WinterSim: Lidar data analysis

Introduction

The effect of wintertime weather conditions on lidar (RoboSense RS-LiDAR-16) signals was studied in spring 2021. The data used in the research was collected between January and March. The main purpose of the analysis was to study the effect of snowfall on intensities measured from test objects. However, it was learned that also other weather conditions than snowfall may have effect on lidar signals.

Although a weather station was included in the experiment, the automatically collected data did not contain any information about the quality or quantity of snowfalls. Therefore, methods to evaluate the amount of snowfall based on lidar data were first needed. During May 2021, several snowfalls were visually observed. Using the measurements taken in those snowfalls, some computation methods were tried and later used in evaluating the snowfall from the wintertime measurements.

The data used in the research is introduced first. Then, the methods used in characterizing the snowfall are shown. The effect of observed and estimated snowfall on the lidar intensity is studied. Also, the effect of other weather conditions on lidar signals is discussed.

Data structure

Data used in the analysis was recorded in January, February and March 2021. A measurement was done automatically every time the weather changed significantly. Total of 898 measurement were recorded in January, 989 in February and 934 in March. Almost all measurements include 98 subsequent lidar sweeps collected during the 10 s recording time. The measurement setup included five plywood plates, approximately 40 cm x 80 cm, as test objects, located at approximately 21 m, 22 m, 41 m, 56 m and 71 m from the detector.

Data from lidars was analyzed as a list of (x, y, z) coordinates, and the corresponding intensities. Each measurement was connected to weather data from the weather station. The weather data includes temperature, relative humidity, air pressure, wind speed and direction, and dew point.

In addition to the mentioned data, some measurements from May 2021 were analyzed. Those measurements were taken during mild to heavy snowfalls. This data was used for (1) different approaches to detect snowfall from the data without visual confirmation of the weather conditions, and (2) analysis of detected lidar intensities with confirmed snowfall. The temperature during the snowfalls in May was between 1 °C and 9 °C, and the relative humidity between 74 % and 81 %. During one snowfall event, the snowflakes were particularly large (diameter about 1 cm), and in other snowfalls relatively small (few millimeters in diameter). For comparison, also one measurement taken without snowfall and one taken in rainfall were analyzed.

Data from visually observed snowfalls

The rain meter in the weather station used in this experiment measures the velocity of a falling raindrop and then computes the size of the drop and the corresponding rain amount. However, the falling velocity of snowflakes is strongly affected by the size and shape of the snowflake [1]. Different weather conditions result in a wide variety of snowflake types [2]. Therefore, the amount of snowfall cannot be directly detected from the rain amount reading from the weather station. Instead, the effect of visually confirmed snowfalls in May on the lidar data was analyzed. This information was subsequently used to evaluate the snowfall amount in the data recorded in January-March.

The lidar data from the snowfalls observed in May was studied with three methods: (1) counting the number of detected points in a volume which should not contain any solid objects (thus, the density of snowflakes), (2) studying correlations of lidar sweeps in one measurement, (3) identifying the points that were detected roughly in the same place in most of the measurements, and labelling the non-repeating points as snowflakes.

The first method was chosen to evaluate the snowfall in the data collected in January to March. It seems to be the most accurate of these methods compared with the visual observation of the snowfall. The second method also successfully differentiated between clear weather, mild/moderate snowfall and heavy snowfall, but it was computationally more time-consuming. An important note in the analysis was that the rain amount from the weather station was indeed not correlated with the observed snowfall intensity.

The density of the snowflakes was determined as follows. The volume that was analyzed was 8 m in the horizontal direction, 1 m in the vertical direction, and from 1 m to 5 m from the detector. The number of points whose coordinates were in the given limits were computed in each of the 98 sweeps recorded during the measurement time. The intensities of these points were relatively low and stable, and thus it is reasonable to believe that the points represent similar objects, in particular snowflakes. The mean values for the number of points, and their standard deviations, are given in Figure 1.

In a heavy snowfall (labelled as category 4) the snowflakes were much larger in size than in milder snowfall (labelled as 2 and 3), and thus the number of detected snowflakes was significantly larger. The probability that the lidar beam hits the snowflake is relatively to the snowflake size. Comparing the average number of detected snowflakes in heavy snowfall, approximately 3.4 $1/m^3$, and the number in a milder snowfall, approximately 0.4 $1/m^3$, gives the ratio of snowflake diameters of roughly 2.9, which seems reasonable. It seems that this method cannot differentiate between mild or moderate snowfall, but a lack of snowfalls and, on the other hand, a heavy blizzard with large snowflakes, can be identified.

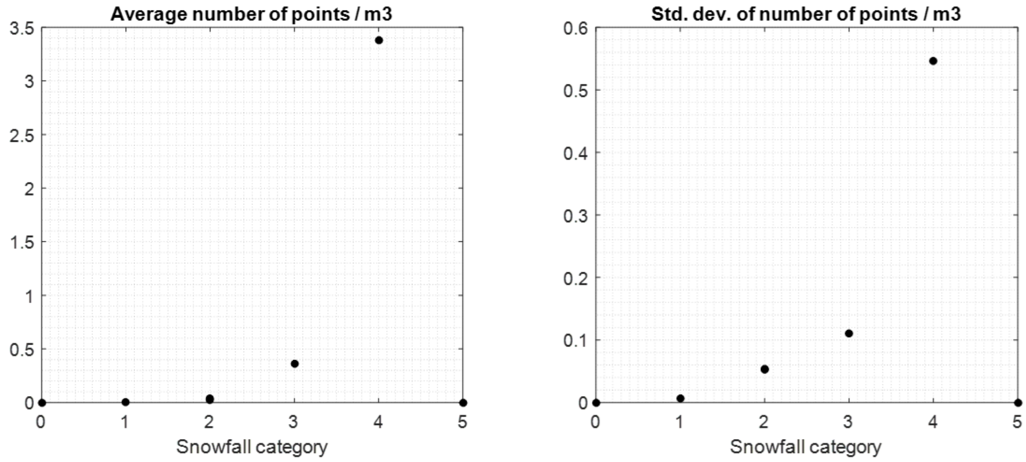

Figure 1: Average numbers of detected points in a test volume and their standard deviations, computed from lidar data taken in visually confirmed snowfall. The number describing the snowfall is subjective (0 = no snowfall, 5 = rain, other numbers: the higher the number, the heavier snowstorm and/or larger snowflakes).

The density of detected snowflakes at different distances was also analyzed. The volume that was analyzed was limited to the horizontal angle of -10° to 10° and the vertical angle of -5° to 5° degrees, in 1 m slices in the forward direction up to 20 m. From Figure 2 it can be seen that the snowflake densities can be modelled with sums of Gaussian functions (black lines). However, the relation between the function parameters (peak value and width) and the snowfall characteristics is not clear yet.

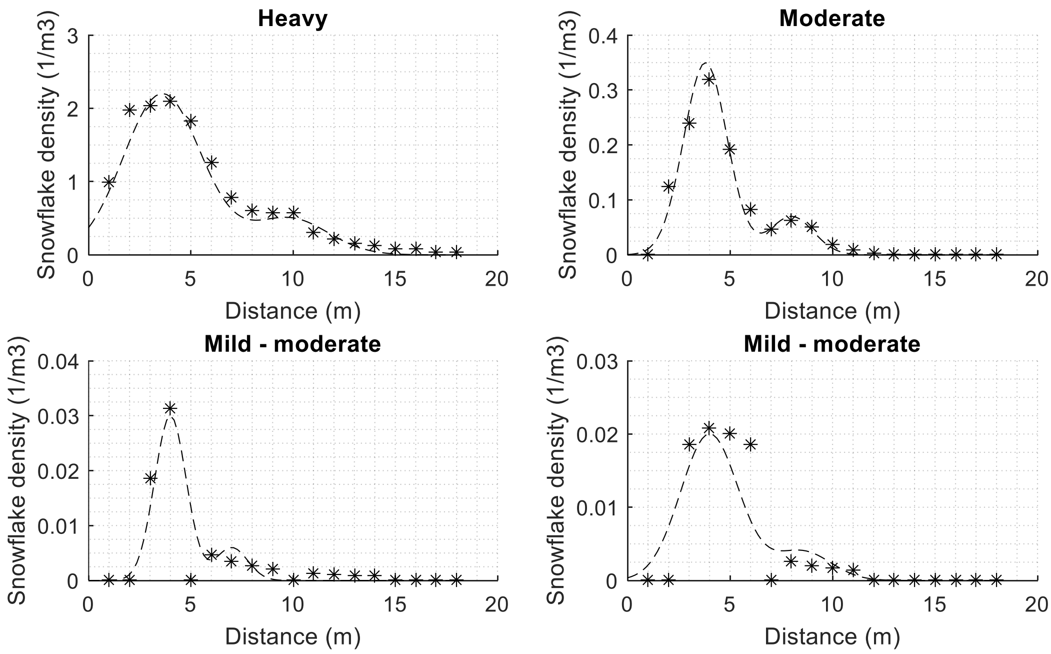

Figure 2: The density of detected snowflakes in different snowfall conditions. The characterization of snowfalls is subjective and based on visual observation.

The intensity measured by a lidar is strongly affected by the number of snowflakes that the laser beam encounters while propagating to the target and back to the detector. Propagation through each snowflake decreases the intensity of the beam. To examine this effect, the cumulative number of snowflakes at different distances was computed from the data collected in May. The results are shown in the following figure. The mathematical functions (solid lines) are the integrals of the fitted functions in Figure 2, so clearly the fitted function is applicable also in modelling the cumulative number of flakes. In a heavy snowstorm with large snowflakes, the number of snowflakes that the beam encounters within, for example, 10 meters distance, can be about hundred times as large as the corresponding number in a mild or moderate snowfall. Also, in a heavy snowfall the cumulative number of snowflakes reaches its maximum value further from the detector than in a milder snowfall.

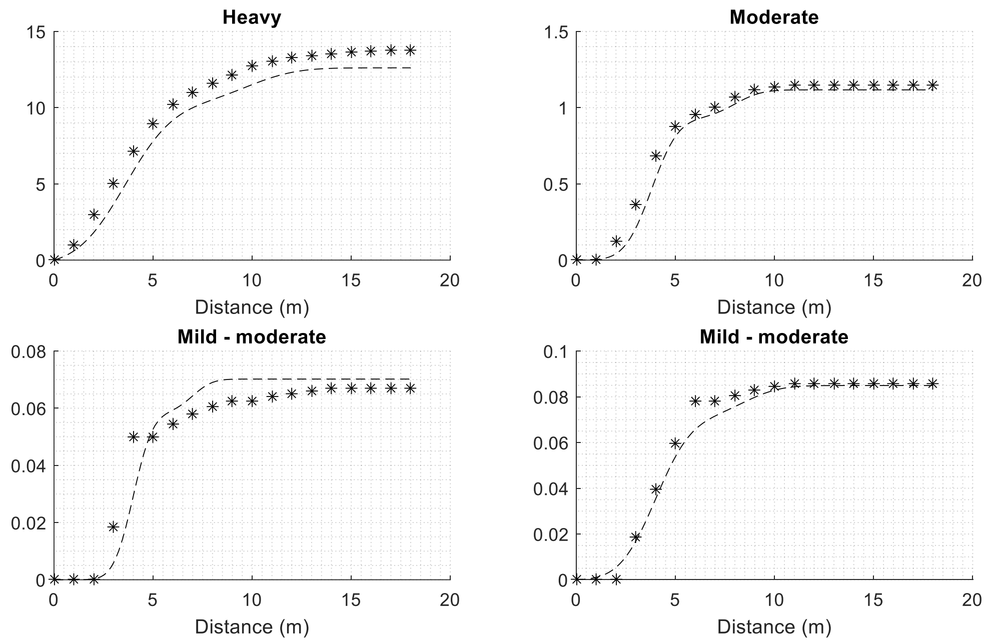

Figure 3: The cumulative number of detected snowflakes at different distances. The characterization of snowfalls is subjective and based on visual observation.

The effect of snowfalls on the intensity measured from the test objects at different distances was examined using different quantities for the snowfall amount. Firstly, it was noted that if snowfalls are described by the maximum density of detected snowflakes, it is very difficult to differentiate between mild or moderate snowfalls. In the figure below, the intensities from test objects are compared to the corresponding intensities measured in a clear weather. The values on the right correspond to the intensities measured in a heavy snowfall with large snowflakes.

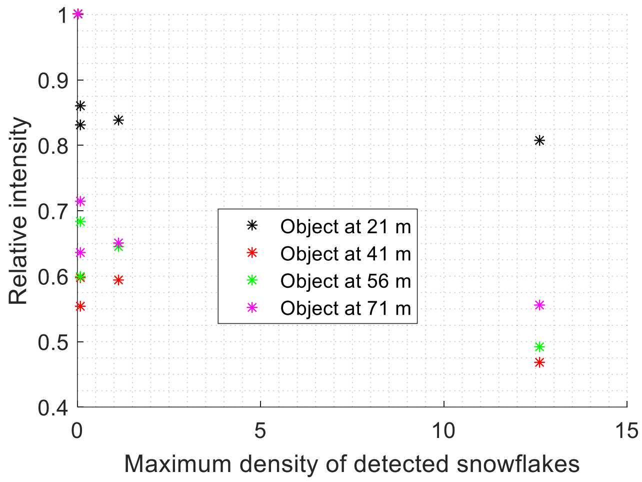

Figure 4: The intensities measured from the test objects in a snowfall compared to the corresponding intensities measured without snowfall. The snowfall is characterized by the maximum density of the detected snowflakes.

In the following figure, the value used in characterizing the snowfall is the distance at which the cumulative number of detected snowfalls reaches 99 % of its maximum. Using this value, the snowfalls can be categorized in more detail. Also, for targets that are relatively close (black stars in the figure), the effect of the snowfall on the intensity seems linear. More data would be needed to analyze the effect of snowfall on the intensity measured from objects at further distances.

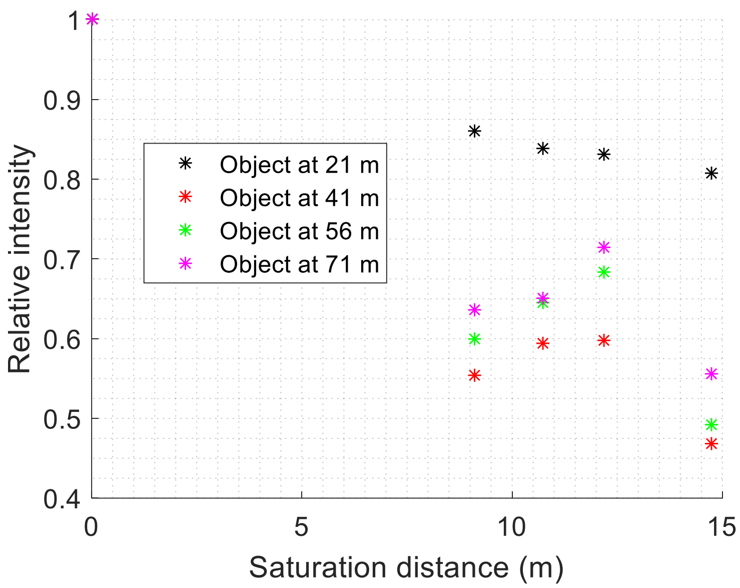

Figure 5: The intensities measured from the test objects in a snowfall compared to the corresponding intensities measured without snowfall. The snowfall is characterized by the distance at which the cumulative number of detected snowflakes reaches 99 % of its maximum.

Theoretically, the effect of snowfall on the power of a lidar signal is [3]

$$P(z_T) = P_0 \frac{\rho_T}{\pi} \frac{A}{z_T^2} e^{-2 \cdot OD}$$

where OD (optical density) characterizes the snowfall, and other constants depend on the measurement setup. The optical density can be calculated from the visibility value, but it was not possible to measure visibility with the equipment used in this research. However, visibility is widely used for characterizing snowfall conditions [4]. In the left figure below, the theoretical effect of visibility on the intensity is shown. The results from the measurements taken in May are in the right figure. However, since the visibility values could not be measured, they are only estimations based on values that are usually related to similar weather conditions that were observed.

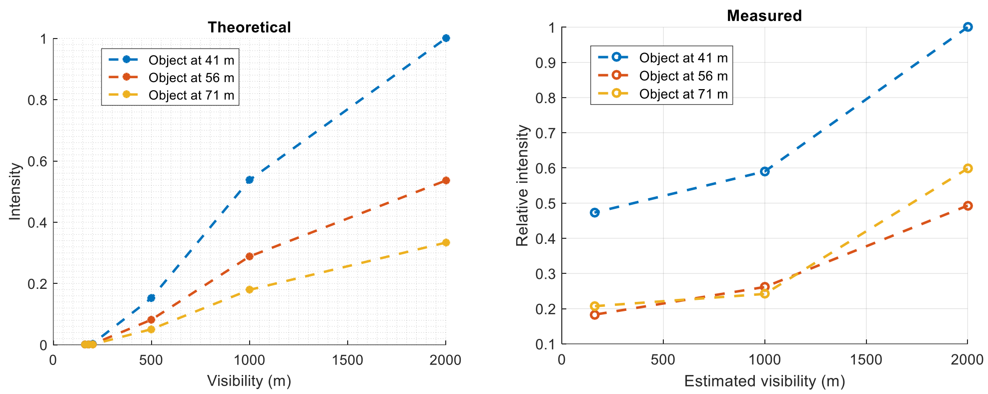

Figure 6: Relative intensities from objects at different distances and in different snowfall conditions: theoretical and measured values. The visibility values in the right figure are estimations.

Finally, a mathematical model for the intensity affected by the target distance and weather conditions was constructed based on the data measured in May. In Figure 7, the intensities measured from the test objects at different distances and in different weather conditions are shown together with the fitted models (dashed lines). The effect of the distance seems to be a log-normal function, whose parameters probably depend on the equipment. The effect of the snowfall in this model is a constant factor between 0.4 (heavy snowfall) and 1 (clear weather). It must be noted that some of the intensity values (41 m, clear / mild snow) were saturated at the detector. Theoretically, the measurement angle also effects on the intensity, but it is not considered in this model since the angles in this experiment were relatively small.

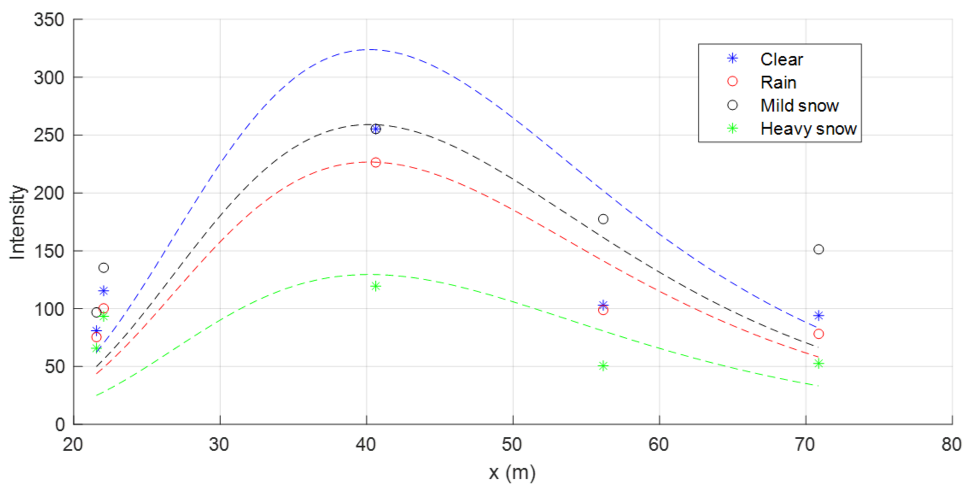

Figure 7: A mathematical model (dashed lines) based on the experimental results, describing the combined effect of the snowfall and distance on the measured intensity.

Automatically collected data

In the following sections, the effect of different weather parameters (temperature, relative humidity, and snowfall) on the intensity measured from the test objects is analyzed. The data was collected in January, February and March with a measurement setup described in earlier chapters. The maximum number of points that were returned from the test objects varied from 4 (from the plate at 72 meters) to 17 (from the plates at 21 or 22 meters).

Measurements without snowfall

Firstly, only the measurements taken in clear weather were used. The lack of snowfall was defined as zero points in the test volume, similarly as in characterizing the lack of snowfall in the data from May. The intensities measured in clear weather vary significantly, and it was attempted to find correlations between the intensities and weather conditions.

In Figure 7, the relative intensities compared to the maximum intensity from the test mirror at the specified distance are shown. The red circles indicate the that the brightness measured by the weather station was at least 50 % of the maximum value of brightness measured in January – March. The highest intensity values from test objects at all distances were measured in conditions with high brightness. However, the exact relation between the brightness and other weather conditions is not yet clear.

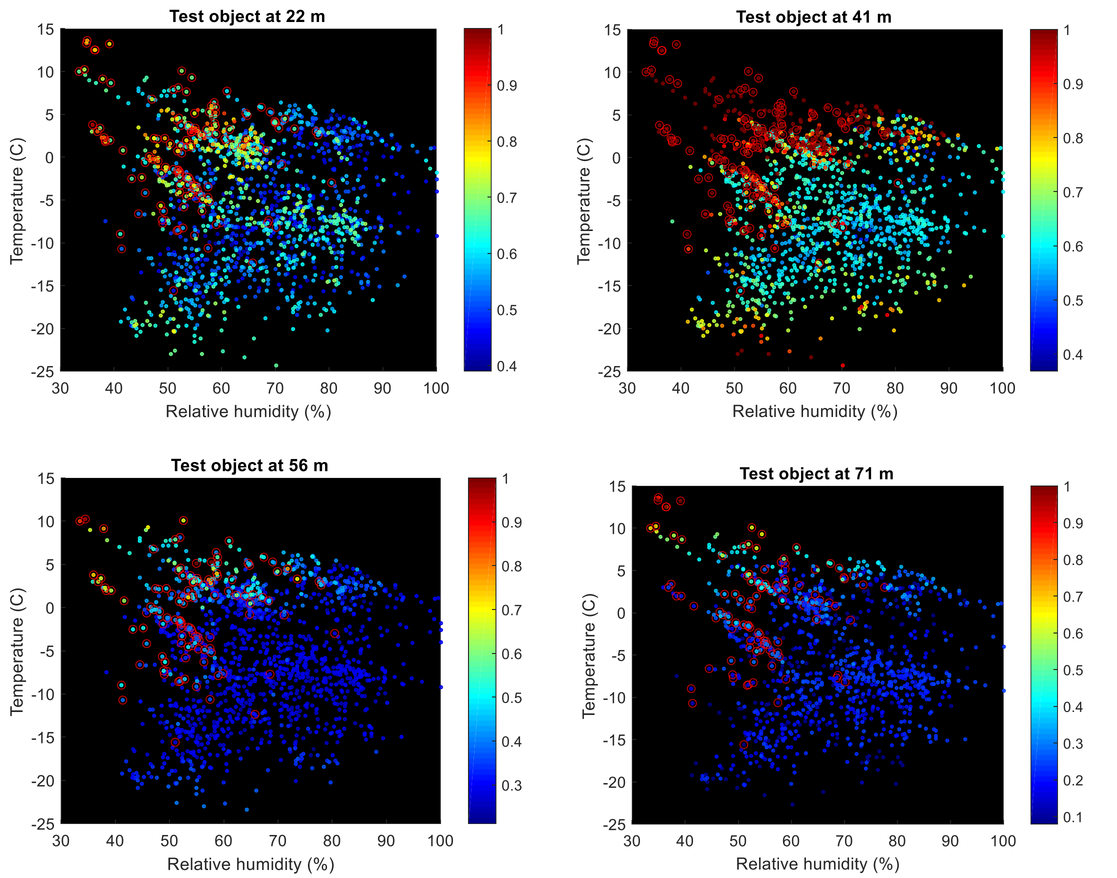

Figure 8: The effect of the temperature and the relative humidity on the intensity measured from the test objects at different distances.

Figure 8 indicates that the temperature alone has an effect on the intensity measured from the test objects. To study this more closely, the intensities from the targets measured in a relative humidity between 60 % and 80 % are collected to Figure 9. The intensities in subzero temperatures are generally lower than those measured in temperatures above 0 °C. The reason for this has to be analyzed.

It is known that the laser wavelength can change in lower temperatures, and that the reflectance of different surfaces is dependent on the wavelength. The effect of high temperatures on lasers has been investigated in e.g. [5]. It is estimated that the wavelength of a laser diode increases about 2 nm with a 10 degree rise in temperature. Correspondingly, the wavelength decreases as the temperature lowers. In Ref. [6] the wavelength dependence on the reflectance of different wood surfaces was studied, and it was shown that the reflectance can decrease significantly with shorter wavelengths. However, the wavelength of the laser in our experiment, 905 nm, was not studied in Ref. [6]. The reflectance of metal surfaces is also highly dependent on the wavelength [7]. However, these effects this might not be a problem in detecting e.g. cars, since the reflectance is still high enough for detection regardless of temperature.

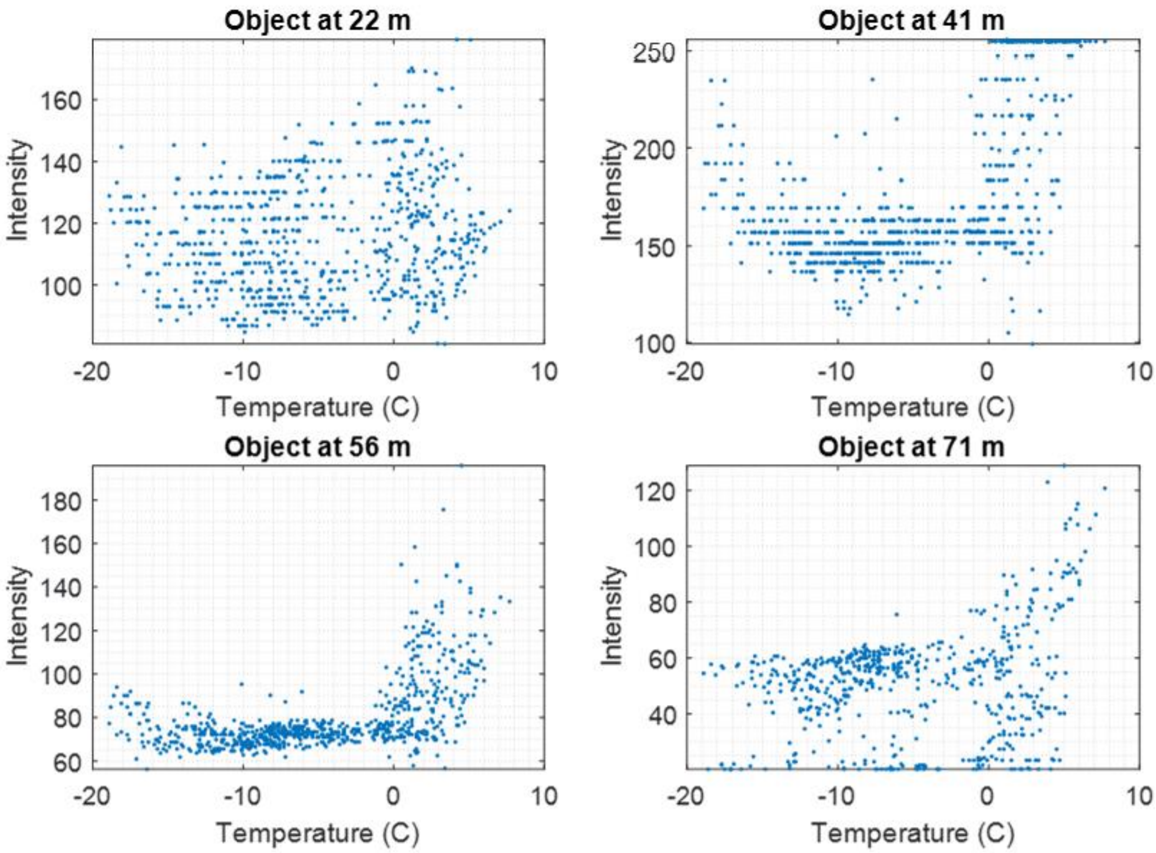

Figure 9: The effect of the temperature on the intensity measured from the test objects at different distances. Only data measured at a relative humidity between 60 % and 80 % is used.

Measurements with snowfall

To evaluate the effect of snowfall on the intensity measured from the test objects, measurements taken in different amounts of snowfall were compared. The snowfall characteristics were estimated based on the conclusions made from the analysis of the observed snowfalls in May.

The snowfall events in May occurred in quite stable weather conditions (temperature and relative humidity), but in the assumed snowfalls in January - March the weather parameters varied widely. Therefore, the data collected in January - March was analyzed by comparing intensities measured in different snowfall events in otherwise similar weather conditions.

The data from January, February and March was analyzed based on the number of points detected in a test volume. In 876 measurements (36 %) there were more than 0 points in the test volume. In 12 measurements there was an exceptionally high number of points. In all cases of extreme snowfall, the relative humidity was above 88 %. The temperatures during those extreme snowfall events varied between 0.3 °C and -19.8 °C, most being around approximately -16 °C, and the difference between the temperature and dew point was less than 3 °C. Some of these combinations of weather parameters are typical conditions for a snowfall with relatively large snowflakes [2]. The distribution of the other snowfall conditions is shown in Figure 10, indicating that in most of these snowfall events the snowflake size has been so small that the probability for the lidar to detect it is not very high.

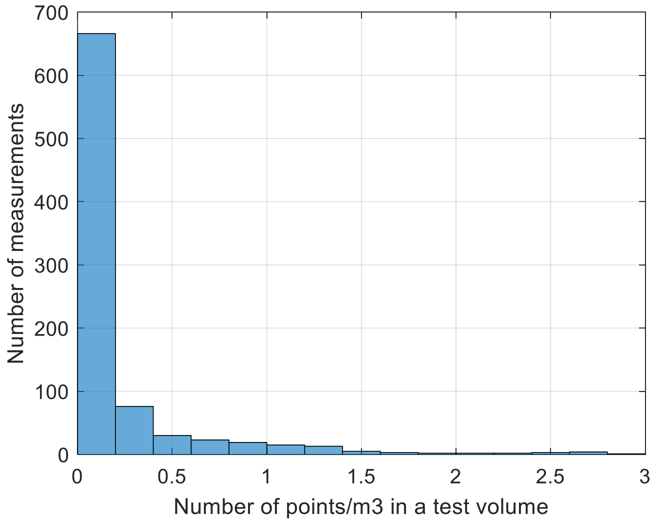

Figure 10: The distribution of the number of points/m³ detected in a test volume, possibly related to the intensity of the snowfall and the snowflake size, from lidar data collected during January - March.

To analyze the effect of the snowfall independently of the temperature and relative humidity, four different categories of weather parameters were chosen. In all of those weather classes, the intensities from the test objects at different distances were compared to the mean value of the intensities from the same object in corresponding weather parameters but without snowfall (i.e. measurements where the number of points in the test volume was zero). The weather categories and the corresponding figures are given in the table below.

Category	Humid & warm Figure 11	Dry & warm Figure 12	Humid & cold Figure 13	Dry & cold Figure 14
Rel. humidity (%)	≥ 90	≤ 75	≥ 90	≤ 75
Temperature (°C)	≥ -5	≥ -5	≤ -10	≤ -10

From Figures 11-14 it can be deduced that snowfall has some effect on the intensity measured by lidar, but the relationship is not very clear. In humid conditions, regardless of temperature, it seems that even a mild snowfall can reduce the intensity up to 40 %. In warm temperatures, the amount of snowfall does not have a clear relation with the intensity. However, in a humid and cold weather where also more intense snowfall events were present, the measured intensity and the amount of snowfall seem to be linearly correlated. At dry conditions, mild or moderate snowfall can reduce the intensity with up to 50 %, but there is a lot of variation in the intensities measured with low number of observed snowflakes. This is the case in both warm and cold temperatures.

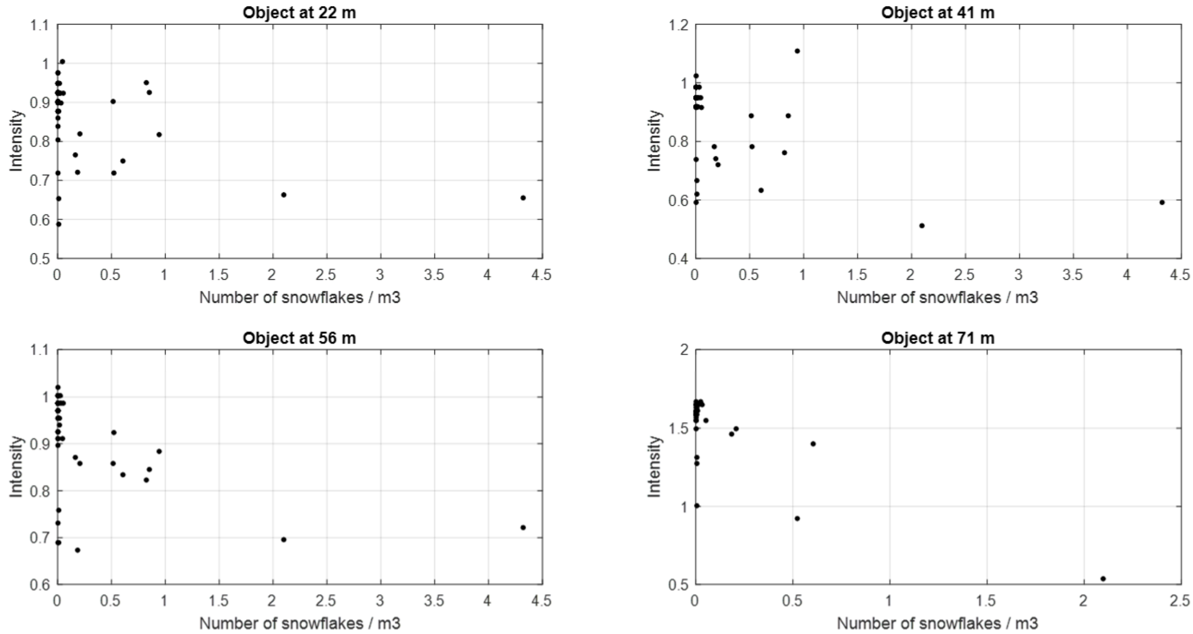

Figure 11: Intensities from the test objects at humid and warm winter conditions with snowfall, relative to the average of intensities measured in similar conditions without snowfall.

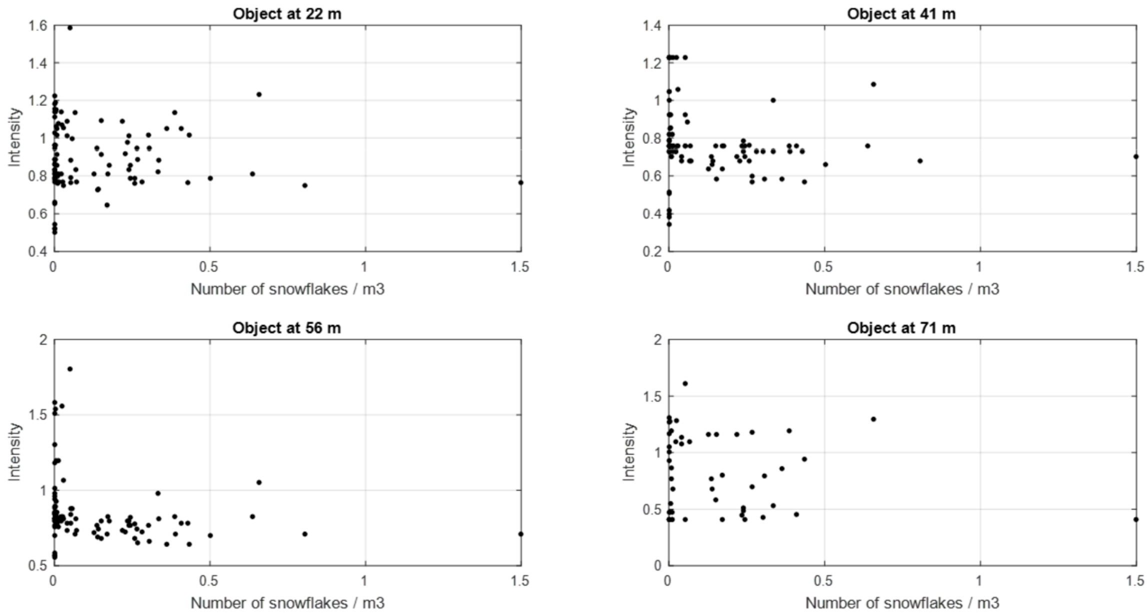

Figure 12: Intensities from the test objects at dry and warm winter conditions with snowfall, relative to the average of intensities measured in similar conditions without snowfall.

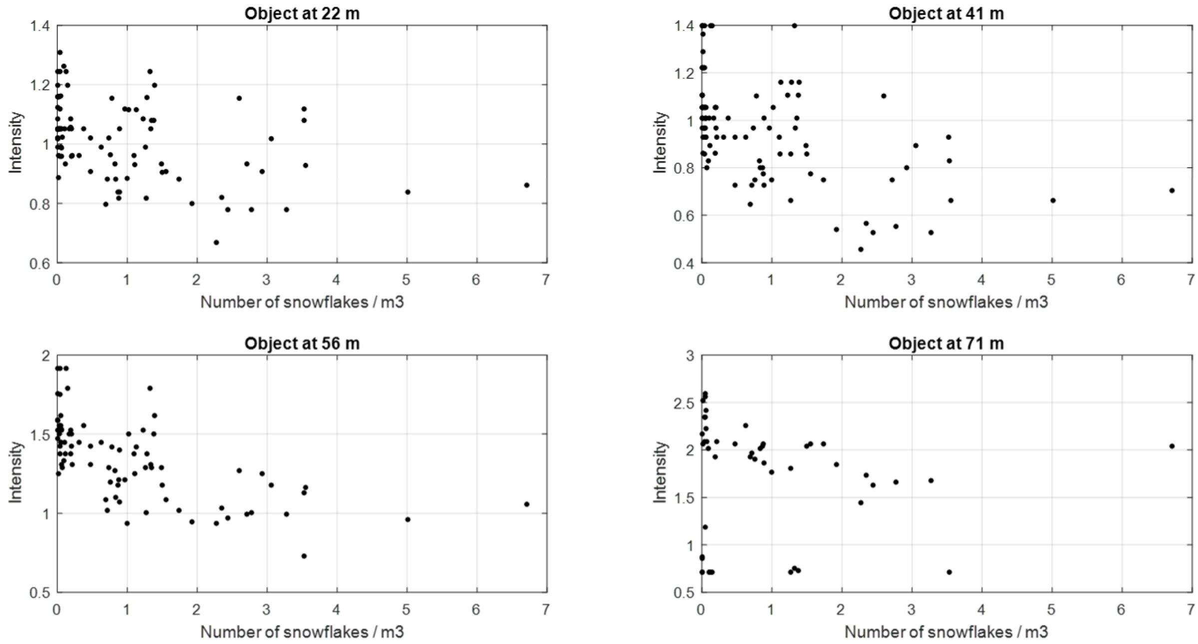

Figure 13: Intensities from the test objects at humid and cold winter conditions with snowfall, relative to the average of intensities measured in similar conditions without snowfall.

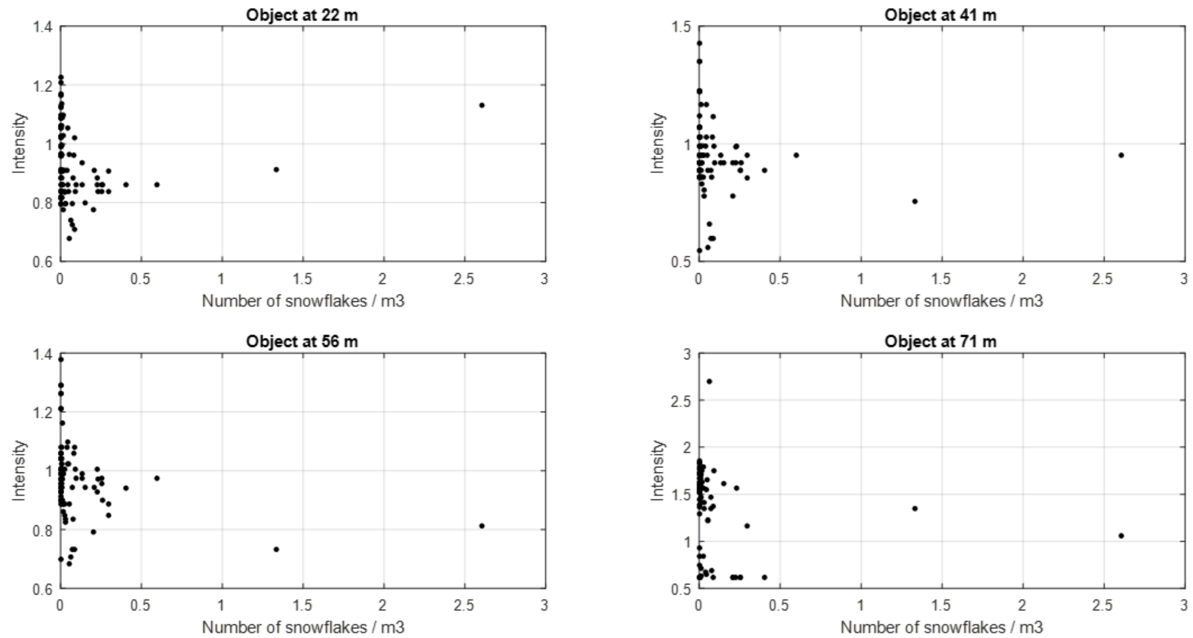

Figure 14: Intensities from the test objects at dry and cold winter conditions with snowfall, relative to the average of intensities measured in similar conditions without snowfall.

The performance of the lidar was also examined using a different value for the characterization of snowfall. Specifically, the distance at which the cumulative number of detected snowflakes reached its maximum, was used as a measure for snowfall. The intensities measured in different snowfalls were compared with the intensities measured without snowfall. Again, the intensities varied significantly, possibly because of the temperature and the relative humidity, and therefore the analysis was limited to weather conditions with the temperature between -10 °C and 0 °C, and the relative humidity between 70 % and 80 %. Even with these restrictions, the intensity values with or without snowfall vary a lot.

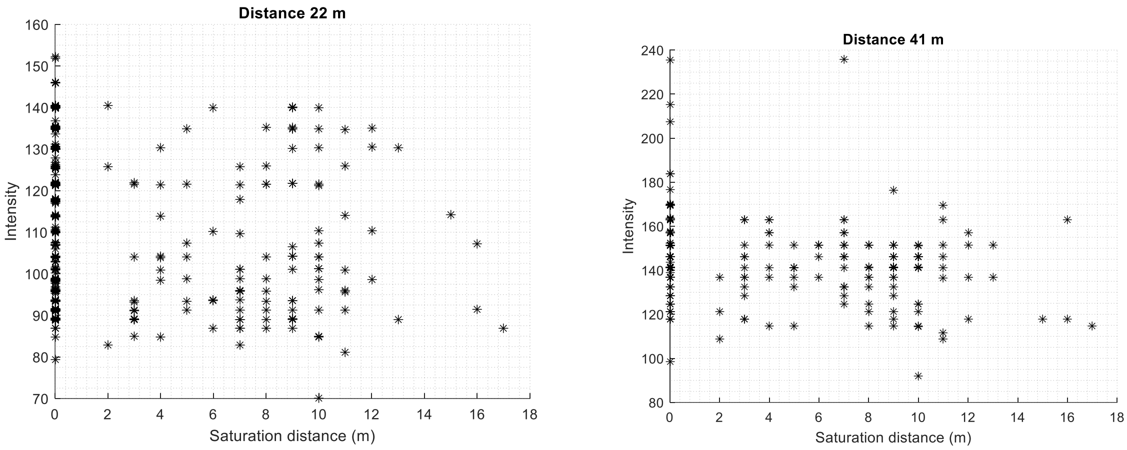

Figure 15: Some examples of intensitities from the test objects at given distance measured in January - March. The x-axis “saturation distance” is the distance at which the number of detected snowflakes reaches its maximum. The points at the vertical axis (saturation distance 0 m) correspond to intensities measured without snowfall.

Conclusions and future research

The performance of lidars in artic conditions has been studied in [8]. It is already known that powder snow on roads decreases the subjective visibility, but also the performance of sensors, when following another vehicle. Wet snow, road salt or dirt can cover sensor lenses. In low temperatures the mechanical performance of the lidar may decrease, and also the laser wavelength can change. The effect of the temperature can be seen also in the results shown in this document.

Although a large amount of data is analyzed in this document, there is not yet a reliable method to confirm the snowfall from the recordings of the lidar or the weather station. Snowfalls are characterized by both the density and size of the snowflakes. Characterization of snowfalls based on human observations might be beneficial for future research. Also, analysis of suitable camera images could be used. In the landscape images taken by a forward-facing camera used in these measurements, snowflakes could not be seen. Finally, assuming that the size distribution of snowflakes is quite stable in similar temperatures and humidities, some conclusions about the snowfall characteristics could be done based on weather data.

References

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