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Characterization of a commercial LIDAR module for use in camera triggering system

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Title: Characterization of a commercial LIDAR-module for use in camera triggering system

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Problem statement

The objective of this thesis is to evaluate how suitable Leddar M16 modules is for detecting vehicles in a roadside electronic toll collection system. Performance of this module is assessed against existing equipment used in Q-Free's systems today. In its simplest form the purpose is to detect vehicles to trig a camera that capture the vehicle number plate. Hence the surveys will be conducted to assess the sensors ability to detect objects passing a cross-section of the road and how it is affected by factors such as:

- Sensor configuration.
- Vehicle speed.
- Vehicle variations in terms of surface, shape and size.
- Weather conditions.
- Multiple passing vehicles at a time.

This thesis is a continuation of the specialization project conducted autumn 2017. Here the mounting tilt angle and sensor configuration was investigated as test factors which influence the ability to detect vehicles.

To complete this objective the student should:

1. Develop a model for collecting data from the modules.
2. Design experimental tests to investigate test factors.
3. Collect data trough conducting planned tests.
4. Analyze and conclude on the data and present relevant results.
5. Assess the sensor performance and suggest possible use and/or further testing.

Supervisory professor: Tor Engebret Onshus

Abstract

Light based time of flight sensors have seen a rapid development from traditional rotating lidar sensors in the recent years. Lower price, smaller form-factor and increased robustness trough solid-state are key factors for the new modules entering the commercial marked. The development is largely driven by the work of partly and fully autonomous vehicles which require sensors to map the surroundings. This development bring new areas of use and this project regards possible use of a commercial available lidar-module in a electronic toll collection system.

Multiple techniques exist for detecting, tracking and classifying vehicles in tolling applications today. Where Q-Free use multiple traditional lidar-modules to perform these tasks. If one or more of these tasks could be performed by a new smaller lidar-module, a cost reduction and simplification of the system could be obtained. A central goal is being able to implement the new lidar-module into an existing housing together with the OCR camera. This would reduce the need for housings, cabling, brackets, power supplies etc. and would reduce the complexity and cost of the system.

The lidar units used is the Leddar M16 modules from LeddarTech, where both the laser and LED version are investigated. These modules was installed in a gantry at the Q-Free test track at Lånke where all data collection and testing was performed. The project objective is to test and characterize the Leddar-modules for detecting passing vehicles, with the purpose of triggering a OCR camera that capture the number plate. This characterization is divided into five tests; sensor configuration, vehicle variation, vehicle speed, weather conditions and multiple close driving vehicles. These tests forms the basis for evaluating the sensor trough post processing and analysis of the collected data. The factors are investigated to see how they affect the sensors ability to operate in the desired way.

Sensor configuration was investigated to find the optimal sensor settings. This test was a tradeoff between CPU load and refresh rate which was highly affected by the two sensor parameters accumulations and oversampling. Variations of vehicles is a factor a triggering sensor must handle. Hence a selection of vehicles in different form, size and color was used to see how the module responded. Vehicle speed is another central factor. This is known to influence the point cloud since time inside the sensor FoV is influenced by the vehicle velocity. Weather testing was performed to investigate limited visibility problematics and saturation of the sensor receiver lens. These are well known problems for optical time-of-flight sensors. Multiple close driving vehicles challenge sensor resolution. This ability to separate multiple objects is tested both vertical and horizontal. Hence both queue and side-by-side scenarios was investigated.

Trough these tests it is concluded that both a M16-LSR and M16-LED could be used for triggering purposes. But, the FoV size of the tested M16-LSR unit is found to be too small. A larger FoV is believed to be positive for retrieving more stable and consistent data.

Sammendrag

De senere årene har lysbaserte time-of-flight sensorer for deteksjon av objekter og avstandsmåling sett en rivende utvikling sammenlignet med tradisjonelle lidar-sensorer. Lavere pris, mindre formfaktor og økt robusthet gjennom solid-state er nøkkelfaktorer for de nye modulene som i disse dager entrer det kommersielle markedet. Utviklingen av autonome kjøretøy, som krever kartlegging av omgivelsene, er en viktig teknologidriver for disse nye modulene. Dette gir nye bruksområder, og oppgaven ser på mulighetene for å benytte en kommersielt tilgjengelig lidar-modul i en bomring.

Det finnes flere teknikker for å detektere, spore og klassifisere kjøretøy i dagens bomringer. Her benytter Q-Free flere tradisjonelle laser skannere for å utføre disse oppgavene. Hvis en eller flere av disse oppgavene kan utføres av de nye lidar-modulene kan man oppnå en vesentlig kostnadsreduksjon og forenkling av dagens bomsystemer. Et sentralt mål er å kunne implementere de nye modulene i en eksisterende kapsling sammen om kameraet som leser bilskiltene. Dette vil redusere behovet for kapslinger, kabler, braketter, strømforsyninger etc. og vil redusere kompleksiteten og prisen på systemet.

Lidar-enhetene som er benyttet i dette prosjektet er Leddar M16-modulene fra LeddarTech, hvor både laser og LED versjoner er testet. Disse modulene ble installert i et gantry på testbanen til Q-Free på Lånke, hvor all datainnsamling og testing ble utført. Prosjektets mål er å teste og karakterisere Leddar-modulene for å detektere passerende kjøretøy, med det formål å utløse et OCR-kamera som fanger nummerplaten. Denne karakteriseringen er delt inn i fem tester; sensor konfigurasjon, variasjon av kjøretøy, kjøretøyhastighet, værforhold og nært kjørende kjøretøy. Disse testene danner grunnlaget for å evaluere sensorens ytelse gjennom behandling og analyse av de innsamlede dataene. Faktorene undersøkes for å se hvordan de påvirker sensorens evne til å operere på ønsket måte.

Sensor Konfigurasjon testen ble utført for å finne de optimale sensorinnstillingene. Denne testen var en avveining mellom CPU-belastning og målefrekvens, som igjen er sterkt avhengig av de to sensorparameterne accumulations og oversampling. Variasjon av kjøretøy er en faktor som en trigger sensor må håndtere. Derfor ble et utvalg av kjøretøy i forskjellig form, størrelse og farge brukt for å se hvordan sensoren håndterte dette. Kjøretøyets hastighet er en annen sentral faktor. Dette vet man påvirker punktskyen siden kjøretøyets hastighet henger sammen med kjøretøyets tid inne i sensorens synsfelt. Værtesting ble utført for undersøke ytelse i begrenset sikt og metning av linse problematikk. Dette er velkjente utfordringer for optiske time-of-flight sensorer. Flere nærtkjørende kjøretøy utfordrer sensorens oppløsning. Denne evnen til å skille flere objekter ble testet både vertikalt og horisontalt. Derfor ble både kø og side om side situasjoner testet.

Gjennom disse fem testene konkluderes det med at både en M16-LSR og M16-LED kan brukes som trigger. Men, størrelsen på synsfeltet til den testede M16-LSR enheten er funnet å være for liten. Et større synsfelt antas å være positivt for mer stabil og konsistent data.

Conclusion

Work and results in relation to the five tests performed lay the foundation for this conclusion. The configuration test investigated how different settings affected the sensor. Four setting combinations of accumulations and oversampling was tested. These four combinations gave the desired refresh rate of 100Hz. The only setting that clearly can be excluded due to high CPU load and hence a decreasing and noisy refresh rate was 4 accumulations and 8 oversampling. It is concluded that the remaining setting combinations could work while using the sensor for triggering purposes. These are the combinations 8/4, 16/2 and 32/1 (accumulations/oversampling). In general it seems that lower oversampling values result in a lower amplitude and hence possibly more noise. Due to this, 8/4 was chosen as the main setting for the remaining tests but the two other combinations should not be excluded if the sensor were to be implemented into a toll system. This since all three settings seems to have no significant impact on whether the sensor can be used for triggering or not.

Vehicle variation test was performed to investigate how different types of vehicles influence the sensor performance. The results indicate that vehicles with high reflective capabilities resulted in a very high amplitude which again made the sensor reduce the emitted light intensity and hence lose detection of low reflective targets. The loss of detection points was mainly from the road and it is concluded that these sample should not be necessary in an operating toll system. If one get road detections while installing the system at site one should be able to tune the system to trig on point clouds that exceeds a given threshold. When comparing the two tested modules, the LED-module would work best since the measurements is more stable and consistent for all vehicles. The data samples for the front part of the vehicle look very similar independent of which vehicle is detected. This is believed to be positive for an triggering algorithm. Why the LED-module data is more stable is most likely due to the FoV size difference between the two tested modules. Since the LED have a larger FoV the averaging processing performed by the Leddar technology have a larger surface on the objects to retrieve measurements from. The module then becomes more robust to specular reflection, for instant, than the laser with the smaller FoV. Hence it can be concluded that a $0.2°$ vertical extension of the FoV is too small for sufficient triggering performance. The LED-module has in comparison a $8°$ vertical FoV extension.

Speed of vehicles influence the number of samples in the point cloud since the vehicles time inside the FoV decreases as the speed increases. This was clearly seen in the test data but otherwise there was no indications of the Leddar modules being affected by the tested speeds. 60km/h was the highest speed tested and when investigating the data for this one saw that quite a small number of data points would be returned at higher speeds. Considering that some data points are lost due for example specular reflection problematics, the small size on the M16-LSR module is not considered sufficient for the module to operate as desired. Hence another factor votes for a larger vertical FoV.

Weather bring various challenges to optical time of flight sensors. Limited sight through rain, snow and fog is a classic problem for light based measuring. The sensors was tested in heavy snowfall which did not affect the sensor measurements significantly. Hence the stated robustness of the Leddar sensors can be confirmed for snow and most probably for rain. Limited sight trough fog is recommended to be tested since this differ from rain an snow by its being denser and more evenly distributed. The sun could cause other challenges related to reflections and saturation of the detector. It is concluded that the combination of rain/wet surfaces and sun increase the specular reflection problematics both on vehicle and road. Still, the problem was not so big that the sensors did not manage to detect objects passing the gantry. The sensor is concluded to handle the tested weather factors sufficiently for triggering.

Multiple close driving vehicles passing the toll site was expected to bring the most challenging scenarios for the Leddar-modules to handle. Results from the queue testing was surprisingly good. A gap of two meters between the vehicles gave no problem for the sensors to separate as two objects. This was the closest gap tested and is regarded as quite close in an slow driving queue situation. Results from the side-by-side testing was also fairly good where the scooter and van was driven past the gantry with about a one meter gap. Considering that the Leddar-modules only has 16 segments covering the road width, separation of the vehicles should be possible with the data from the test. Due to the results seen from both the queue and side-by-side testing it seems that the M16-modules has sufficient performance from triggering when regarding multiple close driving vehicles.

The housing where the Leddar sensors was installed during the testing had a polycarbonate window for the sensor to see the road. Although the sensors was mounted close to this window and a separating piece was used to prevent the sensors to interfere with each other, both modules retrieved detections form the glass. LeddarTech state that this might lower the sensor performance since the modules must use resources to process these detections. Hence, better performance may be expected. In worst case the performance should be the same. Anti-reflex treatment of the glass can provide improved transmission of the light and thus a better signal. This is discovered in tests performed by LeddarTech.

Overall conclusion of the results and considerations from this project is that both the M16-LED and M16-LSR module could work as a trigger. For the M16-LSR a larger FoV than the tested unit is recommended. When it comes to tracking and classification with Leddar sensors it is concluded that it is best to await for a module with a larger detection matrix than 1x16. It is stated that this is under development at LeddarTech.

Preface

The basis for this project stemmed from a summer internship at Q-Free ASA and the specialization project conducted during the semester autumn 2017. In a cooperation with Q-Free an appropriate project was modeled to fit the master thesis TTK4900 and Q-Free's interest within new time of flight technology that is commercially available. Present report represent the work done in TTK4900 which constitutes 30 credits. The intended audience is the external examiner, as well as Q-Free or other that have some extent of general technical understanding and interest.

The specialization project TTK4551 is a mandatory course of 7.5 credits conducted at the last year of the masters degree within Cybernetics and Robotics at NTNU. This project had the same overall objective only with a smaller scope and other sensor models. Relevant work done in the specialization project is referred to and cited in this report. Larger sourced sections is clearly marked in the beginning of the section.

I appreciate excellent guidance from Jon Honne at Q-Free and Tor Engebret Onshus at NTNU, throughout the whole project. In addition, I would also like to thank Alexandre Desjardins at LeddarTech for answering all my questions regarding the Leddar sensors. At last I want to thank Q-Free very much for a fun project and all facilitation.

Børge Godejord
Trondheim, June 2018

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Abbreviations

ToF	=	Time of Flight
LiDAR	=	Light Detection and Ranging
LEDDAR	=	Light Emitting Diode Detection and Ranging
OCR	=	Optical Character Recognition
FoV	=	Field of View
IP	=	Intellectual Property (or; Internet Protocol)
IC	=	Integrated Circuit
MCU	=	Micro Controller Unit
ADC	=	Analog to Digital Converter
UV	=	Ultraviolet
OBU	=	On-Board Unit
USB	=	Universal Serial Bus
RMSE	=	Root Mean Square Error
SD	=	Standard Deviation
ETC	=	Electronic Toll Collection
R&D	=	Research and Development
MEMS	=	Micro-Electro-Mechanical Systems
NAF	=	Norwegian Automobile Federation
FWHM	=	Full Width Half Maximum
OS	=	Operating System
SSH	=	Secure Shell
HTTP	=	Hypertext Transfer Protocol

- The shortening LiDAR can be written in many ways. Lidar and lidar is commonly used in technical reports hence also in this paper.

Chapter 1

Introduction

The introduction chapter discloses motivation and background information for the project followed by scope and objective. Chapter outline for this report is found at the end.

1.1 Motivation

The work on autonomous cars is an important technology driver in the development of sensors for detecting objects and measure distance. Lidar technology is one of the areas where we have seen a rapid development in recent years. This has led the price and form factor of lidar-modules to a level that makes them relevant for other applications than the traditional area of use. Q-Free uses various techniques for detection, tracking and classification of vehicles in applications such as tolling and parking. In tolling traditional lidar-modules are commonly used to perform several of these tasks and hence multiple units are used at a single installation site. If one or more of these tasks can be carried out with a smaller and cheaper lidar-module one can look at a cost reduction and simplification of the system that makes it worth to implement the new modules in future tolling systems. The key here is integration of the new modules together with existing products. This will give cost reduction in form of:[1]

- Less need for power supplies, housings, brackets and corresponding material.
- Lower power consumption.
- Less and easier maintenance as a result of less cable connections, housings etc.
- Less work hours for setting up system at site.

Lower unit prize on the new module contra existing sensors would be another cost saving. This cost reduction would most likely be less than the total saving from the listed bullet points above. On the other hand work hours on software implementation would be a extra cost if to implement the new module into existing ETC solutions.

The request for lidar technology has lead many actors to invest and many companies are working heavily with R&D on the technology. Lidar has in fact emerged as a key technology theme at the Consumer Electronics Show taking place in Las Vegas early January each year. AEye, Innoviz, LeddarTech, Luminar, Valeo, Quanergy, TetraVue, and Velodyne are among the lidar companies presenting their latest visions of technology.[2] Among the many ideas and great visions are the California startup Luminar Technology which has the ambitious goal of delivering a module with 40 times the laser power, 10 times the range and 50 times the resolution compared to the most advanced lidar sensors deployed in vehicles today.[3] This is one example that paints a picture of the ambitious work that goes on with lidar and the quest towards autonomous cars. Still the general tendency is that most of the firms are showcasing and that the present of commercially available modules with the most cutting edge technology are not launched yet. It has already been worked on this optical technology leap for several years and one of the first here has been the Canadian firm LeddarTech which was founded in 2007 as a successful spin-off of Canada's leading optics and photonics research institute (INO). They are one of few that offers commercial available solid-state lidar-modules and are one of the leading within optical detection and ranging technology. [4]

LeddarTech has named their technology and sensors for LEDDAR which is an abbreviation for Light Emitting Diode Detection and Ranging. This technology is covered by 58 patents and the main essence is solid-state lidar-modules which differs from the traditional mechanical scanning lidar with both pros and cons. The idea behind development of solid-state lidars is to improve the cost, size, reliability and complexity issues of mechanical scanning lidars. [5] By utilizing MEMS technology the solid-state Leddar have no mechanical moving parts. Some of the claimed benefits compared to competing technology are; [6]

- High range-to-power ratio.
- No moving parts, providing robustness.
- Wide operating temperature range.
- Immune to ambient light variations.
- Good performance in low-visibility conditions.
- Ability to resolve multiple targets with a single detector element.
- Small form factor.
- Affordable unit cost.

Due to LeddarTech's experience, expertise and commercial available sensors it is the Leddar M16 modules which is classified in this project. Previous testing performed during the specialization project was with the Leddar M16 LED module where both the 24 and 34 degree lens option was used. Now its also desirable to look at a laser module to see which eventual differences the smaller vertical FoV brings. Here it is the Leddar M16-LSR with $36°$x$0.2°$ lens option that is chosen. If this is implemented into the same housing as the OCR camera, the FoV for the Leddar would be about 5 degrees wider than the OCR cameras FoV. Pan adjustment of the OCR camera is in addition 2.5 degrees. Hence the 36°x0.2° is believed to be the best fit for the intended use. In addition the laser module is a bit smaller than the M16-LED modules and will be easier to fit into the existing OCR camera housing. The M16 modules from LeddarTech offers an acceptable mix of performance, price, and size, and it is commercially available off the shelf. Hence the M16 was the chosen model to test. More detailed information about the Leddar-module and technology is presented in chapter 2.4.

Achieving maximum cost gain would be to use Leddar modules for both detection, tracking and classification of vehicles and hence exchange all the traditional laser scanners in todays systems. By ranking the difficulty of implementing a Leddar module to work sufficiently on these tasks it is supposed that detection of vehicles for triggering a OCR camera would be easiest to achieve. To do this it is imagined that the best way is by mounting the sensor to cover a cross-section of the road with its FoV. This is also how it was done in the specialization project. Tracking and classification with the Leddar is assumed to be harder to achieve, then especially classification since this would require quite accurate measurements of the vehicle width, height and length in any speeds. However, mounting the Leddar module for tracking and classification could be done by aligning the FoV width along the road and this way exploit the whole FoV for covering road around the gantry. One know other installations where there are made use of road-side poles, multiple gantry and such for mounting gear belonging to a tolling system, but as the aesthetic requirements to ETC systems constantly gets stricter the only topical way of mounting gear is in a single gantry. Figure 1.1 illustrates thought ways of mounting the sensor module in a single gantry system. Some basics about a Q-Free ETC system is presented in section 2.5 which should help understanding the whole context. With the assumptions around difficulty of sensor tasks, a natural starting point for this thesis is to investigate detection to trig a OCR camera. If this turns out to be straight forward there are numerous expansions in connection with tracking and classification.

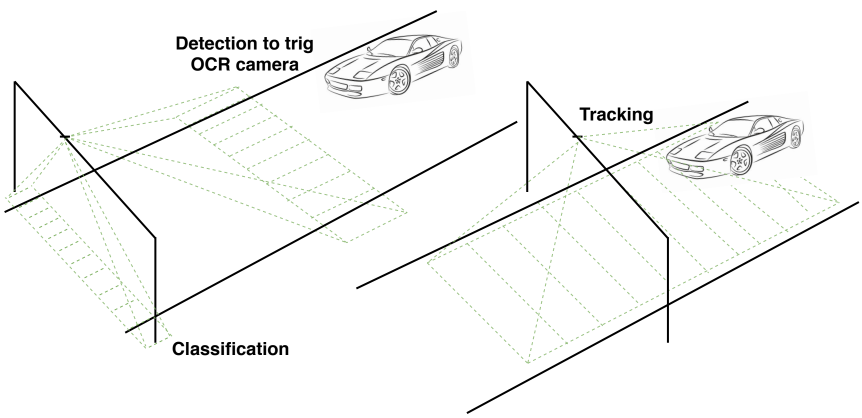

Figure 1.1: Sketch illustrating imagined ways of mounting sensor in gantry.

In the following section one find problem statement and scope of the project. Here is a concretized formulation of the objective followed by a section giving some understanding of the chosen test factors.

1.2 Scope and objective

The goal of this project is to evaluate how suitable Leddar M16 modules is for detecting vehicles in a single gantry ETC system. Performance of the modules shall be characterized trough experimental testing in full scale and results are assessed against existing tolling system-solutions. In its simplest form the purpose is to detect vehicles that approaches the gantry, for then to trig a OCR camera that captures the vehicle number plate. Hence the surveys will be conducted to assess the sensors ability to detect an object (vehicle) passing a cross-section of the road and how it is affected by factors such as:

- Sensor configuration.
- Vehicle speed.
- Vehicle variations in terms of surface, shape and size.
- Weather conditions.
- Multiple passing vehicles at a time.

These factors, in addition to those already worked on in the preliminary project, are assumed to be most central for the sensors performance for detection and ranging of vehicles at a tolling site. Sensor configuration of Leddar M16 modules and mounting angle are factors investigated in the specialization project. Regarding the sensor configuration, two acquisition settings requires retesting due to difference in a parameter caused by the change of light source from LED to laser. In addition some research on vehicle speed was performed earlier but further testing is recommended. All these factors are to be taken into consideration when evaluating the module performance.

The featured factors are chosen on the basis of both theoretical knowledge and practical experience. A lidar sensor use light for measuring distance and hence optics emerges as central for research on the Leddar modules. This branch within physics involves the behavior and properties of light and the most relevant parts and phenomenas for this project is presented in chapter 2. The fact that light reflects from objects it hits make size, shape and speed of the object interesting factors to investigate. Q-Free holds many years of experience within the field of tolling and this practical experience is benefited from when testing and characterizing the Leddar modules. Situations with close driving vehicles is known to bring greater challenge to tolling system than one single passing vehicle. Slow driving queue is in fact one of the most challenging scenarios for a tolling system. Hence this is regarded as the greatest challenge for the Leddar-modules. Another well known challenge occurs with fog, rain and snow where emitted light from the sensor reflects of particles in the FoV. The weather also bring another challenge through the sun. This large source of light emits a wide spectrum of light and could also interfere the module.

1.3 Chapter outline

This paper differs from standard technical reports since each performed test has their own discussion and conclusion. Summary and conclusion for the whole project is found on the first pages of the report together with a problem statement. The main part of this paper starts with some relevant theory in chapter 2 followed by the model developed for collecting data in chapter 3. Design, analysis and discussion for the different surveys is found in the following chapters. These independent test chapters should ease reading and understanding of each test. Test chapters contain three subsections which discloses:

1. Experimental Design and Execution
    - Design of the test and its desired factors to investigate. Execution and other relevant factors is also documented here.
2. Analysis
    - Data is presented trough relevant plots and these are explained.
3. Discussion and results
    - Discussion and conclusion around results and findings in the tests.

In chapter 9 one find further work and other possible scenarios which is desirable to investigate further. Material belonging to the project such as code and data files is found in an zip-file.

Chapter 2

Theory

Since lidar uses light for sensing some basic theory about light and relevant phenomenons is presented in this chapter. Further some theory on lidar, Leddar and a brief introduction to tolling systems is given.

2.1 Light

(This section is sourced from my specialization project report. [1])

Electromagnetic radiation form the infrared spectrum is commonly referred to as infrared light. This light has longer wavelength than the visible light waves. Wavelengths of IR light spans from the edge of visible spectrum at 700nm to the edge of microwaves at 1mm as seen in figure 2.1. The Leddar laser sensor in this project uses IR light with a wavelength of 905nm. This is a eye safe laser, IEC 60825-1: 2014 (class 1), and no protective equipment is needed. [7]

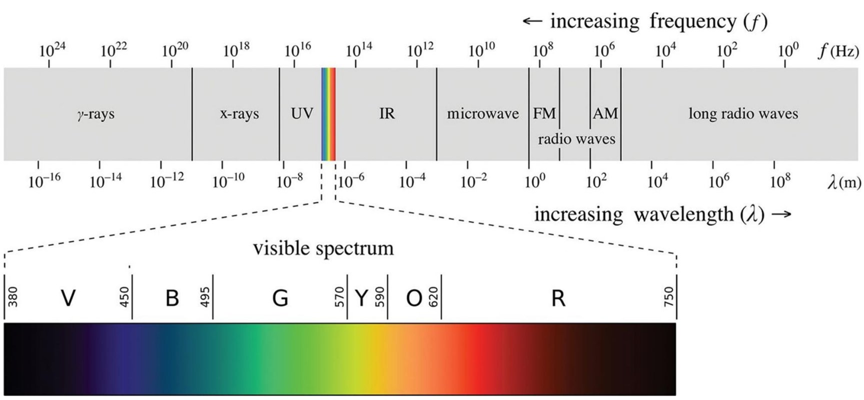

Figure 2.1: Electromagnetic spectrum

2.2 Reflection of light

(This section is sourced from my specialization project report. [1])

Reflection of light is either in form of diffuse or specular reflection [8]. To get a simple understanding of this one can think of diffuse reflection when the incident ray, for example a laser, is reflected in many different direction from the surface. While specular reflection is when the angle of the incident ray relative to a perpendicular line to the surface is same as for the reflected ray relative to the same perpendicular line. In figure 2.2 these two types of light reflection is illustrated. Reflection from a mirror is a common example when illustrating specular reflection. A mirror consists of metal and glass where the metal is where the reflection occurs. Specular reflection can also occur at the surface of transparent medium such as glass or water [9]. Many vehicles has a exterior with a large occurrence of metal and glass. Specular reflection is hence a highly relevant phenomenon in correlation with use of lidar in a tolling system.

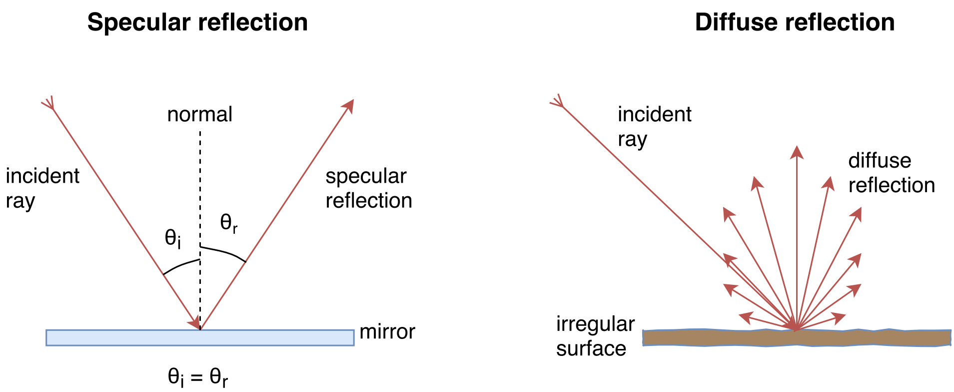

Figure 2.2: Sketch illustrating specular and diffuse reflection.

There are three possible outcomes when light hits a material. The light can be absorbed in the material, it may be transmitted through or it can reflect. Most commonly a mix of these behaviors occurs for many materials. And here reflection most often is a mix of specular and diffuse reflection. Variables that influence this is the angle of incident light, wavelength of the light and properties of the material [10]. For the sensor characterized in this survey the wavelength is set. The sensor tilt angle, that has a direct connection with incident light angle, and the different material properties of the passing vehicles is factors that affect sensor performance related to tolling. Material properties that can be controlled is mainly color of the vehicles together with a roughly estimate of the structure of vehicles. Darker colored objects absorbs more incident light energy from the visible and UV spectrum than white. White is in the other end of the scale and reflects light very well [11]. This is not the rule for IR light where a combination of other factor plays a role unlike for visible and UV light. Still, darker colors most often gives a higher absorption of IR light in practice. Hence dark vehicles is probably preferred if to challenge the sensor on low amplitude.

Another phenomenon that can occur on a vehicle is total internal reflection. This is when the light is trapped inside a medium due to repeatedly specular reflections as figure 2.3 illustrates [9]. Hence this is sort of a special case of specular reflection. It is imaginable that this phenomenon can occur in the windshield or in the sunroof on a car and prevent emitted light from reaching back to the receiver on a lidar-module.

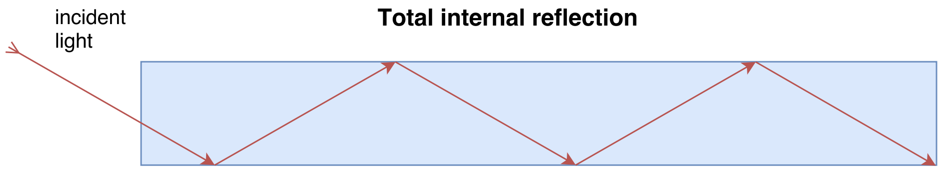

Figure 2.3: Sketch illustrating total internal reflection.

2.3 LiDAR

(This section is sourced from my specialization project report. [1])

LiDAR is the acronym for Light Detection and Ranging and all lidar systems is a remote sensing technology that uses the time of flight principle. Optical ToF sensing is done by measuring the round trip time of light pulses traveling between the sensor and an object. With this time and the speed of light, the distance to an object can be calculated. The speed of light is significantly larger than the speed of the measured objects, in addition the speed of light changes very little over normal temperature and in pressure extremes. Hence optical ToF sensing is one of the most reliable and accurate ways of contactless distance measurement. Optical ToF sensing can be categorized as; direct ToF, range gated imaging and phase detection. Here the direct ToF method is what the Leddar is based on. With direct ToF a discrete pulse is emitted while at least one timer measure the time it takes the echo to return to the receiver. With this time (t) and speed of light ($C = 299,792,458m/s$ in vacuum) the distance can be calculated with equation 2.1. Division by 2 is because the light travels form the sensor via the object and back again. [6]

$$d = \frac{C \cdot t}{2} \tag{2.1}$$

In figure 2.4 a sketch of the fundamental principle for direct ToF sensing is shown. The emitted light is pulsed so the sensor know when the correct echo is received and the sensor can figure out when to stop the timer.

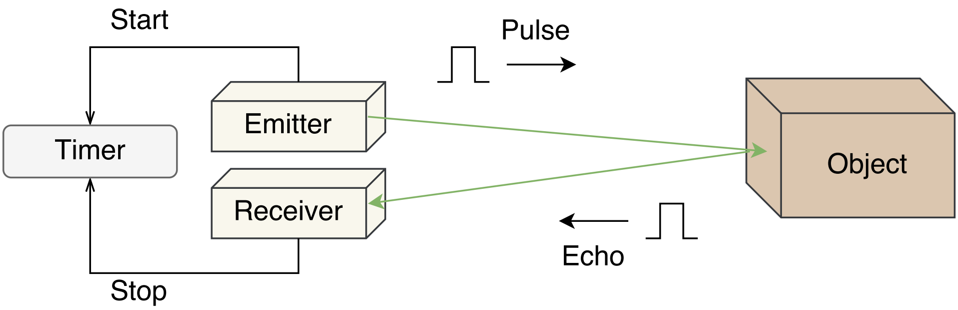

Figure 2.4: Fundamental principle for direct ToF sensing.

2.4 LEDDAR

The Leddar sensing technology is based on direct optical ToF technology. In contrast to traditional direct ToF the Leddar sensing technology does not work directly on the analog signal. Instead the Leddar sensing technology is based on first to sample the received echo for the whole detection range of the sensor. Then sampling rate and resolution of the signal is expanded iteratively before finally the resulting discrete signal can be analyzed and the distance to objects can be extracted. Figure 2.5 shows an intuitive illustration of the Leddar sensing technology. The LeddarCore sequence emitted IR light and this is reflected from objects that is in the illuminated area. Light which is reflected in the FoV, which is set by the lens option, reach the receiver. Further data acquisition is preformed in correspondence with the sequencing to distinguish emitted light from ambient light. The LeddarCore also process the signal further before distance and amplitude is received. Parts of the Leddar technology is explained in more depth later.

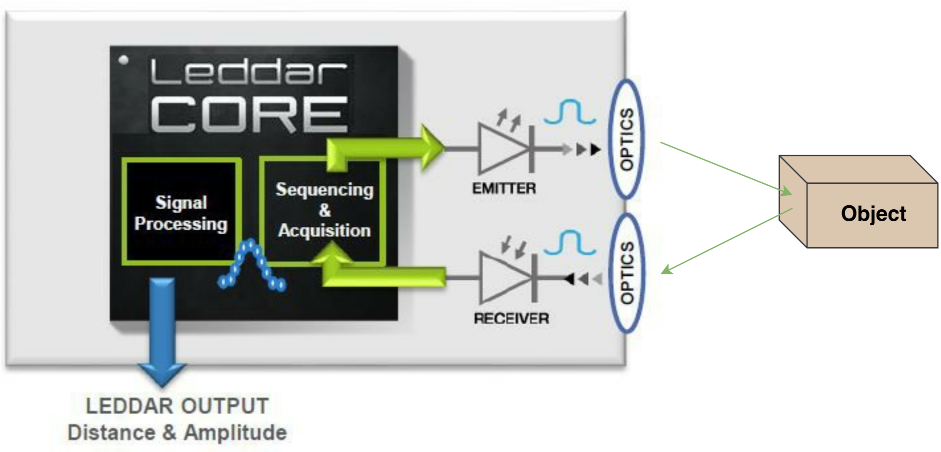

Figure 2.5: Leddar sensor technology. [5]

As mentioned, it is the Leddar M16-LSR 36 degree module that is the newly acquired unit and hence it is the main unit to investigate during this master project. Leddar M16-LED modules that has previously been purchased came with the Leddar Development Kit that enables efficient performance evaluation of the Leddar technology. The kit provides software and code examples to help getting started to use the sensor. Leddar Configurator is the software for Windows that came with the kit. This enables, among other things, to set acquisition settings, view raw detection and log data to *.txt* or a binary *.ltl* file. While this software was used during the specialization project it is now desirable to mover over to Linux and communicate with the sensor trough a terminal based program written in C. Libraries and such needed to interface with the sensor this way is also available and the program can be modified to best fit the test model for fast, efficient and easy data acquisition. More about the test model is found in chapter 3.

In figure 2.6 the sensor module itself is seen. Here one observe the class 1 laser that forms the emission optics and the 36 degree lens optics as constitutes the reception optics. In addition the USB interface seen is the communication link that is used. Not visible in this image is the terminal block connector that provides the possibility for RS485 or CAN bus communication, but this is not relevant before reaching closer to the point of implementing the sensor in a operating tolling system. Connection for power supply is also located on this block where the supply voltage between 10-30V DC are to be connected.[12]

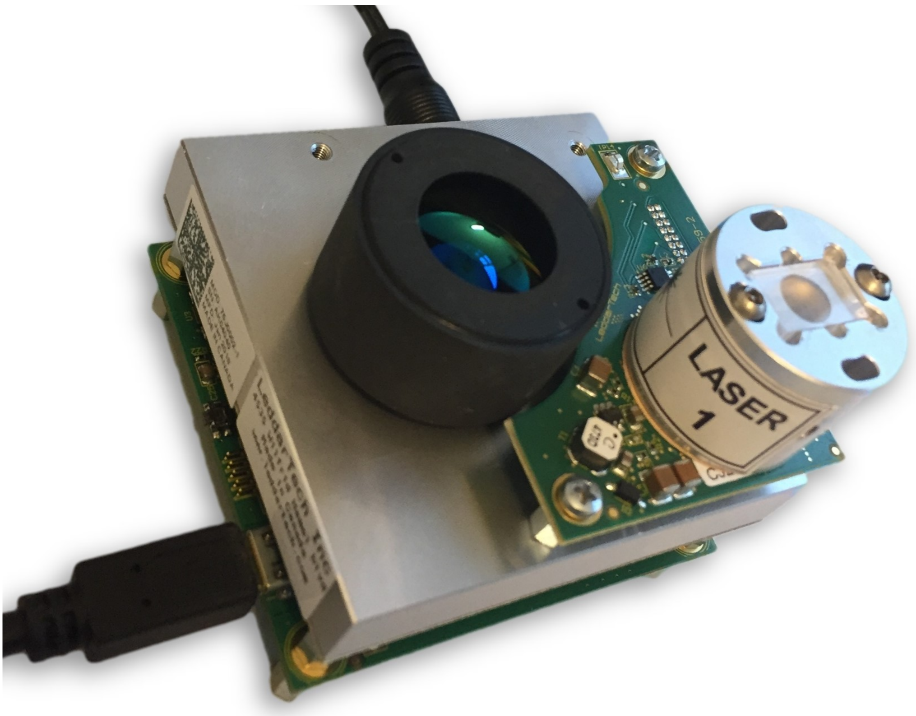

Figure 2.6: Leddar sensor technology.

To get a brief overview of the sensor structure a working diagram from the user guide is displayed in figure 2.7. This illustrates how some of the central components of the sensor interact. The sensor is built up from a receiver, source and control assembly part. In the receiver part, the photodetector array that converts the light pulses into electrical signals and segments the FoV into 16 elements is found together with the controller for the light pulsing and data acquisition. Light pulsing is controlled here since it has to be synchronized with the receiver data acquisition. The MCU is located at the control assembly part. This recovers the waveforms generated by the receiver assembly, preforms full waveform analysis, and generates the data. The data can then be transfered from the sensor via USB, CAN bus or RS-485 as seen in the figure. All external interfaces is located in the control assembly part. Source assembly includes laser, the laser drives and emission optics.[13]

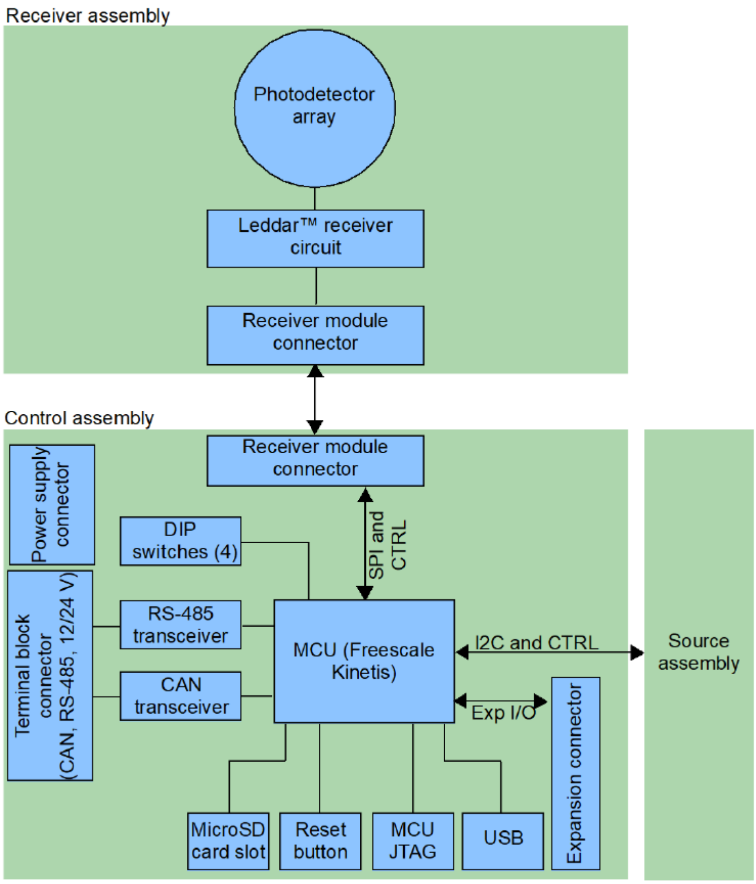

Figure 2.7: Leddar sensor module working diagram. [13]

These parts are build up in a three layer structure which gives an even smaller form factor than the M16-LED modules. As mentioned this is of interest since it would fit the OCR camera housing better. In figure 2.8 one can see the measurements of both the M16 laser and LED module. As one see the laser module has a lower height and instead build more in depth.

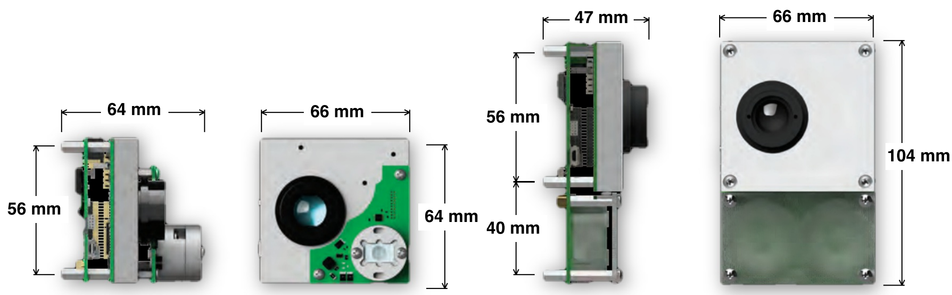

Figure 2.8: Leddar M16 module sizes. [7]

LeddarTech's IP is the LeddarCore which is an IC that handles light sequencing, data acquisition and signal processing. This is a central part of the Leddar module so a basic understanding of this is advantageous when evaluating the test results. The emitted IR light is pulses of 15ns FWHM which is pulsed every 39μs. This pulse width equals 4.5 meters in distance as equation 2.2 show.

$$15ns \cdot C = 1.5 \cdot 10^{-8} \cdot 3.0 \cdot 10^{8} = 4.5m \tag{2.2}$$

On the receiver side there is two ADC's that process signals from two of the segments at a time. The clock speed of these ADC's is 62.5MHz which results in one sample every 4.8 meter in distance.

$$(62.5MHz)^{-1} \cdot C = (62.5 \cdot 10^{6})^{-1} s \cdot 3.0 \cdot 10^{8} m/s = 4.8m \tag{2.3}$$

This would give a poor resolution of the returned echo. Hence LeddarTech has implemented what they refer to as oversampling which together with accumulation is two central features in the Leddar technology. By processing the "same" signal multiple times the resolution of the echo signal is increased. Actually it is not exactly the same echo but time between each collected signal is so small that in practice it is the same. For each time the signal is processed a small time delay, $\Delta\tau$, is added. By merging all these signals more of the echo is displayed. This is the effect that is referred to as oversampling. Maximum oversampling is 8 which correspond to process the "same" signal 8 times as is illustrated in figure 2.9. In these graphs the magnitude of the echo is plotted over distance in meters. On the top graph the red points is what the sensor is able to display of the given echo with oversampling on 1. By drawing a line between these points it would be quite different than the actual echo. Whereas with an oversampling of 8 the echo is displayed with an much higher resolution and the claimed detection accuracy of 5cm should be achieved.[14]

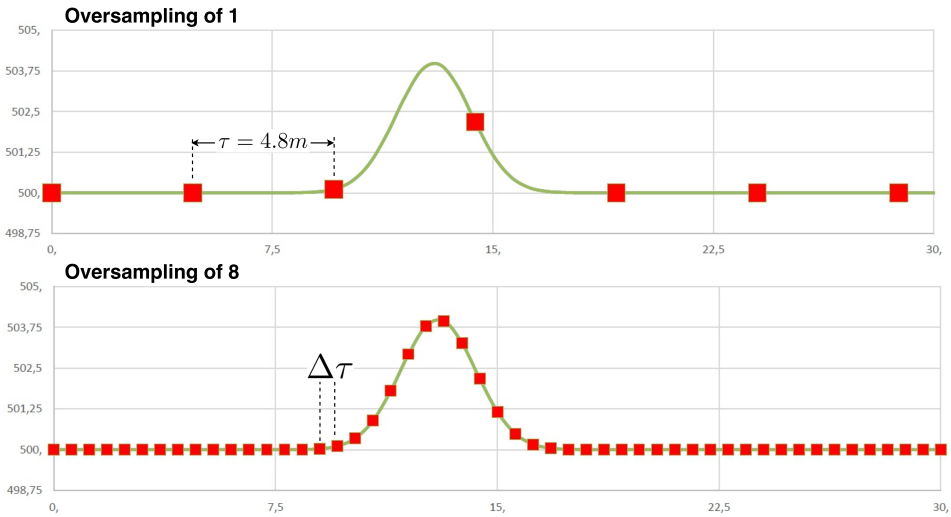

Figure 2.9: Oversampling on echo.[14]

The other central feature is accumulations which reduces white noise. Ambient light causes this noise and accumulations is the feature that LeddarTech claims will make the sensor very robust in all all weather and light conditions. By aggregating a waveform from multiple time series of samples the noise is averaged out [14]. This is seen in figure 2.10 where the signal with an accumulation of 1 is noisy while with 1024 time series aggregated the noise is eliminated.

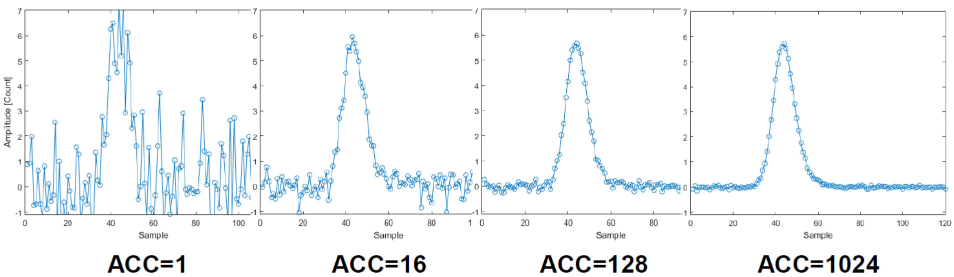

Figure 2.10: Noise canceling effect with accumulation [14].

In addition to oversampling and accumulations there are several digital signal processing algorithms that completes the sensor module. The one of these that is commercially known is explained in chapter 2.4.1.

Trough Leddar technology the M16 sensor is capable of returning up to four measurements in each of the 16 detection segments. These segments is spread horizontally over the sensors FoV as seen in figure 2.11. The 36 degree option is stated to have a beam width of 36° and beam height of 0.2°. By dividing 36° on the 16 segments one get that each segment is $2.25°$ x $0.2°$. A small script is written in Matlab to fast calculate how large the FoV is when projected onto the road, when the sensor is mounted in the gantry. Here sensor mounting tilt and height together with lens option is taken into consideration. In appendix table 9.2 the areas for different lens options is found. Here one see that the laser with only $0.2°$ latitude extension result in an area height on the road between 19-4.5 centimeters for $20°$-$45°$ tilt.

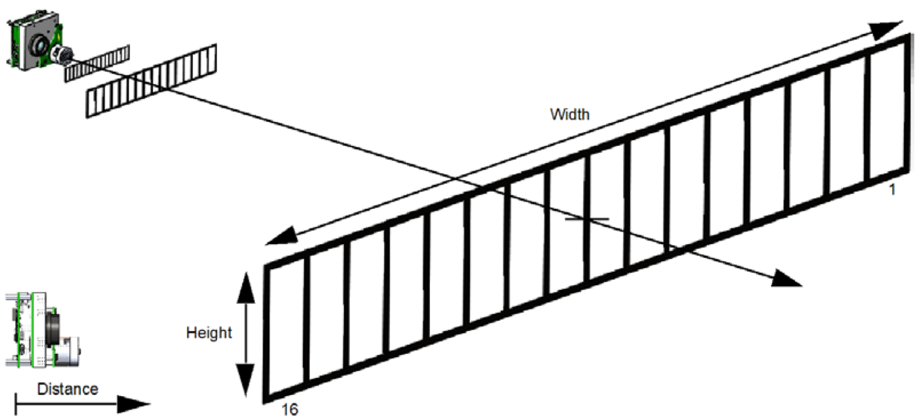

Figure 2.11: Beam pattern width and height [13].

The measurements from the sensor is distance in meters and amplitude that theoretically can be values from 0-1024, however LeddarTech state that signals with amplitude over 512 is unlikely and would only saturate the optics [12]. By running automatic laser control the amplitude values is expected fare below 512. Maximum detection range is also sufficient for the intended use. The data sheet states 20 meters as the lowest range result for the laser module during testing. This is testing performed by LeddarTech where they have used a 20x25cm Kodak Gray Card with 18% reflectivity as reference target. The power consumption, which is an important factor for investigating the Leddar modules, is stated to be less than 4W.[7] In comparison the existing laser scanners used in todays system draws 70W.

2.4.1 Acquisition settings

(This section is sourced from my specialization project report. [1])

The acquisition settings enable the user to define parameters that influences the sensors measurements thought various ways. Values for accumulation and oversampling can for example be set but also values that influence the behavior of different algorithms are set thought these parameters. All the acquisition settings is listed here, table 2.1.

Table 2.1: Acquisition settings [15]

Parameter	Description
Accumulations	Number of accumulations
Oversampling	Number of oversampling
Point Count	Number of base sample points
Threshold Offset	Modifies the detection amplitude threshold
Smoothing	Object smoothing algorithm
Laser Control	Control options for laser power
Change delay	Minimum response time of laser power adjustment
Object demerging	Near-object discrimination
Crosstalk Removal	Inter-channel interference noise removal

Accumulations and oversampling is explained thoroughly in 2.4. The point count parameter determines the maximum detection range and the actual value of the point count parameter most likely has something to do with size of $\Delta\tau$, seen in figure 2.9, which again results in a maximum detection range. Threshold offset is a parameter that through a positive or negative value excludes measurements with too high or too low amplitude and hence can minimize false detections due to noise. The smoothing algorithm can be set to values ranging from -16 to 16 where high values improve precision but reduce reactivity. The algorithm can also be deactivated which will bring the least CPU work load and hence enhance sensor reactivity. LED power control can be set to either automatic or manual. The change delay will influence the response time when set to automatic. Object demerging is an algorithm that can improve the ability to distinguish multiple objects in the same segment. This significantly increases the work load on the microcontroller and can only be activated for low measurement rates. Crosstalk removal is an emission algorithm that randomizes the light pulsing so that multiple sensors can be used with overlapping FoV without crosstalk between sensors. [14][15]

The laser pulses infrared light of 905nm at a frequency of 25.6kHz. This result in a base rate of 3.2kHz after the segment acquisition process. By sampling two segments at a time for all the sixteen detection segments one get the factor of 8. Hence, for each segment the sensor acquires a base input waveform of 3.2kHz. As mentioned, multiple acquisitions are used for accumulations and oversampling to generate the final waveform where the measurement information is found. The final measurement rate is found with equation 2.4 where base rate is the 3.2kHz. [13]

$$Measurementrate = baserate/accumulations/oversampling \tag{2.4}$$

2.5 Tolling

(This section is sourced from my specialization project report. [1])

For increased understanding of how to make use of the Leddar module in ETC system, a brief explanation of a single gantry system is derived in this section. As mentioned, possible tasks for a Leddar could be triggering, tracking and classification of vehicles. Exactly how this should be done is illustrated in figure 2.12. In the first scene the car enters the OCR cameras FoV. A Leddar module should detect the incoming vehicle and trig the camera. This way the camera do not have to process images all the time and continuously scan for vehicle registration plates which is computational heavy. In existing systems it is the front of vehicles that is the interest area when it comes to triggering. This since the region gives the best and most stable reflection of light regardless of vehicle type. Todays OCR cameras is mounted at $30° \pm 10°$ tilt from the horizon and down whit a gantry height of about 6.5 meters. When the front vehicle plate is captured the next task is to track the vehicle. This must be done for linking of all gathered information to the same vehicle. If using a Leddar the module could be mounted perpendicular to the triggering module so the width of the FoV covers the road in driving direction as was seen in figure 1.1. As the vehicle approach the gantry the OBU is read. Next the vehicle passes under the gantry and a laser scanner detect width, height and length. This imposes resolution requirements to the sensor and is expected to be very challenging to do with use of todays Leddar sensors. The last action before the vehicle leaves the tolling system is to capture the rear registration plate.

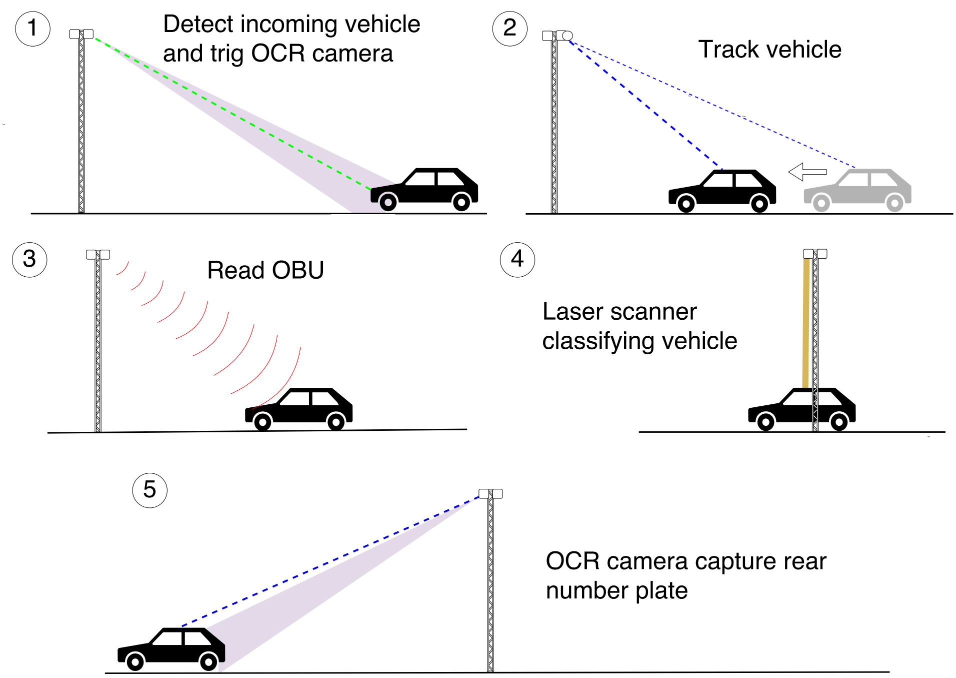

Figure 2.12: Sketch of how a existing single gantry tolling system works.

Chapter 3

Data collection

The model setup, both hardware and software, used during data collection is described in this chapter. In addition a overview image of the test vehicles together with some health and safety points is found here.

3.1 Data collection model

Figure 3.1 show a sketch over how the data collection model is put together.

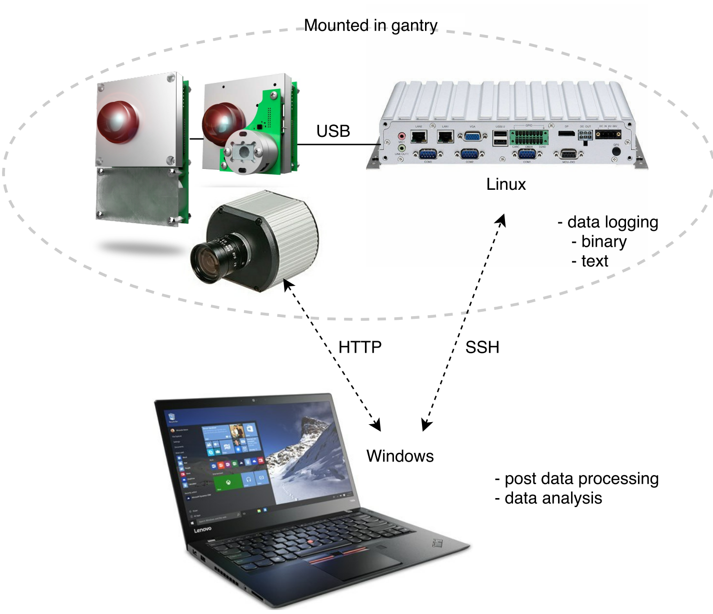

Figure 3.1: Overview of data collection model.

The most central hardware that constitutes the data collecting model consist of Leddar sensors, a camera and an industrial fanless computer. In the specialization project the computer had a Windows 10 OS and the Leddar Configurator software was used to interact with the sensor. This used to much resources and did not work very well. Therefor new software was implemented for this project. A Linux OS is now used where a C-code with command line interface is the new sensor interface. Connection with USB was chosen over the other available bus interfaces due to fast easy use and possibility to retrieve more information from the sensor module. SSH is used to control the Linux computer, over network, from the Windows based laptop. SSH is a cryptographic network protocol that uses little recourses compared to other GUI solutions and it is fast and easy in use. The PuTTy client is a free terminal program for Windows and is used both when controlling the computer and syncing the recorded data files. For fast syncing of data the command is stored in a simple .bat file which is executed when opened. The listing below display the content of the .bat file.[16]

```
pscp -pw password nexcom@10.19.209.3:/home/nexcom/Leddar/data/* "C:\Users\
    borgeg\Documents\40014rLIDAR\data"
```

Listing 3.1: Contetn in sync.bat file.

All data collection is performed at the Q-Free test track at Lånke. This data is recorded to both text files and the binary .ltl files. After the data files is synced to the laptop, Matlab and Leddar Configurator is used for processing and analysis. The IP camera is used to get a reference over what is in the sensor FoV and video is recorded when data is collected. VLC is used to live stream and record video from the camera with HTTP over the network. The local area network is accessible from the head office in Trondheim or at the track itself so video and data can be recorded from both places. This data collection model is found to work quite well besides a few error occurrences in the C-code which is assumed to be caused by the LeddarTech USB drivers. The components mounted in the gantry is encapsulated by a PVC housing and this is mounted in the gantry. Figure 3.2 show the housing and the components inside. In the right image the Leddar M16 LED, Leddar M16-LSR, IP camera and computer is seen inside the housing.

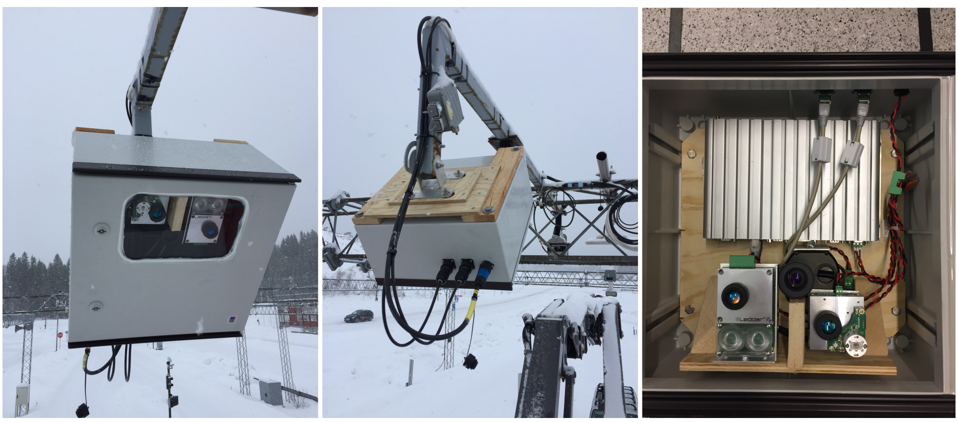

Figure 3.2: Housing mounted in gantry and the components inside.

3.2 Test vehicles

All vehicles used during testing in this project can be seen in image 3.3. These gives variation in size, color and form. The blue station wagon with skibox is a Subaru Legacy and is regarded as a quite normal in terms of detecting it with optical ToF sensors. The black Subaru Forester with auxiliary headlights is on the other hand considered as a challenging object to reflect light on due to color, headlights and sunroof. The van is a Toyota Hiace and the scooter a Yamaha Aerox which gives variation in size.

Figure 3.3: Image off all vehicles used in this project.

3.3 Safety while collecting data

Health and safety is an highly relevant subject while collecting data at the Q-Free test track at Lånke. The track is owned by NAF and many different actors operate at the track to different times. Hence all Q-Free activity must be coordinated to prevent accidents and injuries. A briefing on the regulations was conducted with the Q-Free administrative for the track, and the most important points is listed here.

- Activity at the track is scheduled trough the system Q-Free uses.
- High visibility jackets or vests shall be used when out at the track.
- Follow driving patterns and standards when driving on the track. Take extra precautions to driver training that often takes place at the track.
- Radio is used for fast and seamless communication between drivers and other personnel.
- Use of safety helmets and shoes shall be considered against the type of work.

Chapter 4

Sensor configuration test

Configuration of the sensor has great influence to performance. This chapter describes testing performed to find the best settings for the intended use.

4.1 Experimental design and execution

A sensor configuration test was also performed for the M16 LED-module during the specialization project. But as mentioned the M16 laser-module differs slightly from the LED-module. The difference lies in the light emitting capability the LED has contra the laser. M16 LED-modules pulses at 101.4 KHz compared to the M16 laser that pulses only at 25.6KHz. This is due to the technology itself as a laser is not able to pulse as fast as LEDs mainly due to heat dissipation. This difference affect the measurement rate since the base rate parameter in equation 2.4 is a quarter of the LED rate. Due to this the resulting measurement rate for the laser-module is also a quarter of the LED measurement rate, with the same accumulations and oversampling values. Hence it is necessary to investigate the best values for accumulations and oversampling, and to see how these influence CPU usage and measurement rate.

Many of the sensor parameters introduced in chapter 2.4 was excluded as test factors through theoretical reasoning and recommendations from LeddarTech. This was done in the specialization project and these parameters remain the same and should influence the laser module in the same way as the LED modules. When it comes to the Point Count parameter this could be adjusted down due to the smaller vertical FoV size, and hence save CPU resources. The Point Count parameter is set to a value that correspond with the maximum distance the sensor must be able to detect. For the setup in this experiment the height above ground of the sensor is 6.5 meters. FoV for the laser module is as mentioned earlier $36°\text{x}0.2°$, and together with mounting height and tilt angel this is enough to find the points where the largest distance potential is. A commonly used tilt angle for the OCR camera in existing systems is $25°$ and this is used in the following derivation. If using a lower tilt angle than this the Point Count parameter might have to be adjusted. Figure

4.1 shows a sketch illustrating the interesting points in the sensor FoV, in addition to the height and angles used to find these.

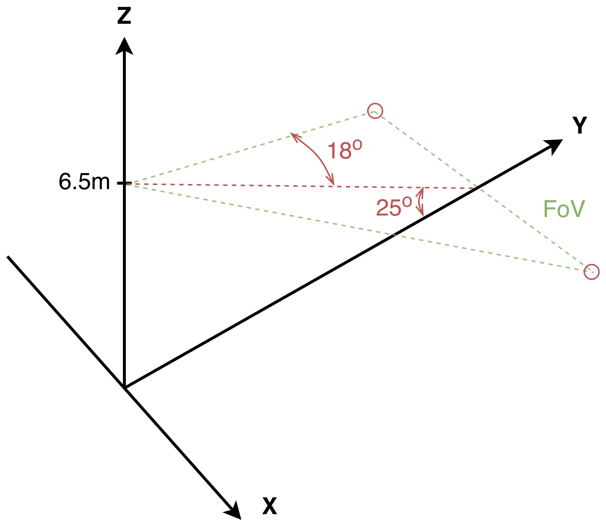

Figure 4.1: Illustration of angles of interest to find maximum possible distance inside FoV from the 36° Leddar laser module, mounted at 6.5m with 25° tilt.

For the LED modules a Point Count value of 11 was found as the optimal with 25 degrees sensor mounting tilt angle. This gave an maximum detection range for the LED module of 18.5 meters. By doing the math for the laser module one get an maximum needed detection range of 16.2 meters. Simple trigonometry is used to find the red dotted hypotenuse when looking at the coordinate system in a YZ-view. The angle between this hypotenuse and the plane which represent the road is then 25° mounting tilt angle. With this angle and the mounting height the hypotenuse is found. In these calculations the FoV height of 0.2° is ignored.

$$\frac{6.5m}{\sin(25^{\circ})} \approx 15.38m \tag{4.1}$$

Next one can imagine looking down on a plane lying parallel with the hypotenuse and through the red marked points of interest. Then one easily see that the points for maximum potential distance is found by:

$$\frac{15.38m}{\cos(\pm 18^{\circ})} \approx 16.17m \tag{4.2}$$

The closest Point Count value that covers the required range of 16.17 meters is then 10. This results in a approximate maximum range of 16.8 meters for the laser module, which gives some error margin. If Point Count is set too high this will waste capacity of the microprocessor by processing at a longer range than needed. Always adjusting the parameter to the model setup is hence advantageous.

This leaves accumulation and oversampling as the two parameters to test. As derived in section 2.4, a high number of accumulation is expected to give measurement robustness by eliminating the noise in the signal. This is advantageous for example in low visibility conditions as rain, snow and fog. Oversampling should give the data stability and precision since it gives the signal processing algorithms more digital samples to work with. A high number of oversampling stabilizes the signal and increase accuracy. But by increasing accumulation and oversampling the measurement rate is rapidly lowered. Todays laser scanners run at a refresh rate of about 75Hz and lower rates than this is not desired with the M16 module. This leaves accumulation and oversampling settings that gives 100Hz measurement rate on the M16. With a vehicle passing at 80km/h one could imagine a single returned measurement every 0.22 meter of the vehicle with the M16 laser module running at 100Hz. If running at 50Hz, as is the next setting below 100Hz, this would be doubled to 0.44m. Due to the extent of the vehicle in z-direction, and height FoV size, one will get more returned data points from the sensor mounted with a tilt different form 90°. Still this simplified calculation in equation 4.3 yields insight to different measurement rates and corresponding distance between samples.

$$\frac{1}{100Hz} \cdot 22m/s \approx 0.22m \tag{4.3}$$

The survey will be a tradeoff between processor resources and the different advantages with accumulation and oversampling. Table 4.1 show the settings that give the desired refresh rate to test. These theoretical rates is calculated by using equation 2.4.

Table 4.1: Combinations of accumulation and oversampling to be tested.

Accumulations	Oversampling	Measurement rate
32	1	100Hz
16	2	100Hz
8	4	100Hz
4	8	100Hz

Maximum desired CPU usage is around 70%. This is to have a margin to corner cases that can give difficult signals to process or cases where more signals is processed. For example noisy low-amplitude signals and/or dense traffic will most certain increase the microprocessor workload. The collection of data was executed as planned. The test factors is summed up here:

Sensor parameter setup:

Point Count:	10
Threshold Offset:	0
Laser Control:	AUTO
Change Delay:	1
Smoothing:	OFF
Object demerging:	OFF
Crosstalk removal:	OFF
Debug:	OFF

Test parameter setup:

Lens option:	36x0.2 laser and 48x8 LED
Vehicle:	Subaru Legacy (blue)
Speed:	20km/h
Lane position:	Center
Sensor tilt:	30 degrees
Sensor height:	6.5 meters
Weather conditions:	Clear, cloudy and snow

4.2 Analysis

Table 4.2 display what was generally seen in the test regarding CPU usage together with the achieved measurement rate for the tested combinations of accumulation and oversampling. Here one notice that CPU usage increases as number of oversampling increases. As a reference value the M16 LED module was found to have 16-8 as the best combination of accumulation-oversampling, where this resulted in 64% CPU load and 100Hz refresh rate.

Table 4.2: Accumulation-oversampling combinations with resulting measurement rate and CPU load for laser-module.

Accumulations	Oversampling	Measurement rate	CPU load
32	1	100Hz/100Hz	47%
16	2	100Hz/100Hz	68%
8	4	100Hz/100Hz	74%
4	8	96Hz/100Hz	84%

In figure 4.2 sensor info is displayed from one selected lap at each of the tested settings. This information is refresh rate, CPU usage and sensor temperature, as the legend states. From the plot one see the tendency of increasing processor load as the number of oversampling increase. In addition one notice the refresh rate for accumulation 4 and oversampling 8 being more irregular than the other rates which vary by about 1 Hz as a maximum. Sensor temperature is approximately the same for all laps.

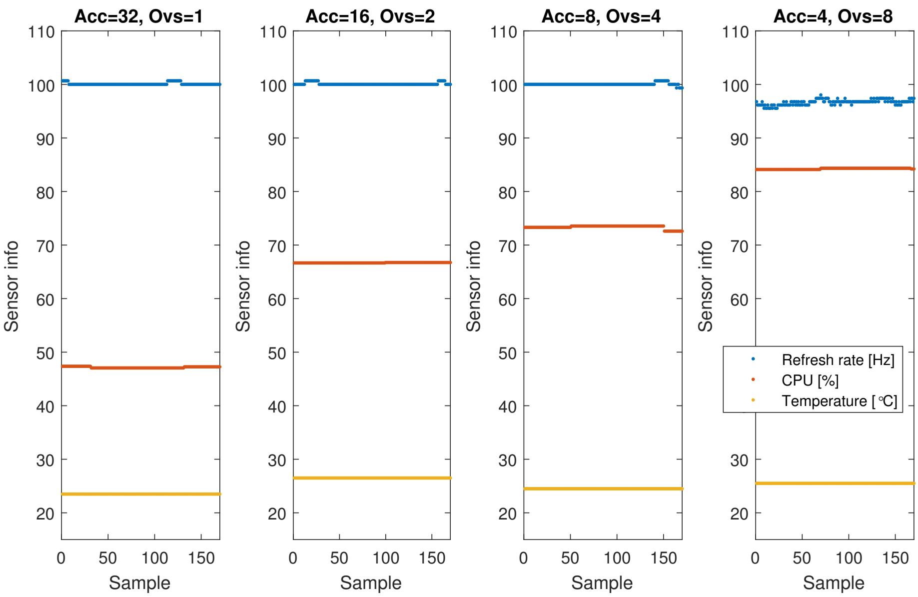

Figure 4.2: Sensor information from selected laps for different accumulation and oversampling settings.

The following four plots show accumulation/oversampling setting 8/4 versus 32/1 for a arbitrarily lap. To the left in figure 4.4 one can see samples from the detecting segments which is extracted with the threshold seen to the right. The bar plot show maximum distance detection for each segment and the threshold that is set manually for extracting segments to plot.

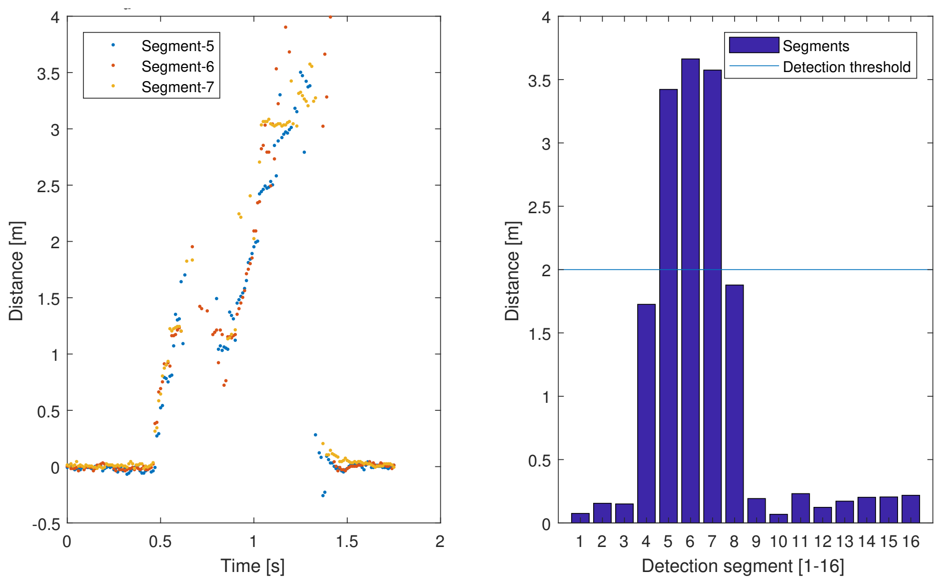

Figure 4.3: Extracted detecting segments at accumulation 8, oversampling 4

Figure 4.4 display the same data samples as the left plot in 4.4 but in addition the mean of the extracted segments together with standard deviation is visualized. The black line represent the mean while the vertical bars indicate standard deviation.

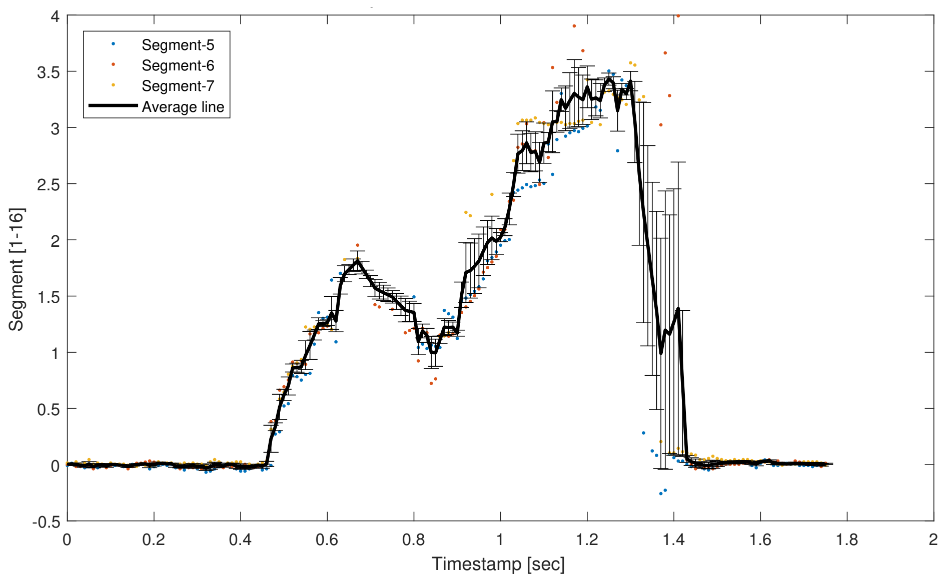

Figure 4.4: Mean and SD of detecting segments at accumulation 8, oversampling 4.

In same fashion as for accumulation-oversampling setting 8-4 figure 4.5 and 4.6 show the same type of plots for 32 accumulation and 1 oversampling.

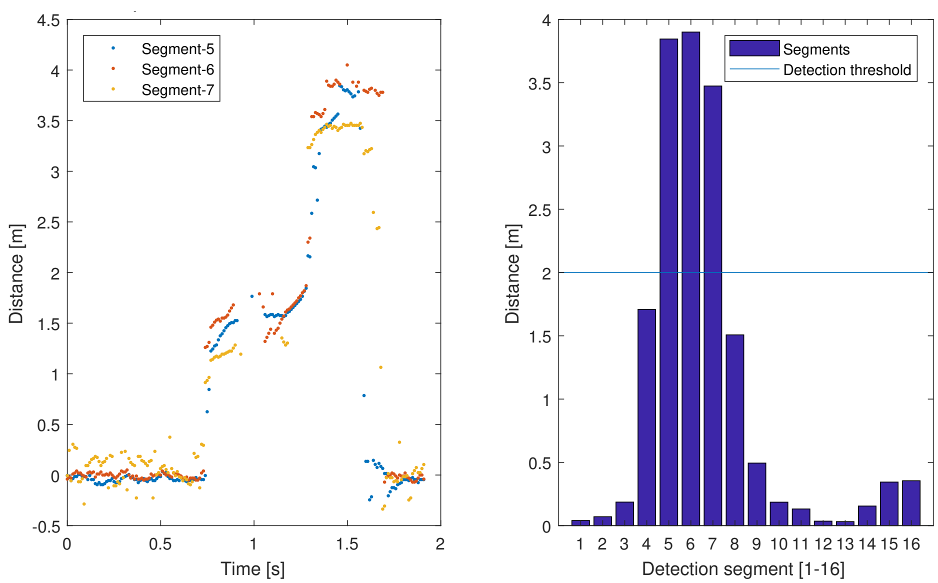

Figure 4.5: Extracted detecting segments at accumulation 32, oversampling 1

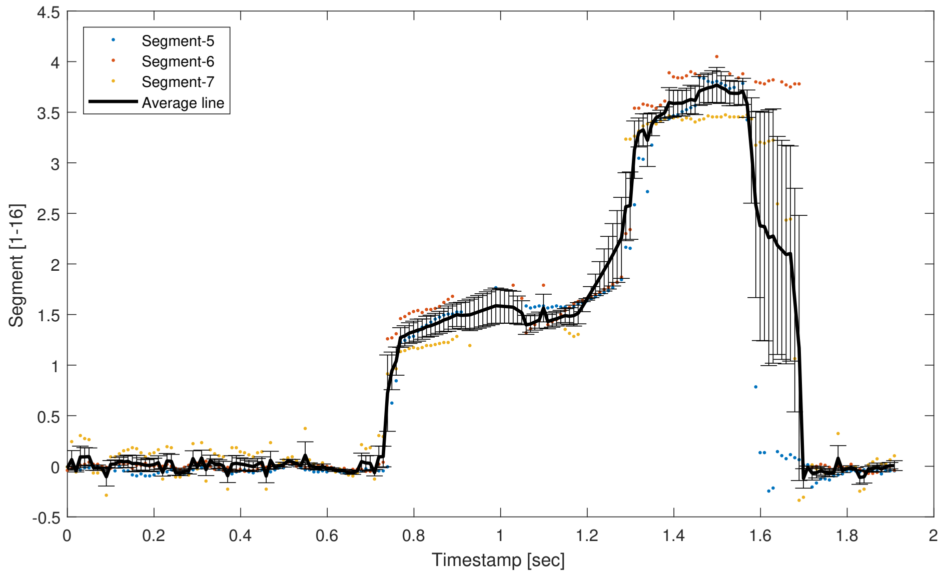

Figure 4.6: Mean and SD of detecting segments at accumulation 32, oversampling 1.

Figure 4.7 show snapshots from the configuration test. The test vehicle, position in lane and weather conditions can be observed. Left image is with 8 accumulations and 4 oversampling, while the right image is with 32 accumulations and 1 oversampling.

Figure 4.7: Reference image for sensor configuration test. Left: 8 accumulations and 4 oversampling. Right: 32 accumulations and 1 oversampling.

The following plots visualize amplitude for the data samples trough color. Data samples is plotted in three dimensions with timestamp, segment number and measured distance difference from the ground. This is a effective way to instigate the data trough its intuitive representation of the vehicle passing the gantry. Figure 4.8 and 4.9 is with a snow covered ground.

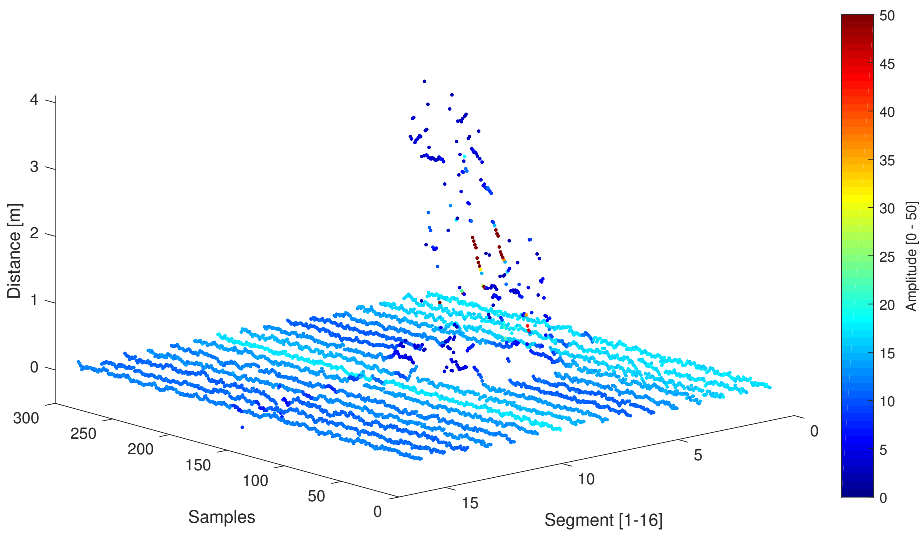

Figure 4.8: Laser-module with 8 accumulations and 4 oversampling.

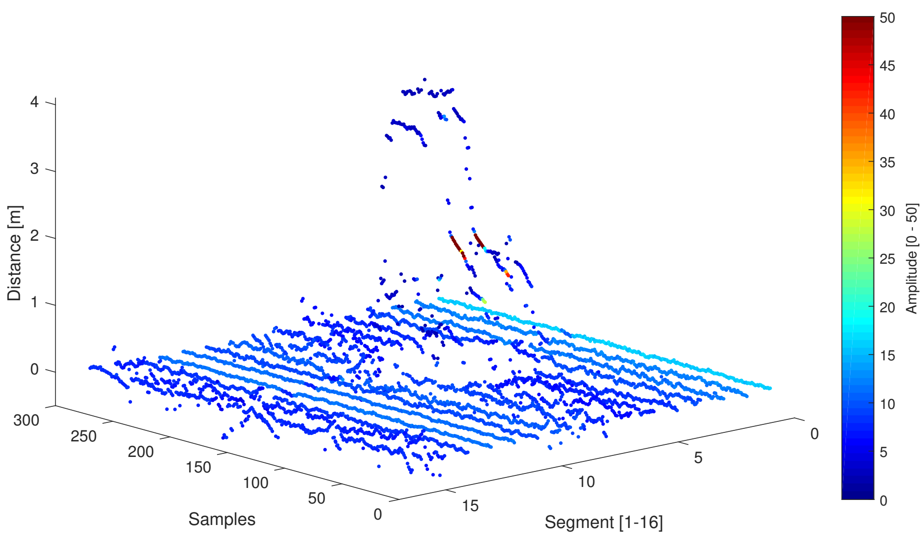

Figure 4.9: Laser-module with 32 accumulations and 1 oversampling.

A lap corresponding to the lap in 4.8 and 4.9 only with the LED-module is plotted for comparison in figure 4.10. Note that the M16-LED module runs at accumulations-oversampling 16-8 during the whole project.

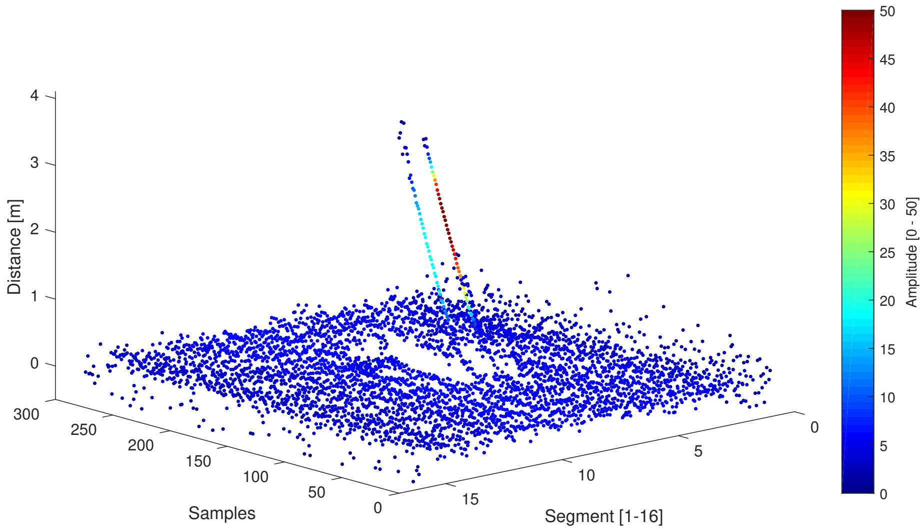

Figure 4.10: LED-module with 16 accumulations and 8 oversampling.

To investigate the low amplitude noise seen on the road measurements in snowy conditions present during the configuration test, a lap with bare ground is seen in figure 4.11 and 4.12.

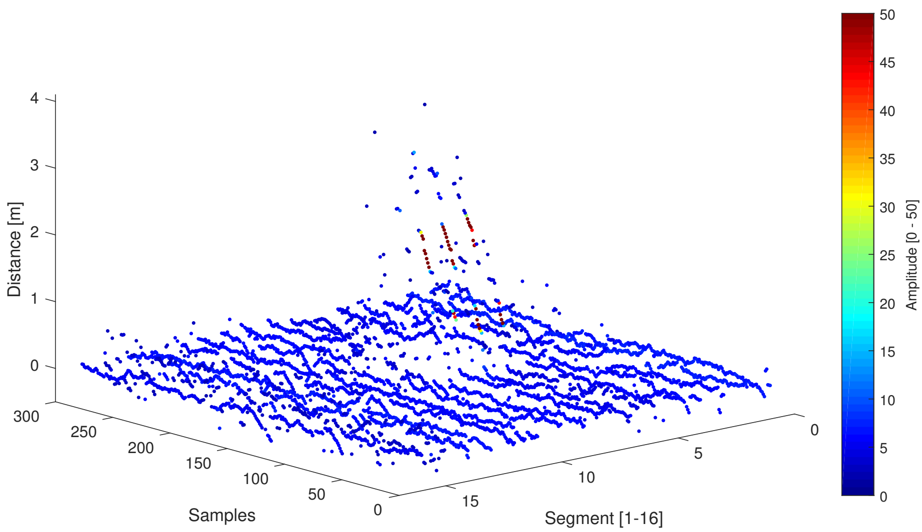

Figure 4.11: Laser-module with 38 accumulations and 4 oversampling on bare ground.

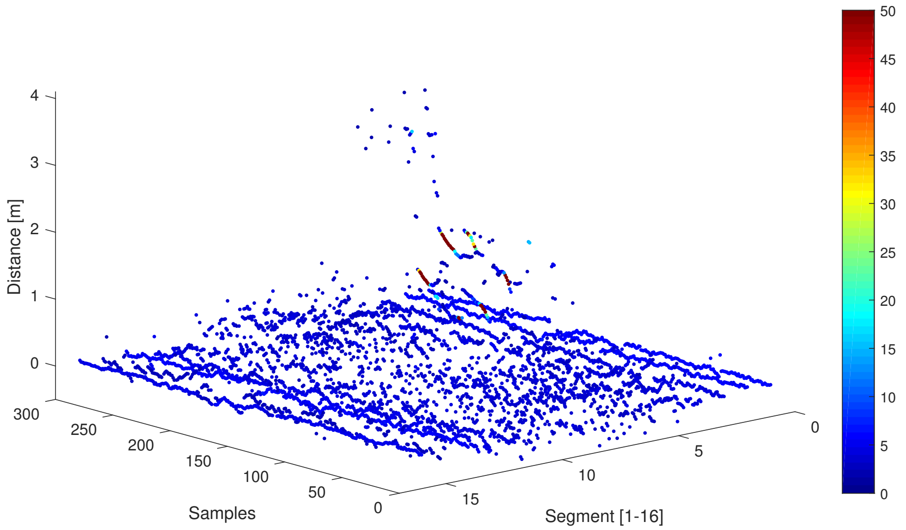

Figure 4.12: Laser-module with 32 accumulations and 1 oversampling on bare ground.

4.3 Discussion and results

From table 4.2 it can be seen that the setting with 4 accumulations and 8 oversampling can be excluded through high CPU usage. In addition the measurement rate gets significantly more unstable than at the other settings, as seen in figure 4.2. When the sensor can not keep the measurement rate stable the processor most likely have to many tasks to perform, although the measured CPU load is not at maximum with a 84% load. Maximum CPU usage of about 70% was chosen to be acceptable in advance of the survey. Hence the three other setting combinations is considered to be sufficient with respect to CPU load.

Further the two extremes with respect to combination of accumulation and oversampling is compared, 32/1 and 8/4. In the bar plot in figure 4.3 and 4.5 one can see that the vehicle position in the lane was quite similar and that the same segments was extracted by the Matlab script. When looking at the left plot in the same figures one notice that detections of the road seems much more noisy for 32/1 than for 8/4. This is also indicated by the increased standard deviation in figure 4.6 contra figure 4.4. But by looking closely at the plot in figure 4.5, it is observed that segment 7 for setting 32/1 is causing the increased standard deviation and noisy appearance of the road measurement. Since the sensor is mounted upside down in the housing, segment 7 is detecting the left side of the car if looking at the images in figure 4.7. The reason for this noise is not known and the only thing that appear to differ between the two laps on video is the shadow. On the lap with accumulations-oversampling setting 32/1 more of the car is exposed to sun while with setting 8/4 the left side of the car is covered by shadow, as the images in figure 4.7 show. Then again all laps done with 32/1 setting has noisy road detections, especially segment 7 and 8 among others stands out as more unstable than the rest. Some of these laps was with shadow conditions just like laps with 8/4, so it seems that the shadow is not the reason for this road noise. The shadow was not expected to influence the sensor in advance of the survey either.

The plot in figure 4.9 revels that some segments consist of more noise than others. These segments has a lower amplitude as seen both in figure 4.9 and 4.8 but the 8/4 setting seems to handle this better. This was seen for all data in hand for this survey. While looking at the images in figure 4.7 and compare it with the 3D plots in figure 4.8 and 4.9 it can look like snowbanks or packed snow in the lane might be in the area where the low amplitude segments is. Note that the FoV width projected onto the ground is approximated to 8.5 meters, as stated in appendix table 9.2. The Subaru Legacy is 1.7 meters wide, which together with the Leddar data provides a basis for estimating where the FoV is approximately projected on the ground. Five times the Legacy width and passing in segment 5,6,7 should indicate a FoV something like the image in figure 4.13.

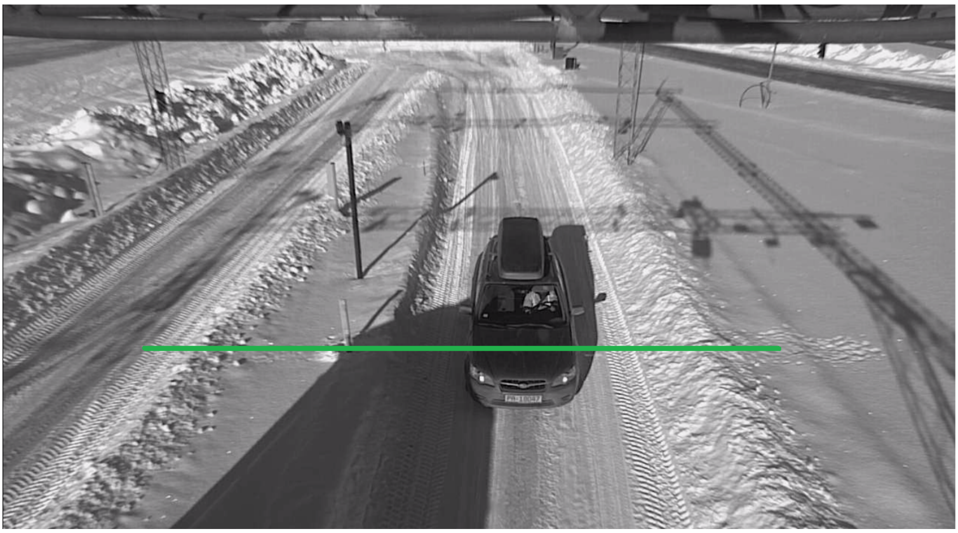

Figure 4.13: FoV estimation for M16-LSR module mounted in gantry.

The segments with low amplitude would be approximately on the snowbank to the left and in the lane where the car is driving. Hence it is interesting to see if this amplitude might change with a bare ground. Figure 4.11 and 4.12 show laps where the ground was bare. Here one see that all segment has quite low amplitude and hence noisy data. Anyway this low amplitude noise on the road detections seems to be handled better with a higher number of oversampling in favor of accumulations regarding the M16-LSR module. In figure 4.10, data from the LED-module can be compared to the laser-module data. From this one see that the M16-LED has a overall lower amplitude. Data samples from the road contain significantly more noisy while the vehicle data samples is quite smooth and linear. More comparison and analysis of the M16-LED module is presented later in this paper.

While the data samples of the road is noisy with 32 accumulations and 1 oversampling as seen in figure 4.9, it seems that the data samples from the vehicle has a more coherent tendency than the other tested settings. The two flatter horizontal regions could indicate the bonnet and roof of the vehicle. For the setting with 8 accumulations and 4 oversampling in figure 4.8, detections of the front of the vehicle is quite coherent and good with a somewhat linear tendency while further back the data samples is more incoherent. It is hard to favor one of these settings in terms of use the data for triggering on incoming vehicles. Both the setting 32/1 and 8/4 is found sufficient to be used for trigging with the sensor. As for the setting with 16 accumulations and 2 oversampling the data appears to be very similar as with the 8/4 setting. Also CPU usage is almost the same, so why chose one over the other is not obvious. Due to the low amplitude noise seen at lower oversampling values it is chosen to proceed with 8 accumulations and 4 oversampling as the main setting.

Chapter 5

Vehicle variation test

How can different vehicles challenge the sensor performance and signal quality? This is interesting to investigate and the following chapter present this vehicle variation test.

5.1 Experimental design and execution

The purpose of this test is to check how different types of vehicles influence the sensors ability to detect vehicles and to see if differences in the data makes sense. Vehicle variations in terms of surface and size are studied, where surface is varying both by color and structure. A polished car will be a harder object to get good reflections of than a object with rougher exterior. When it comes to color, black cars is known to challenge the sensors ability to get sufficient detections. Other factors such as sunroof and amount of chrome is also known to be challenging due to the reflective characteristics. Different vehicle size should give a varying amount of data samples corresponding to the vehicle. One of the test vehicles was a black Subaru Forester with sunroof and auxiliary headlights. This was expected to be the most difficult vehicle in the test due to color, the sunroof and auxiliary headlights that is mounted at the front. As for the vehicle size variation a 50cc scooter and a Toyota Hiace was used. In addition data for the Subaru Legacy is also collected in similar conditions during the configuration test. The vehicles used is listed here:

- Subaru Forester - intended to be difficult vehicle
- Subaru Legacy - intended to be normal vehicle
- Toyota Hiace - chosen as large vehicle
- 50cc Yamaha Aerox - chosen as small vehicle

Images of the test vehicles can be seen in chapter 3.2. The goal is to see if the black car bring more noise and deflects more of the emitted light. For the scooter it is interesting to see how many data points that is returned versus the other vehicles.

The test was executed as planned and data for all the vehicles is in hand. The weather was sunny with snow covering the ground. Center lane position was used and speed was about 20-30km/h. The scooter drove in the ruts from the cars. Test parameters summarized:

Sensor parameter setup:

Point Count:	10
Threshold Offset:	0
Laser Control:	AUTO
Change Delay:	1
Smoothing:	OFF
Object demerging:	OFF
Crosstalk removal:	OFF
Debug:	OFF

Test parameter setup:

Lens option:	36x0.2 laser and 48x8 LED
Vehicle:	4
Speed:	20-30km/h
Lane position:	Center
Sensor tilt:	30 degrees
Sensor height:	6.5 meters
Weather conditions:	Sun and snow

5.2 Analysis

Tree dimensional plot of a arbitrary lap with the scooter is seen in figure 5.1 and 5.2. Note the quite high amplitude scaling, ranging from 0-600, on the colorbar at the side of the plots.

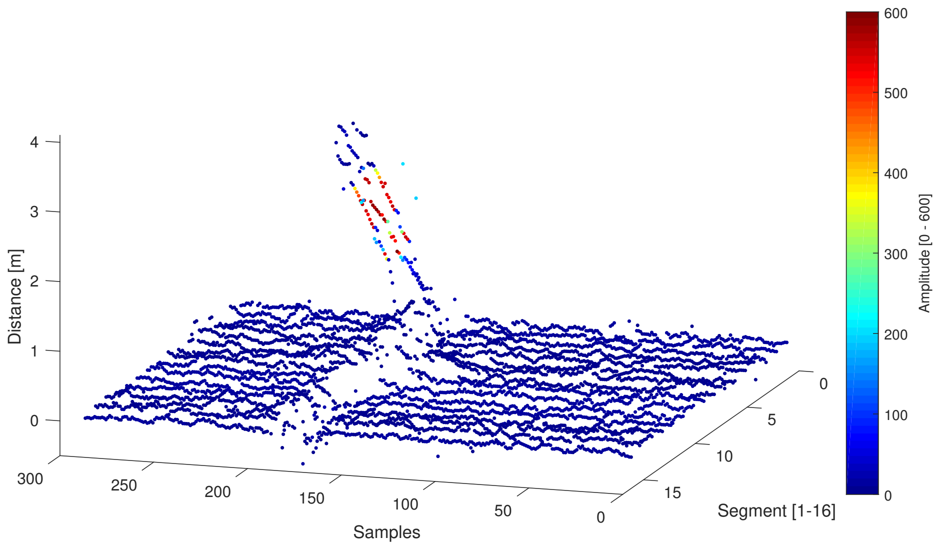

Figure 5.1: Yamaha Aerox lap detected with the M16-LSR sensor.

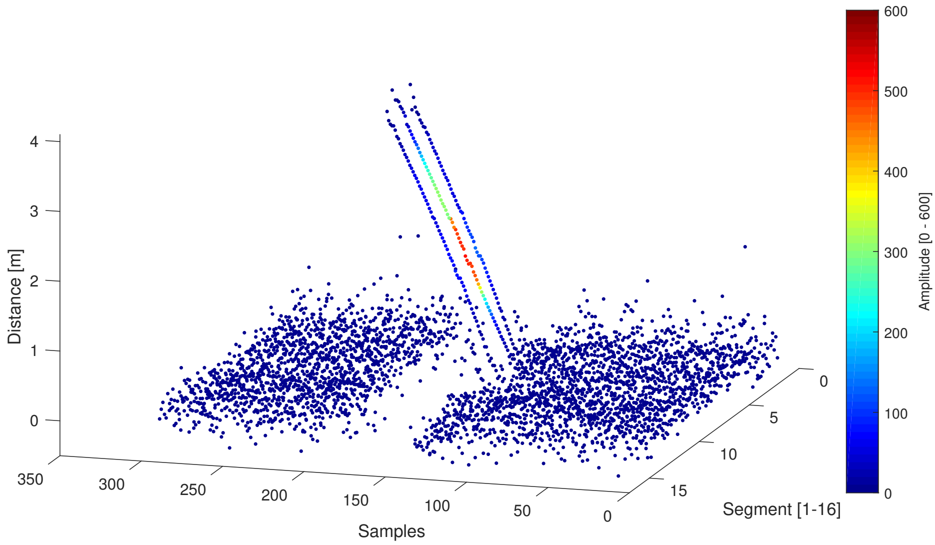

Figure 5.2: Yamaha Aerox lap detected with the M16-LED sensor.

An arbitrary lap with the Toyota Hiace is seen in the 3D plots displayed in figure 5.3 and 5.4. Note that the scaling on the colorbar is now 0-50 again.

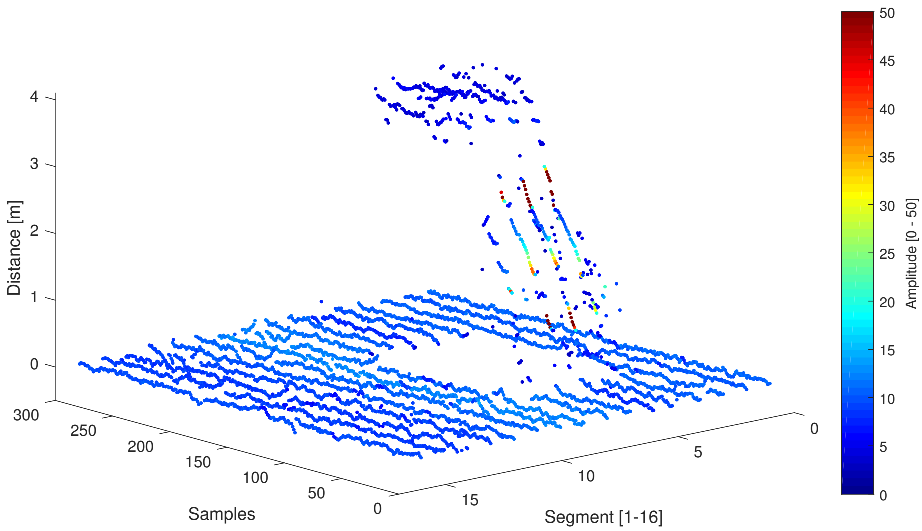

Figure 5.3: Toyota Hiace lap detected with the M16-LSR sensor.

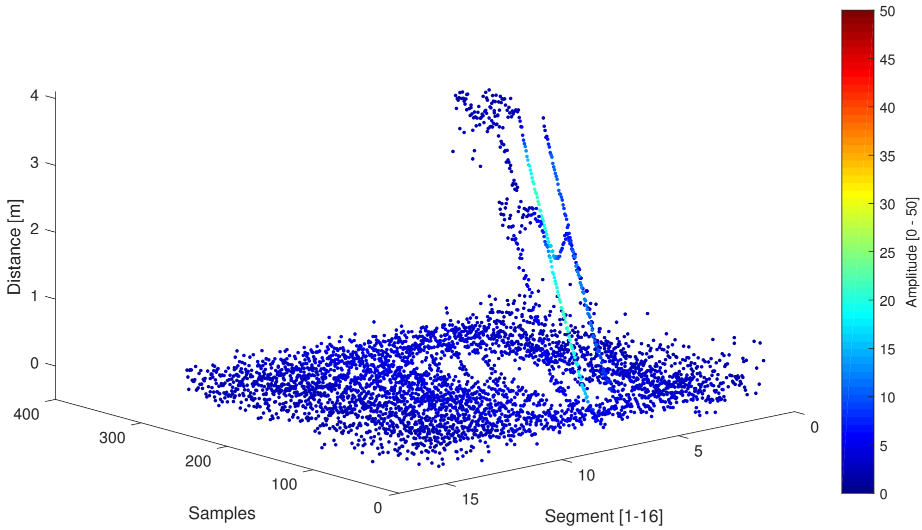

Figure 5.4: Toyota Hiace lap detected with the M16-LED sensor.

Figure 5.5 and 5.6 display an arbitrary lap of the Subaru Forester which was expected to bring noisy data.

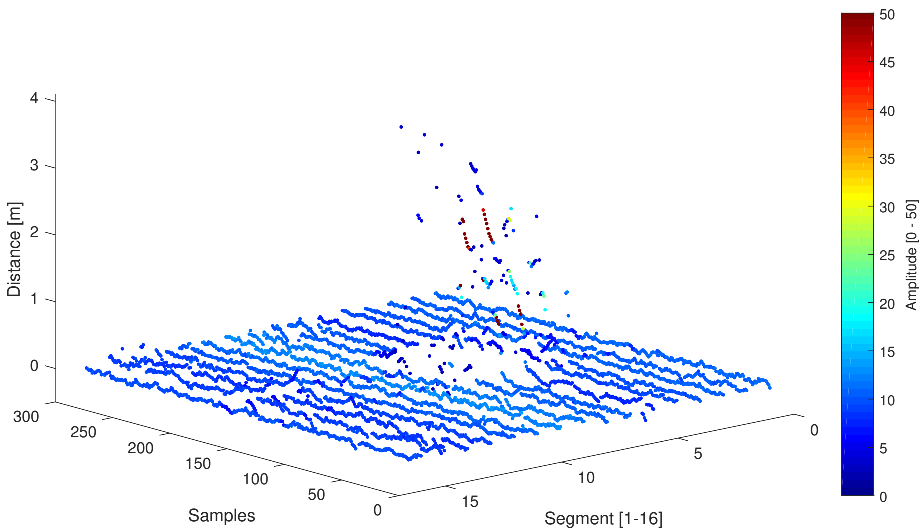

Figure 5.5: Subaru Forester lap detected with the M16-LSR sensor.

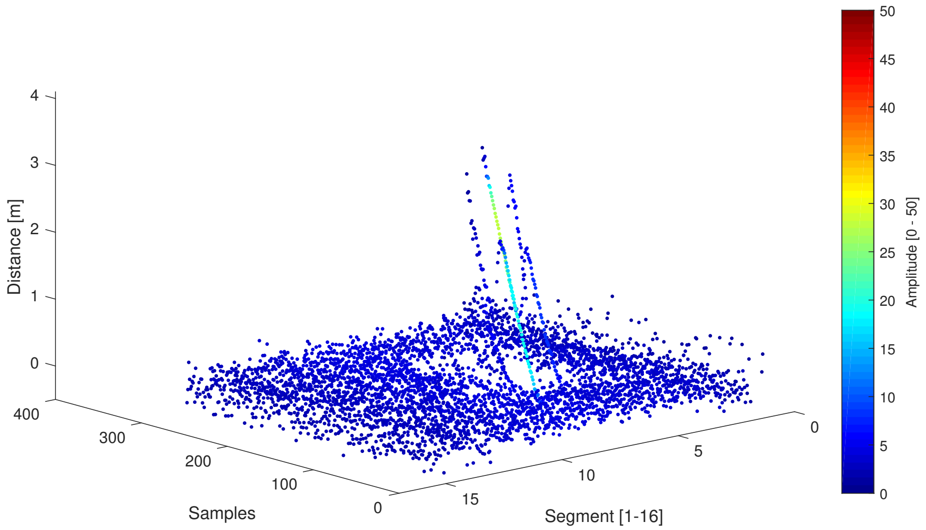

Figure 5.6: Subaru Forester lap detected with the M16-LED sensor.

Multiple laps is plotted to see how laps coincides. Stable and similar looking data for the driven laps is important for evaluating the sensors capabilities in a tolling system. The multiple lap plots for the scooter, Hiace, Forester and Legacy is found in figure 5.7, 5.8, 5.9 and 5.10 respectively. Note that the number of laps plotted is not the same for all vehicles and sensors. This is due to data processing bugs or data logging errors that is not prioritized to fix. The multiple laps plot gives a good insight in trends and how coinciding multiple laps is, anyway. The data samples for one lap is the average of all the extracted detecting segments for that lap. Each lap is color coded and the legend shows number of laps and color.

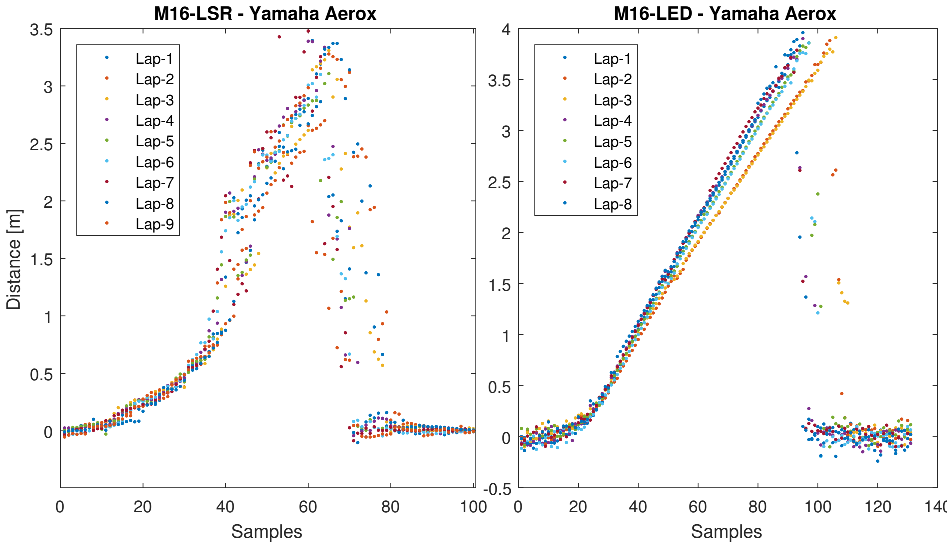

Figure 5.7: Multiple laps plot for Suzuki Aerox.

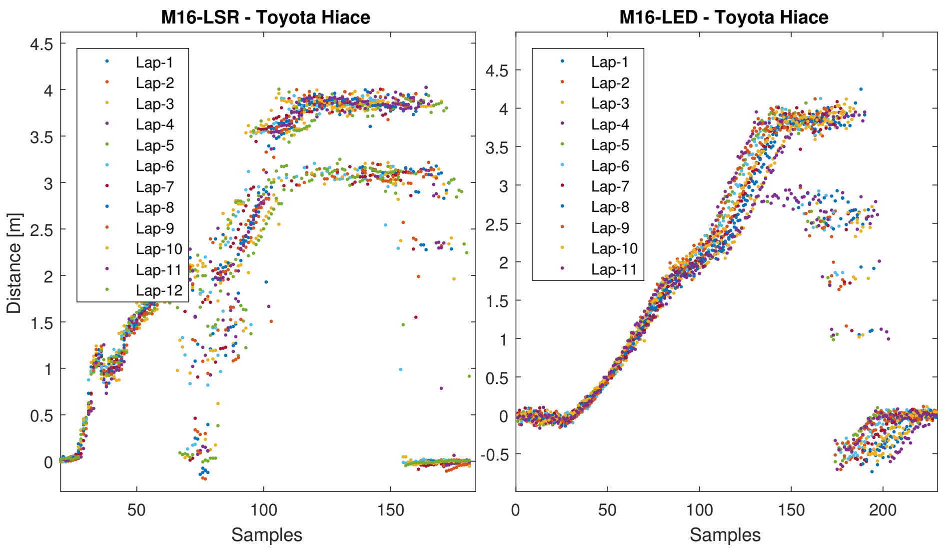

Figure 5.8: Multiple laps plot for Toyota Hiace.

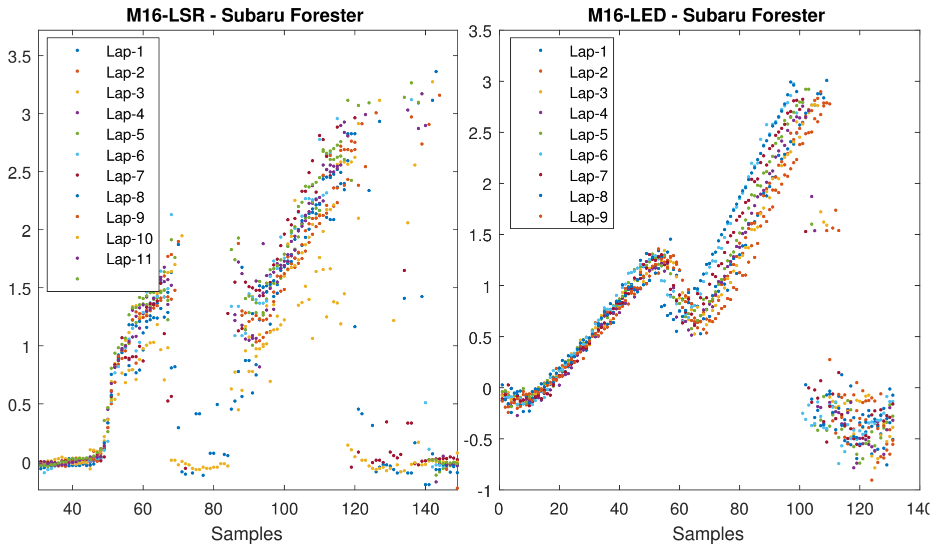

Figure 5.9: Multiple laps plot for Subaru Forester.

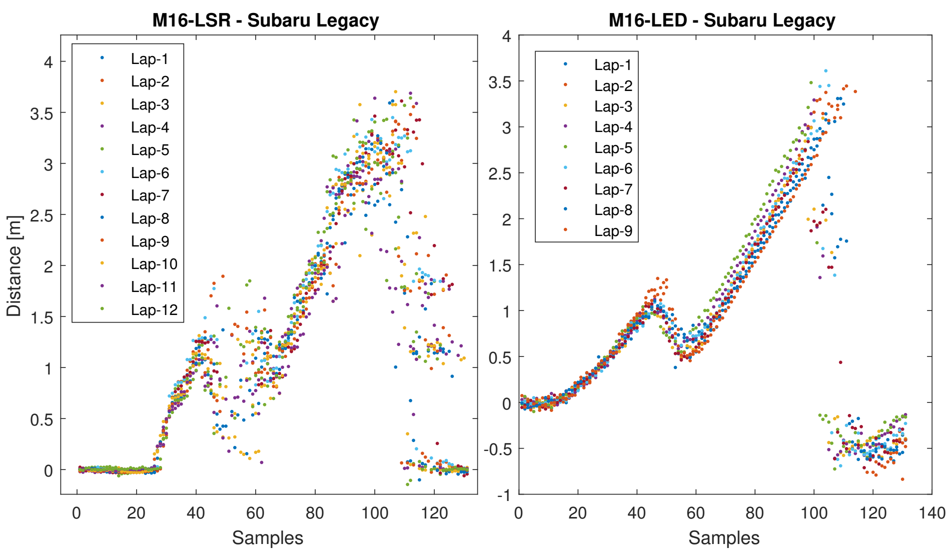

Figure 5.10: Multiple laps plot for Subaru Legacy.

A snapshot of the test vehicles in the FoV is seen in the images in figure 5.11.

Figure 5.11: Snapshot of Yamaha Aerox, Subaru Forester, Toyota Hiace and Subaru Legacy.

5.3 Discussion and results

By looking at figure 5.1 and 5.2 it is clearly seen that the segments that is not detecting the scooter loses its distance measure. LeddarTech confirmed that this is due to the automatic light control and saturation of the receiver lens. Saturation is said to occur with an amplitude around 475-500 counts. When looking at the data one found that the scooter detecting segments had a higher amplitude than this. As a response to the high amplitude the automatic light control compensated with lowering the light intensity. The laser module was adjusted from 100% to 10%, while the LED module goes from 100% to 20%. Hence, detection of the ground was lost. Since the scooter with the reflective vest is a much more reflective object than the ground covered with snow it will not be possible to get detections from both. It should be acceptable to not retrieve detections of the road if using the module as a trigger. If a detection threshold is found during installation of the module at site, it should be sufficient with data samples of the passing vehicle and not the ground.

In figure 5.3 data from the laser module detecting the Toyota Hiace is seen. Here it is seen more data samples from the roof than the other tested vehicles. This is not the case for the LED module in figure 5.4, which is more similar looking no matter what vehicle passes. Still the amount of data samples is higher. The similar looking data is due to the larger horizontal FoV size and averaging process the Leddar module does. Horizontal size of the FoV projected onto the ground is approximated to 3.7 meters with the current setup, as seen of table 9.2 in the appendix. The width is 11.6 meters which means that one segment covers an area of about 0.7x3.7 meters. Within this area the Leddar algorithms are in some way choosing what distance to return. It is likely to believe that these algorithms are averaging measures form the whole area and in addition weighting them after amplitude, as the results from the specialization project indicate [1]. Which is best for classification purposes is hard to tell, but due to the FoV being a 1x16 detecting array the classification capabilities of the sensor is not beveled to be very good. This is also seen if comparing the width of the scooter versus the cars. Considering the 36 degree laser module it was always three detecting segments that stood out quite clear for the scooter laps. For the cars this was not just as evident, but five segments is affected when the cars passes. For example in figure 5.3 the Hiace gives five segments that represent the car quite well. But for the Subaru Forrester data seen in figure 5.5 it is also five segments that is affected but the detections is quite noisy. If using the sensor for classification it is best to mount it pointing straight down as in sketch 4 in image 2.12 show. This will significantly reduce the influence vehicle speed has on length measure. A small sized horizontal FoV will also be beneficial for reduce speed influencing length measure. This is possible to investigate in further work.

As just mentioned the expected noise for the Subaru Forrester did occur as seen in figure 5.5. The 3D plots of the Subaru Legacy in figure 4.8 shows a fair amount of noise and inconsistence between the data samples. Still the Forrester data is a bit more noisy. Figure 5.6 show the same lap of the Forrester just with the LED module. And as seen in all the LED versus laser data, the noise is averaged out into quite linear lines which could be beneficial when using the sensor as a trigger. The reason for the linear tendency could just as well be due to the larger vertical FoV and not the LED light source itself. Hence a laser module with a larger FoV height could be beneficial in terms of trigging.

Low amplitude noise on the road data samples is also seen here when comparing the laser and LED-module, just as in the configuration test. It seems counterintuitive that the LED-module averages out the noise on the vehicle data samples, while the ground itself is much more noisy. One theory for this is the bigger FoV for the LED-module and that the algorithms constantly change where in the FoV the distance measure is retrieved. The geometry between gantry, ground and sensor mounting angle would yield different distance measurements for where in the segment one pick a point. In addition the ground should have similar reflective characteristics for the whole area in each of the detecting segments. This may be the reason for the algorithms to constantly change the point for the returned distance since it is not a strong amplitude area/point that stands out. When a vehicle passes this is probably not a problem due to the sensor retrieving a much higher amplitude and the algorithms settle on which distance to return. In addition the FoV size might influence the amplitude trough intensity of the emitted light. The smaller FoV for the laser-module should mean that the emitted light is more concentrated and the FoV is illuminated with more light. Hence a higher amplitude is retrieved for the reflected signal than it would be for the LED-module with the larger FoV.

When investigating the multiple lap plots the first thing noticed is in general more coinciding data for the LED-module laps than for the laser-module laps. But if looking at the laser-module plots in figure 5.7 to 5.10, it is observed that the first 70 centimeters or so of measured distance difference is very coinciding. This is believed to be good since, in existing systems, the front of passing vehicles is used as basis for trigging. It seems that the laser-module could work just as good as the LED-module for triggering. If looking at the rest of the silhouette of the data samples, the scooter plots stands out with no 'dip' in the distance as seen for the other vehicles. This dip is most likely due to the windshield. The emitted light probably travels trough the windshield and reflects of the interior of the cars. For the laser-module this results in a quit noisy area while the LED-module and the average processing cleans up the samples better. In figure 5.9 this area is larger than at the rest for the cars. This might be due to the sunroof on the Forester that is expected to disturb even more. In total it seems that both tested sensor-modules could work as a trigger on all the tested vehicles.

Chapter 6

Vehicle speed test

This chapter gives a description of testing regarding vehicle speed. The speed factor is known to influence the data but the main interest area is to look for other unexpected findings.

6.1 Experimental design and execution

The speed of passing vehicle is an important factor to study. Sample points are expected to be quite similar looking besides the number of sample points which should be fewer at higher speed. Hence it was planned to drive a vehicle at 20km/h and 60km/h past the gantry and see if the increase in speed and the sensor measurements seems to correlate. The sensor must be able to return a sufficient number of data points for vehicles traveling in speeds over 80km/h. This speed is not possible to test with the current setup but the decrease in data-points from 20km/h to 60km/h can be used to estimate if detection of vehicles in high speed should give a sufficient point cloud. Another interesting thing is to see if one could get a speed estimate of the vehicle. This could supplement existing speed measurement in the system today and would be a plus but not required. These factors was also investigated in the specialization project for the sensor unit used there.

The testing was executed as desired but it was later found that the logged timestamp was -2147483648 for all data samples. This is clearly a bug in the data recording code where the timestamp parameter was not reset and instead reached maximum possible value for that given data type. Hence speed estimation is not investigated. The test factors is summed up here:

Sensor parameter setup:

Point Count:	10
Threshold Offset:	0
Laser Control:	AUTO
Change Delay:	1
Smoothing:	OFF
Object demerging:	OFF
Crosstalk removal:	OFF
Debug:	OFF

Test parameter setup:

Lens option:	36x0.2 laser and 48x8 LED
Vehicle:	4
Speed:	30km/h and 60km/h
Lane position:	Center
Sensor tilt:	30 degrees
Sensor height:	6.5 meters
Weather conditions:	Bare ground and nice

6.2 Analysis

Figure 6.1 and 6.2 visualize the number of data-samples in each segment for two selected laps. One lap is at 20km/h and the other at 60km/h. Data recorded with the laser module is seen in 6.1 while figure 6.2 display the LED data. The labels marks approximately the first and last recorded data-sample of the vehicle. This gives an simple visualization of how many samples one get form the vehicle. Note that many data-samples are missing during the passing og the vehicle.

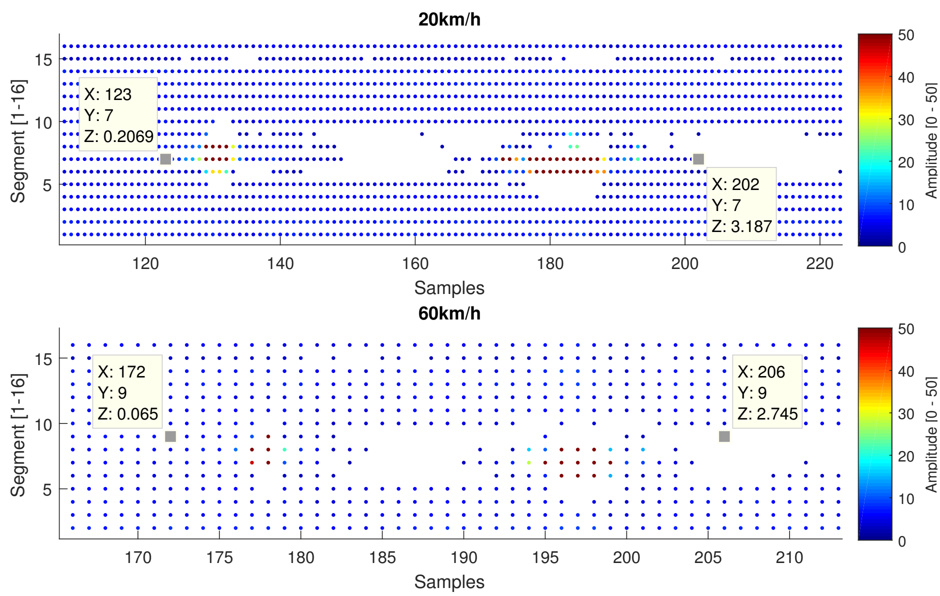

Figure 6.1: Number of data-samples from M16-LSR module visualized.

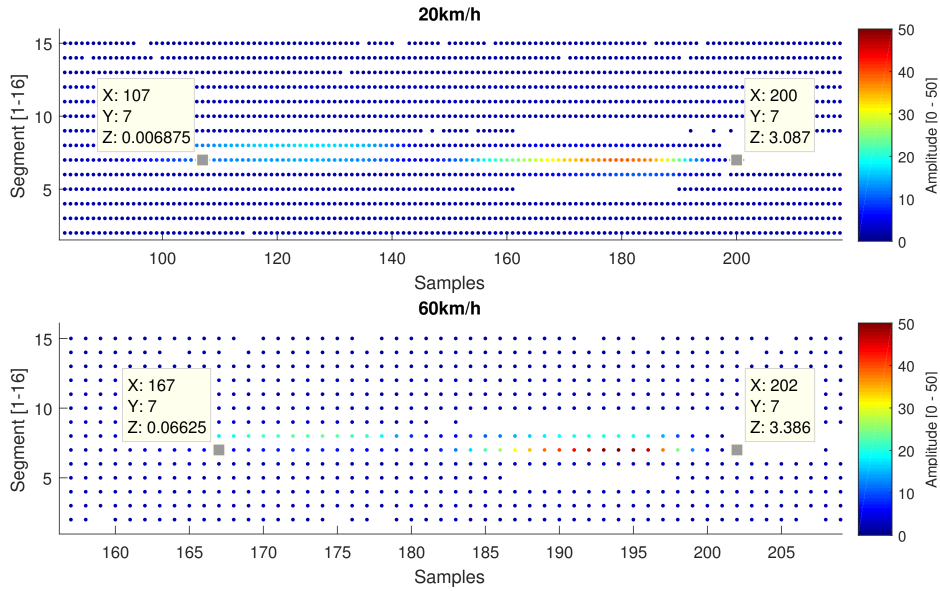

Figure 6.2: Number of data-samples from M16-LED module visualized.

Multiple laps at 60km/h and 20km/h is plotted together to compare if the point cloud looks similar when disregarding number of samples. Figure 6.3 show the 60km/h plots for laser and LED-module while figure 6.4 is for 20km/h.

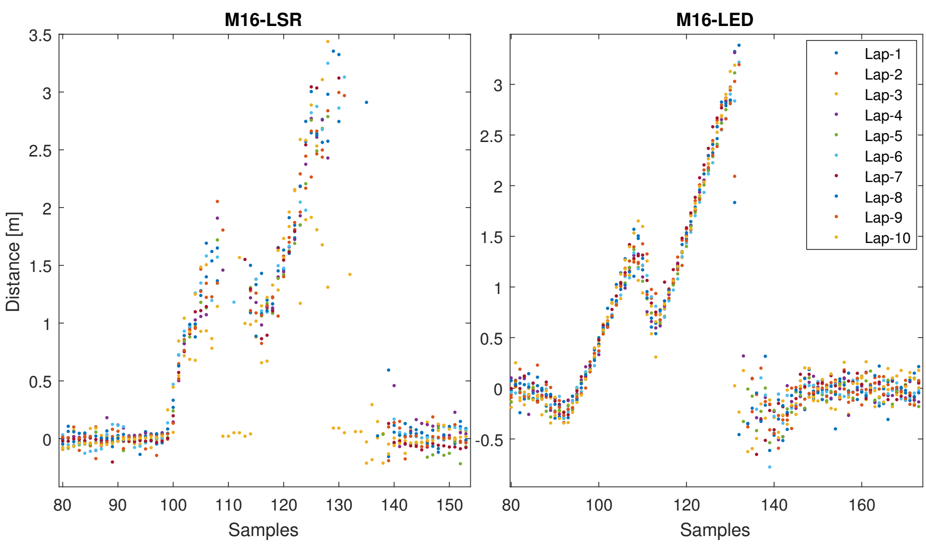

Figure 6.3: Multiple lap plot in 60km/h with laser and LED-module

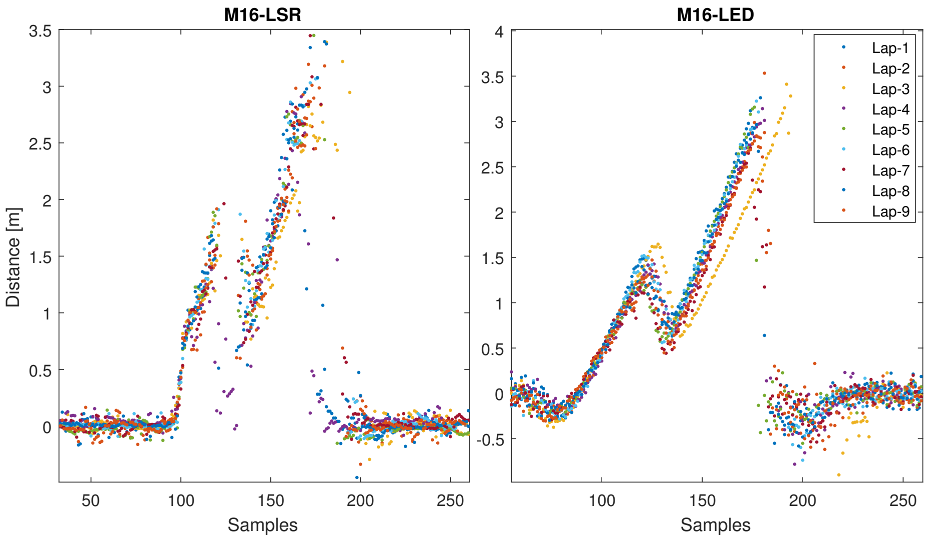

Figure 6.4: Multiple lap plot in 20km/h with laser and LED-module

6.3 Discussion and results

By increasing the speed one see, in figure 6.1 and 6.2, that the number of data-samples is reduced. The labels marks approximately the first and last recorded data-sample of the vehicle. This show that the number of data-samples at 60km/h is not very large. Especially when one takes into account that many samples is lost due to what is believed to be specular reflection and/or low amplitude problems. Hence one can be skeptical to the number of samples returned for vehicles that exceeds 80km/h, being sufficient for triggering.

There is no indications that other factors than number of samples is affected by increased vehicle speed. Multiple lap plots for 60km/h and 20km/h in figure 6.3, show similar appearance of the data. The dip believed to be due to the windshield and noisy/loss of signal at back is similar. The different vehicle speed seems to only influence number of data-samples.

Chapter 7

Weather test

The weather condition test is carried out to check how weather conditions influence the sensors ability to detect a vehicle.

7.1 Experimental design and execution

It is desirable to test sun, rain, fog and snow conditions to investigate the sensors performance. Sunny dry conditions is expected to not bring a too big challenge for the sensor but could work as a reference to the other conditions. Wet road in sunny weather on the other hand is known to challenge other sensors and hence it is interesting to see how the Leddar module performs. This condition could be challenging since sun light, that also contains infrared light, can through specular reflection on wet tarmac reach the sensor and influence the measurements or saturate the lens. Another phenomenon regarding wet tarmac can be specular reflection of the light emitted from the sensor it self. This is expected to be a bigger problem the more water that lies on the road.

When it comes to limited sight both rain, fog and snow can influence the sensor ability to ”see”. The Leddar sensors is stated to work well in these low visibility conditions. Still there is a point where the sight is so bad that it is not possible to detect a passing vehicle. It would be interesting to look at this extreme to display how low visibility the sensor can handle. The Beer-Lambert-Bouguer law relates attenuation of light to properties of the material light is traveling trough. This was used to find expected amplitude in fog conditions that reduces sight. But, fog did not occur at the track during the project period and hence this factor was not investigated as wanted. In chapter 9 - Further work, one find the derivation of the Beer-Lambert-Bouguer law related to fog. Practical use of the law is assumed to be best with fog due to the smoother density than rain and snow.

Another interesting factor to investigate is accumulations in different weather conditions. Even though the configuration test in chapter 4 investigated different settings it is interesting to see if a high number of accumulations could work better than oversampling in heavy snowfall. LeddarTech states that accumulations is the acquisition technology that gives measurement robustness by eliminating signal noise that can for instant come from rain, fog or snow. The settings was tested in heavy snowfall, cloudy weather and bright sun. Under all these weather types the ground was covered in snow. Accumulations-oversampling settings 32-1 and 8-4 was tested. In addition the signal amplitude in the three conditions is investigated. The heavy snowfall could attenuation signal amplitude.

As mentioned all desired testing was executed successfully with the exception of foggy conditions. To give an overview of the data in hand some bullet points summarize the different combinations of weather factors. For the following bullet points the Toyota Hiace was the test vehicle. This data is displayed in subsection 7.2.1.

- Wet ground and sunny weather.
- Wet ground and cloudy weather.
- Wet ground and rain.

Furthermore both the accumulation/oversampling combinations of 32/1 and 8/4 was used to investigate the effect of these in limited sight. The Subaru Legacy that was used as test vehicle. Results from these data is presented in subsection 7.2.2.

- Snow on ground and sunny weather.
- Snow on ground and cloudy.
- Snow on ground and heavy snowfall.

Overview of test factors:

Sensor parameter setup:

Point Count:	10
Threshold offset:	0
LED:	AUTO
Change Delay:	1
Smoothing:	OFF
Object demerging:	OFF
Crosstalk removal:	OFF
Debug:	OFF

Test parameter setup:

Lens option:	34 laser and 48x8 LED
Vehicle:	Hiace and Legacy
Speed:	30km/h
Lane position:	Center
Sensor tilt:	30 degrees
Sensor height:	6.5 meters
Weather conditions:	Varying

7.2 Analysis

7.2.1 Sight and reflection problem

Figure 7.1, 7.2 and 7.3 display 3D plots from the laser-module detecting the Toyota Hiace on an arbitrary lap in different conditions.

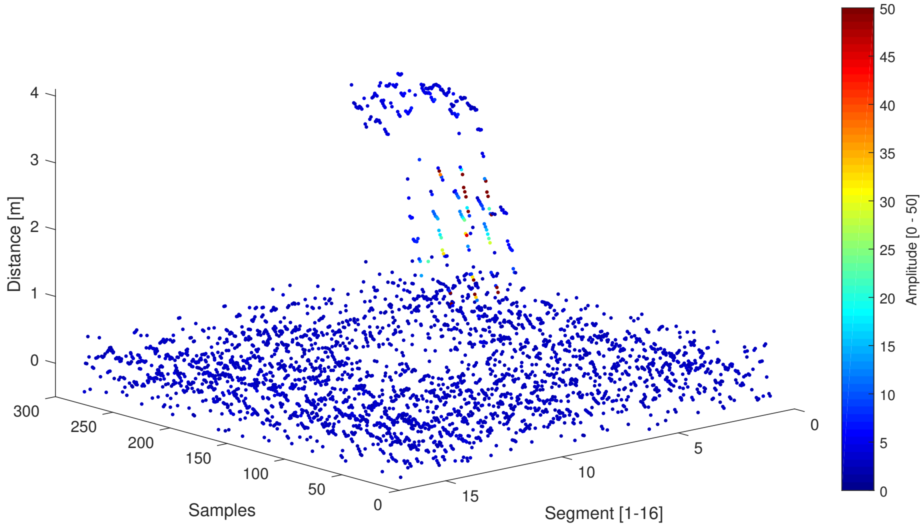

Figure 7.1: 3D plot of laser-module data. Van on wet ground with sunny sky.

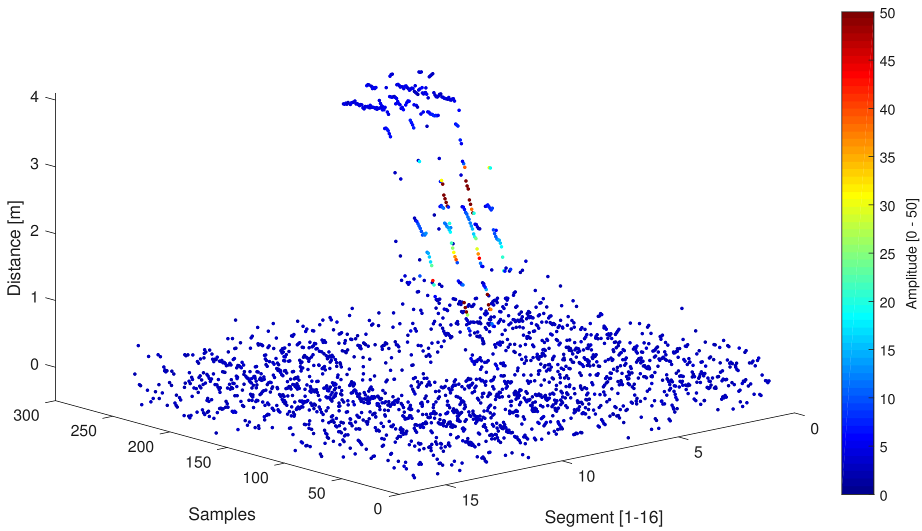

Figure 7.2: Laser-module detecting van on wet ground with cloudy sky.

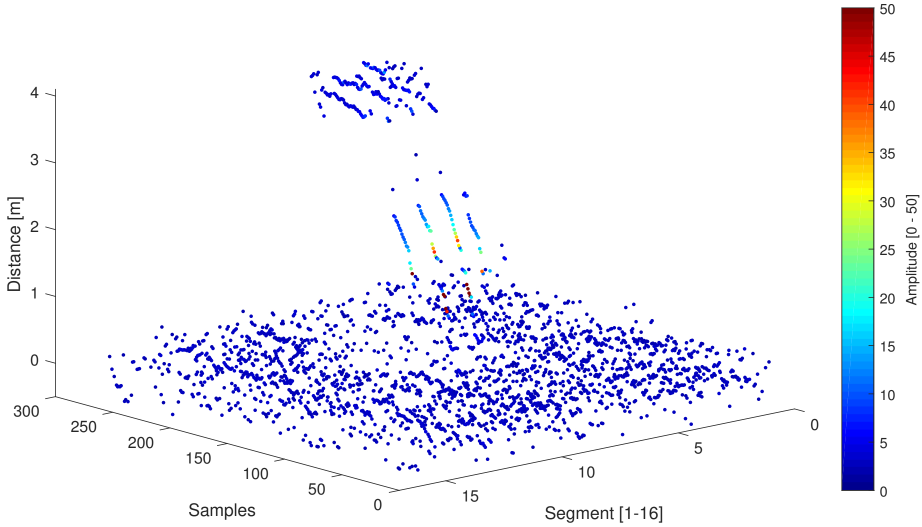

Figure 7.3: Laser-module detecting van on wet ground with rain.

Plots in figure 7.4, 7.5 and 7.6 is the corresponding laps to the tree past 3D plots, only with the LED-module.

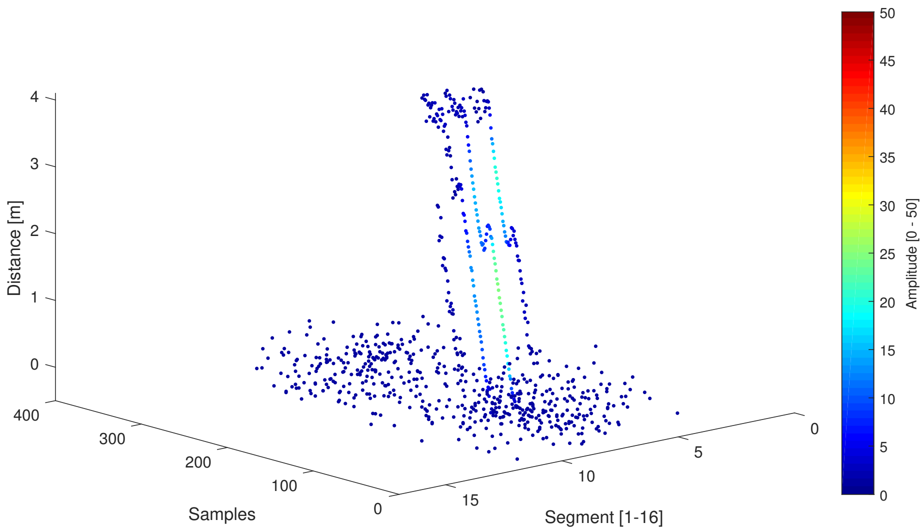

Figure 7.4: LED-module detecting van Van on wet ground with sunny sky.

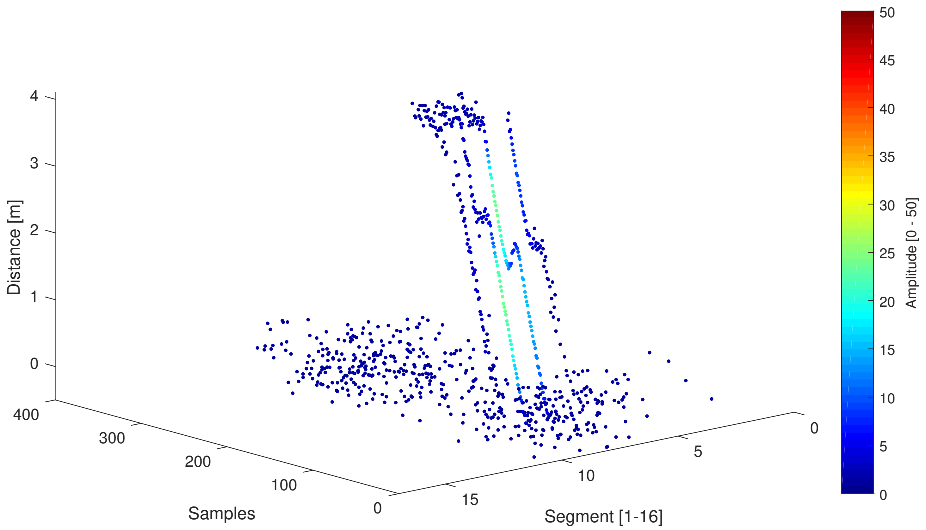

Figure 7.5: LED-module detecting van on wet ground with cloudy sky.

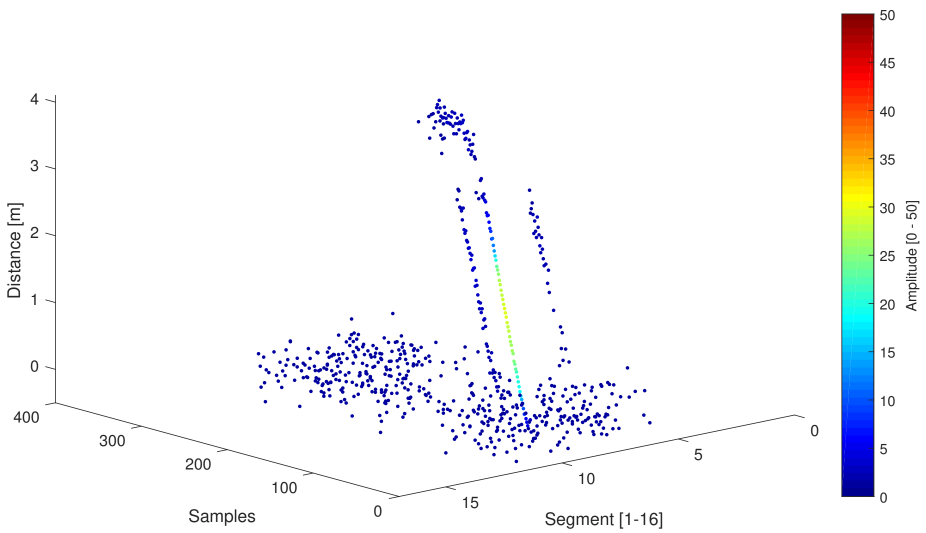

Figure 7.6: LED-module detecting van on wet ground with rain.

In table 7.1 the typical amplitude values for the laser and LED-module detecting the ground is seen. Note that for the LED-module, the amplitude was naturally zero for the segments that did not detect the ground

Table 7.1: Typical amplitude values while detecting wet ground.

	Wet ground and sun	Wet ground and cloudy	Wet ground and rain
Laser-module	$\approx 2.5 - 3$	$\approx 2.5 - 3$	$\approx 5 - 6$
LED-module	≈ 1.2	≈ 1.2	≈ 1.2

The three images in figure 7.7 show the Toyota Hiace in the three different conditions.

Figure 7.7: Snapshot of Toyota Hiace on wet ground with sun, cloudy and rain, respectively.

7.2.2 Sensor configuration considering sight

The following four plots show the point cloud of the vehicle from randomly picket laps. Figure 7.8 and 7.9 show three dimensional plots of the vehicle driving past the gantry in heavy snowfall. Bonnet and skibox of the Subaru legacy is covered in snow as seen in the right image in figure 7.16.

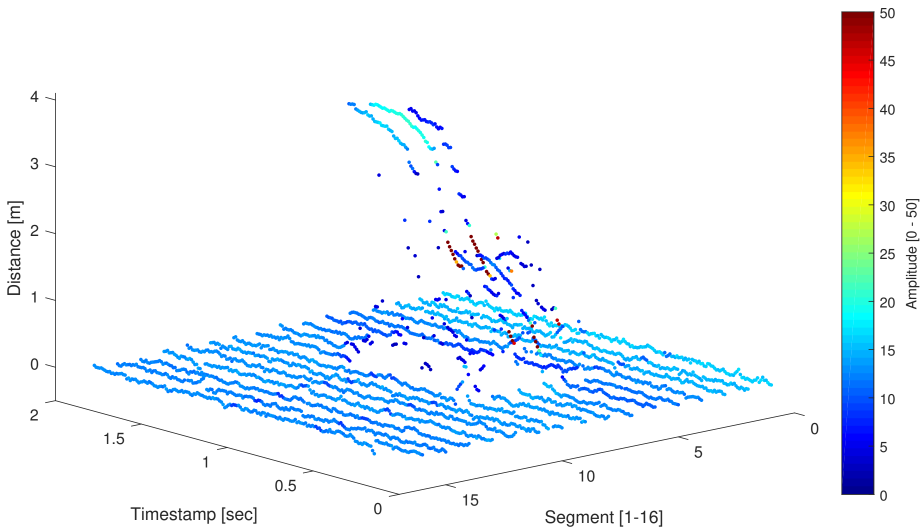

Figure 7.8: Heavy snowing with snow on vehicle, 8 accumulations and 4 oversampling.

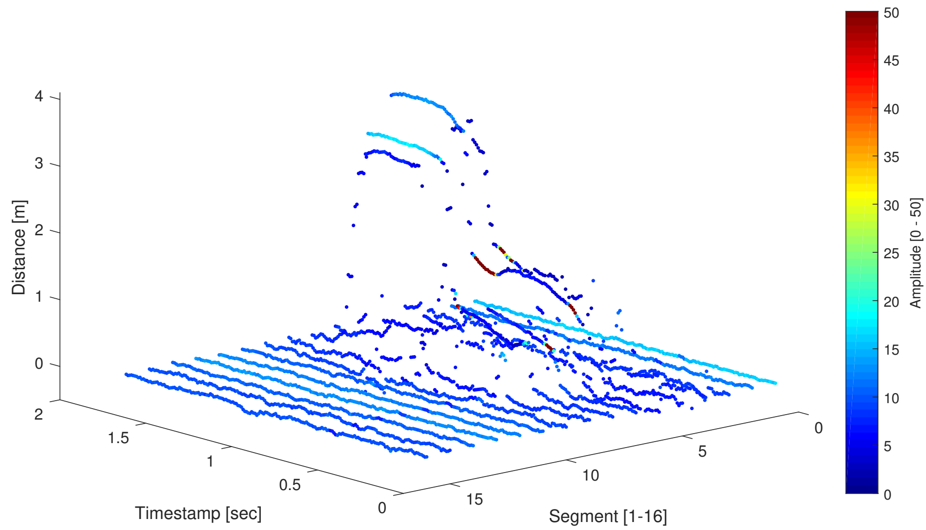

Figure 7.9: Heavy snowfall with snow on vehicle, 32 accumulations and 1 oversampling.

Figure 7.10 and 7.11 represent laps at cloudy weather as seen in the center image in figure 7.16. Note that for the lap with 8 accumulations and 4 oversampling there was still snow on the skibox but not on the bonnet.

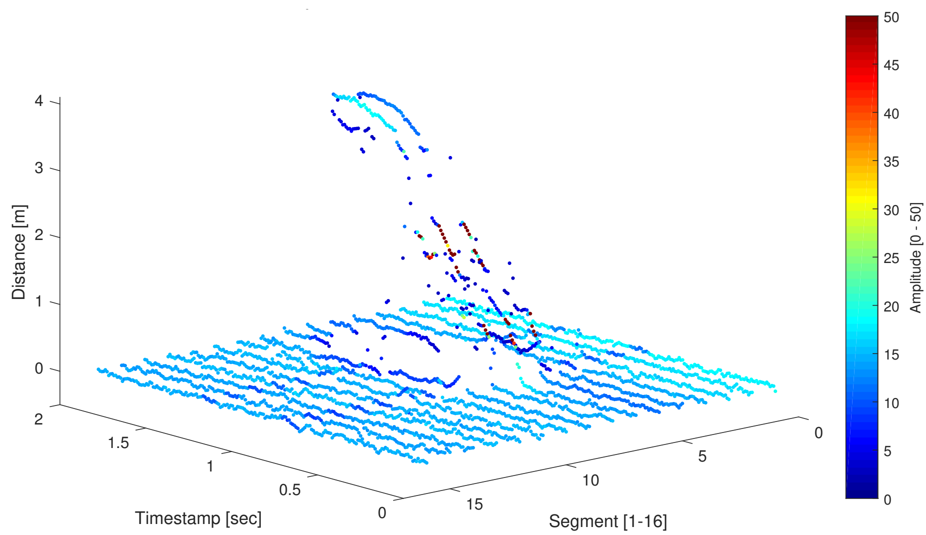

Figure 7.10: Cloudy conditions with 8 accumulations and 4 oversampling.

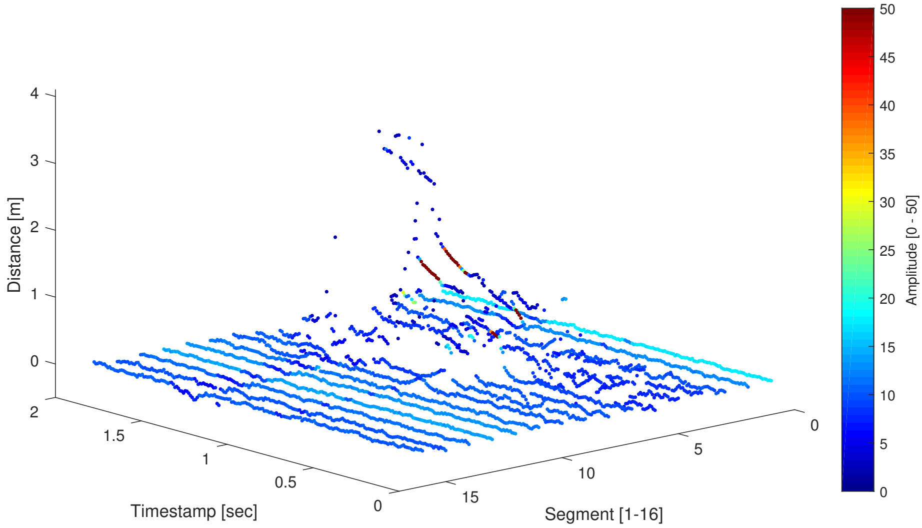

Figure 7.11: Cloudy conditions with 32 accumulations and 1 oversampling.

A clear sky with sun was the conditions for plots seen in figure 7.12 and 7.13. Snapshot of this lap is seen to the left in figure 7.16.

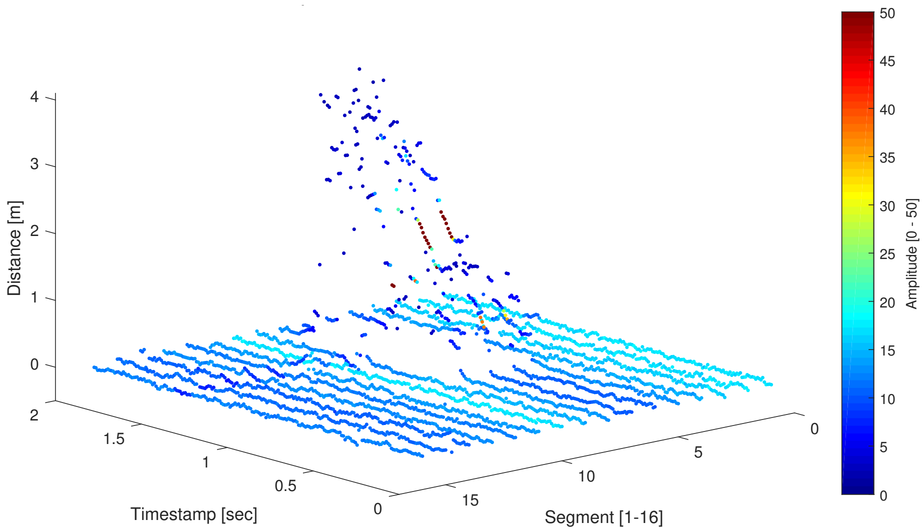

Figure 7.12: Sunny conditions with 8 accumulations and 4 oversampling.

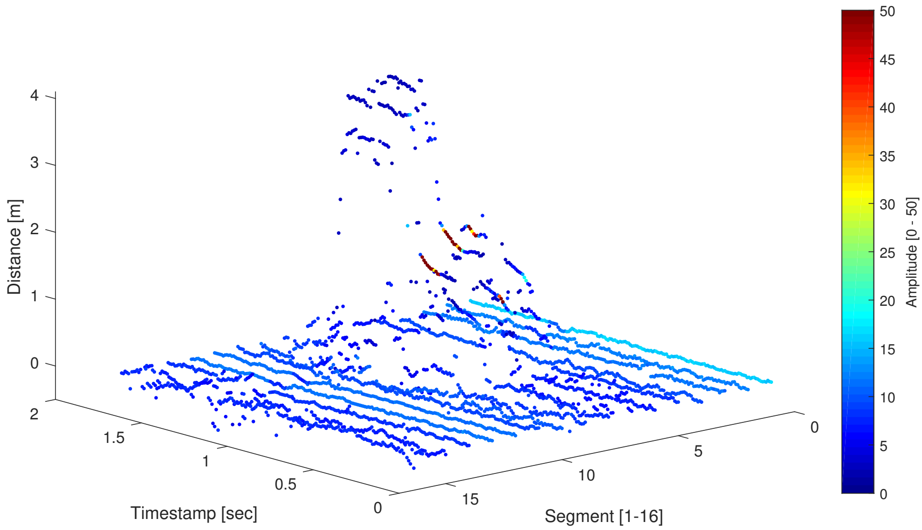

Figure 7.13: Sunny conditions with 32 accumulations and 1 oversampling.

The multiple laps plot displayed is for heavy snowfall and cloudy sky. Figure 7.14 show both tested sensor settings in heavy snowfall while 7.15 is with the cloudy sky.

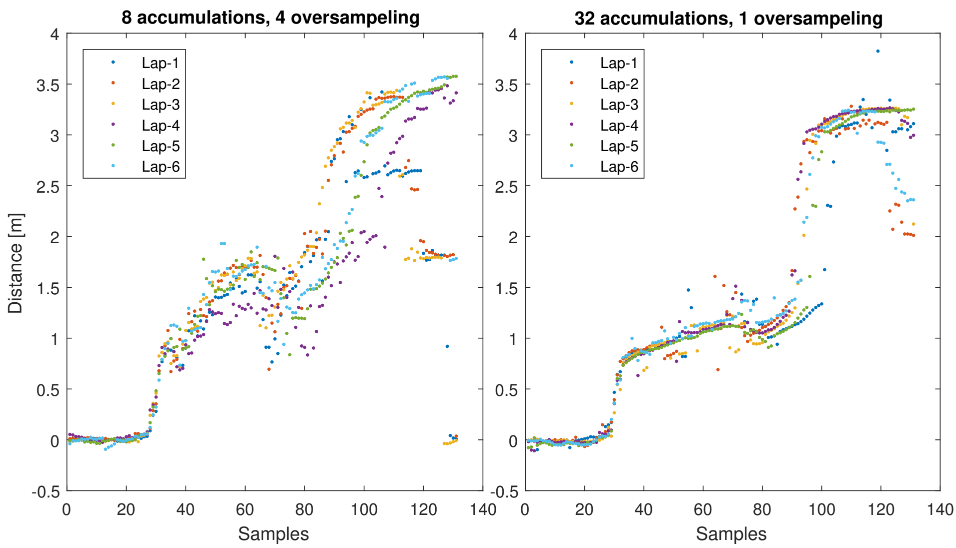

Figure 7.14: Multiple laps in heavy snowfall.

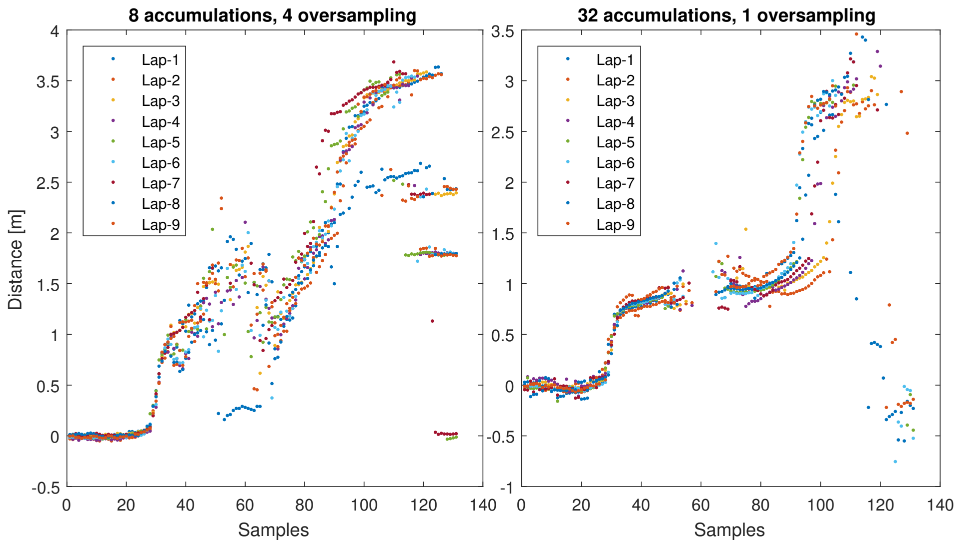

Figure 7.15: Multiple laps with cloudy sky.

Figure 7.16: Vehicle lap in sunny, cloudy and heavy snowfall conditions, with snowy ground.

7.3 Discussion and results

Regarding the sight and reflection problem related to sun, rain and cloudy weather laps seems to be quite similar with respect to data of the passing vehicle. See plots in figure 7.1, 7.2 and 7.3. The only noticeable difference from the vehicle data-samples is that rain seems to make the signal disappear from the windshield. It seems likely that this is due to specular reflection since the glass is wet, which should make the surface even smoother than in a dry state. Regarding the ground data samples the amount of noise is increased significantly compared to snow covered ground plots in subsection 7.2.2. It is then interesting to look at data form the LED-module since it have been seen that this has had more low amplitude noise on ground detections.

In figure 7.4, 7.5 and 7.6 the corresponding laps with the LED-module is seen. Most of the segments is not able to retrieve detections form the ground. Even though the automatic light control runs at 100% for all cases. This gives an indication that bare ground absorbs more light than snow. For the laser-module this leads to increased noise while the LED-module data, that was affected by noise in snow condition, now have too low amplitude for detection. By looking into the amplitude numbers one see that the laser-module is able to retrieve a bit higher amplitude than the LED-module, like seen in table 7.1. Hence, the laser-module with a smaller FoV option is better able to detect low reflective targets than the tested LED-module. The smaller FoV on the laser-module might be some of the reason for this. Figure 7.17 show amplitude for targets with different size and reflectivity. This is testing provided by LeddarTech that it is desirable to verify. The plots is for the 48 degree laser and LED-module.

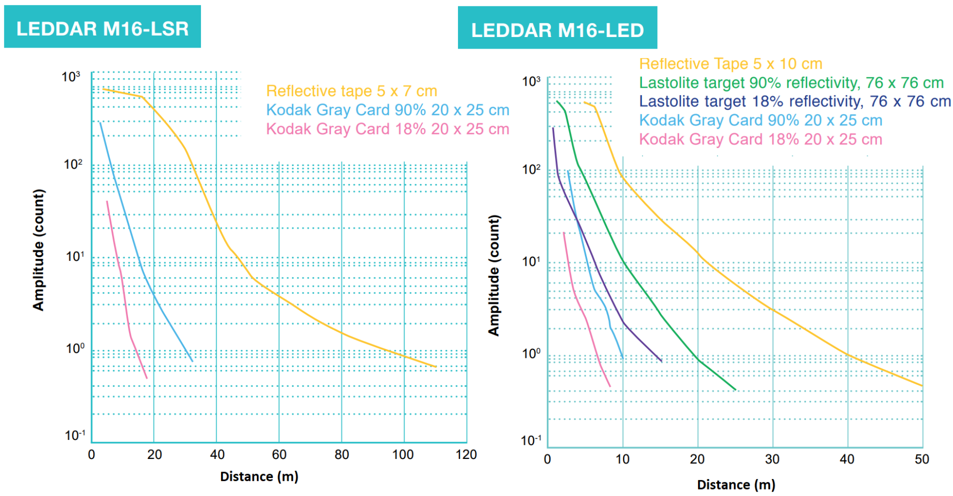

Figure 7.17: Amplitude vs distance plot from LeddarTech. [7]

From the three targets that appear on both plots it can be seen that the laser-module overall has a higher amplitude at the same distances and hence also a larger maximum distance. It correspond with what is seen in my testing and it can be concluded that the laser-module has an advantage over the LED-module when it comes to low reflective targets.

When comparing the 32 accumulations and 1 oversampling setup lap in sun with the ones in cloudy and snowy weather it is observed that the low amplitude ground noise is higher in sun. See figure 7.9, 7.11 and 7.13. The cloudy and snowy lap is with fresh snow while for the sun lap it is a longer time since last snowfall. Here the snow banks is fresher and the snow is plowed and more packet in the lane. Hence the factor of clear weather versus snow and cloudy is not isolated entirely since the snow on the ground is not perfectly the same. Due to this it can not be concluded that the ground measurements is influenced by the sunny, cloudy or snowy weather itself. Instead it seems that snow on the ground causes differences in the data.

By comparing laps with corresponding test factors, the indications are that the 8/4 setting works better than 32/1 in both sun, snow and cloudy weather when regarding the low amplitude ground noise. If comparing figures 7.8, 7.10 and 7.12 with 7.9, 7.11 and 7.13 respectively, a higher amplitude and less noise for 8 accumulations and 4 oversampling is seen from the ground. But when looking at the vehicle data samples, setting 32/1 gives the best coherency and smoothness. By plotting multiple laps this is seen quite clear as shown in figure 7.14 and 7.15. In these multiple laps plots the correlation between multiple laps can be seen. Again the LED module has the advantage of the averaging effect but still the detections from the front of the vehicle with the laser-module is quite good. Taking this into consideration the heavy snowfall does not seem to influence the sensor measurements trough limited sight in any particular way. Also when looking at the signal amplitude, it seems to be sufficient in all the laps with heavy snowfall. The stated robustness of the Leddar sensor in snowfall seems to be correct.

Chapter 8

Multiple vehicles test

This chapter covers the multiple vehicles test which is designed to investigate how close driving vehicles influence the Leddar sensing and detection capability.

8.1 Experimental design and execution

Experience tell that slow driving queue, typically like in rush hours, is one of the most challenging scenarios for a tolling system. Regarding the Leddar modules it is also natural to think that close driving vehicles would be a challenge, especially due to the lower resolution than traditional laser scanners. Therefor, this test is designed to look at how close driving vehicles will influence the sensor data. It is desirable to look at vehicles driving in both queue and side-by-side. The queue experiment is designed to test three different distances between two vehicles. Closest is two meter which is perceived as quite close for the drivers. This is probably the lower bound for how close people would drive to the vehicle in front in a queue. Four and six meters are the other two chosen distances. The leading vehicle in the queue is chosen to be the van since this would cover more of the ground behind seen from the sensors position. The second car is the Subaru Forester. When it comes to the side-by-side testing it is not possible to use two cars since there is only a single lane where the test model is mounted. Hence the Yamaha Aerox is driven side-by-side of the Subaru Legacy.

It is expected that the sensors ability to separate vehicles will be best for the queue driving since the resolution here is influenced by the refresh rate of 100Hz. The vertical size of the FoV projected onto the ground is about 9 centimeters for the laser-module according to table 9.2 in the appendix. In comparison the LED module has about 3.7 meters. Hence it might be that the laser module is better at separating close driving vehicles in queue. The side-by-side resolution is limited by the sixteen segments.

Data collection was executed as planned. During queue testing the weather was sunny with a snow covered ground. While during the side-by-side test it was bare ground, partly cloudy and sunny. Test factors is summarized here:

Sensor parameter setup:

Point Count:	10
Threshold Offset:	0
Laser Control:	AUTO
Change Delay:	1
Smoothing:	OFF
Object demerging:	OFF
Crosstalk removal:	OFF
Debug:	OFF

Test parameter setup:

Lens option:	36x0.2 laser and 48x8 LED
Vehicle:	4
Speed:	20-30km/h
Lane position:	Center
Sensor tilt:	30 degrees
Sensor height:	6.5 meters
Weather conditions:	Varying

8.2 Analysis

Data is presented for analysis in two subsections that represent queue and side-by-side testing, respectively.

8.2.1 Queue

Image seen in figure 8.1 show snapshots from the queue testing.

Figure 8.1: Snapshot from queue testing showing 2, 4 and 6 meters between the cars.

The following four plot show one selected lap with the Hiace and Forester in queue with a two meters gap. Figure 8.2 and 8.3 is the data points from the laser-module while 8.4 and 8.5 is data from the LED-module.

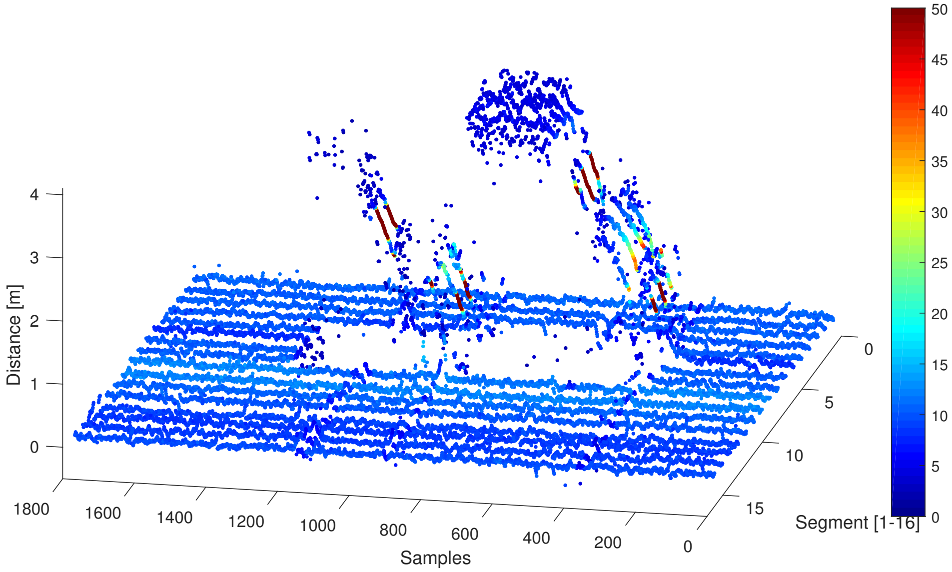

Figure 8.2: Queue lap recorded by laser-module with 2 meters between vehicles. 3D

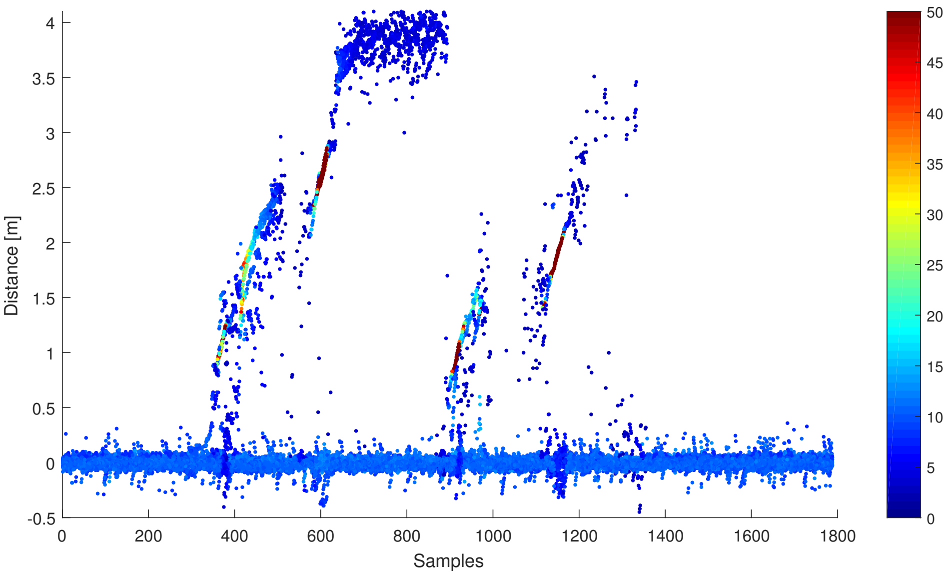

Figure 8.3: Queue lap recorded by laser-module with 2 meters between vehicles. 2D

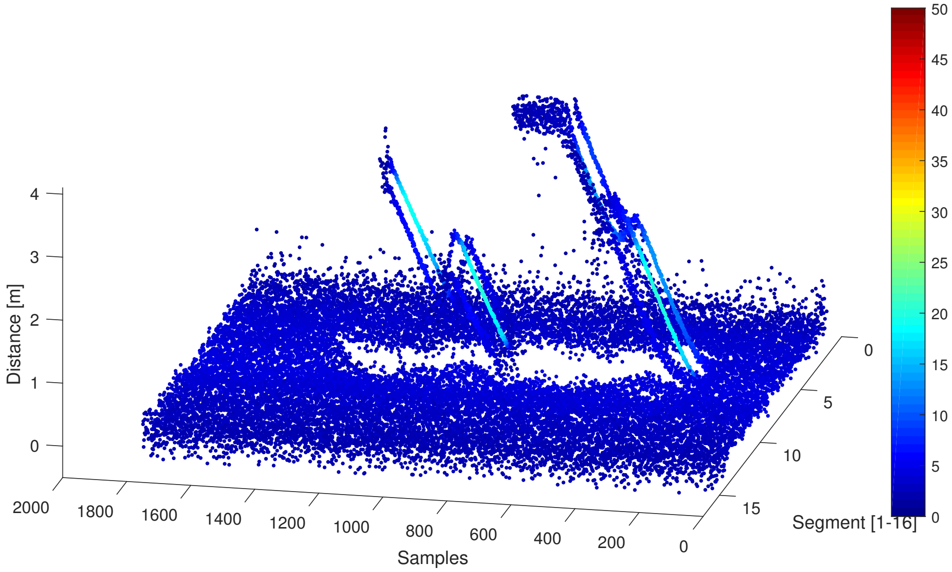

Figure 8.4: Queue lap recorded by LED-module with 2 meters between vehicles. 3D

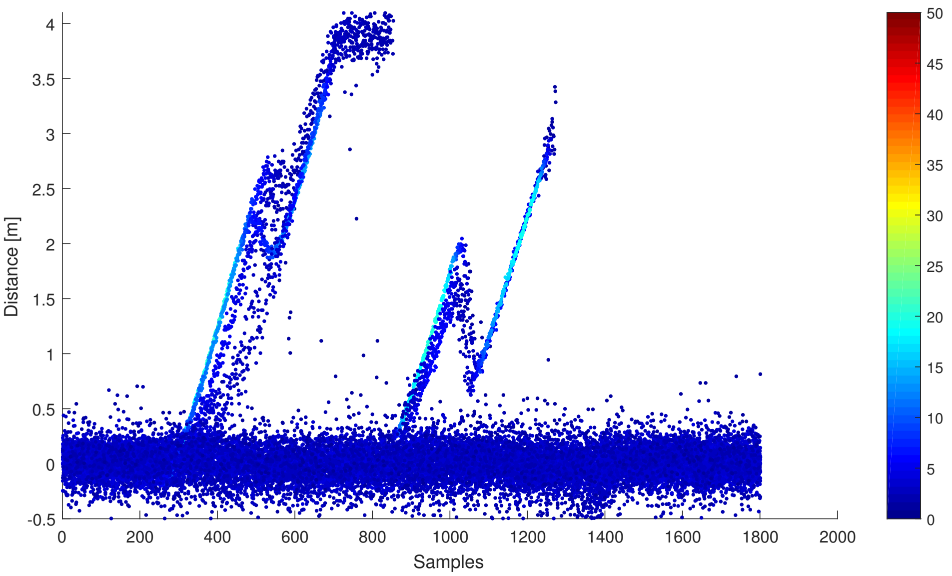

Figure 8.5: Queue lap recorded by LED-module with 2 meters between vehicles. 2D

Figure 8.6, 8.7 and 8.8 show multiple lap plots of the Toyota Hiace and Subaru Forester in queue with 2, 4 and 6 meters gap, respectively.

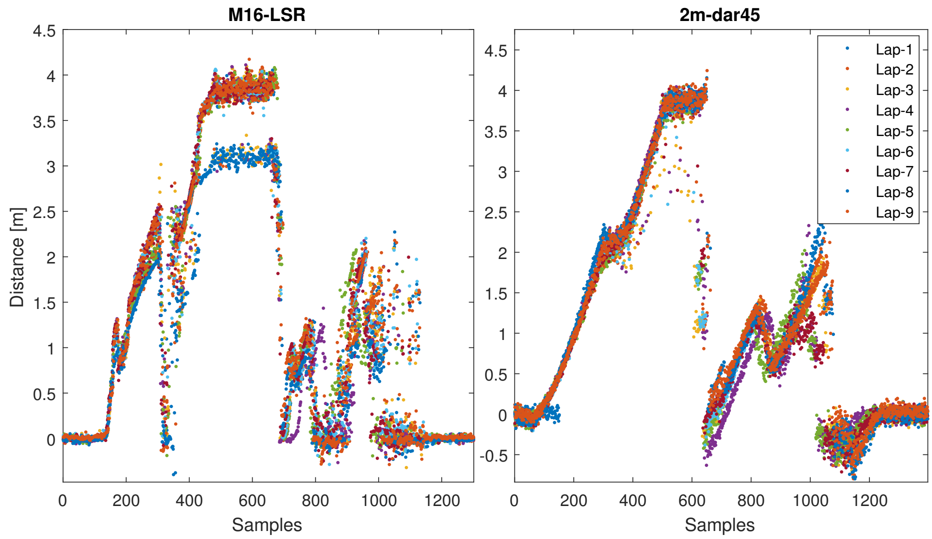

Figure 8.6: Multiple laps of Hiace and Forester in queue with 2 meter gap.

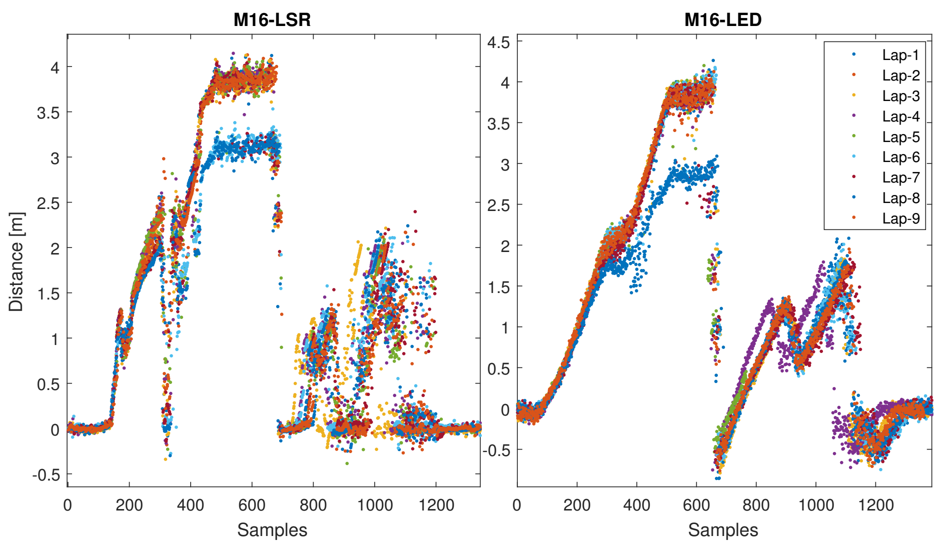

Figure 8.7: Multiple laps of Hiace and Forester in queue with 4 meter gap.

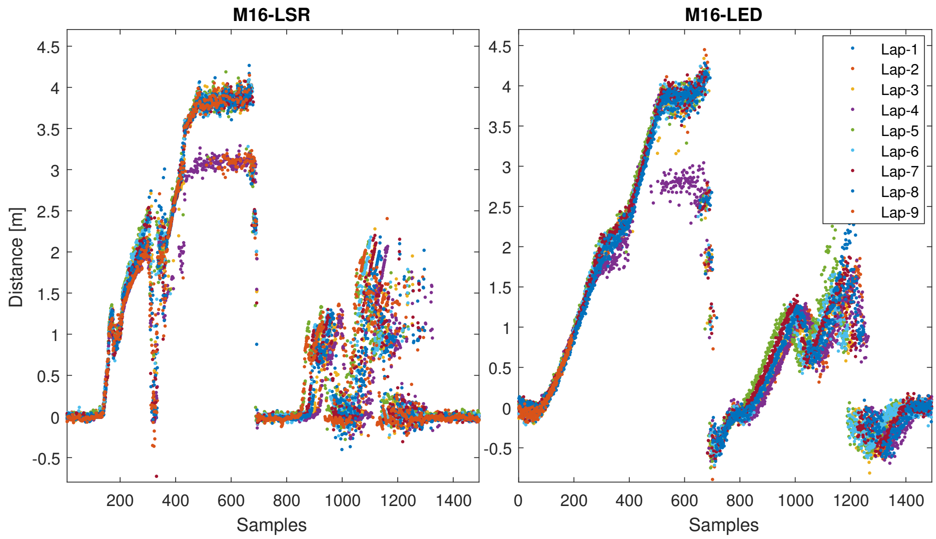

Figure 8.8: Multiple laps of Hiace and Forester in queue with 6 meter gap.

8.2.2 Side-by-side

A snapshot from the side-by-side testing is seen in image 8.9. The snapshot correspond to the following plots of a chosen lap.

Figure 8.9: Snapshot from testing with Yamaha Aerox and Subaru Legacy side-by-side.

The three following figures is from an chosen arbitrary lap where the scooter and Legacy was driving side-by-side. Both plots in figure 8.10 display the point cloud looking straight at the vehicles driving towards you. That is, the data points on the left is of the scooter and the right ones of the Legacy. Left plot is from the laser-module and right plot is of the

LED-module. Note that the distance still is distances seen from the sensors point and not transformed to Cartesian space.

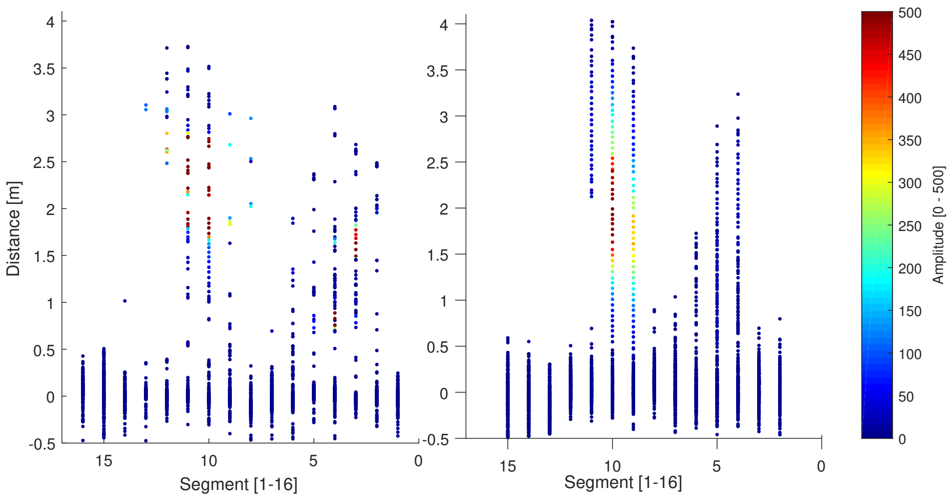

Figure 8.10: XZ-view on point cloud from arbitrary lap. Laser-module left and LED-module right.

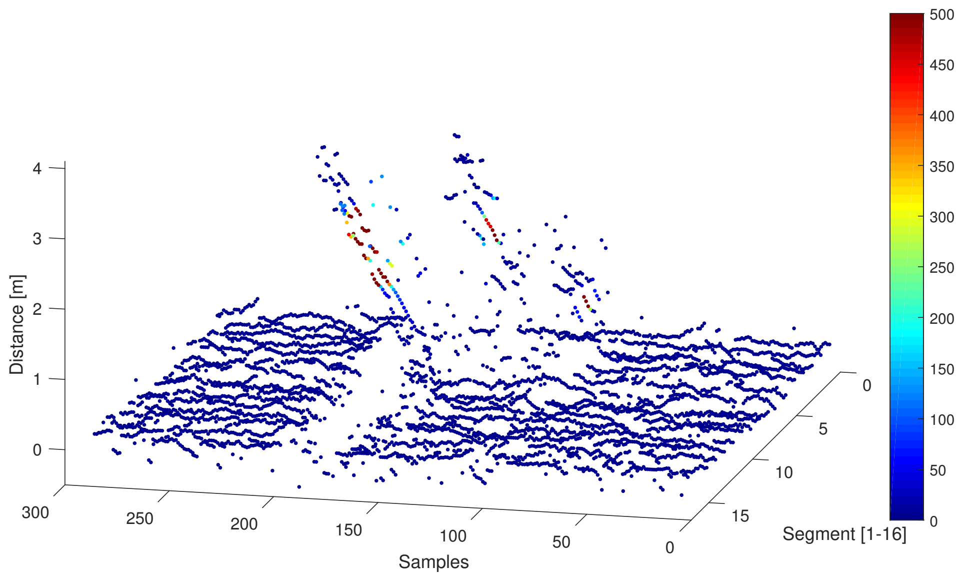

Figure 8.11: Point cloud from arbitrary lap detected with laser-module.

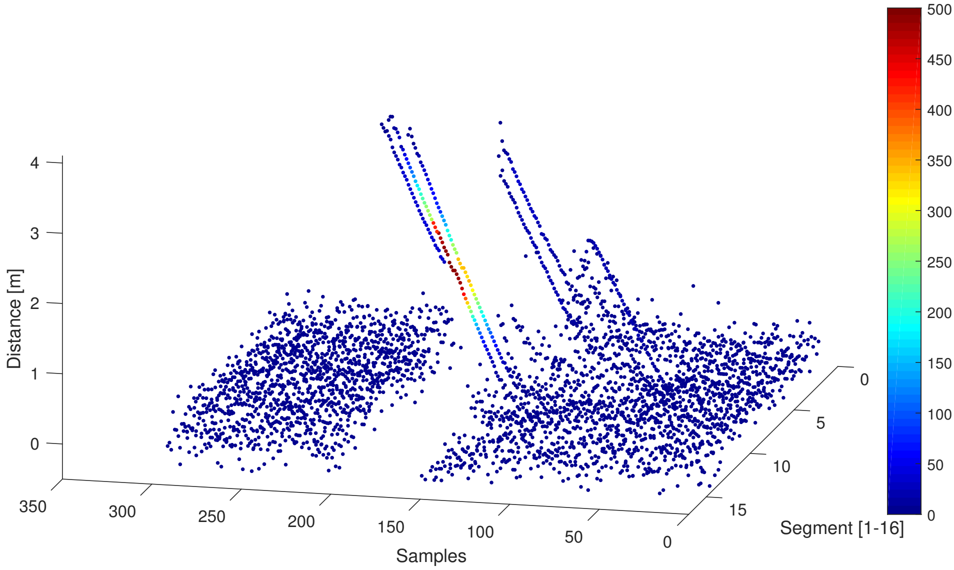

Figure 8.12: Point cloud from arbitrary lap detected with LED-module.

8.3 Discussion and results

By comparing queue plots from the same lap recorded with the two different modules it is seen see that detections of two objects is fairly good. See figure 8.2 and 8.4 where the closes gap of two meters between the cars is used. In advance of the testing it was expected that the data samples for the second car would not start from road level, around zero on the plots, but instead look like an extension of the first car. Hence the results is positive in terms of using the module for triggering. If comparing the LED-module against the laser, one see that separation of two objects seems to be easiest with data from the LED-module. Figure 8.5 show the two vehicles trough a set of similar looking data points. The linear lines is expected to be an advantage for a trigging algorithm to recognize as a object to trig on. In comparison the laser-module data seen in figure 8.3 seems to be harder to separate when one does not know how many vehicles is passing. Four and six meters gap between the cars gave similar looking point-clouds as for two meters gap.

In the multiple lap plots in figure 8.6, 8.7 and 8.8 quite similar looking data for the different tested gap is seen. It is also here emphasized that the LED-module seems to have most stable and coherent data. This is clearly seen of the point cloud from the laser-module for the second car, that has very noisy and chaotic data samples. If looking at the closes tested gap, seen in figure 8.6, it can look like around two meters is just enough for the sensors to separate the vehicles. Hence one could test even closer distances to see how the point cloud would appear then.

The scooter was used during the side-by-side testing as mentioned, this was in the vehicle variation testing found to give a very high amplitude and loss of road detection. Hence it was interesting to see if detection of the Subaru Legacy still was possible. This turned out to not be a problem as seen in the plots in figure 8.11 and 8.12. Still the modules was not able to detect the road while the scooter was in the FoV, due to saturation of lens and therefor reduced intensity of the emitted light. In figure 8.10 one see the point cloud as the vehicle drives towards the camera. From this plot one can see the resolution of the 1x16 segments which was expected to be quite low. The results is as expected and to estimate size of a vehicles is not possible from these data. It should still be possible to use an algorithm for determine that it is two objects form this point cloud, and hence triggering a OCR camera.

Chapter 9

Further work

Fog was not investigated as desired during the weather testing and hence experimental design for this is found in section 9.1. It is determined to continue the work in this project during the upcoming summer. It is several scenarios and factors that is desired to investigate and in section 9.2 these are presented in short.

9.1 Experimental design - Fog testing

Fog was one factor that was not investigated as desired since this weather phenomena did not occur during the project period. It is desirable to do some practical testing with the sensor-module to investigate the stated performance in low visibility conditions. Since fog is more evenly distributed and consistent than rain and snow it is expected that dens fog at one point would "blind" the sensor entirely. Amplitude of the light signal is attenuated in fog and a too low amplitude will make the sensor to loose the ability to detect. The Beer-Lambert-Bouguer law can be used to calculate the attenuation of signal amplitude in fog with equation 9.1. Fog is for this project the most convenient to apply the law onto since it is more evenly distributed and dense than rain and snow. But still the density of fog constantly changes so the calculations is approximations. [17] [18]

$$L = e^{-k_L \cdot d \cdot x_L} \tag{9.1}$$

where,

$d \approx \frac{3}{k_E \cdot V_m}$

V_m are the visibility in meters.

$k_E \approx 10$

x_L travel distance for the emitted light.

$k_L \approx 10$

Some values for visibility in meters together with a description is found in table 9.1.

Table 9.1: Visibility fog.

Visibility [m]	Description
< 40	Dense fog
40-200	Thick fog
200-1000	Fog

By utilizing this formula the expected attenuation related to this project can be found. One example can be dense fog, lets say 40 meters visibility, $V_m = 40$. The current tilt angle and gantry setup gives about 12 meters distance to the road. Since the light must travel back and forth for the sensor to measure distance, this means that $x_L = 24$. With the constant approximations made above this gives the attenuation in fog as seen in equation 9.2.

$$L = e^{-k_L \cdot d \cdot x_L} \approx e^{-10 \cdot \frac{3}{10 \cdot 40} \cdot 24} \approx 0.165 \tag{9.2}$$

This yields an approximation of the attenuation in fog. Both constants regarding light and medium properties is approximated, but still these values should give a good idea of what to expect when investigating the test data. The expected amplitude for a given visibility is found by multiplying the signal amplitude with the attenuation factor. In practice, an amplitude greater than 1 is stated to be sufficient for detection with the Leddar-modules[18]. This was also seen in the weather testing in chapter 7. Here an amplitude around 1 gave detections although the stability was not very good. The amplitude for segments covering the lane is found to typically lie around 10 for the data in hand with snow conditions. This gives an amplitude of 1.65 as seen of equation 9.3.

$$Expected\ amplitude = 10 \cdot 0.165 = 1.65 \tag{9.3}$$

This means that the sensor still should work in the given example with dens fog. During data collection the visibility in meters should be estimated to see if this theory correspond with the actual data.

9.2 Other

Water clouds challenge laser scanners.
In existing tolling systems high resolution laser scanners is used for trigging the OCR camera on incoming vehicles. A challenge for these laser scanners is water clouds that vortices from wet tarmac by fast driving vehicles. These water clouds with tiny water drops stay in the air a long time after the vehicle has passed the tolling site. The water clouds are dense enough for the laser scanners to measure and hence the system gets an false trig. It is desirable to investigate the Leddar-module performance in this scenario due to the solid-state technology and claimed performance in low visibility condition. This could make the Leddar-modules advantageous over the traditional laser-scanners as a trigger.

Sun ahead of Leddar-sensors
Another challenging scenario can be a wet tarmac with the sun aligned ahead of the sensor. During this project the sun appeared behind the sensor and this seemed to not give any big challenges. But by aligning the sun ahead of the sensor specular reflection should reflect more of the sunlight to the receiver lens which could saturate the sensor. Since the sun is such a large source of light it is beveled that this could be quite challenging for any light based time of flight technology.

Classification and Tracking with Leddar
Investigating the possibilities of using a Leddar-module for classification purposes is found best to await since sensors with larger detection matrices than 1x16 is under development. This since classification tasks is known to require good resolution. The sixteen segments covering the road width is not beveled to be sufficient. In order to test a sensor for classification it should be mounted so the lens point straight down into the road. This should give the most stable measurements for determine height, width and length of the vehicles.

It is concluded best to wait for a larger detecting matrix for tracking also. If this new sensor is to be tested I would align the largest number of detection segments with the road. If the road is two lane one could for example have one row of detection segment at each lane.

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Appendix

Table 9.2 show the FoV size projected onto the ground. The calculation is done with MATLAB.

Table 9.2: FoV size approximation on road, at different tilt angle with 6.5 meters mounting height.

Tilt angle	24° **M16-LED**	34° **M16-LED**	45° **M16-LED**	36° **M16-LSR**
20°	8.8x4.1 m	12.3x5.8 m	16.9x8.0 m	12.3x0.194 m
25°	7.1x2.7 m	10.0x3.8 m	13.7x5.2 m	10.0x0.127 m
30°	6.0x1.0 m	8.5x2.7 m	11.6x3.7 m	8.5x0.091 m
35°	5.2x1.5 m	7.4x2.0 m	10.0x2.8 m	7.4x0.069 m
40°	4.7x1.2 m	6.6x1.6 m	9.0x2.2 m	6.6x0.055 m
45°	4.2x1.0 m	6.0x1.3 m	8.2x1.8 m	6.0x0.045 m