# Benchmarking Automotive LiDAR Performance in Arctic Conditions

Kutila, Matti; Pyykönen, Pasi; Jokela, Maria; Gruber, Tobias; Bijelic, Mario; Ritter, Werner

*Published in:*
2020 IEEE 23rd International Conference on Intelligent Transportation Systems, ITSC 2020

*DOI:*
10.1109/ITSC45102.2020.9294367

Published: 20/09/2020

*Document Version*
Early version, also known as pre-print

# Benchmarking Automotive LiDAR Performance in Arctic Conditions

Matti Kutila[1], Pasi Pyykönen[1], Maria Jokela[1], Tobias Gruber[2,3], Mario Bijelic[2,3], Werner Ritter[2]

***Abstract*— This work shows and analyzes the LiDAR performance in real-world heavy winter conditions captured in Northern Europe. We review how low temperatures, salted roads and turbulent snow in front of a passenger car influence LiDAR systems developed for automated driving functions. Two test cars were driven in the north of Finland and Sweden for 1.5 weeks to gather a large amount of point cloud data in different urban and rural scenarios. We show that the benchmarked LiDAR sensors have surprising performance differences in winter. Some of the sensors got mechanically frozen whereas others went out of the measurement range and were completely blind. Especially the latest multi-layer sensors showed significant problems. We propose countermeasures such as heating and protecting in order to improve the performance and suggest how the software can take the performance degradation into account.**

Fig. 1: The instrumented test and development vehicle *Martii* with the sensors installed on the roof.

## I. Introduction

The EU-project aDverse wEather eNvironment Sensing systEm (DENSE) aims to develop better sensing systems for automated driving under adverse weather conditions. The first new sensor prototypes are ready and benchmarking against state-of-the-art sensors has started. In particular, this paper focuses on light detecting and ranging (LiDAR) measurements conducted in Northern Europe. The aim of this test drive was to gather experimental data, benchmark the latest sensors, define challenges in these conditions, and analyze countermeasures for improving existing sensors.

Cameras, radar and LiDAR systems have been investigated for many years by the automotive industry for the development of advanced driver assistance system (ADAS) functions [1]. However, until recently, all commercial ADAS systems such as autonomous emergency braking (AEB), electronic stability control (ESC) and lane departure warning (LDW) are based on radars and cameras because of incredulity of mechanical components in the available LiDAR sensors. For automated driving, significantly better sensors are needed compared to ADAS functions [2]. The resolution requirements are much higher since automated driving needs pattern recognition capability. Instead of just detecting obstacles, classification (pedestrian, bicycle, car, truck, etc.) is inevitable for safe autonomous driving. Therefore, LiDAR systems together with high-resolution radars and traditional camera technology are needed to complement the weaknesses of each other sensor system. Recently, the LiDAR systems have been even considered as the main stream in high resolution range measurement for automated vehicles [3]. Although current LiDAR systems show impressive 3D perception performance, they severely fail in adverse weather situations [4]. The illumination laser beam of LiDAR systems is backscattered or absorbed by the water particles in the atmosphere, which degrades the range of all LiDAR sensors. The severity of the degradation depends on the droplet size and many other physical factors [4], [5]. Nevertheless, the measurement principle of the utilized LiDAR system has impact on the laser power in a single point and thus for the robustness in inclement weather. Although LiDAR benchmarks in controlled laboratory environments exists [6], [7], [4], there is a lack of comparisons of state-of-the art LiDAR systems in real-world adverse weather conditions that validate these experiments. This article provides a very detailed insight into a testing campaign where we have collected a huge amount of LiDAR data and experiences under bad weather influence.

## II. Related work

### A. LiDAR systems

Most state-of-the-art LiDAR systems are based on spinning mirrors for mechanical beam steering [8]. The laser beam is collimated with optical arrangements for acquiring maximal laser power back to the imager. Scanning LiDAR systems are currently the most mature technology and provide the ranges up to 100 m, which makes them a reasonable perception system when driving more than 80 km/h. However, moving components are always vulnerable to mechanical damage especially in cold temperatures and in a vibrating environment. Therefore, LiDAR suppliers

[1]The authors are with VTT Technical Research Center of Finland Ltd., Visiokatu 4, 33720 Tampere, Finland. Tel. +358 40 820 8334; e-mail: matti.kutila@vtt.fi, pasi.pyykonen@vtt.fi, maria.jokela@vtt.fi

[2]The authors are with Mercedes-Benz AG, Wilhelm-Runge-Str. 11, 89081 Ulm, Germany. e-mail: tobias.gruber@daimler.com, mario.bijelic@daimler.com werner.r.ritter@daimler.com

[3]The authors are with the Institute of Measurement, Control and Microtechnology, Ulm University, Albert-Einstein-Allee 41, 89081 Ulm, Germany

are focusing their research and development effort to bring solid-state LiDAR systems on the market where all moving components are replaced by micro-mirrors or other beam-steering technologies. There exists a variety of solid-state LiDAR technologies. A flash LiDAR illuminates the whole scene in one shot and does not need any scanning [9], [10]. Micro-electro-mechanical system (MEMS)-LiDAR systems scan the area by actively steering the beam with MEMS mirrors [11], [12], [13], [14]. Optical phase array LiDAR systems can steer the light beam by controlling the optical properties in a phase array [15], [16], [17], [18]. A detailed overview of state-of-the-art automotive LiDAR systems is given in [19].

These technical solutions have their benefits and drawbacks depending on their planned operation design domains (ODDs). Solid-state or non-spinning LiDAR systems do not have wearing components which are in shaking automotive environment always vulnerable for mechanical damages. On the other hand, flash LiDARs or **ToF!** (**ToF!**) cameras are free of mechanical components but due to that, resolution is poor since steering laser beams becomes challenging when keeping output energy below the eye safety tolerance. There are also differences between LiDARs how band-pass filtering has been implemented. Low band means less noise which is benefit but in cold weather laser wavelengths are drifting and sometimes cause illumination band shifting to cut-off region and leading to performance drop down.

### B. *LiDAR in adverse weather*

A first performance decrease of LiDAR systems due to environment influences was experienced by Peynot et al. where dust particles in the air hide obstacles behind the dust cloud [20]. Trickey et al. investigated, the penetration performance of LiDAR systems in dust, fog, snow white-outs and snow is investigated [6]. Rasshofer and Gresser [1] derived a theoretical model how optical laser sensor performs in various weather conditions. However, the model is theoretical and ignores many of the real world incidences. The behavior in foggy conditions has been investigated by Kutila et al. [21] where the main conclusion is that typical 905 nm LiDAR performance may degrade even 25 % due to absorption caused by water droplets in fog. Thus, the weather usually have serious impact on resolution, reliability and range of the LiDAR sensor. Wojtanowski et al. [7] have investigated the perfomrnace of the two primary wavelengths of LiDAR systems, i.e. 905 m and 1550 nm, in different conditions by calculating the impact of water. Zang et al. [22] observed problems with radars and LiDAR due to heavy rain caused by absorption. Hasirlioglu et al. [23] show the effect of exhaust gases at low temperatures on LiDAR systems. Jokela et al. [24] has performed the study concerning 905 nm LiDAR performance in foggy conditions and also pre-studies in specific conditions in winter. Automotive LiDAR behavior in turbulent snow is a field that has been less experimented on, except in some studies conducted by the space industry [25]. In those experiments the target range is different and even snowflakes are not similar to the arctic powder snow

TABLE I: Details on all six different LiDAR sensors that have been tested in this experiment.

| Sensor | Type | Wavelength | Resolution |
|---|---|---|---|
| Velodyne PUCK | Rotating | 905 nm | 16 layers |
| Robosense | Rotating | 905 nm | 32 layers |
| Cepton HR80T | Flash | 905 nm | 80 px × 80 px |
| Cepton HR80W | Flash | 905 nm | 160 px × 64 px |
| Ouster OS-1 | Rotating | 850 nm | 64 layers |
| Ibeo LUX | Rotating | 905 nm | 4 layers |

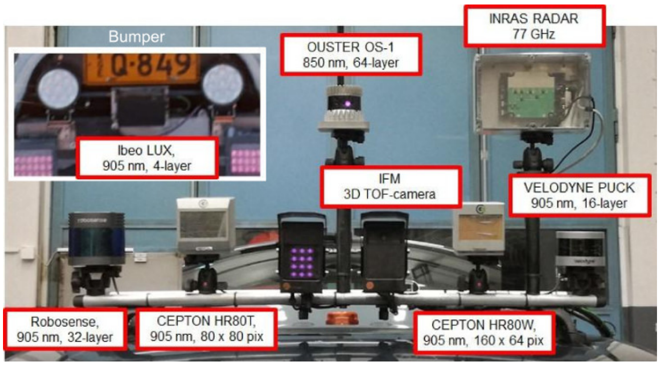

Fig. 2: Mounting positions of the different LiDAR sensors in the "Martti" car.

on the roads of Northern Europe or North America. They have shown that the turbulent snow has significant impact on the LiDAR performance due to degraded visibility. However, their work is based on specific trials in test fields and not in real driving for long duration and various conditions.

Even though that there are theoretical and also short term investigations of the behavior of LiDAR sensors in adverse weather conditions, there is a lack of measurements and evaluations of real driving in order to understand adverse weather conditions. In particular, heavy winter conditions are challenging, which is a mixture of cold, turbulence of snow, strong reflections and wet and dirty snow. In this work, we have recorded a huge amount of LiDAR recordings in heavy winter conditions with different LiDAR sensors. We show a qualitative and quantitative evaluation. With our experiences we want to pave the way to meet safety standards of environment perception systems even under adverse weather conditions.

## III. Test setup

### A. *VTT - Martti*

The test vehicle *Martti* as shwon in Fig. 1 is an automated passenger car with a variety of environment perception sensors. It was equipped with modern LiDAR and radar sensor technologies during the winter testing, see Fig. 2. Six different types of LiDAR from different suppliers were integrated. An overview is given in Table I. All LiDAR systems consist of at least 8 and up to 64 vertical layers. The LiDAR systems can be classified into flash LiDARs (Cepton HR80T and Cepton HR80W) and rotating LiDAR systems (Velodyne PUCK, Robosense, Ouster OS-1, Ibeo LUX). All

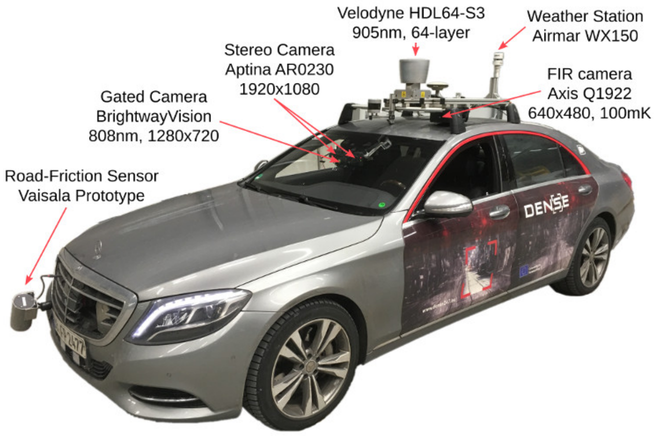


Fig. 3: The measurement platform of Daimler in winter test sessions.

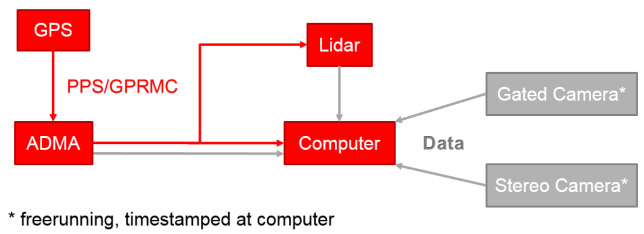


Fig. 4: The time synchronisation platform of the Daimler experiment car. While gray arrows visualize data streams, red arrows describe an explicit time synchronization by PPS signal and GPRMC messages. Gray sensors cannote be triggered and are freerunning, but temporally synchronized according to their arrival timestamp.

except the Ouster OS-1 operate in the 905 nm wavelength, which is the dominating operating band today. We have also integrated a prototype radar and time-of-flight cameras but in this work we focus on the performance of LiDAR systems. The computers for running global positioning system (GPS) time synchronization were installed in the trunk of the car. The data gathering was supervised with laptops and displays in the car cockpit. The point clouds dedicated to automated driving functions were recorded to hard drives (10 TB) and are further analyzed in the laboratory. The data was recorded in a proprietary format to ensure that the third party players did not filter any important data and that the different sensors were well synchronized.

### *B. Daimler - instrumented car*

Fig. 3 illustrates the second experimental car for gathering LiDAR data for the purpose of training intelligent algorithms The aim is to establish training algorithms that improve winter driving scenarios and minimize the influence of winter conditions compared to clear weather. A car was setup with a large variety of sensors for perception with the focus on sensor fusion. We equipped the car with:

- Stereo camera (Aptina AR0230) with a resolution of $1920 \times 1080$ and a framerate of 30 Hz


Fig. 5: The winter test session route in the north of Finland and Sweden on December 2018.

- Gated camera (BrightWay Vision BrightEye) with a resolution of $1280 \times 720$ and a framerate of 120 Hz that is split up into different gated slices
- FIR camera (Axis Q1922) with a resolution of $640 \times 480$ and a framerate 30 Hz
- LiDAR with 64 lines (Velodyne HDL64-S3) at a framerate of 10 Hz

In addition to these important perception sensors, a road friction sensor and a weather station record the current weather and facilitate data selection and labeling. The precise movement of the car is recorded with an automotive dynamic motion analyzer (ADMA) that fuses GPS position information with very accurate acceleration sensors. A powerful computer (Asus X99-E-10G WS, Intel Core i7-6900K, Nvidia Titan Xp, 64 GB RAM) in the trunk records the huge amount of sensor data (~700 MB/s). The whole sensor setup is set up with robot operating system (ROS) that allows easy and fast integration of all sensors in a common framework [26]. For sensor fusion, time synchronization is inevitable. Therefore, we use the GPS timestamp from the ADMA for timestamping LiDAR point clouds and synchronizing the computer time. As Fig. 4 shows, both stereo camera and gated camera are freerunning but can be synchronized according to their timestamps by the ROS Approximate-TimeSynchronizer[1]. During this test drive, we recorded more than 40 TB of data that will help to develop intelligent and robust fusion algorithms and enable driving in all weather conditions.

## IV. Testing Arrangements

Time and route of data gathering was optimized to capture data from various arctic and driving scenarios. The typical weather conditions that exist in winter are:

[1] `wiki.ros.org/message_filters/ApproximateTime`

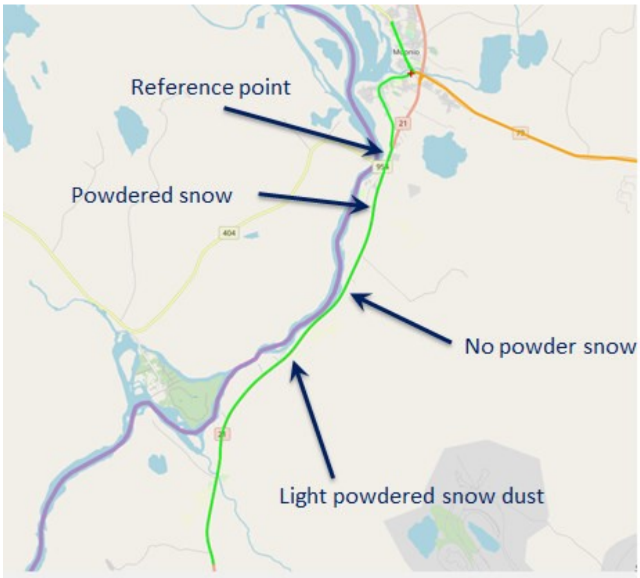


Fig. 6: Powdered snow test sections in the north of Finland.

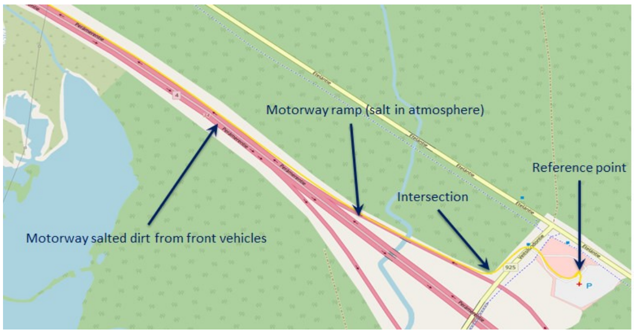


Fig. 7: Salted road test sections.


Fig. 8: The pictures of the different test scenarios in winter.

- *powder snow*: This snow makes the sensors blind especially on highways when following a big car or truck
- *wet snow on the road*: The wet snow covers the sensor lenses when the temperature is close to zero or less than 5 °C above.
- *salted highway*: Salt and dirt makes the sensor windows blind and absorb the light beams
- *low temperature*: For very cold temperatures, mechanical problems with spinning elements arise and slight variations in wavelength decrease the performance, because many of the state-of-the-art high-resolution LiDAR sensors are designed for operation at temperatures above -10 °C

Fig. 5 shows the test route, which took 1.5 weeks of traveling and planning ad-hoc different scenarios for data gathering. The route includes different temperatures and road types. Changing population density in different locations and the amounts of powdered snow required quick reactions and well designed measurement tools, which were self-programmed.
Fig. 6 and 7 show how the scenarios on roads were planned to record multiple different scenarios with the same measurement setups. The planning was important since changing parameters in the measurement section or cleaning the devices would make the measurements non-repeatable and therefore, useless for future automated parameter adaptation.

The important trial scenario is to benchmark the sensors in conditions where the turbulent snow in front of the sensors degrades signal-to-noise ratio. This disturbance is typical when on-coming heavy good vehicles raise snow from the road surface (see Fig. 8). Also, driving behind other passenger cars causes powdered snow walls, which limit the range of the sensors. The impact on LiDAR systems depends on filtering algorithms and the sensitivity of the sensor. During the snow test, the temperature was around -8 to -15 °C and the atmosphere was dry, i.e. optimal conditions for having strong snow turbulence. The road sections were selected for having slushy snow on salted roads to assess the influence and speed of salted roads for the environment perception capability of the car. The main questions were whether a slushy road causes additional absorption of the LiDAR signal and whether there are differences in between sensors due to the dirt in the LiDAR window. During the salted road tests the temperature was between -3 and +4 °C and snow was melting on the road surface due to liquid salt on the road sections. Fig. 9 shows how the visual range of optical devices drops in salted road areas.


Fig. 9: The visual view of different scenarios where salted/wet road feasibility studies were carried out.

## V. Experimental results

The tests have been focused on assessing different type of LiDAR systems (spinning vs. flash and 905 nm vs. 1550 nm) in winter conditions. The aim was to evaluate how environmental factors influence the LiDAR performance in terms of measurement range. The used LiDARs were the ones which do not exist in serial production cars but have the technologies which could potentially improve performance and will be introduced in within 3 - 10 years time span. All the studied LiDAR sensors are spinning types except the one which bases on frictionless micro movements of optical components. However, the different spinning LiDARs depend on their construction and band-pass filtering how they are impacted by snow or being robust against large outdoor temperature variations. Fig. 10 shows the testing principle between the LiDAR and target. The LiDAR beam is reflected at the target with having two parameters: (1) intensity and (2) distance value. Distance is calculated according to the time the light needs to travel from the emitter and return to the receiver. The intensity value is higher for close reflective targets compared to dark targets in far distance. The intensity of the back-scatter light is typically higher for

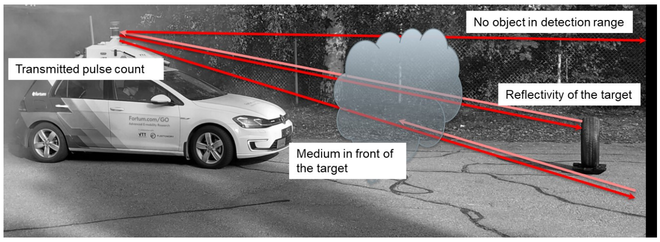


Fig. 10: LiDAR performance can be made comparable by using the maximum measurement range that is influenced by the transmitted number of pulses, the reflectivity of the target and the medium in front of the target.

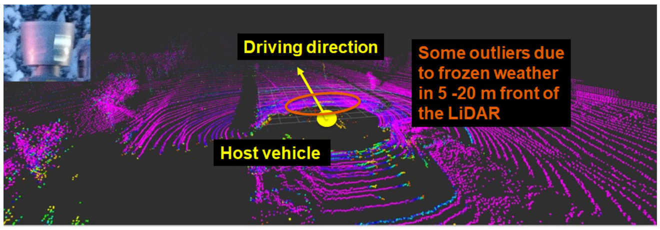


Fig. 11: Qualitative test results of the Velodyne HDL64-S3 when driving in frozen weather. The temperature is less than -10°C. The missing sector on the left is due to other sensors next to the LiDAR.

the objects near the sensor receiver. Therefore, in Figures 16 and 17, dark correlates with higher intensity. The ranges of the sensor are very short (< 20 m) compared to typical LiDAR ranges (50-100 m). The main reason are the high snow banks in the road section. In these measurements, the aim is to assess the maximum range of different weather conditions. Assuming that there are enough objects around the car sampling the distance range, this metric can be considered approximately scene-independent. The following sub-sections are discussing LiDAR performance in adverse weather conditions, (a) cold weather, (b) powder snow, and (c) salted/wet road. The challenges in these different Northern European conditions are quite unique compared to foggy and rainy conditions which are the main automated driving obstacles in middle of Europe. For understanding influence of LiDAR performance, validation has been measured in terms of variation in received laser echoes and whether amplitude variation remains large. In normal conditions, variation should be in reasonable level since scene around the vehicle is changing in reality.

### A. *Experiences in frozen weather*

Fig. 11 shows the Velodyne (64-layer) LiDAR point clouds when driving in frozen weather when the temperature is about -15 °C, which is outside of the operating range of many LiDAR on the market today. Nevertheless, the LiDAR produces stable point cloud data. Fig. 12 and 13 show the problem arising with some of the mechanical LiDARs when the window gets frozen. In these conditions the interior parts of the sensor may also suffer from additional friction or could even get stuck without external heating. Moreover, the wavelength bands in lasers may slightly shift being out of the

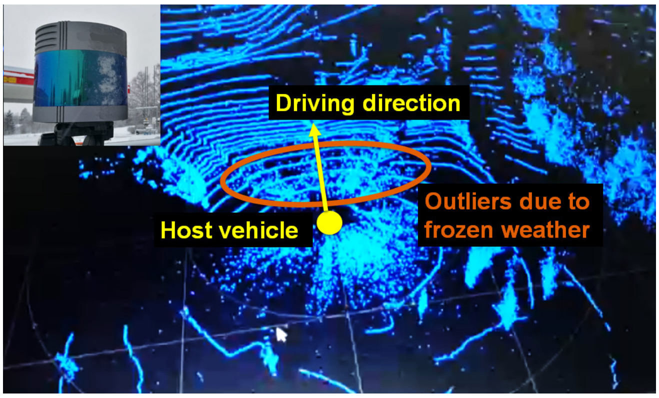


Fig. 12: Frozen weather causes both mechanical problem for spinning LiDARs but also reflections from frost in the sensor window.

Fig. 13: Frozen LiDAR sensor causes disturbance to the measurements and blocks the laser beam.

bandpass ranges, which makes the sensor completely blind. When the temperature rises, the sensor usually starts working perfectly again, but sometimes a software reboot is required.

### B. *Results in powdered snow*

Fig. 16 shows the performance in powdered snow according to the maximum measurement range. The flash LiDARs Cepton HR80W was in trouble when there was turbulent snow in front. We assume that in addition to backscatter the cold temperature caused false measurements. Ouster OS-1 kept its performance well even though snow was in front of the sensor. The Ibeo Lux and Velodyne sensors were also quite stable but Robosense's technique suffered from snowflakes in front of the vehicle as seen from the increased maximum measurement range. Fig. 14 shows how powdered snow causes a lot of noise to the point cloud and makes sensor distance limited. The distance of reasonable pattern recognition drops from 70 m to 25 m ahead of the vehicle and, furthermore, an intelligent data filtering process is needed to handle such situations.

### C. *Performance on salted roads*

Fig. 17 shows the maximum measurement range of different LiDAR systems when driving on salted roads. The main

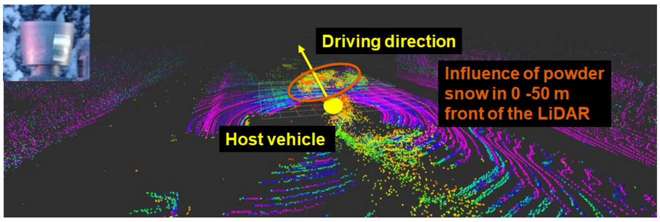


Fig. 14: Powedered snow causes strong noise to the point cloud.

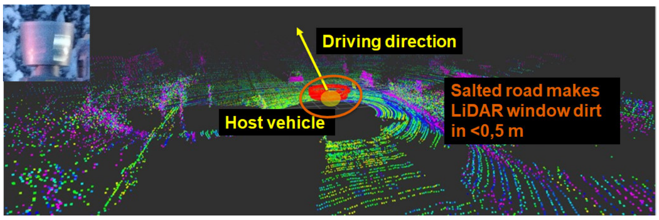


Fig. 15: Salted road in an urban area. The sensor gets partly blind due to dirt but also due to absorption of the light signal.

problem is caused by the fact that the sensor becomes blind due to dirt in the cover of the sensor box. However, that is not the only challenge as the moisture in the atmosphere also absorbs the laser beam. All sensors were affected due to dirty water, which contains a lot of salt. However, the Ibeo Lux sensor, which has already been on the market for years, did not suffer as much as the newer sensors. The benefit of the Lux sensor is that it can record three echoes [27] making it more robust against media between the transmitter and receiver, evidenced in the less than 5 % decrease in the maximum measurement range after the sensor becomes dirty. Fig. 15 shows the LiDAR sensor signal degradation when the road is heavily salted and the sensor becomes blind. The main reason is dirt in front of the vehicle but also absorption caused by the liquid water. Practically, the phenomenon is visible at a close distance from the LiDAR sensor where the red point cloud is shown.

## VI. Conclusions

This article provides an overview of the sensors used in a winter testing campaign in the north of Finland and Sweden. We saw that the traditional LiDAR suppliers, having been in the market for years, have taken the restrictions caused by arctic weather conditions for optical components better into account. The newer suppliers, who have improved the vertical resolution, suffer when visibility becomes limited due to powdered snow or slush. The range of the multi-layer sensors can drop from 100 m down to 20 m even in the case of light snow. The objectives of this study were to analyze what kind of algorithms are needed to process the data and how the benefits of different sensors can be utilized in order to minimize the impact of signal degradation. Some of the sensors need heating which improves their operating performance in cold temperatures. On the other hand turbulent snow in front of the sensor is like noise and many times the patterns are still available if noise is more strongly filtered out compared to a normal situation.

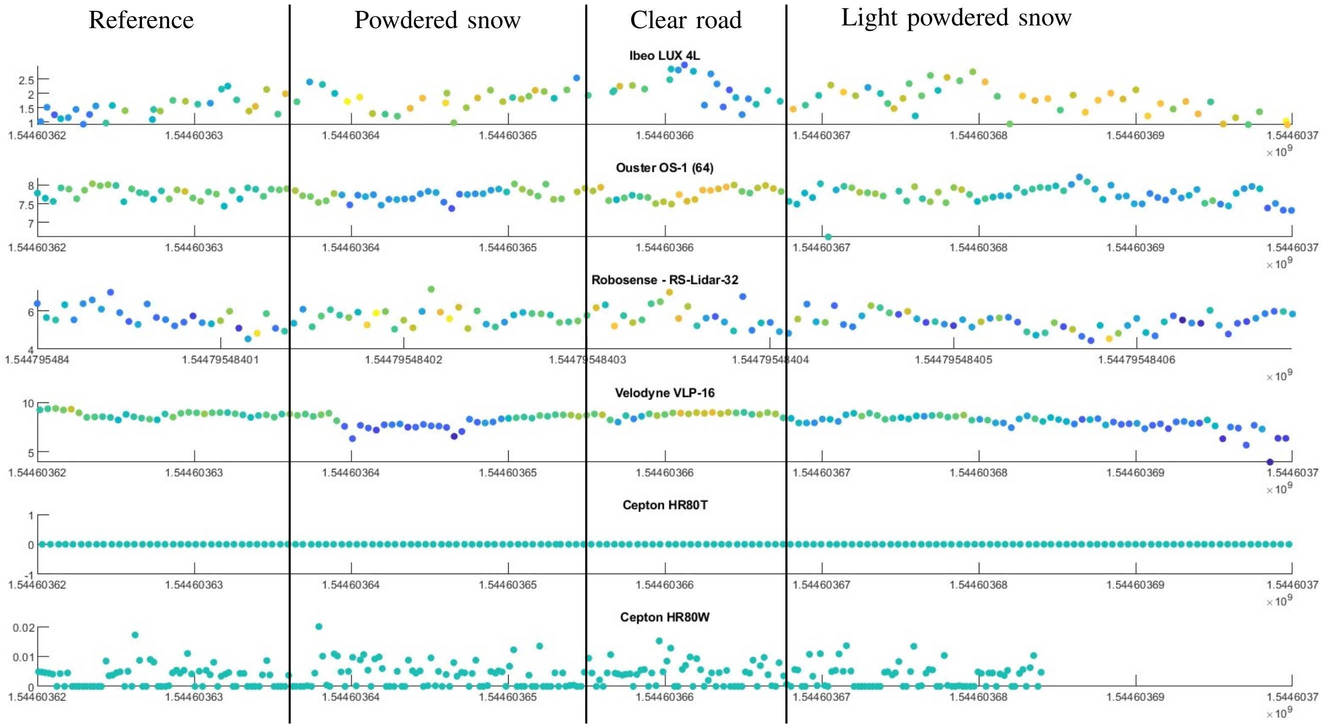


Fig. 16: The measurement results of different LiDAR systems when driving in powdered snow road sections. The color correlates with the intensity of the backscattered beam (light $\rightarrow$ low intensity, dark $\rightarrow$ high intensity).

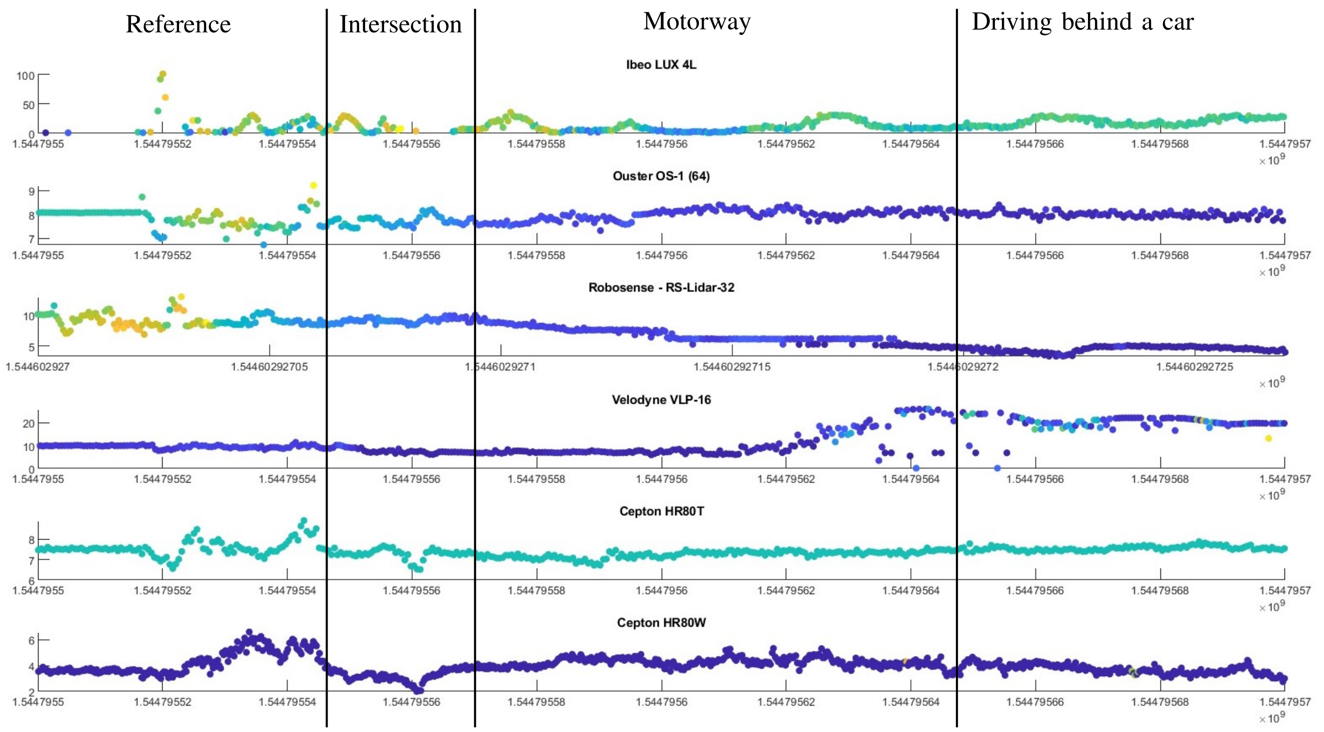


Fig. 17: The measurement results of different LiDAR systems when driving on salted road sections. The color correlates with the intensity of the backscattered beam (light $\rightarrow$ low intensity, dark $\rightarrow$ high intensity).

The other important aspect is to keep the sensor clean. The front bumper is not the optimal mounting position for optical sensors due to dirt and slush. It is better to install sensors at a higher position (e.g. roof of the vehicle) and ensure that freezing water or salted water is not directly sprayed on the front coverage. From a software point of view, we need algorithms that analyze when the coverage is too dirty and assess what the right speed for the vehicle is and when cleaning is needed. Of course, software algorithms can partly handle outliers and artifacts but this article is focusing on understanding signal quality of the future automotive sensors. This is crucial since without feasible signal quality, software tricks cannot compensate information lost in the sensor.

The target of the DENSE project is to develop technologies which enables 24/7 automated driving in all weather conditions. Fog and heavy rain are the main concerns in for level 5 autonomous driving. However, arctic conditions remain one of the bottlenecks which requires different technological approach to keep sensor signal confidence sufficient for highly automated driving. There are basic things like mechanical robustness against coldness but also more complex things like wavelength bandwidth drifting which correlates with temperature. The different LiDAR techniques (flash, spinning, etc.) have their benefits and drawbacks. The main future work is to further develop confidence of the optical sensor devices step by step. With sensor data fusion, the optimal sensors can be selected according to the weather which then extends the automated driving range even if the weather conditions change during the trip.

## ACKNOWLEDGMENT

We would like to express our gratitude to the DENSE project (Grant Agreement ID: 692449) consortium for encouraging designing of the weather robust LiDAR for automotive use. In addition, the algorithm development has been partly done in the AI4DI project (Grant Agreement ID: 826060). The projects has been cofounded by EU-H2020 ECSEL Joint Undertaking and national funding agencies like Business Finland and the Federal Ministry of Education and Research in Germany.

## REFERENCES

[1] R. Rasshofer and K. Gresser, "Automotive radar and lidar systems for next generation driver assistance functions," *Advances in Radio Science*, vol. 3, no. B. 4, pp. 205–209, 2005.

[2] High Level Group on Automotive Industry (GEAR 2030), "Automotive radar and lidar systems for next generation driver assistance functions," 2016.

[3] J. Hecht, "Lidar for self-driving cars," *Optics and Photonics News*, vol. 29, no. 1, pp. 26–33, 2018.

[4] M. Bijelic, T. Gruber, and W. Ritter, "A benchmark for lidar sensors in fog: Is detection breaking down?" in *IEEE Intelligent Vehicle Symposium*, 2018, pp. 760–767.

[5] A. Mäyrä, E. Hietala, M. Kutila, and P. Pyykönen, "Spectral attenuation in low visibility artificial fog: experimental study and comparison to literature models," in *IEEE International Conference on Intelligent Computer Communication and Processing*, 2017, pp. 303–308.

[6] E. Trickey, P. Church, and X. Cao, "Characterization of the OPAL obscurant penetrating LiDAR in various degraded visual environments," in *Degraded Visual Environments: Enhanced, Synthetic, and External Vision Solutions 2013*, vol. 8737, 2013, pp. 113 – 121.

[7] J. Wojtanowski, M. Zygmunt, M. Kaszczuk, Z. Mierczyk, and M. Muzal, "Comparison of 905nm and 1550nm semiconductor laser rangefinders' performance deterioration due to adverse environmental conditions," *Opto-Electronics Review*, vol. 22, no. 3, pp. 183–190, 2014.

[8] Yole Developpement, "The automotive lidar market," Mar 2019, Truckwww.woodsidecap.com/wp-content/uploads/2018/04/Yole_WCP-LiDAR-Report_April-2018-FINAL.pdf.

[9] T. E. Laux and C.-I. Chen, "3D flash LIDAR vision systems for imaging in degraded visual environments," in *Degraded Visual Environments: Enhanced, Synthetic, and External Vision Solutions*, vol. 9087, 2014, pp. 14–25.

[10] R. Rohrschneider, J. Masciarelli, K. L. Miller, and C. Weimer, *An Overview of Ball Flash LIDAR and Related Technology Development*. American Institute of Aeronautics and Astronautics, 2013.

[11] H. W. Yoo, N. Druml, D. Brunner, C. Schwarzl, T. Thurner, M. Hennecke, and G. Schitter, "MEMS-based lidar for autonomous driving," *e&i Elektrotechnik und Informationstechnik*, vol. 135, no. 6, pp. 408–415, Oct 2018.

[12] Ç. Ataman, S. Lani, W. Noell, and N. De Rooij, "A dual-axis pointing mirror with moving-magnet actuation," *Journal of Micromechanics and Microengineering*, vol. 23, no. 2, 2012.

[13] L. Ye, G. Zhang, and Z. You, "5V compatible two-axis PZT driven MEMS scanning mirror with mechanical leverage structure for miniature LiDAR application," *Sensors*, vol. 17, no. 3, p. 521, 2017.

[14] H. Schenk, P. Durr, T. Haase, D. Kunze, U. Sobe, H. Lakner, and H. Kuck, "Large deflection micromechanical scanning mirrors for linear scans and pattern generation," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 6, no. 5, pp. 715–722, 2000.

[15] Y. Wang and M. C. Wu, "An optical phased array for LIDAR," *Journal of Physics: Conference Series*, vol. 772, p. 012004, Nov 2016.

[16] M. J. Heck, "Highly integrated optical phased arrays: photonic integrated circuits for optical beam shaping and beam steering," *Nanophotonics*, vol. 6, no. 1, 2016.

[17] R. C. Hansen, *Phased array antennas*. John Wiley & Sons, 2009, vol. 213.

[18] D. N. Hutchison, J. Sun, J. K. Doylend, R. Kumar, J. Heck, W. Kim, C. T. Phare, A. Feshali, and H. Rong, "High-resolution aliasing-free optical beam steering," *Optica*, vol. 3, no. 8, pp. 887–890, 2016.

[19] S. Royo and M. Ballesta-Garcia, "An overview of lidar imaging systems for autonomous vehicles," *Applied Sciences*, vol. 9, no. 19, p. 4093, 2019.

[20] T. Peynot, J. Underwood, and S. Scheding, "Towards reliable perception for unmanned ground vehicles in challenging conditions," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2009, pp. 1170–1176.

[21] M. Kutila, P. Pyykönen, W. Ritter, O. Sawade, and B. Schäufele, "Automotive lidar sensor development scenarios for harsh weather conditions," in *IEEE International Conference on Intelligent Transportation Systems*, 2016, pp. 265–270.

[22] S. Zang, M. Ding, D. Smith, P. Tyler, T. Rakotoarivelo, and M. A. Kaafar, "The impact of adverse weather conditions on autonomous vehicles: How rain, snow, fog, and hail affect the performance of a self-driving car," *IEEE Vehicular Technology Magazine*, vol. 14, no. 2, pp. 103–111, 2019.

[23] S. Hasirlioglu, A. Kamann, I. Doric, and T. Brandmeier, "Test methodology for rain influence on automotive surround sensors," in *IEEE International Conference on Intelligent Transportation Systems*, Nov 2016, pp. 2242–2247.

[24] M. Jokela, M. Kutila, and P. Pyykönen, "Testing and validation of automotive point-cloud sensors in adverse weather conditions," *Applied Sciences*, vol. 9, no. 11, p. 2341, 2019.

[25] J. Kerekes, J. Zhang, A. Goodenough, and S. Brown, "Theoretical modeling of lidar return phenomenology from snow and ice surfaces," in *IEEE International Geoscience and Remote Sensing Symposium*, 2013, pp. 616–619.

[26] A. Koubaa, *Robot operating system (ROS): The complete reference*. Springer, 2018, vol. 3.

[27] Y. Lin, J. Hyyppä, H. Kaartinen, and A. Kukko, "Performance analysis of mobile laser scanning systems in target representation," *Remote Sensing*, vol. 5, no. 7, pp. 3140–3155, 2013.