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Automotive LiDAR performance verification in fog and rain*

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***Abstract*—This article focuses on testing and investigating further development needs for LiDARs in self-driving cars in adverse weather. The article compares two different LiDARs (Ibeo Lux and Velodyne PUCK), which both use the 905 nm wavelengths, which are used in more than 95 % of currently available LiDARs. The performance was tested and estimated in stabilized fog conditions at Cerema fog chamber facilities. This provides a good basis for repeating the same validation procedure multiple times and ensuring the right development decisions.**

However, performance of the LiDARs suffers when the weather conditions become adverse and visibility range decreases. A 50 % reduction in target detection performance was observed over the exhaustive tests. Therefore, changing to higher wavelengths (1550 nm) was considered using redesigned "pre-prototype LiDAR". The preliminary results indicate that there is no reason to not use 1550 nm wavelength, which due to eye safety regulations gives an opportunity to use 20 times more power compared to the traditional 905 nm. In order to clarify the expected benefits, additional feasibility studies are still needed.

I. Introduction

To enable automated driving not only on sunny days but also when weather conditions are challenging, even for human drivers, advanced sensor technologies are needed. The sensor devices that exist today in markets are designed for Advanced Driver Assistance Systems (ADAS), which do not meet the measurement requirements of automated driving [1]. The objective of the European DENSE project is to develop new sensor sub-systems (see Fig. 1) based on:

- Gated SWIR camera
- Light Detection and Ranging (LiDAR)
- SWIR LiDAR
- Radio Detection and Ranging (Radar)
- High resolution radar
- On-board road friction measurement unit
- Hyper-spectral imaging for material detection

This study focuses on LiDAR sensor alternatives, which will be a key component in automated vehicles due to a range of up to 150 m and their high lateral resolution [2]. The aim of this study is to understand how the performance of the automotive LiDAR sensor dedicated to automated driving is affected in adverse weather, especially in low visibility due to fog or rain.

All of these new sensor prototypes are expected to enhance vehicle environment perception capability in foggy and rainy conditions by providing complementary components for the existing sensor sub-systems. Since the project is in the R&D phase and the new functions are under investigation the project partly ignores the size and cost constraints of automotive products. On the other hand, these limitations are not completely forgotten by selecting the sensors that, after entering the mass market, could be considered as real automotive products with a reasonable price.

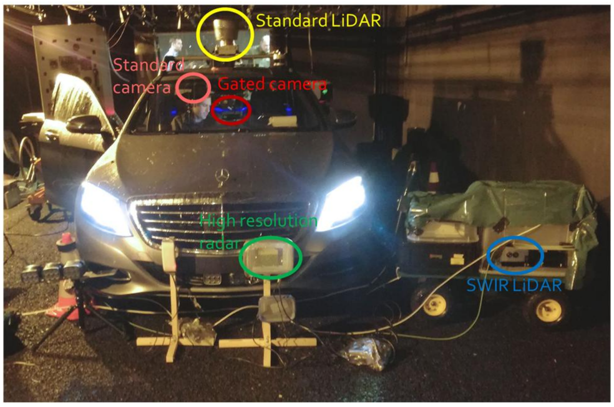

Figure 1. The new adverse weather sensors for automated driving under development

For current automotive Time-of-Flight (TOF) LiDAR sensors, operating at a wavelength just outside the visible range of the human eye, e.g., at 905 nm, fog becomes particularly challenging. This is due to light being scattered by fog particles (radius varying from 0.01 μm to 15 μm [3]), which not only drastically reduces the detection range, but also leads to false detections [4]. There is a controversial and ongoing discussion on whether scattering effects, the potential of which are studied using Mie's theory [5], can be lessened by moving to a higher operating wavelength, such as 1550 nm [6]. An operating wavelength of 1550nm has two potential benefits:

- Less scattering in fog,
- Use of more optical energy due to relaxed eye safety regulations.

In this article we investigated if we can measure less scattering in fog at 1550 nm in comparison to 905 nm, neglecting the effects of more optical power. However, more optical power is of at least equal importance for LiDAR

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development, since the performance of a sensor (be it a classical scanning or a solid-state system) will always be influenced by the amount of optical power emitted. In this regard, 1550nm is clearly superior to 905 nm. Some studies were conducted on this topic in the past, see [7] or [8]. With the measurements introduced here, this article contributes to the discussion by finding out the potential benefits of using 1550 nm laser instead of the traditional 905 nm wavelength in foggy conditions.

II. Test facilities

To investigate the impact of adverse weather conditions on traffic safety and mobility Cerema, the French center for studies and expertise on risks, environment, mobility and urban and country planning [9], operates a specific research infrastructure at Clermont-Ferrand laboratory [10]. The labs have been tailored for development of advanced driving assistance systems and of new sensors dedicated to autonomous driving. In order to reach Level 5 automation [11] a huge amount of test scenarios need to be carried out. The objective is that one day, automated vehicles can take complete responsibility for driving 24/7 in all weather conditions (rain, snow, mist, sleet, hail, fog, smoke, dust, etc.) in which even a human driver may have difficulties [12]. Therefore, testing facilities are needed to repeat the same scenarios multiple times in order to adapt different sensors. In a natural driving situation, environmental conditions are random and not possible to repeat on request. The testing facility provides controlled and reproducible conditions for running series of tests in similar conditions (see Fig. 2).

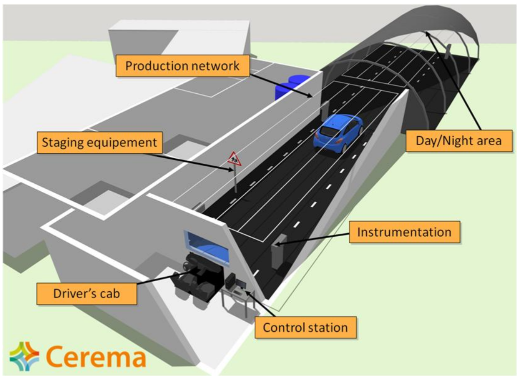

Figure 2. The Cerema fog and rain platform

This fog and rain platform [10] allows the reproduction and control of droplet size of fog, meteorological visibility, and the particle size of rain and its intensity. The infrastructure is 30 meters long, and can be shared in 2 parts, a tunnel, of durable construction, and a greenhouse of lightweight construction to provide night and daytime conditions respectively. The infrastructure is equipped with calibrated weather sensors for measuring the relevant parameters:

- Meteorological visibility from 5 to 1000 m, with a transmissometer,
- Fog particle size distribution: from 0.4 to 40 microns with an Optical granulometer,
- Rainfall intensity from 0.001 to 1200 mm/h, with a rain gauge and a spectro-pluviometer

For the characterization of road environment, road surface, markings, road signs, pedestrians and cars, the following measurement instruments are used:

- a Video-photocolorimeter to measure Luminance from 0.003 to 50000 cd/m² in the visible range,
- a spectroradiometer to determine the reflection properties of surfaces in the range of wavelengths from 330 to 2000 nm
- Camera in visible, near infrared, short-range infrared and long wavelength infrared.

The red line of testing methodology is to reproduce testing of the DENSE novel sensor suite to enable an iterative development process. Furthermore, the baseline data has been gathered for evaluating progress beyond the stated of end of the project.

As regards the definition of fog, it corresponds to a visibility of less than 1 km distance [13]. In transportation, fog is a critical factor when the visibility is less than 400 m. The French norm NF P 99-320 (AFNOR, 1998) defines road fog into 4 classes, as shown in TABLE I. A road fog has a lower threshold of visibility than a meteorological fog (1 km). This standard also specifies that visibility measures have to be taken at 1.20 m above the ground.

TABLE I. Definitions of fog classes from the AFNOR norm NF P99-320 (April 1998)

	Road visibility class	Visibility distance (m)
Meteorological fog		< 1000
Road fog	1	200 to 400
	2	100 to 200
	3	50 to 100
	4	< 50

During tests in the Cerema Fog and rain platform, fog is reproduced multiple times especially in the critical visibility classes (2, 3, 4). The fog density can be increased slowly from 7 up to 200m (dissipation mode) or can be maintained at a certain level for a while if needed. Fig. 3 and Fig. 4 illustrate how the visibility can be adapted in the chamber over time. During sensor data gathering, the weather characterization parameters are also recorded to analyze their behavior later on.

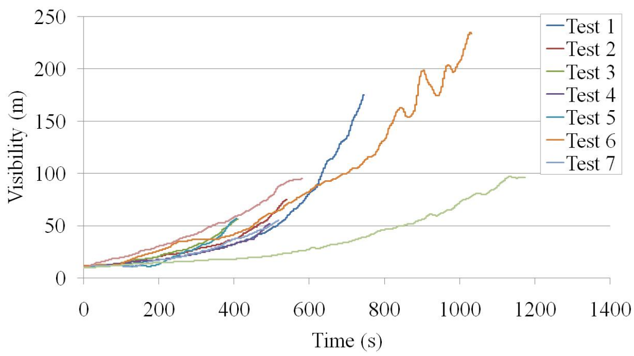

Figure 3. Visibility versus time during natural fog dissipation in the fog and rain platform

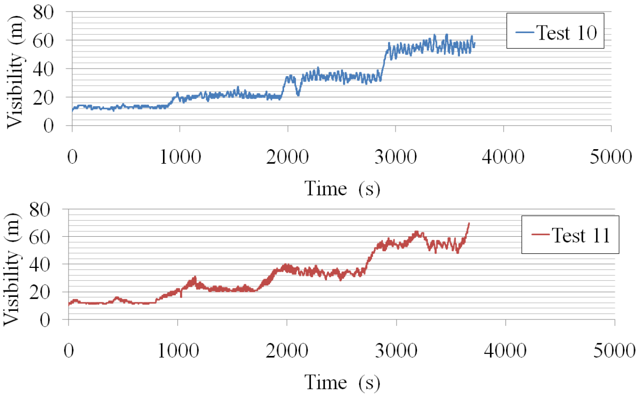

Figure 4. Visibility versus time during stabilized foggy conditions

In addition to fog, the second main parameter was rain intensity and 50 mm/h was used in the tests, which is kind of extreme. Table 2 from standard NF P 99-320 provides information about the range of rainfall intensities used (in mm/h).

TABLE II. STANDARD NF P 99-320 GIVES THE RANGE OF RAINFALL INTENSITIES (I IN MM/H)

Rain fall intensity in mm/h	**Rain**	**Drizzle**	**Snow water equivalent**
Very light	< 0.1	< 0.1	< 0.1
Light	0.1 ≤ I < 2.5	0.1 ≤ I < 0.25	0.1 ≤ I < 2.5
Moderate	2.5 ≤ I < 7.5	0.25 ≤ I < 0.5	2.5 ≤ I < 7.5
Strong	I ≥ 7.5	I ≥ 0.5	I ≥ 7.5
Strong rain recorded in Europe (France)	25	---	---
Tropical Cyclone data (Réunion)	250	---	---

III. TEST EQUIPMENT

A simple, 1550 nm LiDAR, called Hello World LiDAR (HWL), with opto-mechanical parameters similar to the parameters of the existing 905 nm Ibeo Lux LiDAR [14] was built. They both utilize avalanche photo diodes as detectors, their emitted light pulses have the same Full Width at Half Maximum (FWHM) and their spot sizes (the solid angle that is illuminated as well as the solid angle the detector receives reflections from) is equal. The only difference is the emitted pulse energy, $E_{p,HWL} \approx 100\ \mu J$ and $E_{p,Lux} \approx 100\ nJ$, due to different class 1 laser safety limitations at 1550nm and 905nm respectively. Both sensors measure in the same direction on one common target (see Fig. 5).

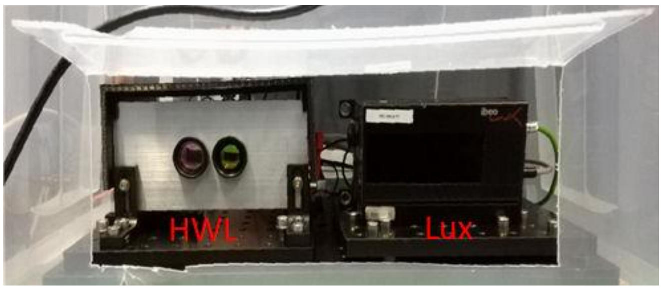

Figure 5. LiDAR test setup (HWL on the left, Lux on the right).

Two fog chamber test run periods were carried out, one in April 2017 and a second in December 2017. In both periods, the HWL/Lux setup was used at different target distances d and different meteorological visibilities V. There were also two different droplet sizes s, measured on two different days in Dec 2017. The parameters are listed Table 3.

TABLE III. MEASUREMENT PARAMETERS OF OUR TWO TEST RUNS.

VARIABLES	**Apr 2017**	**Dec 2017**
target distance d / m	15	05, 10, 15, 20, 25
meteorol. visibility V / m	25, 30, 40, 50	10, 20, 30, 40, 50
target color c	wooden	black, white
droplet size s	big	small, big
measurement days	day 1	day 1, day 2

IV. LIDAR RESULTS

A. *905 and 1550 nm LiDAR tests*

The data was analyzed to achieve a 'relative comparison' between the two wavelengths, 905 nm and 1550 nm. A TOF signal, as recorded by an oscilloscope attached to the detector of either HWL or Lux sensor, is schematically shown in Fig. 6.

The target's distance can be calculated from the TOF, i.e., Δt, with $d = c*\Delta t/2$. For such a measurement, the 'target reflection' peak is obviously of huge interest, since the hatched area can be thought of as the optical energy reflected back from our target. The more reflected energy we detect, the better our signal becomes. The challenge in fog is that a lot of our signal is 'lost' in the 'fog reflection' peak due to reflection, scattering and absorption of fog particles.

With the measurements, the aim was to find out if the optical power reflected by our target decreases more with increasing fog density for one wavelength or the other. The following procedure was used in the analysis:

1. recorded signals for various configurations of parameters
2. defined the 'reflected energy' E, i.e., the detected optical energy reflected back from our target at different visibilities $V = \{10\ m, 20\ m, 30\ m, 40\ m, 50\ m\}$, to be the hatched area enclosed by the second peak in Fig. 7,
3. defined the reflected energy from measurements taken at $V = 50\ m$ to be our 'reference energy' E_{ref}, i.e., $E50 = E_{ref}$ for both sensors,
4. divided all reflected energies $E\{10,20,30,40,50\}$ by the reference energy E_{ref} to get a 'comparison value' $\alpha = [0, 1]$ (assuming the measured reference energy is highest, which does not hold true as is analyzed below).

A small example of this procedure is schematically shown in Fig. 7, where $\alpha = E_{meas}/E_{ref} = 0.5$, i.e., the measured energy E_{meas} at visibility V_{meas} is half of the reference energy E_{ref}. Consequently, we expect α to become smaller for decreasing visibilities V.

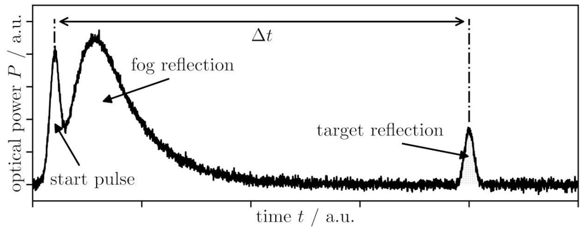

Figure 6. Schematic TOF Signal

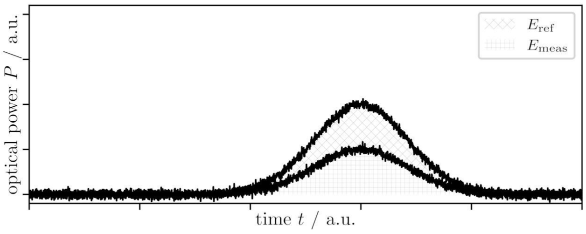

Figure 7. Illustration of the α = Emeas/Eref calculation

The analysis contains three measurement runs from December 2017 as well as one measurement run from April 2017. The selected measurements are the ones where the detector did not saturate to avoid nonlinearities. Differences in, e.g., target distance or target color should not matter since they would only have an influence on the absolute amount of reflected energy. However, the purpose of relative comparison is to eliminate absolute values and get rid of any opto-mechanical dependencies. In Fig. 8-Fig. 10, one can see two curves, which show a relative comparison of our HWL and Lux sensors.

On the x-axis the meteorological visibility *V* is shown, decreasing from left to right, i.e., the fog becomes denser, and on the y-axis we have our comparison value α. Fig. 11 shows the relative comparison of the measurements executed in April 2017. At that time only two/three measurements were done in different visibilities, which is why the calculated values are shown without any error estimation.

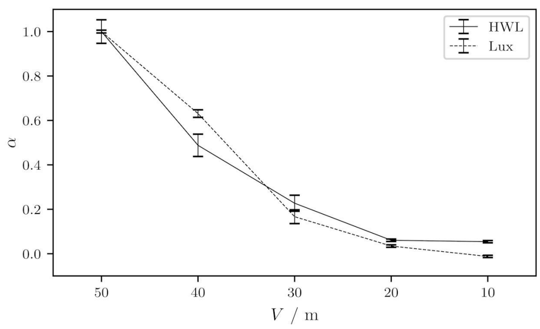

Figure 8. α for a white target in big fog droplets on day 1 (Dec. 2017).

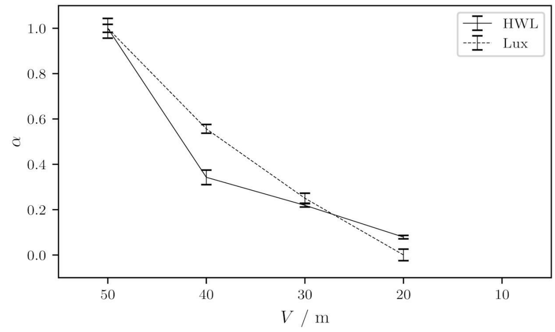

Figure 9. α for a white target in small fog droplets on day 1 (Dec. 2017).

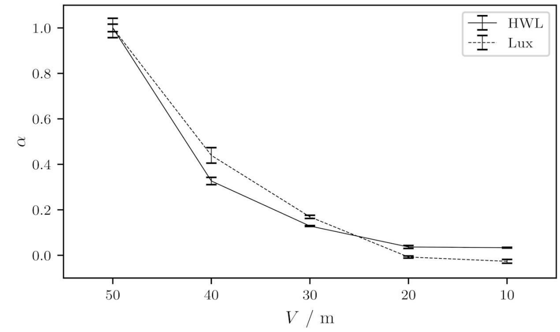

Figure 10. α for a white target in small fog droplets on day 2 (Dec. 2017).

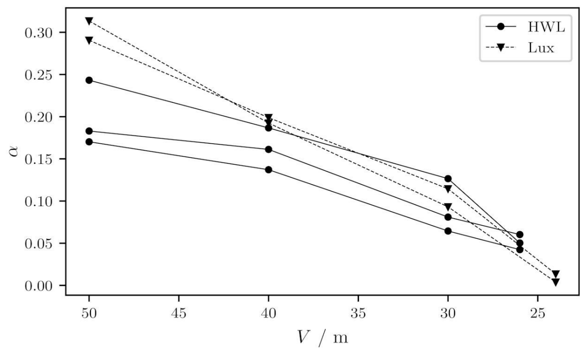

Figure 11. α for a wooden target in big fog droplets (Apr. 2017).

B. VTT's LiDAR tests

The Ibeo Lux and Velodyne VLP-16 Puck LiDARs were used in April 2017 to acquire benchmarking data for the final evaluation at end of the project. Both LiDARs were operating in the 905 nm band and tests were carried out partly in the fog chamber on Apr 2017 simultaneously with the Hello World LiDAR. The test targets for analyzing visibility were selected to represent the typical scenarios in road traffic shown in Fig. 12.

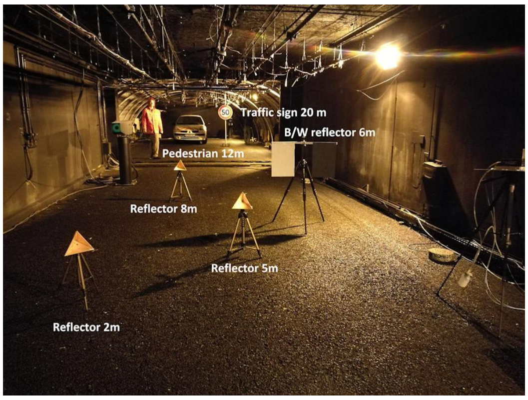

Figure 12. Test arrangements in the Cerema fog chamber

In Fig. 13-Fig. 16 the signal strength of the LiDAR, which in practice refers to the laser intensity reflected back from the targets, is shown. In this case, the signal strength refers to the width of the echo pulse. The horizontal axis is the distance measured in the fog chamber, which is 30 m long. Some measurements were up to 80 m, which are obviously false measurements. When considering rainy conditions, the intensity of which is quite high (33 mm/h), the Ibeo Lux LiDAR practically lost no targets in front. However, when fog is in front the performance drops and the signal strength in proximity to the sensor increases by 1.4 times, which is due to reflections from the fog wall instead of real targets. In dense fog, the small targets are completely lost and only the white reflector is visible.

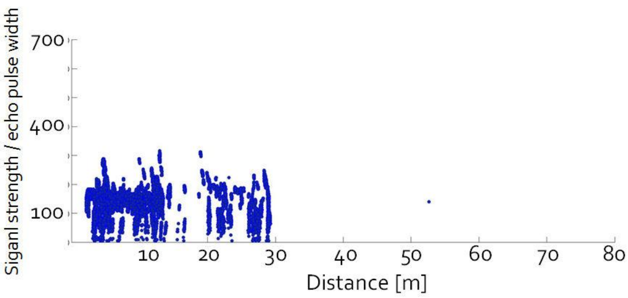

Figure 13. Reference measurement for the Ibeo LUX 905 nm LiDAR

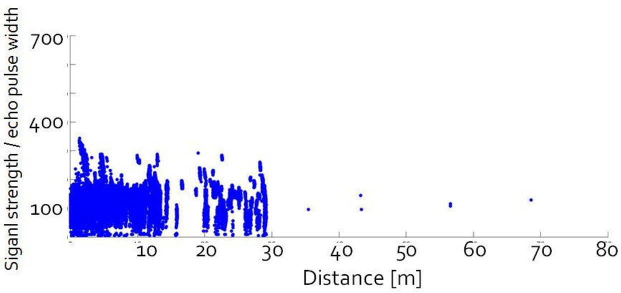

Figure 14. Rain (33 mm/h) measurements for the Ibeo LUX 905 nm LiDAR

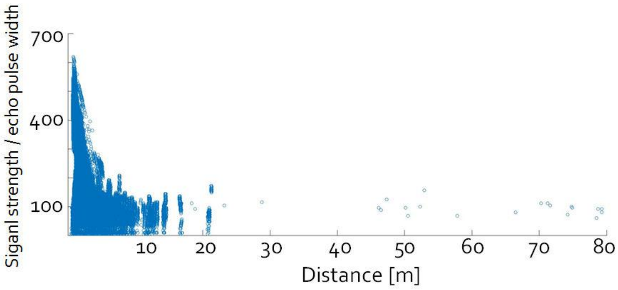

Figure 15. Light fog (visibility 40 m) measurements for the Ibeo 905 nm LiDAR

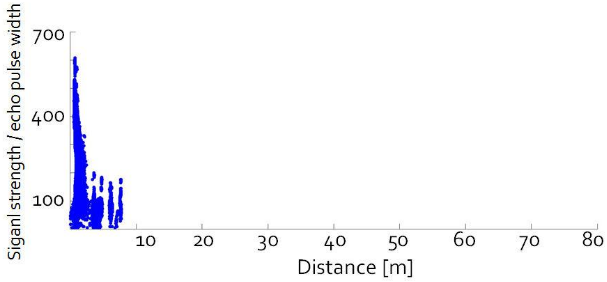

Figure 16. Dense fog (visibility 15 m) measurements with the Ibeo Lux 905 nm LiDAR

The results of the VELODYNE PUCK sensor are shown in Fig. 17-Fig. 20. Correlation with the Ibeo Lux LiDAR is obvious. However, in the Velodyne case the signal strength is not the same as for the Ibeo Lux since instead of echo pulse width this reflects the received laser pulse intensity. Furthermore, the output intensity measurement is also negative compared to the Ibeo Lux since a decrease in signal means a reflective target in front. As an analysis, the rain wall does not influence the sensor as much as fog. Even light fog causes loss of perception of the test targets in front (no clear drops in the signal is measured).

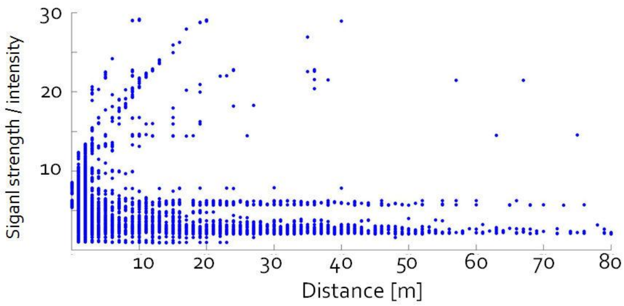

Figure 17. Velodyne PUCK 16-layer reference measurements

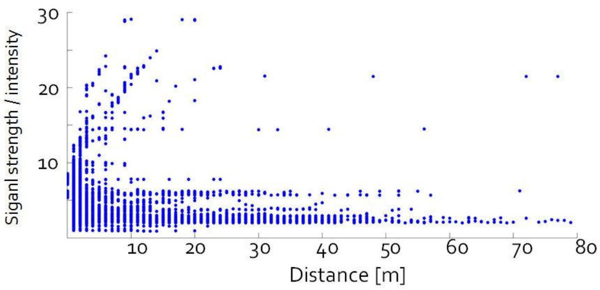

Figure 18. Velodyne PUCK 16-layer in rain (33 mm/h)

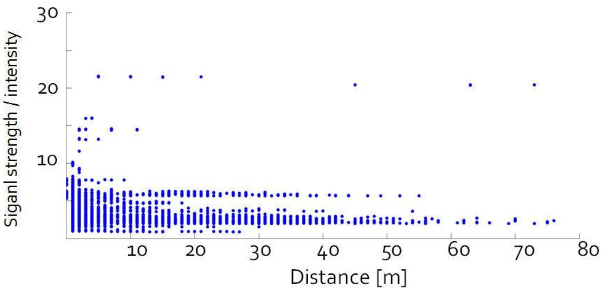

Figure 19. Velodyne PUCK 16-layer LiDAR in fog (visibility 40 m)

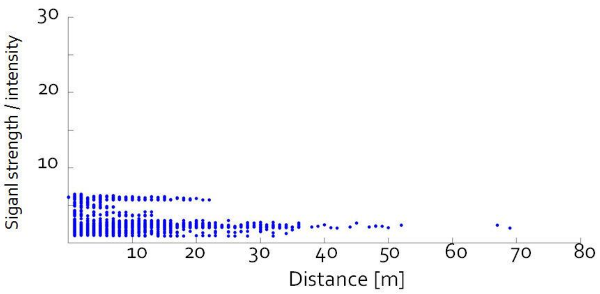

Figure 20. Velodyne PUCK 16-layer LiDAR in fog (visibility 15 m)

V. LIDAR AND RADAR COMPARISON

In Table 4, the comparison between different typical automotive sensors feasibility in adverse weather conditions (foggy and rainy) are reported. The short range Continental SRR 20X 24 GHz radar, Ibeo LUX LiDAR and Velodyne PUCK 16-layer LiDAR were compared. Even if the radar has good performance in almost all weather conditions there remains a problem with resolution and therefore LiDAR is mandatory equipment for automated driving due to its good resolution and far distance ranging (> 70 m). Furthermore, radar is not a solution for pedestrian detection; however, this is also a problem for LiDAR in foggy conditions and provides motivation for development of the 1550 nm LiDAR.

TABLE IV. COMPARISON OF DIFFERENT SENSORS IN THE FOG AND RAIN ENVIRONMENT

Weather type	Sensor	Reflector 2m	Reflector 5m	B/W reflector 6m	Reflector 8m	Pedestrian 12m	Traffic sign 20m
scale: 0=not visible, 1=on/off visible, 2=50% points, 3=70% points, 4 = 90-100% points							
Reference	Velodyne/LiDAR	0	0	4	4	3	1
	Ibeo/LiDAR	4	4	4	4	4	4
	Continental/Radar	4	4	0	4	0	4
Rain: 33mm/h	Velodyne/LiDAR	0	0	4	0	3	1
	Ibeo/LiDAR	0	4	4	4	4	0
	Continental/Radar	4	4	0	4	0	4
Rain: 55mm/h	Velodyne/LiDAR	1	0	4	0	3	2
	Ibeo/LiDAR	0	4	4	3	3	0
	Continental/Radar	4	4	0	4	0	4
Fog, visibility 40 m	Velodyne/LiDAR	0	0	3	0	1	0
	Ibeo/LiDAR	0	2	4	2	1	0
	Continental/Radar	4	4	0	4	0	4
Fog, visibility 15 m	Velodyne/LiDAR	0	0	3	0	0	1
	Ibeo/LiDAR	0	0	2	2	0	0
	Continental/Radar	4	4	0	4	0	4

VI. CONCLUSIONS

As the evolution of the ration of energy measured to the reference energy, α of HWL and α of Lux is similar with decreasing visibility, the conclusion is that the attenuation of the reflected optical power at 1550 nm wavelength compared to 905 nm is not less. Even though we tried to take account of all possible differences between the HWL and Lux so as to only have a variation in wavelength and eliminate the discrepancies in emitted optical power by our relative comparison, there are probably still some opto-mechanical deviations. HWL and Lux remain two different sensor models after all. However, besides similar attenuation of the optical power at both wavelengths, we noted that the massive amount of optical output power, which one is allowed to emit at 1550 nm due to relaxed eye safety regulations at the higher wavelength, clearly does have a positive effect on the LiDARs TOF signal. It significantly increases the Signal-to-Noise Ratio (SNR). In the next phase, the aim is to try to describe both sensors' opto-mechanical properties in order to be able to directly, not relatively, compare 905 nm to 1550 nm.

The fog chamber is mandatory for repeating tests and further continuous elaboration in the right direction. The Cerema fog and rain platform provides a great opportunity to stabilize the conditions at a certain fog level and further facility development needs to be seen during the sensor tests, such as having longer and more rain intensities available.

The comparison between 905 nm LiDAR (Ibeo Lux and Velodyne PUCK) indicates the same bottleneck in foggy conditions. Radar is not as sensitive in adverse weather but its performance for detecting non-metallic objects is quite unreliable in general and, therefore, LiDAR is a crucial component for self-driving vehicles. Even if LiDAR markets are changing and solid-state ones adopt a dominant role the spectral challenges remains. Whether introducing flash, self-sweeping, or micro-mirror LiDARs, the eye safety limits power in the 905 nm band, which is not a major problem in clear weather but is a challenge in adverse weather where more power is needed to penetrate through fog. The solution and results given in this article are valid for all types of LiDAR arrangements (solid-states, scanning, etc.).

ACKNOWLEDGMENT

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