Optical properties of snow in backscatter

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ABSTRACT. We present an overview and the first systematic results on the backscatter properties of snow samples with different grain properties. During a 2 year study we investigated the effect of the apparent characteristics of the samples on the intensity enhancement in the direction of exact backscatter (retroreflection), using a specific instrument designed for backscatter measurements. We observed that a sharp peak in intensity (the hot spot) occurs for most types of snow, which is not observable with traditional goniometers. The key factors in the peak properties are the temperature (related to the changes in grain structure) and grain shape and size. These results form the basis of a larger backscatter data archive which is being applied in the systematic study and exploitation of 'hot spots' in remote sensing of natural targets, as well as in the development of airborne laser intensity measurement.

1. INTRODUCTION

The optical properties of snow play a major role in remote sensing of the cryosphere and mapping of icy regions. Methods for deriving the key factors of snow- and ice-cover variations, such as albedo, metamorphism and grain characteristics (Grenfell and others, 1994; Fily and others, 1997, 1998, 1999), are developed for more effective detection of changes in snow cover. Mapping of snow- and ice-covered areas provides important indications of climate change, hydrological processes and water resources (Fily and others, 1998; Magagi and Bernier, 2003).

Remote sensing of snow and other land surfaces is based on spectral and directional features of light scattered from the surfaces (see Fily and others, 1998; Nolin and Liang, 2000). The bidirectional reflectance distribution function (BRDF) describes the directional properties of light reflected from a surface, and it is used both in directional corrections of, and as a source of information in, remote-sensing data (Verstraete and Pinty, 2001, and references therein). Comparisons with models and in situ measurements are important for more reliable information to be derived from remote instruments. Computational studies of the directional reflectance of snow are found in Leroux and others (1998) and Mishchenko and others (1999). Among the most recent goniometric experiments of the bidirectional reflectance of snow are those by Aoki and others (2000), Painter and Dozier (2004) and Peltoniemi and others (2005).

The increased reflectance at small phase angles (light-source–target–detector angle; see Fig. 1) is observed as a 'hot spot' in remote images for targets such as forest and vegetation (Hapke and others, 1996; Comacho-de-Coca and others, 2004). The increase is particularly pronounced at zero phase and its immediate vicinity, which is often referred to as 'exact backscattering' to distinguish it from backward scattering in the same hemisphere in which the light source is placed (also termed retrosolar scattering in remote sensing). Backscattering has recently gained more importance in terrestrial remote sensing, since there are new instruments that observe at, or close to, exact backscatter (e.g. POLDER and HyMap; see Comacho-de-Coca and others, 2004). The most important observational property of exact backscatter is that it cannot be reached with goniometers, as in these the detector necessarily blocks the light source. However, the effect at zero-angle vicinity undoubtedly contains a significant amount of information on the target material: as Van Albada and Lagendijk (1985) note, the effect is simply much too sharp to be observed without a beam-splitter.

There are few ground reference data available on natural hot spots, even though the backscatter effect has been measured systematically for various substances in laboratory experiments. Laboratory experiments on backscattering patterns have been carried out mostly for powders and particles, and applied in the fields of optics, condensed matter physics, astronomy and medicine (for more references see Yoon and others, 1993; Shkuratov and others, 2002; Kaasalainen and others, 2005a). Small-scale laboratory measurements of natural targets have been made, for example for clumps of grass or needles (Hapke and others, 1996). However, a large number of measurements, particularly field measurements made more or less in situ, would be required to understand and exploit better the hot spot signatures and establish a remote-sensing ground reference databank.

Snow (back)scattering, exact or general, is still a relatively unexplored field. It has been studied mainly for snow crystals in the atmosphere (e.g. Borovoi and others, 2000) and mapping of snow cover at zero phase angle by radar or microwave, with connections to physical parameters (Fily and others, 1998; Strozzi and Mätzler, 1998; Magagi and Bernier, 2003). This is essentially the objective in the optical regime as well. In astronomy, strong backscatter peaks (called opposition effect in this context) have been observed for numerous ice-covered surfaces (including those with water ice), such as rings and satellites (Domingue and Verbiscer, 1997; Poulet and others, 2002). Optical backscattering of snow on the ground has been addressed in only a few studies thus far (Piironen and others, 2000; Shkuratov and others, 2002; Kaasalainen and others, 2003), with a few peaks observed for some samples. These studies have focused mainly on the effects of impurities. Systematic backscattering experiments are lacking, and no description of snow backscatter, or the key parameters related to it, is available. This lack of information is one of the main incentives for undertaking the present study. Another key factor is that this study makes use of a standard experimental set-up that has been used widely in backscatter studies of materials other than snow. Therefore its use here is a natural extension of these applications.

On the theoretical side, there are a number of studies on exact backscattering in both optics and light scattering, so the need to access the zero phase-angle vicinity properly is also important for developing the theoretical methods. Indeed, much of current backscatter theory has remained tentative due to a lack of the systematic experiments needed for building any hypotheses into a theory. In fact, current theoretical results and recent experiments have several mutual inconsistencies or uncertainties (Nelson and others, 2002), so there is an obvious need for new measurements. Although the backscatter effects are extremely strong, even their basic physical interpretation requires both experimental and theoretical studies. The current physical interpretation of hot spots is based on shadow hiding in rough surfaces and coherent backscatter, which is a microscopic-scale interference effect (Hapke and others, 1996; Shkuratov and others, 2002).

This paper presents the results of a 2 year campaign of snow backscattering measurements, the first extensive study with systematic variation of snow parameters. The existing, well-established techniques for measurement of backscattering were applied to snow surfaces to obtain information on the backscattering properties of snow and to search for the main contributors to snow hot spot. The potential applications to glaciology and snow studies via remote sensing are obvious as airborne laser intensity measurements are under development (Geist and others, 2003; Kaasalainen and others, 2005b). The laser altimetry measurement deals with the retroreflected laser beam, but the intensity information has not been discussed thus far. The search for a tool for change detection is of primary importance to glaciology in this context. It is essential to realize that this approach is quite feasible even when exact quantitative inference of the physical properties of the target is uncertain due to insufficient theoretical modelling, noisy data, or even fundamental ambiguities in the inverse problem: change detection is possible without any parametric modelling of the physical properties of the target.

The paper is organized as follows: in section 2 we present the experimental and sampling methods; in section 3 we discuss the results, with particular emphasis on melting and refreezing, specular reflections and grain properties; and in section 4 we present our conclusions and discuss plans for future work.

2. METHODS

2.1. The experiment

From the first experimental demonstration of coherent backscatter (Van Albada and Lagendijk, 1985), experimental studies of backscatter have been developed in many fields, and the techniques based on the use of a beam-splitter have become well established, as well as the use of charge-coupled device (CCD) detectors in the measurement of (backscattered) laser intensity (e.g. Yoon and others, 1993; Wiersma and others, 1995; Nelson and others, 2000; Shkuratov and others, 2002). The measurement presented here is based on these techniques, and has been used widely in laser-based backscatter measurement in optics and related fields for laser intensity measurement and standard CCD photometry used in the laboratory and, for example, in astronomical studies.

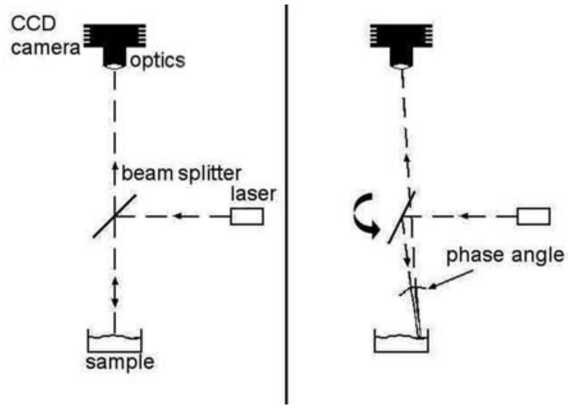

Fig. 1. The small-angle laser goniometer. Retroreflection from the sample is observed through the beam-splitter by the charge-coupled device (CCD) camera (left). Non-zero phase angles (source–target–detector) are obtained by rotating the beam-splitter (right). The distance from beam-splitter to sample was 12 cm, and from the CCD to the sample 120 cm.

The measurements were made using the small-angle goniometer constructed particularly for backscattering measurements, as shown in Figure 1. A 632.8 nm He–Ne laser was used as a light source. The backscatter geometry is worked out using a beam-splitter. The sample was placed on a rotator to smooth out the laser speckle and obtain a larger sample area as the spot (about 4 mm in diameter) moved on the surface. Transmittance filters of 10% and 3% were used in front of the light source to keep the signal in the linear range in the CCD frame. More detailed descriptions of the instrument are provided by Näränen and others (2004) and Kaasalainen and others (2005a, b). We modified the original laboratory set-up to be robust enough for field conditions.

Two separate measurement campaigns were carried out: the first in February/March 2004, producing a set of preliminary results and mainly aimed at instrument development; and the second in February/March 2005 with an improved instrument and measurement facilities. Both campaigns took place at the Sodankylä Observatory (67.368° N, 26.633° E, 179 m a.s.l.) of the Arctic Research Center (Finnish Meteorological Institute). The site is located in a riverside area covered with coniferous forest and surrounded by typical Lappish marshland. The 2004 measurements were made outside or in a covered entrance room with no heating, and the 2005 measurements were made inside a small hut with no heating. The hut had no windows, which allowed measurements to be made during the daytime (a dark workspace was needed to minimize the background noise). The space was occasionally heated (e.g. up to –5°C) during periods as low as –30°C, which prohibited optical measurements (because of precipitation of humidity into the surfaces of the optics).

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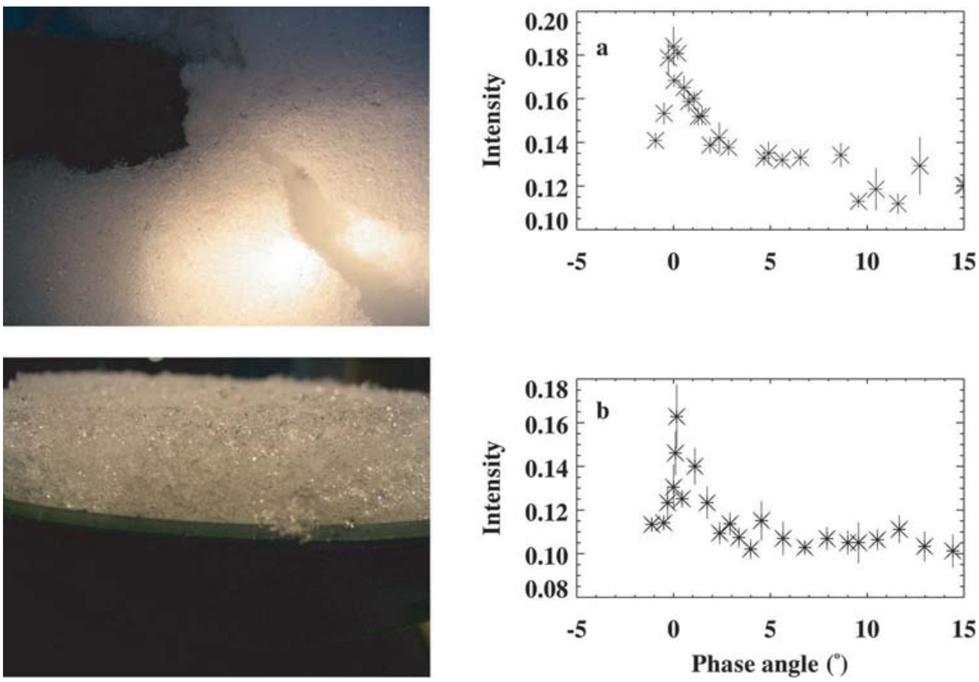

Fig. 2. Refrozen layers from the 2004 campaign measured (a) below (11 March 2004) and (b) above 0°C (19 March 2004).

Typically 25 data points were measured for each phase curve (averaged from five images at the same angle). Fast data acquisition was important to minimize the effects of grain sintering and metamorphism on the sample. On the other hand, camera exposures of sufficient duration were needed to allow a large fraction of the (rotating) sample to be exposed. The range in phase angle varied from –3° to +10–15°; the positive and negative signs denote the viewing geometry around zero phase, from where the spot moved towards and away from the light source, respectively (see Fig. 1). The nominal angular resolution (determined from the source and detector apertures) of the instrument varied between 1.3° (2004) and 0.4° (2005). This causes some rounding of the peaks near zero, especially in the 2004 data, but the differences in the peak properties are well observable because of the extreme sharpness of the effect itself (for more details of the effects of resolution see Kaasalainen and others, 2005a).

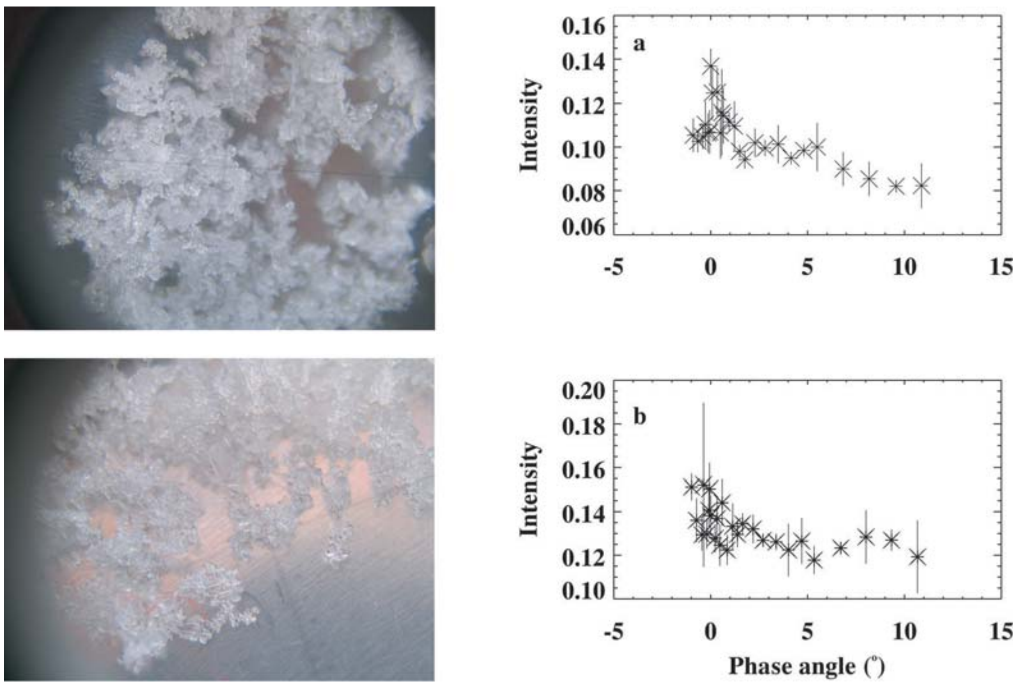

Fig. 3. (a) Melting and (b) frozen surface grains measured on 2 March 2005. The grain images were taken with a millimeter scale (more clearly visible in the bottom left image in Fig. 4).

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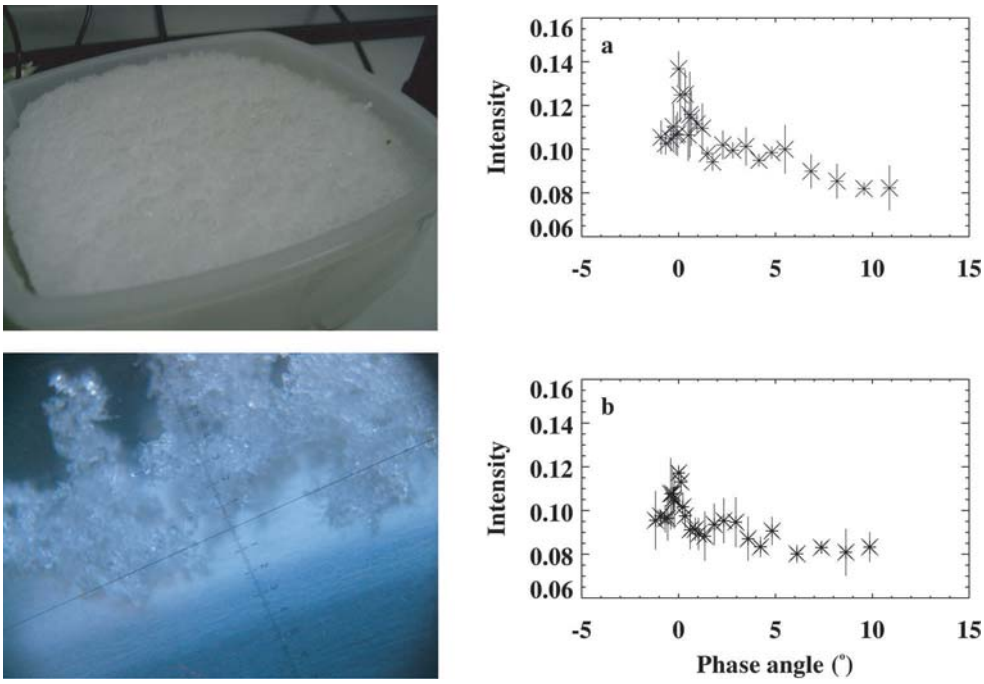

Fig. 4. (a) Melting grains (same sample from 2 March 2005 as shown in Fig. 3a) and (b) same sample after refreezing. The millimeter scale visible in the bottom left image is the same in all the grain images.

2.2. Sampling

To achieve systematic sampling, we made several measurements over a long timescale; there is little opportunity for a priori sample variation with natural snow targets, especially in field conditions. The device has to operate on a solid foundation to achieve the proper optical alignment (cf. Kaasalainen and others, 2005a), so the samples from the snowpack were transferred into a small plastic container, which was placed underneath the beam-splitter. This results in small sample sizes (the sample thicknesses varied between 3 and 5 cm; see Tables 1 and 2), but this does not affect the comparable properties of the backscatter peak shape, since the directional signal from the platform adds to the diffuse (rather than the directional) reflection as it is scattered on the sample layer above. The sample surfaces were smoothed with a spade (essentially just wiping out the excess snow), except for hard (refrozen) layers which were extracted as a

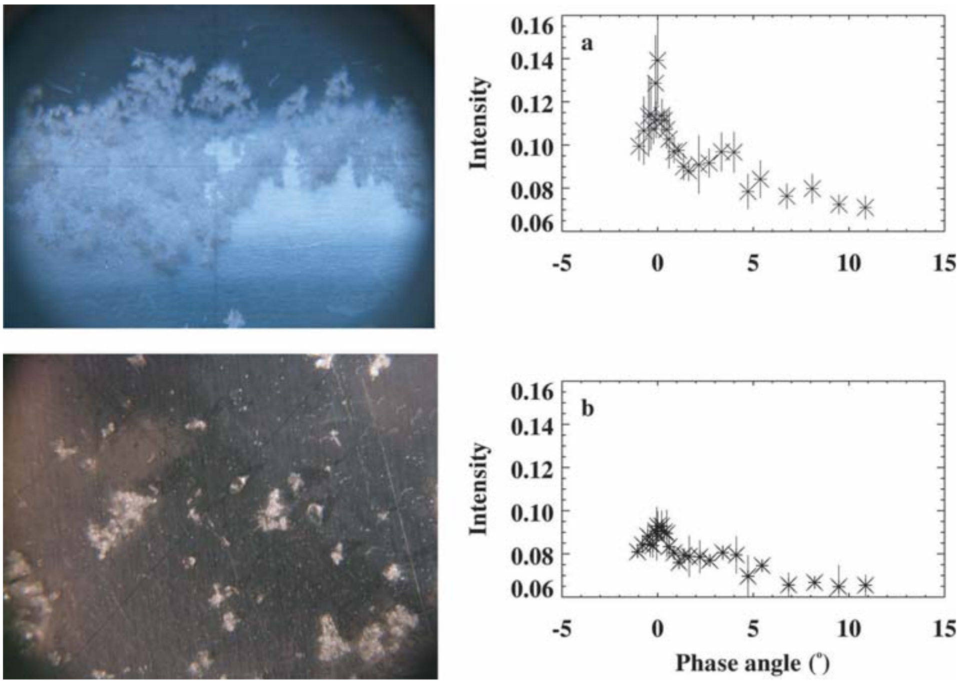

Fig. 5. (a) Melting new snow produces a stronger backscatter effect than does (b) the refrozen sample (both from 3 March 2005). Both surfaces were tilted to elimintate the effect of specular reflection.

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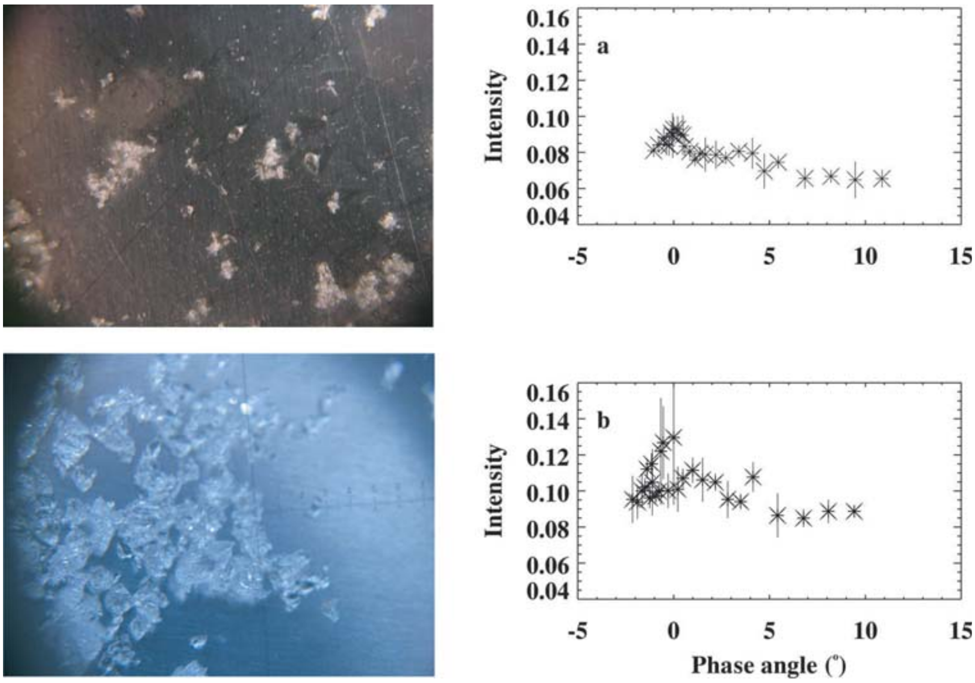

Fig. 6. (a) Refrozen (rounded) grains (same sample as shown in Fig. 5b) and (b) grains of a coarser structure taken from 40 cm depth in the snowpack (also measured on 3 March 2005). The difference in the smoothness of the phase curve is visible (cf. also Fig. 9).

chunk (see the layers photographed in Fig. 2). The approximate sample densities were measured by weighing the sample in its container (of known volume), and the grain properties were analyzed visually using a 0.1 mm scaled field magnifier loupe. In the 2005 campaign, we also took images of the grains through the loupe (see Figs 3–10).

The snow properties were classified according to Colbeck and others (1990). The characterization presented here is sufficient to enable us to highlight the differences in backscattering peaks of different types, and we concentrated on the characteristics that were shown to have an effect on backscatter in previous experiments for other samples (Nelson and others, 2000; Shkuratov and others, 2002; Näränen and others, 2004; Kaasalainen and others, 2005a).

3. RESULTS AND DISCUSSION

We employed the standard practice of relative CCD photometry, normalizing all intensities to the Spectralon spectroscopic standard (Labsphere Inc.). For this we used its

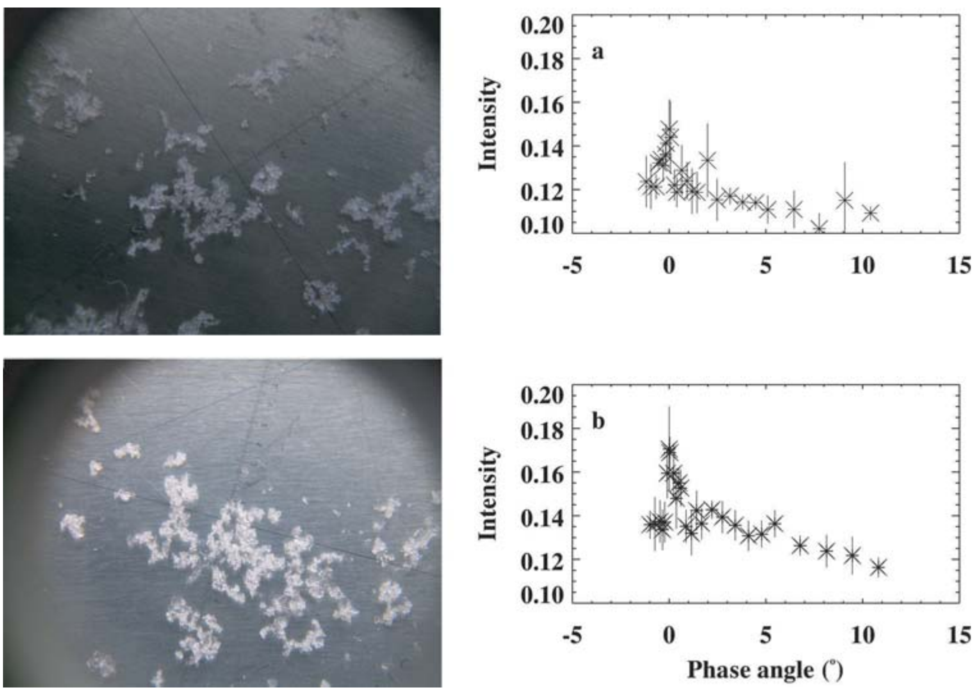

Fig. 7. Effect of compression on surface (needle) grains: (a) slightly compressed (7 March 2005) and (b) compressed overnight (8 March 2005).

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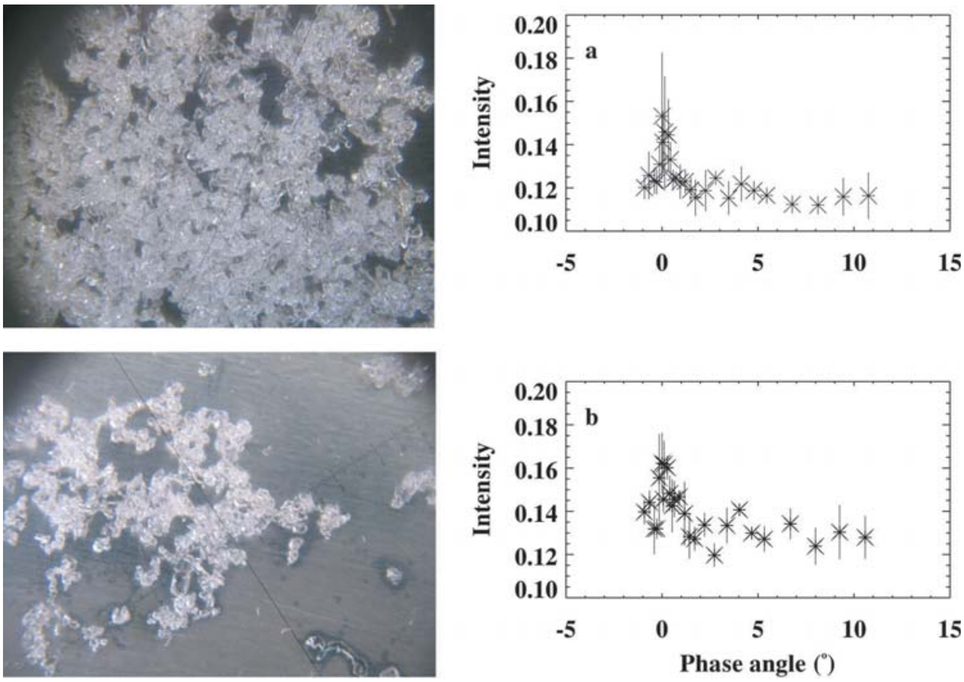

Fig. 8. Comparison of the effect of grain size: (a) 0.7–1.0 mm rounded grains from 5–10 cm depth in the snowpack (12 March 2005) and (b) same sample slightly melted and refrozen (13 March 2005).

phase curve average, excluding the smallest phase angles where its (linearly polarized) reflectance is not constant. To compare more easily the intensity levels at 0° and 5° (i.e. outside the backscatter peak) phase angles, a four-parameter empirical function was fitted to most data to achieve a better approximation of the intensity level at 0° and 5° and compute the peak amplitude, $I(0°)/I(5°)$, and the half-width–half-maximum (HWHM, which is a measure of the apparent width of the backscatter peak) phase angle (see, e.g., Nelson and others, 2000; Kaasalainen and others, 2005b). The exponential function gives the relative intensity, $I(\alpha)$, as a function of phase angle: $I(\alpha) = a\exp(-\alpha/d) + b + k\alpha$, where a, d, k and b are empirical parameters (see also Piironen and others, 2000; Kaasalainen and others, 2005a). The intensities, $I(0°)$, peak amplitudes, $I(0°)/I(5°)$, and HWHMs are tabulated with the sample characterizations in Tables 1 and 2.

Large deviations in the data are typical for snow (cf. earlier measurements in backscatter and other direction, (e.g. Kaasalainen and others, 2003; Peltoniemi and others, 2005)).

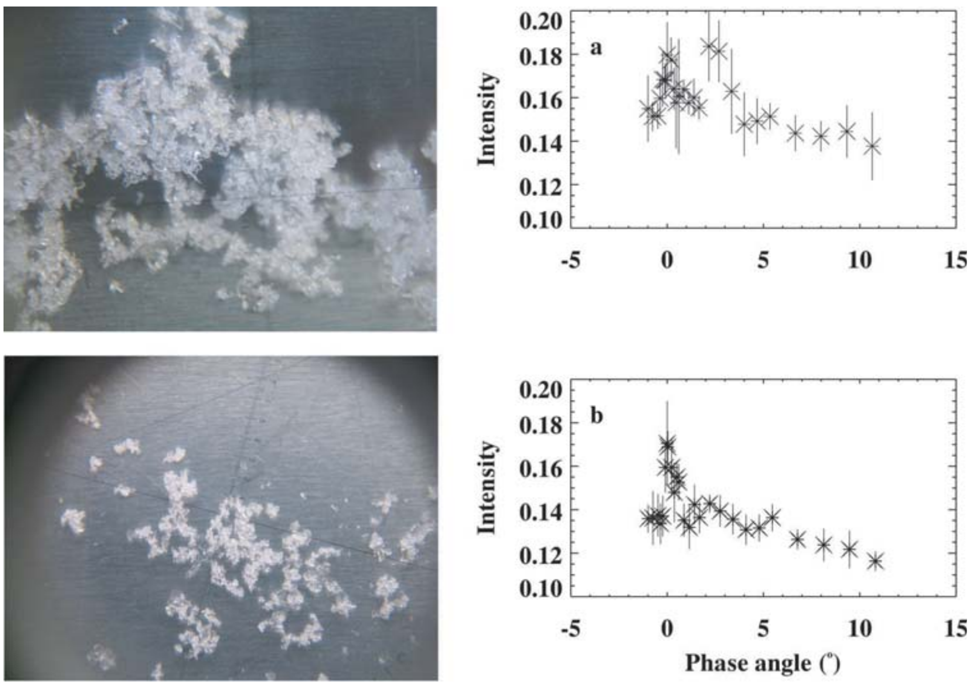

Fig. 9. Effect of grain-size: (a) 0.2–0.5 mm surface grains from previous day's snowfall (8 March 2005) and (b) 0.1–0.3 mm surface grains from previous day's snowfall (8 March 2005; same sample as shown in Fig. 7b).

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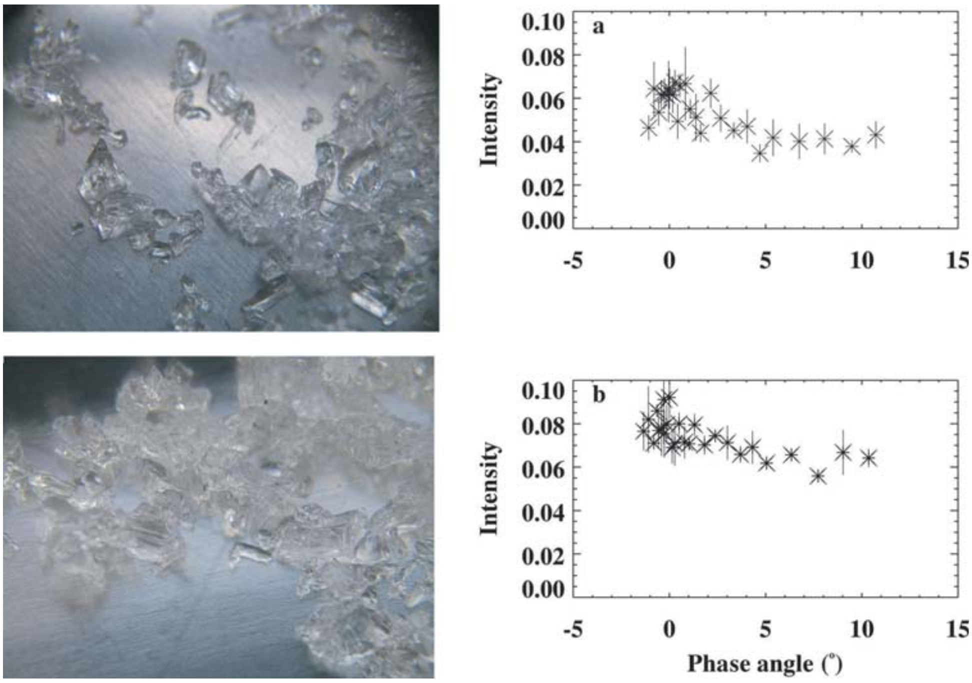

Fig. 10. Larger grain sizes (than those shown in Figs 8 and 9): (a) depth hoar with grains of 2 mm from about 80 cm depth in the snowpack (4 March 2005) and (b) a similar sample with grains of 2–3 mm (10 March 2005).

2005)). Another feature in snow measurements is that the calibrated intensity levels are lower than reported snow albedo values at 633 nm (see Grenfell and others, 1994). This results from the laser beam entering deep into the snow layer due to strong multiple scattering inside the layer, which, unlike for other types of samples or standards, is not observable with all photometric techniques. Since the diffuse radiation only adds to the background intensity, and the strongest directional signal comes from the surface, the comparison of backscatter peak characteristics is still possible in a relative sense. These results must be considered preliminary, but they give a qualitative overview of the most typical effects present in the backscatter direction. Further investigation of laser-based snow measurement techniques remains an important objective of future study. It is also apparent that, for snow data, many features are visible from a large bulk of repeated measurements rather than a single curve. Representative datasets are plotted in Figures 2–12,

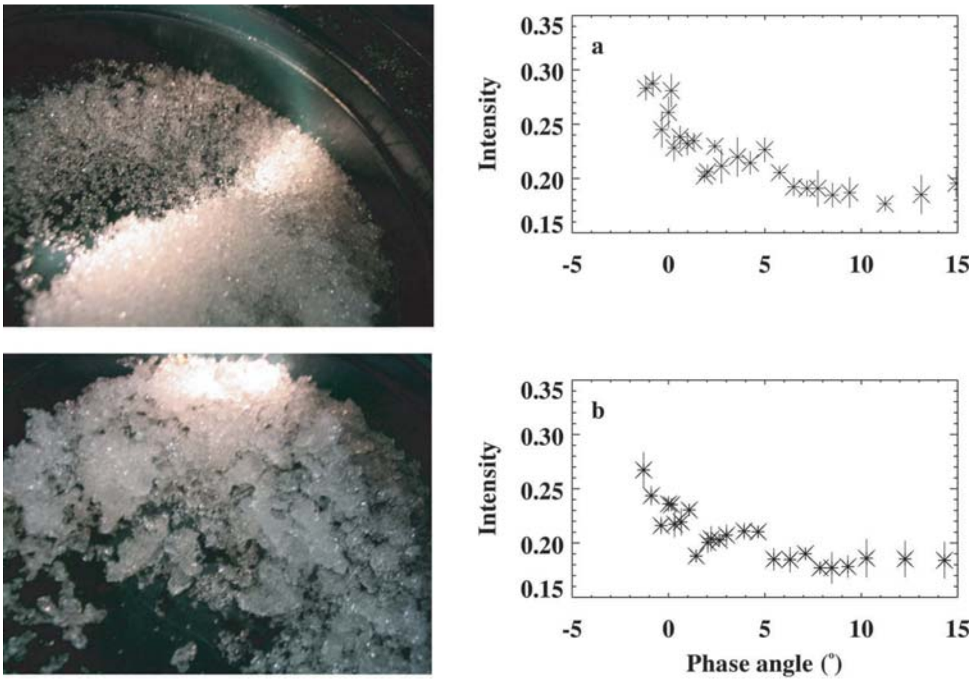

Fig. 11. Comparison with data from 2004: (a) aged snow from about 40 cm depth in the snowpack and (b) depth hoar from 60 cm depth in the snowpack. The samples (both measured on 23 March 2004) are photographed in a sample cup of about 11 cm diameter.

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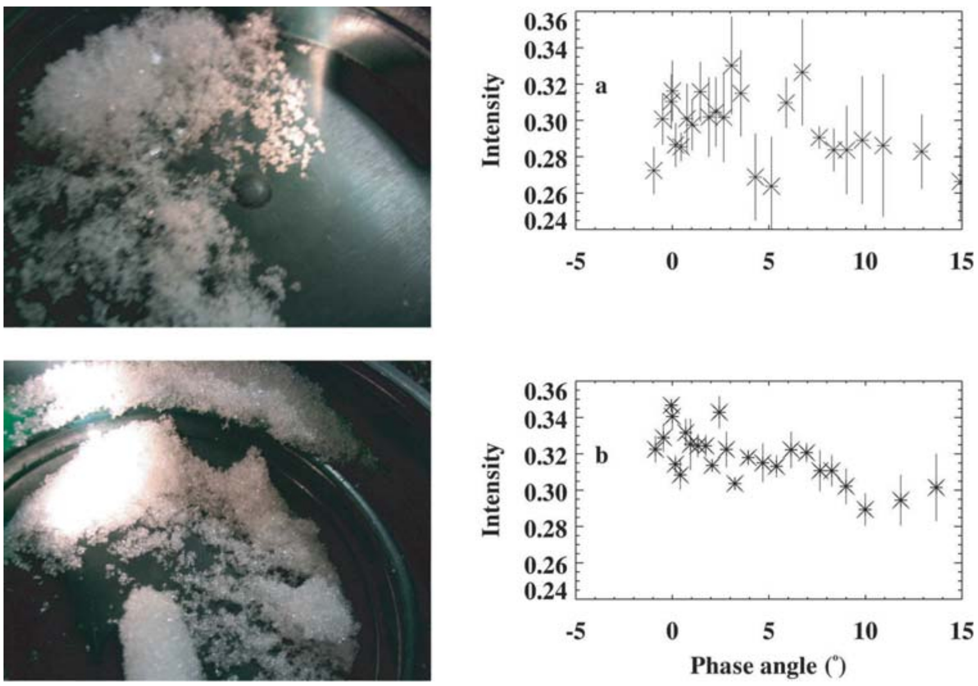

Fig. 12. Data from 2004 measurements: (a) new snow from the surface and (b) aged snow from about 20 cm depth in the snowpack (both samples measured on 23 March 2004). The effect of rounded grain structure (compared with fresh fallen grains of a finer structure) on the smoothness of the phase curve is also clear in this case. The sample grains are photographed in a sample cup of about 11 cm diameter.

and photographs of the grains taken with the aid of a millimeter-scaled viewing loupe are presented. No small-scale photographs are available for the 2004 samples, but large-scale images are presented to give an overall view of the sample structure.

3.1. Melting and refreezing

As seen from Figures 2–12, the graphs are smoothest and the results more accurate for melted and refrozen samples. These samples also produced the strongest and most distinguishable peaks, whereas much greater deviation in data is observed for the samples measured below 0°C, which may also have masked the peak. This is observed most clearly in Figure 3 for the two similar samples, the other of which (Fig. 3a) was measured after heating the hut up to 3°C. There is a notable difference in the relative peak amplitude (Table 2). A strong peak was still observed a few hours later after refreezing the same sample (Fig. 4), which suggests that the role of grain structure (which changes greatly in the process of melting) is stronger than that of temperature. This is also supported by comparison with the 2004 data: there is no substantial difference in the peak amplitudes of a refrozen surface measured below and above the freezing point (Fig. 2). In earlier studies of the effect of liquid water on snow reflectance (see Warren, 1982, and references therein), the spectral reflectance of refrozen snow

Table 1. Data from 2004. Snow sample characterization (approximate) and backscattering properties from the fits of the exponential function (see section 3.1)

Date	Mean snow/grain size mm	Air temperature °	Density $g\,mL^{-1}$	Thickness cm	$I(0)$	$\frac{I(0)}{I(5)}$	HWHM °
Surface – new							
23 Mar	Columns, 0.1	–5.0	0.08	4.0	0.32	1.09	0.1
Surface – aged							
11 Mar	Refrozen layer, 1.5	–7.5	0.22	5.0	0.18	1.37	1.2
19 Mar	Refrozen layer, 2.0	+2.0	0.18	4.5	0.14	1.34	1.0
Layers							
23 Feb	15–20 cm, agglomerate, 0.7	–20.0	0.28	4.0	0.29	1.25	0.5
18 Mar	15–20 cm, decomposed, 0.7	+2.0	0.22	3.5	0.24	1.18	0.3
23 Mar	20 cm, decomposed, 0.5	–5.0	0.27	3.5	0.35	1.10	0.1
23 Mar	40–50 cm, rounded, 1.5	–5.0	0.33	3.5	0.27	1.30	0.5
Depth hoar							
23 Mar	60 cm, facets 4.0	–5.0	0.35	4.0	0.24	1.23	0.5

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Table 2. Data from 2005. Snow sample characterization (approximate) and backscattering properties from the fits of the exponential function (see section 3.1). R = sample taken from the snowpack on top of the river ice; T = surface tilted. The approximate sample thickness was 4 cm, except for the melted/refrozen samples for which it was 3 cm for samples taken between 1 and 3 March and 3.5 cm for both samples taken on 13 March

Date	Snow, grain size	Air temperature	Density	$I(0)$	$\frac{I(0)}{I(5)}$	HWHM
	mm	°C	g mL^{-1}			°
Surface – new						
27 Feb	Facets, 0.2–1.0	–5.5	0.10	0.19	1.25	0.2
3 Mar	Melting (T), 0.1–0.3	+3.0	0.06	0.14	1.63	0.3
3 Mar	Refrozen (T), 0.1–0.4	–1.0	0.12	0.10	1.30	0.6
4 Mar	Hexagons, 0.1–1.0	–4.0	0.07	0.17	1.41	0.6
7 Mar	Needles, 0.3	–1.0	0.10	0.15	1.32	0.1
Surface – aged						
1 Mar	Melting, 0.5–1.0	+2.0	0.11	0.14	1.55	0.4
2 Mar	Melting, 0.5	+2.5	0.12	0.13	1.42	0.5
2 Mar	Frozen, 0.5	–3.0	0.12	0.14	1.10	0.1
2 Mar	Refrozen, 0.5–1.0	–3.0	0.15	0.12	1.40	0.2
8 Mar	Compressed, 0.1–0.3	–6.5	0.08	0.17	1.32	0.4
8 Mar	1 day old, 0.2–0.5	–5.0	0.10	0.18	1.18	0.3
8 Mar	1 day old, shaken, 0.2–0.5	–5.0	0.14	0.19	1.16	0.8
10 Mar	Rounded, 0.2–0.5	–7.5	0.11	0.16	1.25	0.4
11 Mar	Layer (R), 0.2–0.5	–9.0		0.24	1.11	1.1
12 Mar	Layer (R), 0.2–0.5	–8.0		0.24	1.17	0.4
Layers						
3 Mar	40 cm, coarse, 0.7–1.0	–1.0	0.29	0.12	1.27	0.1
4 Mar	1 cm, columns/facets, 0.5–1.0	–4.0	0.10	0.16	1.21	0.2
4 Mar	60 cm, agglomerates, 0.8	–3.5	0.31	0.11	1.17	1.1
11 Mar	30 cm, rounded (R), 0.2–2.0	–9.0	0.28	0.14	1.32	0.3
11 Mar	30 cm, rounded, 0.5	–5.0	0.30	0.10	1.13	0.4
11 Mar	60 cm, round/agglomerate, 1.0	–5.0	0.33	0.03	–	–
12 Mar	30 cm, rounded (R), 0.5–1.5	–8.0	0.32	0.13	1.35	0.2
12 Mar	30 cm, agglomerates, 0.5–0.8	–6.0	0.29	0.12	1.19	0.1
12 Mar	5–10 cm, rounded, 0.7–1.0	–6.0	0.20	0.15	1.28	0.4
13 Mar	5–10 cm, melt/refreeze, 0.7	–6.5	0.19	0.16	1.25	0.5
13 Mar	30 cm rounded, 0.5–1.0	–6.5	0.28	0.14	1.28	0.9
Depth hoar						
4 Mar	80 cm, faceted, 2.0	–3.5	0.28	0.06	1.53	1.2
10 Mar	80 cm, facets, 2.0–3.0	–7.5	0.31	0.08	1.24	0.1

was found to be very similar to that of melting snow. Temperature seems to have an indirect effect by affecting the grain structure and hence the optical properties.

3.2. Specular reflection from the surface

The effect of specular reflection from a wet surface can be investigated by comparing the measurement in Figure 4a with that in Figure 5a, and Figure 4b with Figure 5b. The samples are otherwise similar, but those in Figure 5 have been tilted (by tilting the other edge of the sample cup about 1 cm higher) to avoid the normal incidence into the sample surface, and hence the possible specular reflection back to the camera at 0° phase angle. As strong backscatter peaks are still observed (see also Table 2), it is apparent that they are not caused by specular reflection from the surface. More studies on the role of these reflections on bidirectional reflectance of snow would still be worthwhile.

3.3. Grain proprties

The mean grain size of the samples was approximated as the diameter of the longest dimension of the grains. As discussed above, factors other than grain size seem to have a stronger effect on the backscatter peak. However, comparing the samples measured in freezing temperatures, the curve shapes appear sharper for those with larger grains, whereas the smallest peaks occur for those with a grain size of ≤0.5 mm (Table 2). The samples with large grains mostly have smaller reflectances, which emphasizes the relative increase in brightness towards 0°. This is in agreement with the 2004 data, for which the samples with grain sizes >1 mm generally produced the largest peaks (Table 1). Also, depth hoars have large enhancements from 5° towards 0°, but there is deviation in the data which is likely to be caused by the grain structure (see the images of the typical depth-hoar grains in Fig. 10).

The effect of grain rounding is presented in Figures 6 and 9. The effect is also seen for 2004 data in Figure 12, where the phase curve of the rounded grains from 20 cm depth in the snowpack is also smoother than that of the finer-structured column/hexagon-type grains, and the errors are smaller. Overall, the winter of 2004 was warmer, with several periods of temperatures above zero, which seems to have had an effect on all samples: all the grain structures were

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observed to be smoother than those observed in 2005, which were mostly coarser in structure. Therefore the results agree with observations for melted and refrozen samples (Figs 3 and 4): the smoother structure causes a stronger hot spot.

We also attempted to determine the effects of packing density by mechanically compressing some samples or allowing the sample to flatten out overnight (Fig. 7). The only observed effects were an increase in surface brightness and greater deviation in data. Thus factors other than packing density had a stronger effect on the backscatter peak properties. We found no strong links between surface brightness and the amplitude or HWHM of the peak (Table 2). The reflectance also increased for the samples taken from the dense surface layer on top of the river ice, but here too the other properties (such as grain size or the decomposed and faceted structure) played a stronger role.

We found no correlation of the HWHM values with any observable parameter in the samples, except for the 2004 data, for which the HWHM appears to increase with increasing grain size; however, more measurements are required.

4. CONCLUSION

This study confirms the earlier assumption that snow in general exhibits a backscatter peak (Piironen and others, 2000; Kaasalainen and others, 2003), i.e. most snow types present a sharp intensity surge at phase angles approaching zero. This is also the first and thus far most extensive overview of backscatter (hot spot) effects from different snow types. The key factors in the existence and properties of the peak are temperature (the effect of which is indirect and related to grain rounding) and the grain structure and size, as the (refrozen) samples with the largest grain/agglomerate size produced the most prominent peaks. The results observed here are preliminary, but they represent the first systematic approach to the snow parameter variation in the investigation of snow backscatter.

As far as the physical interpretation of the backscatter peak is concerned, it seems that this effect is dominated by coherent backscatter since the peaks are narrow and other experiments indicate that shadowing starts to take effect at larger angles. This is one explanation for the fact that snow does not show backward scattering in large-angle-scale bidirectional reflectance measurements, whereas rough substances show substantial shadowing effects (cf. lichens in Kaasalainen and Rautiainen 2005).

There is evidence from other fields that backscattering peaks can be applied in target characterization, but the development of methods to be used in remote sensing of snow calls for a large data archive, for which these measurements are a starting point. More accurate laser measurement techniques for snow are also a subject of further investigation. Because of the combined effects of snow properties, backscatter measurements alone may not be suitable for accurate retrieval of surface parameters, but combined with simultaneous data from other sources they could provide an important source of information about the ongoing changes in snow and ice surfaces. Laser intensity data from glacier altimetry may in some cases be a major source of information on a particular surface, which makes the further investigation of laser backscatter intensity worthwhile. Since change detection is possible from repeated (relative) experiments, our results support the application of backscatter measurements in the study and calibration of intensity information from laser scanning, which has recently become a common method in glacier altimetry. Exploiting the intensity information would enable an airborne laser-based change detection method for snow and ice surfaces, which would have a strong impact on climate study.

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