were included in the simulation anyway. Since if the methods work for a wide range of signals, they will probably work for a more specific range of signals. To retrieve more certain results, the laser rangefinder's signals must be studied further and simulations would need to be done with more specific signal values or actual sampled signals. The signal characteristic would probably also differ depending on the APD. If the signal range is found to be more specific, fine-tuning (like changing cut-off frequencies for the filter and the threshold values in the detection method) might be needed for different APDs or for different systems depending on what level of optimization is liked to be achieved.

A minor drawback of the simulations is that they can be somewhat irregular. When shot noise pulses are added to the signal, they can not be added on top of each other as mentioned in Section 4.3. This process of finding an empty position in the signal has a timer. This is to ensure that simulations do not take an excessive amount of time. Therefore if not all shot noise pulses have been placed in the signal after a certain amount of time, the rest of the shot noise pulses are left out. This is not an issue that is manipulating the detection statistics, but when doing simulations and expecting e.g. 15 shot noise pulses in every signal, this might not always be the case. So when viewing Table 5.1 and the number of shot noise pulses is set to 15, this might not be true in reality. The mean value of the number of shot noise pulses for all signals in the simulation might in reality be slightly lower.

Another irregularity is the optical pulse shape. When looking at all figures with plots of the signal containing an optical pulse and comparing the optical pulse shape to each other, it is clear that it is varying. This is because of the merging of the two pulse shapes (Gaussian and rectangular) as explained in Section 4.3. In the construction of the optical pulse, sometimes the two pulses with different pulses shapes do not exactly match in position and a slight asymmetry in the merged pulse is found. This asymmetry may have affected the detection of optical pulses slightly in favor since the shift in positions can have resulted in the resulting optical pulse having a slightly wider pulse width than intended.

7.2 Sensitivity and False Alarm Trade-Off

The simulations and results viewed in Section 5.1 and 6.1, show that the digital solution with digital signal filtering and pulse detection is superior to the analog solution under the circumstances of this thesis. The increased sensitivity level of 10.57 dB is profound and does not consider the APD gain from the possible increase of bias voltage. By using the digital solution, the bias voltage can most likely be increased since in the simulations the shot noise frequency was increased from 16 Hz to 15 MHz with stable results. This increase in frequency can be difficult to correspond to a particular increase of bias voltage since it differs depending on the APD. Therefore, the gain from the increase of bias voltage is not something that can be estimated and is needed to be studied as the other signal characteristic explained in Section 7.1. Though the results can be assumed to represent a definite increase in gain as can be seen in Figure 2.8.

In Section 5.1.1, the cases when the method is failing can be seen. Based on the simulations from this section, it is shown that the threshold values can be changed depending on the situation. The thresholds used for the simulations in Section 5.1 can be determined to be suitable for the wide range of used signals, but as mentioned in Section 7.1, the threshold can be fine-tuned when there is more information on the signals.

7.3 Time Estimation

The time estimations presented in Section 6.3, are somewhat vague since the method used is not that specific. It also seems to be unreliable, as when producing the results the values differed from time to time.

When analyzing the times for the signal filtering and detection method in Table 6.1, the times do not seem to be varying due to the different test cases. When studying the maximum, minimum, average and median time it seems like the maximum time is increasing the average time since the median is closer to the minimum time. Therefore the median time might be a better static representation of the time than the average time. Another explanation for the average time being slightly higher can be that the average time is calculated by measuring the time for all simulations and then dividing the time by the number of simulations. By doing this method the times that have been set to zero when measured separately (due to being too small for the MATLAB function as explained in Section 4.8) are included in the average. The results in Table 6.2, illustrate this clearly since in the table all measures for the CPU time, expect the average is set to zero.

It is a problem that the MATLAB time functions set small time values to zero since it does not provide a proper result and can manipulate the result slightly. Another method for estimating process power or process time should probably be used if more accurate results are needed. Overall, based on the times presented in

Section 6.3, a capable data system should be able to process the digital methods presented in this thesis without any particular issues or time delays, but if an optimized CPU is wanted more specific studies need to be done.

Another factor that can minimize the CPU time, if the digital methods are decided to be implemented, is to code efficiently. The code for all simulations in this thesis is not in particular time optimized. They are coded to have reasonable simulation time, but not in particular to have minimal CPU time. This was not done due to a shortage of time and skills.

7.4 Opportunities of Development

There are several ways to use digital techniques to further develop the laser rangefinder. To develop the detection performance, multi-pulse correlation as described in Section 2.5.2 could be used. If this method would be used the false alarms would probably decrease, the detection of optical pulses would increase and smaller optical pulses could be detected. This would need to be simulated and tested though. By using multi-pulse correlation, the speed of the object might also be estimated. Since by using several measurements, the difference in range could be estimated and thereby the velocity.

Another method that might improve the detection performance is to change the transmit pulse so correlation with this pulse can be used on the received signal to retrieve only optical pulses. This kind of correlation method was tested in the thesis and the method, simulations, results, as well as a short discussion, can be found in Appendix B. The result from this investigation was that since the optical pulses and shot noise pulses are too similar the method does not work for this kind of transmit pulse. The transmit pulse needs to be more complex to achieve some useful results of the correlation. There were some attempts to enhance the correlation but did not achieve reliable results. As mentioned this can be viewed in detail in Appendix B. If the correlation method described in Appendix B were to be used, it would probably be used as a parallel system since the system only performed well for particular signals. Though if the method were to be used in parallel to the method used for the simulations in Section 5.1, the increase in detection sensitivity of the optical pulse amplitude would be 37.5 mV compared to the analog detection method, which corresponds to 12.04 dB.

Other signal processing and more complex methods could also be explored to improve detection further. The methods used in this thesis are very basic and not very complex. This promotes a fast and easy system, but if further improved detection performance is wanted and CPU time is of no issue, there are many possibilities with more complex signal processing that can be investigated. For example, signal processing techniques using transforms could be investigated. Transforms enable more complex signal processing, like the EMD and Wavelet method presented in Section 2.5.2. It is not certain that a more complex signal processing method will improve detection results, but it is worth investigating if CPU time is of no concern.

Deep machine learning, described in Section 2.6, could be another method that would improve detection performance. It is unclear how much this method would improve performance, but since deep machine learning can be used with good results for most decision-making systems, it would probably be useful in a laser rangefinder's detection system as well.

Adaptive threshold and adaptive noise reduction as described in Section 2.5.1 and 2.6, could also be used to further develop the digital pulse detection. Adaptive noise reduction would be useful if the system is noisier than expected or if the noise is varying severely. An adaptive threshold would be useful if the shot noise pulses or optical pulses are varying much. Adaptive thresholds could also be used in a dynamic system where the thresholds can be changed depending on what kind of pulses are searched for.

If a dynamic system is wanted, a windowing function could also be used to only search for pulses/targets at specific ranges. Like the method used for the replacement of the analog TVG described in Section 4.7, the same kind of windowing could be used on the whole signal. This type of method was also presented to be useful for a LiDAR system in Section 2.6. The method would set all values outside a specific time interval to zero. Then the system would only detect pulses in the window which represents searching for a target at a specific range interval.

8

Conclusion

The main purpose of this master's thesis was to investigate if and how digital techniques can be used to separate false alarms from true optical pulses in the laser rangefinder's received echo signal. As argued in the thesis, digital techniques can be used for this to a certain extent. By using digital signal filtering and pulse detection, the sensitivity of the laser rangefinder can be improved vastly. When using this kind of method, the bias voltage in the APD can be increased, due to the fact that the false alarms can be separated from the true optical pulses. This in return would improve the sensitivity of the laser rangefinder even further. It is concluded that a trade-off between detecting optical pulses and false alarms is inevitable for the system.

The thesis also investigated if the analog TVG could be replaced by a digital solution. It was proved that the analog TVG has a reliable digital solution and that the digital solution is probably performing more stable than the analog TVG, due to the digital solution not depending on fluctuations in the electronics.

The CPU time needed for the digital solutions is reasonable for a capable data system and should not be a problem when implementing a digital system in a laser rangefinder. Also, it is possible to make the algorithms used in the thesis more efficient.

Correlation between signals could be used, either between an ideal optical pulse and the signal or by multi-pulse correlation. If the first method were to be used, a more complex transmit pulse is needed, which is not possible for the laser rangefinder modeled in this thesis. The multi-pulse correlation method seems to be beneficial, but how much it would improve detection results would need to be tested to know if it is worth the extra processing.

In summary, an analog laser rangefinder receiver would benefit from being digitalized, since the digital solution performs better under the circumstances of this thesis. A digital receiver will most likely have better detection statistics, be more sensitive, make an increase in bias voltage possible, as well as offer more stable results. Though, there are other problems with digitization since it introduces other types of noise and errors, especially from the ADC. The introduced noise and errors will need to be handled in a digital receiver, but should not interfere with getting reliable and stable digital signals.

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A

Appendix 1 - Investigation of Filters

In this appendix, the simulation and result from the investigation of filters described in Section 4.4 are presented.

In Figure A.1, the first graph views a simulated signal and the signal filtered with the different filters. In the second graph, the signal components are presented. By just looking at the figure, it is difficult to determine what filter is preferred for the system. What is possible to see is that all filters manage to reduce some of the shot noise pulses, as well as the Gaussian noise. Both the band-pass and the low-pass seem to create some oscillations, while the moving average filter seems to slightly shift the peaks compared to the other filters.

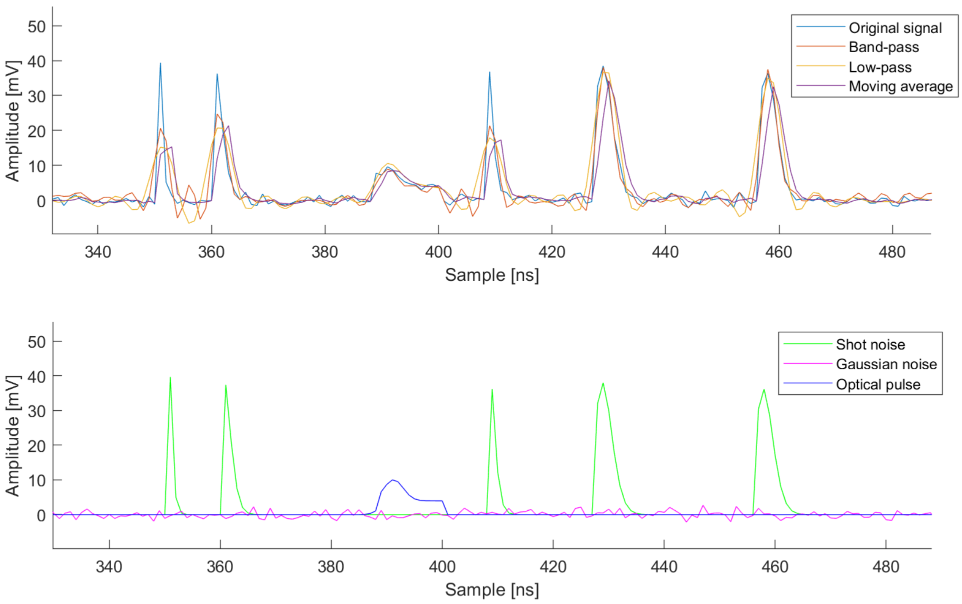

Figure A.1: Original signal and the signal filtered with different filters, as well as its different segments.

As described in Section 4.4, 100 simulations were done when using the different filters. In Table A.1, the signal values and detection statistics for when using the different filters are presented.

The percentage of detected optical pulses was almost the same for all filters. The band-pass filter had many false alarms and the moving average had a few false alarms, while the low-pass filter had no false alarms. According to the statistics in Table A.1, the moving average and low-pass filter seem to be the most advantageous. The low-pass filter was chosen for the method in this thesis because the moving average is slightly moving the peaks as described previously. Shifting the peaks might affect the range calculation for the laser rangefinder, which is not wanted.

Table A.1: Detection statistics and signal values for the different filters.

Filter	**Low-pass**	**Band-pass**	**Moving average**
Samples [ns]	1000	1000	1000
Gaussian noise amplitude *	3	3	3
Number of optical pulses [#]	1	1	1
Optical pulse width [ns]	10	10	10
Optical pulse amplitude [mV]	10 - 20	10 - 20	10 - 20
Optical fullness [%]	60 - 80	60 - 80	60 - 80
Number of shot noise pulses [#]	15	15	15
Shot noise pulse width [ns]	1 - 7	1 - 7	1 - 7
Shot noise pulse amplitude [mV]	35 - 40	35 - 40	35 - 40
Pulse amplitude threshold for digital detection method [mV]	2	2	2
Pulse width threshold for digital detection method [ns]	9	9	9
Percentage of detected optical pulses using digital detection method [%]	97	98	98
Percentage of detected shot noise pulses using digital detection method [%]	0	0.15	8.8
Number of detections in Gaussian noise using digital detection method [#]	0	0	0
Percentage of false alarms of all detected pulses using digital detection method [%]	0	2.0	53.5

*The Gaussian noise amplitude setting does not have a unit since the value only represents a scalar multiplication with the simulated noise in MATLAB, as explained in Section 4.3.

B

Appendix 2 - Correlation Between Signals

One of the tasks included in the scope of the thesis was to use correlation between signals. Due to the task not contributing significant results, the method, simulations, results and discussion for this task were decided to be presented in this appendix.

B.1 Method

The scope of this thesis included investigating if correlation can be used to increase detection performance. By analyzing the results in Section 6.1, performance is already improved using digital techniques. Therefore the goal of the correlation method was to improve it further, which meant to increase the detection of optical pulses, detect even smaller optical pulses or have fewer false alarms. The detection limits were the same as in Section 5.1, i.e. detecting less than 50 % of optical pulses or more having more than 0.1 % false alarms were not acceptable detection statistics.

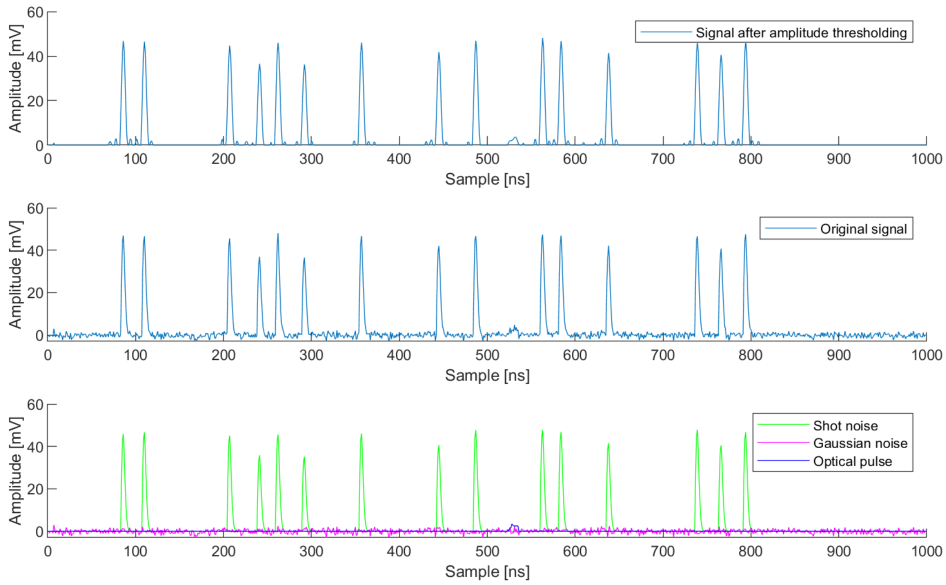

Figure B.1: Signal after amplitude thresholding, original signal and its different segments.

The correlation method consisted of, after the signal filtering described in Section 4.4, the first step was to use amplitude thresholding to obtain only peaks in the signal. The signal after signal filtering and amplitude thresholding can be seen in the first graph in Figure B.1. The next step was to normalize the peaks since this would enhance the correlation. The result of this operation can be seen in the first graph in Figure B.2.

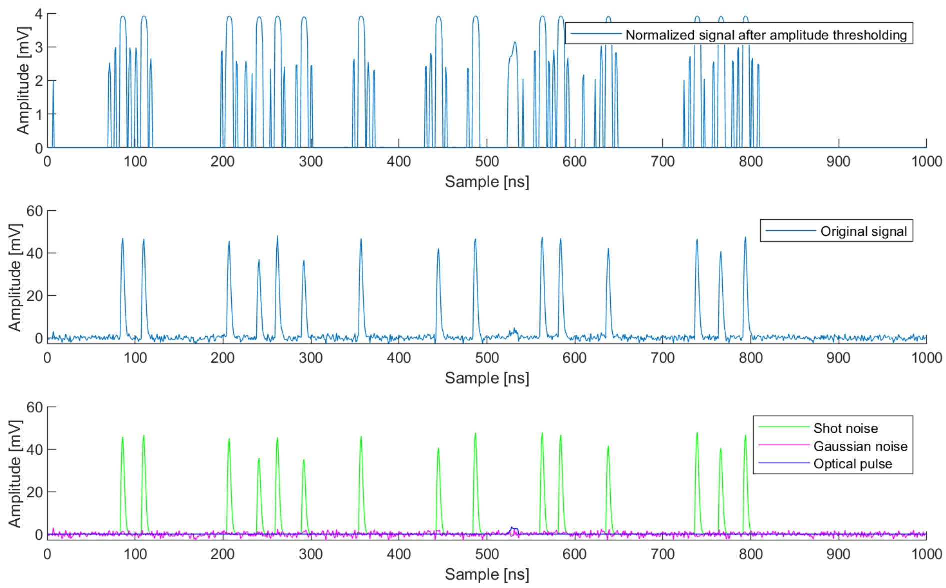

Figure B.2: Signal after normalizing, original signal and its different segments.

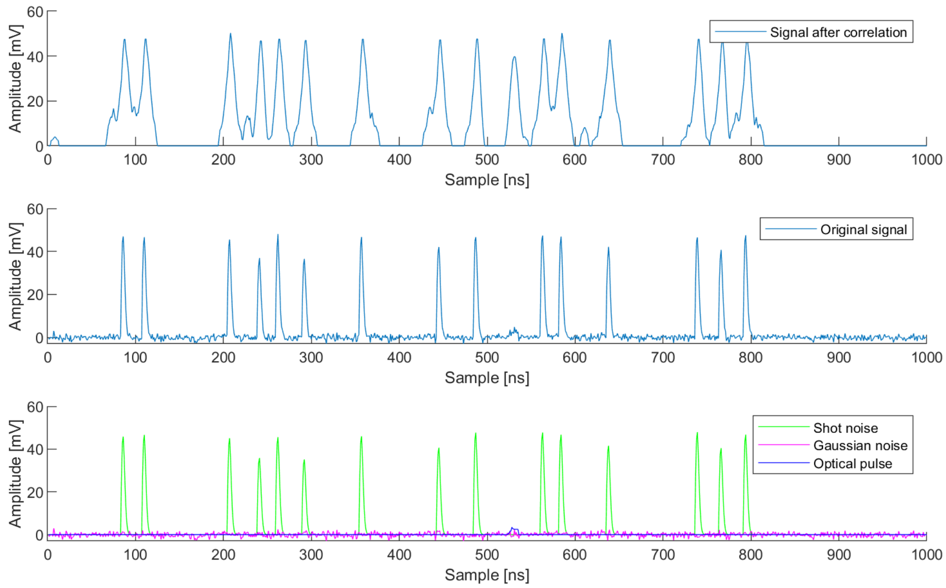

Figure B.3: Signal after correlation, original signal and its different segments.

Then correlation was done with an ideal optical pulse. In simplicity, the purpose of the correlation with an ideal optical pulse is to decrease all pulses that were not similar to the optical pulses as explained in Section 2.5.2. The signal after correlation can be seen in the first graph in Figure B.3.

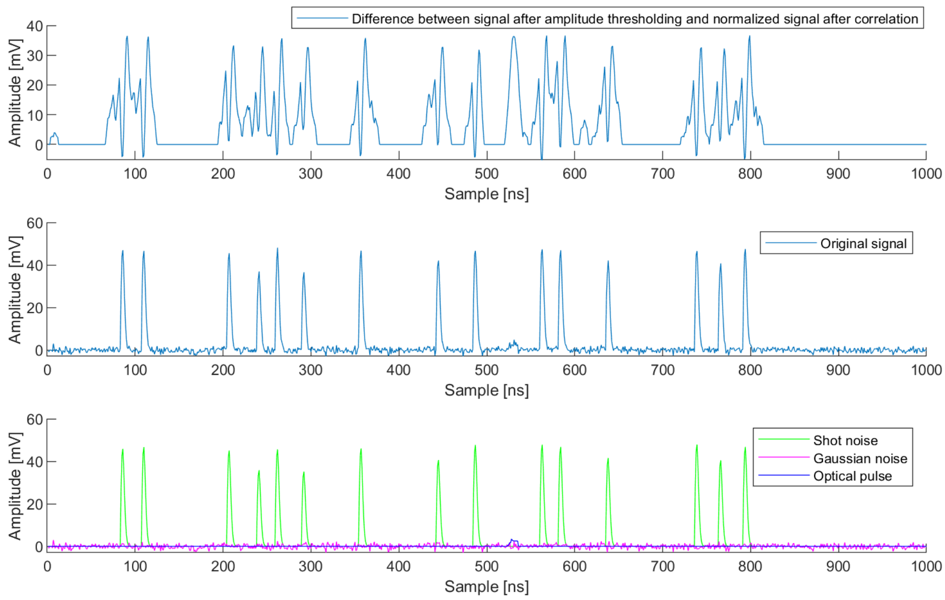

Figure B.4: Signal after calculating the difference between the signal after amplitude thresholding and after correlation, original signal, as well as its different segments.

Since the correlation was not strong enough to get clear results. The difference between the correlated signal and the signal after amplitude thresholding was calculated to get a new signal, which further highlighted the impact of the correlation. The result of this operation can be viewed in the first graph in Figure 5.4.

Then the detection method was performed on the signal to retrieve detection statistics. The thresholds in the detection method was needed to be changed to fit this method and were found by trial and error. The correlation method was performed on a few test cases, in a similar manner as explained in Section 4.6. 1000 simulations were done for each test case and the resulting detection statistics are presented in Section B.2.

B.2 Simulations

In this section, the simulations for the correlation method are presented. In Table B.1 the signal values and detection statistics for two test cases are presented. Test case 5 uses the same signal values as in test case 5 in Section 5.1. By doing this the correlation method can be compared to just the signal filtering and detection used in Section 5.1. In test case 6 the optical pulses are as small as they can be while still meeting the minimum detection demand for optical pulses.

Table B.1: Detection statistics and signal values for different test cases using the correlation method.

Test case	**Case 5**	**Case 6**
Samples [ns]	1000	1000
Gaussian noise amplitude *	3	3
Number of optical pulses [#]	1	1
Optical pulse width [ns]	9 - 20	9
Optical pulse amplitude [mV]	3.5 - 42	2.5
Optical fullness [%]	60 - 80	60
Number of shot noise pulses [#]	15	15
Shot noise pulse width [ns]	1 - 8	8
Shot noise pulse amplitude [mV]	35 - 50	50
Pulse amplitude threshold for digital detection method [mV]	21	21
Pulse width threshold for digital detection method [ns]	8	8
Percentage of detected optical pulses using correlation method and digital detection method [%]	80.7	50.6
Percentage of detected shot noise pulses using correlation method and digital detection method [%]	0.17	0.06
Number of detections in Gaussian noise using correlation method and digital detection method [#]	66	5
Percentage of false alarms of all detected pulses using correlation and digital detection method [%]	5.8	2.7

For test case 5 the correlation method performs worse than the method used in Section 5.1. Only 80.7 % of the optical pulses are detected and false alarms are 5.8 % of all detections. In the second graph in Figure B.5, a typical signal for test case 5 can be viewed. In the first graph, the result of the correlation method for the signal is shown and in the third the signal segments.

In test case 6, the optical pulse amplitude is set even lower than what was possible for the method used in Section 5.1. In this case, the optical pulses were set to 2.5 mV in amplitude and still, 50.6 % of them were detected. The shot noise pulses were set to the largest span value used in test case 5. In this case, 2.7 % of the detected pules were false alarms. In the second graph in Figure B.6, a typical signal for test case 6 can be viewed. In the first graph, the result of the correlation method for the signal is shown and in the third the signal segments.

*The Gaussian noise amplitude setting does not have a unit since the value only represents a scalar multiplication with the simulated noise in MATLAB, as explained in Section 4.3.

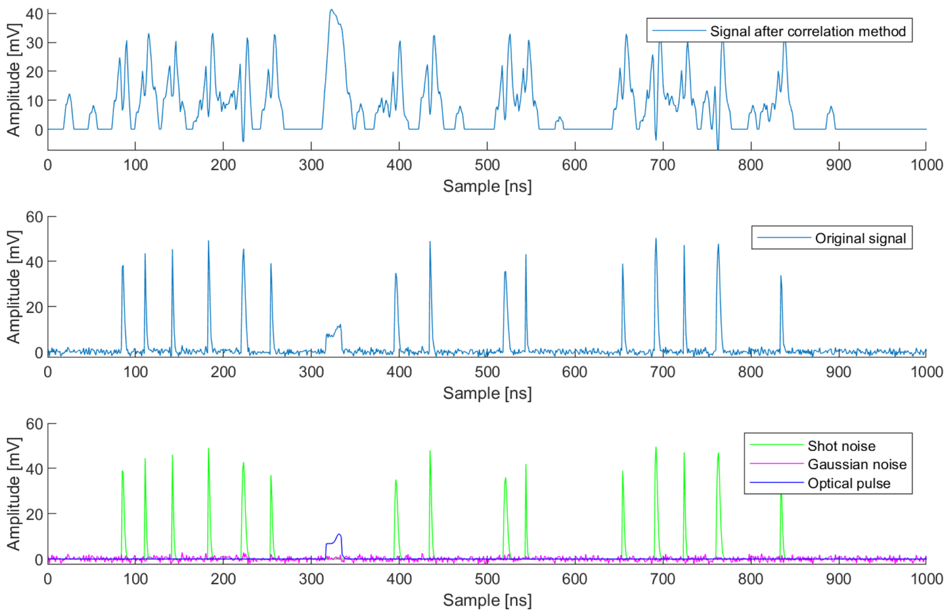

Figure B.5: The signal after correlation method, the original signal and signal segments for test case 5.

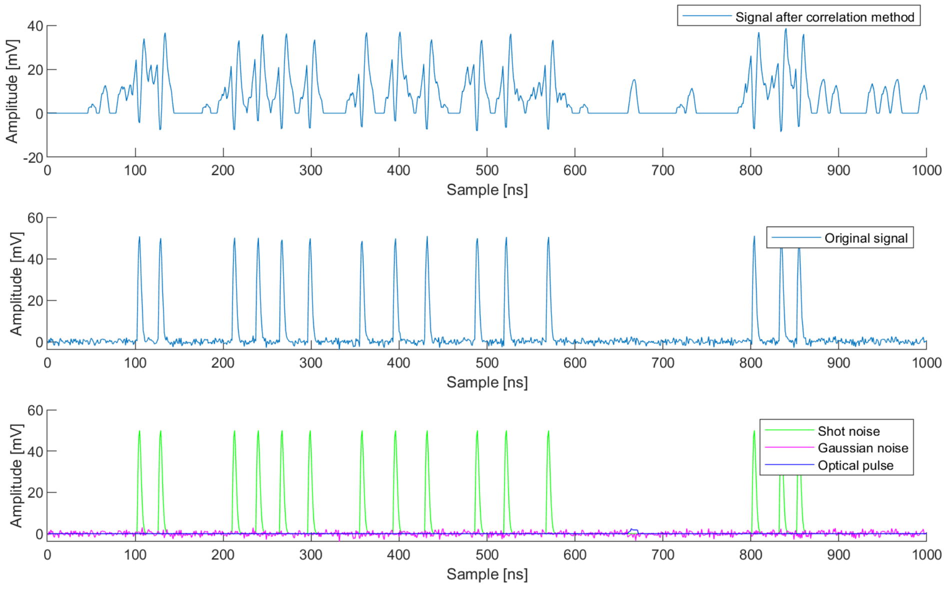

Figure B.6: The signal after correlation method, the original signal and signal segments for test case 6.

B.3 Results

Based on the simulations in Section B.2, it seems like by using the correlation method, it is possible to detect even smaller optical pulses than the method used in Section 5.1. When using the correlation method the smallest optical pulses that can be detected had a pulse amplitude of 2.5 mV and were 9 ns in pulse width. This is an increase in detection sensitivity of the optical pulse amplitude with 37,5 mV compared to the analog detection method, which corresponds to 12.04 dB. The correlation method does not seem to be filtering out false alarms as well as the method used in Section 5.1, since the false alarm rate is higher for all test cases. When comparing test case 5 for both methods, the detections for larger optical pulses seem to be lower as well.

B.3.1 Time Estimation

In Table B.2, the times for the correlation method simulation in Section B.2 are presented. The time is only measured for the correlation method, not for the simulation of the signal, other signal filtering, detection method, etc. The method used is the same as for the other time estimations and described in Section 4.8.

Table B.2: Time measures for the correlation method.

Average time [ms]	3.1
Median time [ms]	1.3
Maximum time [ms]	10
Minimum time [ms]	1.1
Average CPU time [ms]	9.37
Median CPU time [ms]	0
Maximum CPU time [ms]	63
Minimum CPU time [ms]	0

B.4 Discussion

The results in Section B.3 are slightly difficult to use and put into context. When analyzing the method step by step in Section B.1, the method can be seen to use the top half of the peaks to determine detection. Therefore, for detection to work properly, the optical pulses need to be small in amplitude since this affects the top of the peak less when taking the difference. Respectively, the shot noise pulses need to be large in amplitude so the top of the peak is interrupted. Considering this, the results make sense.

When conducting the simulations in Section B.2, the detection statics were unstable. This might be due to drawbacks in the method which gives a nonrobust system.

In Section 7.4, an analysis is presented of how the correlation method can be used in parallel to the system used in Section 5.1, as well as how the correlation method would need to be developed to be improved and work for a wider range of signals.

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