

AUTOMATED LiDAR REMOTE SENSING FOR MEASURING THE SPATIAL AND TEMPORAL EVOLUTION OF SURFACE HOAR FORMATION

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ABSTRACT: Surface hoar buried within a snowpack by subsequent snowfall forms a weak layer that may fail and result in an avalanche. The spatial variability of surface hoar formation depends on slope aspect, elevation and on local meteorological conditions, making it difficult to predict when and where weak layers form. The aim of this study is to assess the potential of LiDAR remote sensing for the detection and characterization of the spatial and temporal variability of surface hoar. We used an automated laser scanner to periodically scan surface hoar while growing on a snow sample in a ring wind tunnel under laboratory conditions. Our results show that the mean surface reflectance during surface hoar formation may increase or decrease with little changes of $\approx 4\%$, making it rather useless for surface hoar detection in the field. However, the spatial variability of the reflectance was found to strongly increase up to 600% during surface hoar formation, which is the result of the continuously increasing, plate-like surface hoar crystals of various orientation favouring specular reflections. We propose that the standard deviation of the spatial reflectance variability may be a useful, empirical metric for the detection of surface hoar formation in the field during cold clear nights.

Keywords: Surface hoar, LiDAR, Remote sensing, Reflectance.

1. INTRODUCTION

Dry snow slab avalanches occurring in steep terrain due to the failure of a weak layer that is buried below a cohesive slab are the most frequent and most dangerous avalanche type (Gaume et al., 2018). Jamieson and Schweizer (2000) found that in Switzerland, 40% of the avalanches emerge from a buried surface hoar weak layer. Surface hoar layers are typically a few millimeters up to a centimeter thick, consisting of large plate like crystals with a large pore space resulting in a low density. The few bonds between the surface hoar crystals and the snow layers above and below result in a low mechanical stability of the surface hoar layer. Due to external loading (e.g. by a skier or new snow) a surface hoar weak layer may fail. Depending on the spatial distribution of the surface hoar layer and the weight and cohesion of the slab above, the fracture may propagate and the snow slab slide down as an avalanche.

Surface hoar is a type of snow crystal that forms on the surface of a snowpack under specific atmospheric conditions during clear nights with cold snow surface temperatures, warm humid air, and low wind speeds (e.g. Stössel et al., 2010). The

snow surface temperature needs to be at least 5°C colder than the air temperature (Hachikubo and Akitaya, 1997). The air in the boundary layer directly above the snow surface cools down, becomes supersaturated, and water vapor from the air resublimates on the cold snow surface forming surface hoar crystals. The crystal size and type, and the growth rate mainly depend on the temperature difference between the snow surface and the air and on the degree of supersaturation (Kobayashi, 1961). The Nakaya diagram (e.g. Chandel et al., 2023) shows the crystal types that form during different atmospheric conditions. Large plate-shaped surface hoar crystals typically result in the most fragile, mechanically instable weak layers and are particularly relevant for avalanche formation.

The formation of surface hoar typically strongly varies spatially on a slope scale, depending on the slope aspect, elevation and on the local micro-meteorological conditions. This makes it difficult to predict the occurrence of surface hoar in the field and thus to assess the regional avalanche danger. Horton and Jamieson (2017) measured the spectral reflectance of different surface hoar types and found needle-shaped surface hoar being more reflective than plate-shaped crystals. However, they found no difference in reflectance between different sizes of surface hoar. Champollion et al. (2013) detected the appearance and disappearance of surface hoar using near-infrared photography and passive microwave satellite data at Dome C in

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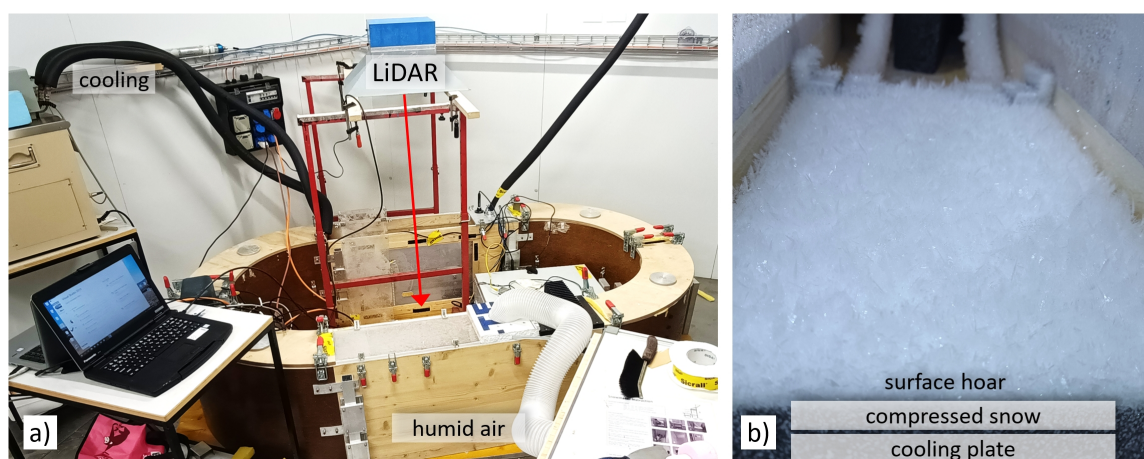


Figure 1: a) Experimental setup showing the closed-circuit ring wind tunnel (center), the automated laser scanner (LiDAR) above the measurement section, a warm water bath (lower right) to produce humid air, and a heat exchanger (left) to cool the snow sample. b) Surface hoar growing on a compressed snow plate on the cooling plate.

Antarctica. They found that the snow surface is covered almost half of the time by surface hoar. To our best knowledge, there is no reliable method available that allows to automatically detect surface hoar in the field, although better knowledge about the occurrence, spatial distribution and crystal type and size of surface hoar would be invaluable for improving avalanche risk assessment. The aim of this study is to analyze the potential of a near-infrared automated laser scanner in detecting the spatial and temporal evolution of surface hoar formation.

2. METHODS

We used an automated 3D terrestrial laser scanner (Faro® Focus3D S120) to measure the spatiotemporal variability of surface hoar formation under controlled cold laboratory conditions (Fig. 1). The laser scanner is a short range (120 m) full waveform LiDAR operating at a wavelength of 905 nm with a spot size of 3mm in diameter.

The laboratory setup for growing surface hoar includes a closed-circuit ring wind tunnel (RWT, Sommer et al., 2018, Walter et al., 2023) for producing an air flow at a low wind speed ($\approx 0.5 \text{ ms}^{-1}$) while warm humid air is blown from a warm water bath (Snowmaker, Schleef et al., 2013) into the RWT. A heat exchanger (Julabo®) is used to cool an 18 cm x 30 cm x 1 cm aluminum plate to temperatures as cold as -50°C . A similar sized plate of highly compressed dendritic new snow produced in the Snowmaker is placed on top of the cooling plate. The relatively good thermal conductivity (e.g. Calonne et al., 2019) of this high density (350 kgm^{-3}) compressed new snow slab allows for cooling the snow surface to temperatures well below the air temperature (Table 1). Similar setups

were introduced by Ozeki et al. (2020) and Chandel et al. (2023). The laser scanner was mounted 1.5 m above the measurement section of the RWT to periodically (every 10 or 20 min) scan the snow surface while the surface hoar formed.

We performed four experiments at slightly different atmospheric conditions (Table 1). The wind speed $V_{0.4m}$ was measured with a fan anemometer at a height of 0.4m above the snow samples. A low wind speed of $V_{0.4m} = 0.5 \text{ m s}^{-1}$ was chosen to allow for the development of a super-cooled air layer directly above the snow surface and thus the formation of surface hoar. However, a minimum wind speed is required for the supply of fresh humid air from the warm water bath. The snow surface temperature (T_{ss}) was measured with an Apogee (SI-131) infrared temperature sensor. The air temperature (T_a) and relative humidity (RH) were measured with a Rotronic® (HC2-S) sensor. We used Spectralon® reflectance targets with 50% and 95% reflectance in the near infrared to calibrate the backscattered laser intensity values on absolute reflectance.

3. RESULTS

3.1. Surface hoar formation - atmospheric conditions

The surface hoar was grown in the RWT under controlled atmospheric conditions as summarized in Table 1. Fig. 2 shows the temporal evolution of the atmospheric conditions for experiment 3. The temperature difference between the snow surface and the air was approximately 10°C . The relative humidity was about 91% and mainly controlled by the air temperature in the lab and the water bath temperature. The cooling of the air directly above the cold snow sample results in super-saturated air with a relative humidity higher than 100% resulting

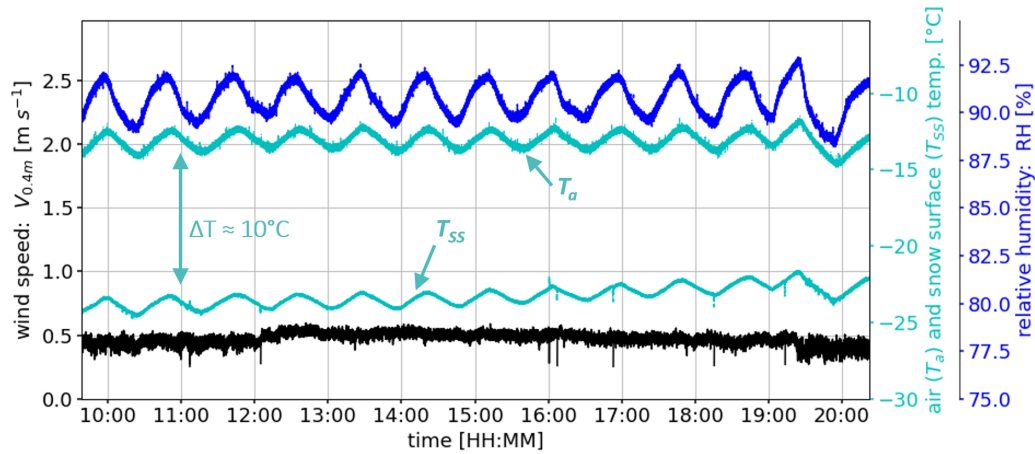


Figure 2: Atmospheric conditions for experiment 3. The wind speed was set to 0.5 m s^{-1} . The snow surface temperature was about -22°C while the air temperature was about -12°C , resulting in a temperature difference of 10°C and a relative humidity of $RH \approx 90\%$.

Table 1: Overview of the atmospheric conditions for the experiments (1-4) including the wind speed $V_{0.4m}$, snow slab thickness h_{slab} , cold plate temperature T_{jul} , snow surface temperature T_{ss} , air temperature T_a , water bath temperature T_{wb} and relative humidity RH.

Exp	$V_{0.4m}$ [m s^{-1}]	h_{slab} [cm]	T_{jul} [$^\circ\text{C}$]	T_{ss} [$^\circ\text{C}$]	T_a [$^\circ\text{C}$]	T_{wb} [$^\circ\text{C}$]	RH [%]
1	0.5	2.2	-50	-20	-10	+20	97
2	0.5	1.2	-50	-31	-12	+4	92
3	0.5	2.0	-35	-22	-12	+4	91
4	0.5	2.0	-35	-20	-11	+4	93

in the formation of surface hoar. The temperature (and thus RH) show sinusoidal fluctuations with a periodicity of a bit less than an hour, which are the result of the cold lab cooling control system. The slight increase in T_{ss} from $\approx -24^\circ\text{C}$ to $\approx -22^\circ\text{C}$ indicates that the thermal conductivity between the snow surface and the cooling plate decreases due to the surface hoar formation.

3.2. Spatial reflectance maps

Spatially resolved reflectance maps (Fig. 3) provide information on the evolution of the surface reflectance during the hoar formation and thus the process of surface hoar crystals growth. Fig. 3a shows the reflectance of the compressed new snow sample at the beginning of the experiment with a homogeneous reflectance of about $r_{mean} \approx 0.76$ across the entire snow slab. Several spots of increased reflectance ($r \approx 0.9 - 0.98$) occur after about 2.5 h as the result of local surface hoar

crystal growth. The number and intensity of these bright spots of high reflectance further increases at $t = 5.5 \text{ h}$ (Fig. 3c). Additionally, first spots of lower than the initial reflectance with $r \approx 0.6 - 0.7$ occur. These low reflectance spots become larger with even lower reflectance values ($r \approx 0.5 - 0.6$) at $t = 10.5 \text{ h}$ (Fig. 3d).

To relate these spatial reflectance variability to the emerging surface hoar surface morphology, Fig. 4 shows 3D micro Computer Tomography (μCT) reconstructions of the initial snow surface (Fig. 3a) and the surface hoar for the experiment 3 after $t = 10.5 \text{ h}$ (Fig. 3b) and experiment 4 after $t = 17.5 \text{ h}$ (Fig. 3c). Fig. 4a shows the compressed new snow surface with snow grains of very low optical equivalent diameter (OED). Fig. 4b shows medium sized plate like surface hoar crystals whereas Fig. 4c shows large surface hoar crystals with the largest extension of up to one centimeter. The atmospheric growth conditions (Table 1) were similar for experiment 3 and 4, however, experiment 4 lasted 7 h longer which is the reason for the significantly larger hoar crystals. Therefore, the end of experiment 3 (Fig. 4b) can be considered as an intermediate stage of experiment 4 (Fig. 4c).

3.3. Temporal evolution of surface reflectance

To analyze the evolution of the reflectance during the surface hoar growth process, the spatial mean (r_{mean}) and standard deviation (r_{std}) of the LiDAR reflectance variability is shown in Fig. 5 for all four experiments. For each experiment, both the mean and standard deviation strongly increase initially for the first four to six hours of surface hoar growth. The mean reflectance (r_{mean}) then asymptotically converges against a constant value (experiment 1 and 3, Fig. 5a and c) or slightly decreases (experiment 2 and 4, Fig. 5b and d) during the second half of

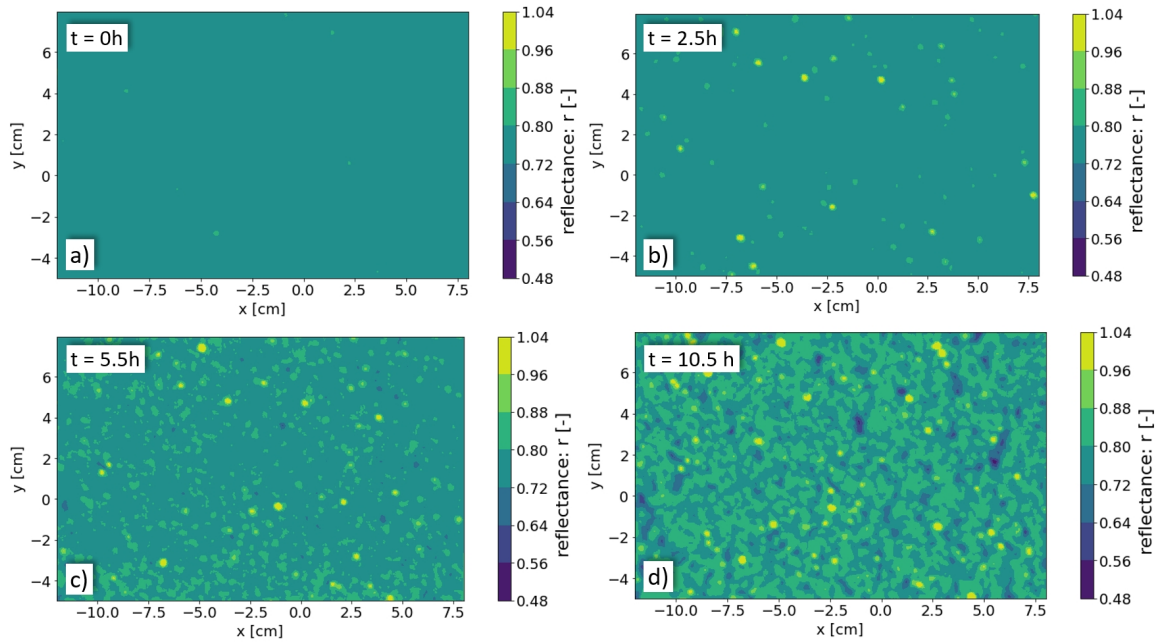


Figure 3: Reflectance distribution of four scans during Experiment 3: a) compressed new snow at the beginning and after b) 2.5h, c) 5.5h and d) 10.5h of surface hoar growth.

the experiments. As the experiments 1 and 3 only lasted 8 h and 10.5 h, whereas the experiments 2 and 4 lasted longer (15 h and 17.5 h), we would also expect a decrease in r_{mean} for experiments 1 and 3 for longer growth durations. That the standard deviation (r_{std}) converges against a constant value for experiment 1 (Fig. 5a) which is the result of issues with the warm water bath that stopped the humid air supply after 4h resulting in a gradual decrease of RH from 99% to 85% limiting the crystal growth. For the experiments 2 and 4 (Fig. 5b and d), r_{std} continues to increase at a lower rate after the strong initial increase. These results suggest that the evolution of the surface reflectance can be divided into an initial phase that is lasting about 5-10 hours with a strong increase in both r_{mean} and r_{std} , and a second phase afterwards where r_{mean} is constant or even slightly decreases and r_{std} continues to increase at a lower rate. These observed changes in the surface reflectance characteristics provide a basis for the detection and characterization of surface hoar formation in the field using LiDAR remote sensing.

4. DISCUSSION

The spatial and temporal surface hoar reflectance variability (Fig. 3 and 5) provides distinctive characteristics that may allow to discern surface hoar growth on snow surfaces (and thus the formation of a potential weak layer) from invariant snow surfaces using terrestrial or airborne laser scanners. Therefore, the origin of our measured reflectance variability must be understood to identify features

that can unambiguously be attributed to surface hoar formation.

Generally, the reflection of the near-infrared collimated laser beam at the snow surface and thus the backscattered laser intensity depends on i) the (surface hoar) grain size (OED), ii) the snow density (ρ_s), and iii) the distribution of facet orientations. Large snow grains result in a lower reflection of the near-infrared radiation, thus reducing the intensity of the backscattered light (Wiscombe and Warren, 1980). A low snow density ρ_s (or ice volume fraction ϕ_i) results in volume scattering with high lateral dispersion of the radiation and thus in a reduction of the radiation being scattered back towards the laser scanner. To our best knowledge, this effect is not documented for snow, however, Mariscala et al. (2020) demonstrate it for silica foam in the visible wavelength range. The surface hoar crystal orientation affects surface scattering and thus the bidirectional reflectance distribution function (BRDF) of the surface (Knowles Middleton and Mungall, 1952; Tan and Cheng, 2017). Depending on the surface hoar crystal orientation, a part of the incoming laser beam will be specularly reflected at flat crystal surfaces, thus modifying the BRDF from a typically diffuse (Lambert) reflectance distribution to a BRDF with a significant specular contribution as illustrated in Fig. 4.

4.1. Spatial mean reflectance

One possibility of characterizing the evolution of the surface reflection is by the 1st order moment

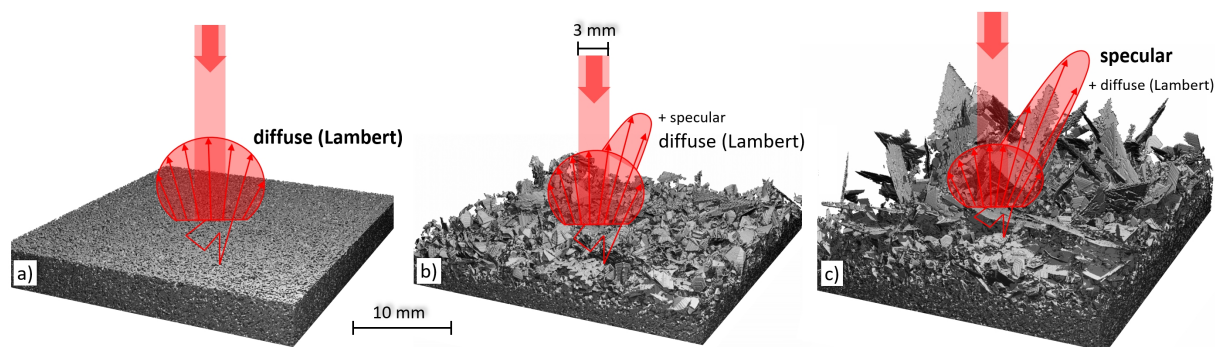


Figure 4: 3D μ CT reconstructions of a) the initial compressed new snow surface, b) the surface hoar at the end of experiment 3 (after 10.5 h, Fig. 3d) and c) the surface hoar of experiment 4 (after 17.5 h). The different, likely dominating BRDF distributions are illustrated for each surface, changing from predominantly diffuse back-scattering towards an increasing contribution of specular reflection.

of the spatial reflectance distribution which is in our case r_{mean} . The initial, spatially homogeneous reflectance signal of the compressed new snow (Fig. 3a) originates from the new snow crystals with small OED which is one to two orders of magnitude smaller than the beam diameter. The primary interaction of the beam with the compressed new snow surface is similar to a planar illumination experiencing volume scattering within the topmost snow layers as illustrated in Fig. 4a (Kokhanovsky and Zege, 2004). This multiple scattering results in a Lambert (diffuse) back-scattering of the beam. As a result, similar reflectance signals are obtained at any location for the initial snow surface. The continuous strong increase of the mean reflectance r_{mean} during the first period of crystal formation (Fig. 5) is likely the result of an increasing contribution of specular reflectance directed towards the laser scanner with increasing surface hoar crystals size as illustrated in Fig. 4b and c. In this study, the initial new snow reflectance values were $r \approx 0.75-0.8$ (Fig. 5), resulting in a moderate increase of $\approx 4\%$ of the mean reflectance r_{mean} for all experiments. However, different initial snow surfaces than those investigated in this study with higher initial mean surface reflectances may result in a decrease of the mean reflectance r_{mean} or even in a constant value of r_{mean} during surface hoar formation. A first preliminary analysis of field data indicates the existence of all three eventualities of an increasing, decreasing, or constant r_{mean} during surface hoar formation. For the above reasons, r_{mean} is likely not a good metric for an explicit identification of surface hoar formation.

4.2. Variance of spatial reflectance distribution

The 2nd order moment of the spatial reflectance variability (r_{std}) increases continuously during the growth process (Fig. 5), even while the mean reflectance decreases during the second period of

experiment 2 and 4 (Fig. 5b and d). The spots of increased reflectance ($r > 0.9$) occurring after 2.5 h (Fig. 3b) can be explained by surface hoar crystals (plates) growing on the substrate with crystal orientations that favour specular back-reflectance (Fig. 4b and c). After $t = 2.5$ h, the surface hoar crystal size is likely already of the same order of magnitude as the beam diameter. The first spots of low reflectances emerging after $t = 5.5$ h (Fig. 3c), i.e., lower than the reflectance of the initial snow surface, are likely the result of large surface hoar plates oriented at steep angles resulting in specular reflections directed away from the scanner (Fig. 4c). Another hypothesis is that a local arrangement of hoar crystals results in cavity like structures forming radiation traps. This effect of local reflectance reductions is further intensified by the increasing surface hoar crystal sizes after $t = 10.5$ h (Fig. 3d and 4b). A first visual inspection of the size of the low and high reflectance spots (Fig. 3d) suggests a length scale of approximately a few millimeters, a value that agrees well with the surface hoar crystal size visually estimated from the μ CT measurements (Fig. 4b). Beside experiment 1 (Fig. 5a), all experiments show a continuous increasing of the standard deviation r_{std} of the reflectance. This increase is the result of an intensification of the high and low reflectance spots (Fig. 3) due to the increase of the surface hoar crystal size. Therefore, unlike any other natural snow surface, the large surface hoar crystals seem to result in an unambiguously strong spatial reflectance variability and a general, strong (up to 600%) and continuous increase in the standard deviation r_{std} . This increase may be a distinct feature of surface hoar growing on any snow surface with a lower spatial reflectance variability. All natural snow surfaces, except large depth hoar, likely have a significantly lower spatial reflectance variability than surface hoar. Our preliminary field data analysis indicates a distinct increase in r_{std} whenever surface hoar growth, independent of initial snow surface

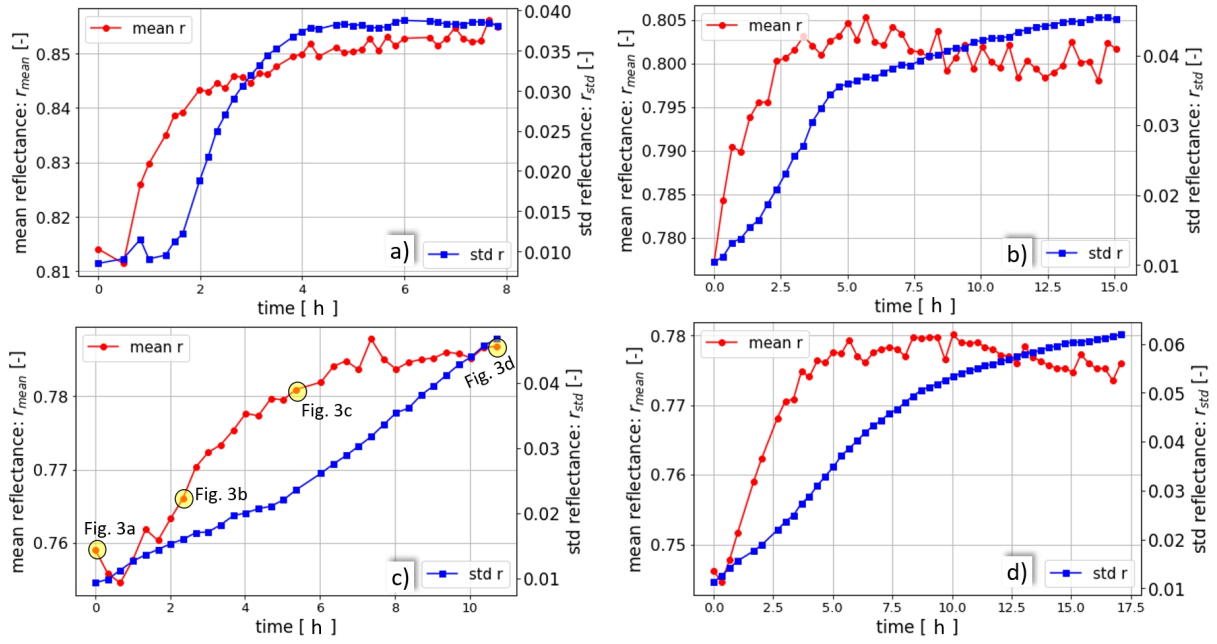


Figure 5: Temporal evolution of the mean (r_{mean}) and standard deviation (r_{std}) of the spatial surface reflectance variability (Fig. 3) for the experiments 1-4 (a-d).

properties and the evolution of the mean surface reflectance r_{mean} . Our results therefore suggest that r_{std} could be a useful parameter to monitor the appearance (and disappearance), and thus the evolution of surface hoar in the field.

4.3. Outlook - Crystal size and orientation

The temporal increase of the 2nd moment of the spatial reflectance distribution (r_{std}) discussed in the previous section may be used to generally observe the occurrence of surface hoar formation on a snow surface in the field. Higher order moments like the skewness (3rd moment) may have the potential to additionally provide information on the main crystal orientation. A reflectance distribution that is negatively skewed could be an indication for an aggregation of low reflectance spots (Fig. 3d) and thus surface hoar crystals whose orientation is predominantly vertical. Contrarily, a positive skewness could mean that the crystals are more horizontally oriented. Such additional information on the crystal orientation would be valuable, as vertically aligned surface hoar crystals are more persistent and fragile, forming the most unstable weak layers within a snowpack (Jamieson and Schweizer, 2000). Finally, a horizontal length scale that may correlate with the average surface hoar crystal size can potentially be derived from a 2D auto-correlation analysis of the spatial reflectance distribution (Fig. 3d).

5. SUMMARY AND CONCLUSIONS

Our findings show that LiDAR remote sensing may be a useful tool for observing the occurrence and the spatiotemporal variability of surface hoar in the field. The increase of the spatial mean reflectance r_{mean} was found being rather small ($\approx 4\%$) and likely depending on the microstructural properties (OED, ρ_s) of the initial snow surface. Therefore, r_{mean} is considered not being a useful indicator for surface hoar formation. However, a continuous and strong ($\approx 400\%$) increase of the standard deviation of the spatial reflectance variations r_{std} was found for all experiments. This can be explained by the fact that, amongst most naturally occurring snow crystal types, randomly oriented surface hoar plates with crystals of a size of several millimetres up to centimeters will always significantly increase the spatial reflectance variability. Therefore, a rapid increase of r_{std} is thus expected being a good indicator for surface hoar formation. To substantiate these findings, additional RWT experiments with different initial snow surface properties under different atmospheric conditions are required. Furthermore, a detailed analysis of an available field data set from winter 2022/2023 with laser scans performed on an hourly basis will be useful to demonstrate the proposed method for field applications. For the field measurements, the laser footprint slightly increased to 4.2 mm due to beam divergence, as the laser was mounted on a 7 m high mast. This may already be on the limit for resolving the spatial reflectance variability for small (≤ 4 mm) surface hoar. As a rule of thumb, we expect the

smallest surface hoar crystals being detectable with a certain LiDAR instrument is likely of the size of the beam diameter. LiDAR could thus in future also be used to monitor surface hoar growth also on larger scales using terrestrial or airborne LiDAR systems to provide field data for improving snow-atmosphere models and thus weak layer and avalanche danger forecasts. As LiDAR is nowadays also more often used in avalanche release areas for monitoring the amount of local snow accumulation (e.g. on Wyssen® avalanche towers, Meier et al., 2018), the additional information on surface hoar formation in release areas could be a valuable information for local avalanche risk assessment.

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