Quantifying the stratigraphy of snow profiles

A dissertation submitted to the
SWISS FEDERAL INSITUTE OF TECHNOLOGY ZÜRICHT
for the degree of
DOCTOR OF SCIENCE

presented by
MARGRET MATZL
Dipl. Geogr. HU Berlin
born February 29, 1976
citizen of Germany

accepted on the recommendation of
Prof. Dr. Hannes Flühler, examiner
Dr. Martin Schneebeli, co-examiner
Adj. Prof. Dr. Matthew Sturm, co-examiner

2006
Summary

A seasonal snow cover is composed of several layers which mainly have been formed due to various precipitation events. The stratigraphy of the snow cover describes the sequence and the properties of these layers. It is thus of relevance to all research areas concerned with seasonal snow covers. In particular, successful avalanche forecasting and snow cover modelling require a sound knowledge of the horizontal variability of the snow stratigraphy. Existing methods, which allow us to describe the vertical and lateral variation of the snow cover yield qualitative measurements. Methods which measure snow stratigraphy quantitatively and in two dimensions (2D), and thus allow for to quantify the spatial variability on scales from millimetres to metres, are yet not available.

In this thesis I focus on the development of a method to qualitatively and quantitatively measure snow stratigraphy vertically and laterally. I used a digital camera which was modified to record in the near infrared (NIR) spectrum between 840 and 940 nm. In this wavelength band the scattering properties of snow depend mainly on its grain size. I developed a measurement design to take images from vertical snow pit walls in the field. Calibrated targets with defined reflectance values were used to digitally rectify and calibrate the images and to calculate the reflectance from the pixel intensities. The grain size of the snow was defined as surface-to-volume ratio or specific surface area (SSA) and measured using model-based stereology.

Based on approximately fifty snow samples, I calculated the correlation function between NIR reflectance and SSA. The finding of an exponentially increasing SSA with increasing reflectance was confirmed by the results of a beam-tracing model which was implemented to predict radiative transfer and reflection of real snow structures observed on natural snow samples.

The SSA was then calculated for the NIR images based on the derived correlation function.
The spatial resolution of a NIR image covering an area of $1 \text{ m}^2$ is approximately $1 \text{ mm}$. The resulting images show that variations in the SSA reflect the stratigraphy of a snow cover in high detail. The method visualises layers and also slight vertical and horizontal changes which are difficult to detect by conventional field methods and to perceive by eye. Recording one 2D measurement of the SSA of a $1 \text{ m}^2$ snow profile wall takes half an hour to one hour. The field part takes about as long as the processing of the images.

Digital NIR photography is a promising tool for the observation of temporal and spatial changes in the snow cover. Single NIR images as well as mosaics composed of several adjacent images can be used to quantify the spatial variability on a scale between millimetres and several metres. This spatial analysis can be further extended to three dimensions by photographing a series of snow stratigraphies in close spacing.
Zusammenfassung


Als nächster Schritt wurde, basierend auf den Messwerten von fünfzig Schneeproben, die Korrelation zwischen Reflektivität und SSA bestimmt. Die Korrelationsfunktion zeigt, dass die Reflektivität mit exponentiell steigender SSA zunimmt. Auch die Resultate eines "beam-
tracing” Modells, das den Zusammenhang zwischen SSA und Reflektivität für reale Schneestrukturen simuliert, bestätigten diese Ergebnisse.

In der weiteren Forschungsarbeit verwendete ich die Korrelationsgleichung, um die Reflektivitätswerte der NIR-Bilder in SSA umzurechnen. Ein NIR-Bild mit einem Bildausschnitt von 1.0 m² hat dabei eine räumliche Auflösung von ungefähr 1 mm. In den NIR-Aufnahmen sind sowohl Schichten als auch langsamer horizontale und vertikale Übergänge sichtbar, die mit herkömmlichen Methoden oder auch von bloßem Auge nur schwer erfasst werden können. Die Unterschiede in der SSA beschreiben die Schneestratigraphie also sehr detailliert. Der Zeitaufwand für eine SSA-Messung in 2D beträgt mit dieser Methode für ein bereits gegrabenes Schneeprofil maximal eine Stunde. Je die Hälfte der Zeit ist für die Feldmessungen und für die digitale Bearbeitung und Umrechnung der Bilder nötig.

Dies macht digitale Fotografie im NIR zu einer vielversprechende Methode um räumliche und zeitliche Veränderungen in der Schneedecke zu verfolgen. Einzelne Fotos oder Mosaike aus mehreren benachbarten Bildern können verwendet werden, um die räumliche Variabilität mit geostatistischen Methoden auf einer Skala von Millimetern bis zu mehreren Metern zu quantifizieren. Es besteht auch die Möglichkeit, diese räumliche Analyse noch um die dritte Dimension zu erweitern, indem man mehrere Schneestratigraphien hintereinander aufnimmt.
Chapter 1

Introduction

The seasonal snow cover in the Alps directly affects the life of the residents by the danger of avalanches and spring floods, by the influence on traffic and transportation routes, and its economical importance for villages living on winter tourism. Annually about twenty-five persons die in the Swiss Alps due to avalanche accidents (Tschirky et al., 2000). Reliable avalanche forecast and prevention requires detailed knowledge on the properties and composition of the snow cover. The snow cover receives also increasing attention in the global context of pollutant deposition (Lalonde et al., 2002) and questions of climate change (IPCC, 2001) and of long term supply of drinking water (IPCC, 2001), effects which can only be observed on a longer time scale.

A typical seasonal snow cover is composed of several layers arranged more or less parallel to the soil. The individual snow layers result from the various precipitation and snow drift events. The surface of the snow cover is constantly modified by the local weather, like for example wind, radiation, precipitation and melt processes. Inside the snow cover metamorphic and sintering processes change the snow structure. Metamorphism describes changes in snow structure due to the transfer of energy and mass through the snow cover (De Quervain, 1963; Colbeck, 1987). The process of "temperature-gradient" metamorphism results in a kinetically controlled growth of the ice structures (Sturm and Benson, 1997; Schneebeli and Sokratov, 2004). Isothermal metamorphism results in a reduced surface-to-volume ratio minimising the surface free energy. The driving mechanism of isothermal metamorphism is still being discussed (Legagneux and Domine, 2005; Kämpfer et al., 2006). Sintering is a thermodynamic process during which the particles are bonded together via mass transport (Colbeck, 1997; German, 1996). It results in a consolidation and densification of the
snow cover. These processes, metamorphism and sintering take place at variable rates and intensities, depending on the boundary conditions such as radiation, air temperature, and temperature gradient between ground and snow surface. Above being altered by transformation processes in the snow cover, the layer properties also determine the intensity of these processes by their structural features as specific surface area and density, affecting their thermal conductivity and hence the layer temperature. Under the influence of metamorphism and sintering the layers are no longer identifiable as the result of individual precipitation events. Layer boundaries and layers start blurring.

The increasingly blurred transitions between layers make it imprecise to use the term "layer", which gives the impression of a homogeneous area with discrete boundaries. Lacking a more precise technical term I use the term "layer" throughout the following work referring to a horizon which is "approximately parallel to the surface" of the snow cover, and "distinguishable from adjacent horizons by a distinctive set of properties..." (Soil Survey Division Staff (1993), page 60).

In addition to a vertical differentiation also lateral variations distinguish the different snow cover realisations. The spatial variation of the snow cover is again determined by influences of weather (i.e. radiation and wind) and climate but also by topography (inclination, orientation, surface roughness) and vegetation. For flat areas wind drift has been determined to act as the most active agent, resulting in maximum heterogeneities at a scale of about 100 m (Sturm and Benson, 2004). In alpine terrain wind drift was shown to be a major parameter on the slope scale (Kronholm et al., 2004). A quantitative analysis of the spatial variability on a smaller scale up to one metre is still missing, possibly due to the lack of observation methods to quantify the lateral variation of features on this scale.

The knowledge of the snow stratigraphy and the properties of the layers are important criteria to assess the stability of the snow cover. It is the basis for predicting the rate and the intensity of the transformation processes and thus of future alterations, which affect, for example, the propensity of fracture initiation and propagation (Sigrist et al., 2006). Successful avalanche forecasting and snow cover modelling depend on a sound knowledge thereof. The spatial variability is of special importance for avalanche forecasting, as it largely controls the process of avalanche formation (Schweizer et al., 2003; Kronholm and Schweizer, 2003).

Several methods exist to measure quantitative snow properties in the field. The assessment of snow covers for avalanche forecasting is often carried out in high altitude regions and on steep
slopes which are only accessible by skis, snowshoes, or helicopter. Conventional methods are therefore usually simple manual procedures, as they cannot rely on heavy equipment and should be executable also under bad weather conditions.

Most methods imply the digging of a snow pit, a vertical profile wall to the ground, which allows the observer to identify individual layers based on visually and manually observed variations in the snow cover. The detected layers are then characterised based on their snow type, grain size, hardness, density, and temperature (Pielmeier and Schneebeli, 2003). Snow type and grain size (mean greatest extension) are visually estimated on a ruler plate with a magnification lens (10x). Snow hardness is measured using a Rammsonde (Bader et al., 1939) or applying the hand test (Colbeck et al., 1990) and density is calculated due to the weight of a certain snow volume.

One drawback of conventional field measurements is their subjective nature, particularly regarding grain size and hardness assessment. Although international standards exist for such measurements (Colbeck et al., 1990) the results strongly depend upon the observer’s estimation abilities and experience.

Another problem is the low spatial resolution and the one-dimensional character of the mentioned methods. The measurement schedule assumes homogeneous layers, separated by distinct boundaries and therefore it is not possible to detect more subtle vertical changes or lateral variations of the observed features. A device overcoming this drawback for hardness measurements has been developed at the Swiss Federal Institute for Snow and Avalanche Research (SLF), Switzerland and the Cold Regions Research and Engineering Laboratory (CRREL), Alaska. A high resolution snow penetrometer (SMP) introduced by Schneebeli and Johnson (1998) measures the penetration resistance with a vertical spatial resolution of 4 µm and an accuracy of approximately 0.01 N. While the resulting force signal is vertically quasi-continuous, the horizontal resolution is technically constricted to a distance of 0.5 m for field measurements. The SMP is therefore highly suitable to detect spatial variations in the stratification on a scale from 0.5 to several 100 metres (Kronholm et al., 2004), but it is not applicable to document these variations continuously.

Because of the spatial heterogeneity of the snow cover the spatially continuous assessment of snow properties on various scales is important to evaluate the significance of a vertical measurement for the surrounding snow cover. Methods, as hand-drawings of cross sections (Sturm and Benson, 2004) and translucent profiles (Benson, 1962; Good and Krüsi, 1992) have been developed, which concentrate on the qualitative documentation of stratigraphic
features including horizontal patterns. However, in addition to being very time consuming, spatial variation and transitions of grain size cannot be extracted. A quantitative analysis is not yet possible for translucent profiles, because the intensity of the transmitted light depends on the grain size as well as on the snow density and section thickness. Marshall et al. (2004) uses high frequency (8-18 GHz) Frequency Modulated Continuous Wave (FMCW) radar to map dielectric discontinuities caused by large changes in physical snow properties. With this method, large areas can be measured continuously with a high spatial resolution. Major features as for example hard crusts can be measured reliably. The interpretation of more subtle stratigraphic changes seems to be still challenging and is presently being improved.

The previous section and also a recent review on snow stratigraphy (Pielmeier and Schneebeeli, 2003) show the need for a straightforward method to assess vertical as well as spatial heterogeneities of the snow cover at a high spatial resolution. It is the aim of this work to develop a field method which allows a qualitative and quantitative assessment and documentation of the snow stratigraphy. A high resolution is necessary to detect small features of the snow cover, like for example mechanically weak layers and ice lenses. Two-dimensional measurements are required to account for horizontal as well as vertical variations. And finally, the snow cover measurement should be as objective as possible.

This assessment of the snow stratigraphy will be based on the surface-to-volume ratio (specific surface area, SSA), a parameter describing the structural snow size. Determining the grain size is a crucial part of conventional field measurements. However, the definition of individual snow grains is not unambiguous, considering the sintered nature of snow. For this research I will use the SSA, which is a bulk property and describes the mean property of a certain volume, without requiring the definition of individual grains. According to German (1996) the SSA is an essential microstructural parameter for the characterisation of sintered materials, it is sensitive to metamorphic processes (Legagneux and Domine, 2005; Schneebeeli and Sokratov, 2004) and can be converted into an effective diameter (Giddings and LaChapelle, 1961; Grenfell and Warren, 1999; Mitchell, 2002), which is commonly used for estimating radiative properties of snow in the near infrared (NIR) spectrum (Warren, 1982).

Digital photography has been chosen as an instantaneous, reproductive, and spatially precise technique which meets the requirements described above. Photography is by definition two-dimensional. Its spatial resolution is high and determined by the camera, but can be adapted
to the particular needs by a proper choice of the display window. Digital images are instantly available to be processed and interpretable by image analysis. A careful calibration of the camera and every image allows for a quantitative comparison of photographed stratifications. In the NIR spectrum (700 nm to 1400 nm) the reflectance of snow rapidly decreases from very high values in the visible wavelength range toward the water absorption band at the upper end of this range. The reflectance in the NIR spectrum is determined by the size of the ice structures (Warren, 1982). Impurities (i.e. soot) which have a major influence on reflectance in the visible light can be neglected (Leroux et al., 1999). Because of the expected variance in reflectance due to grain size we decided to focus on photography in the NIR spectrum.

**Structure of the thesis**

In the following chapters I will introduce a stereological method to estimate the SSA of snow samples. I will develop a method to photograph snow pit walls in the NIR spectrum and show that the resulting images map the stratification of the snow cover and its structural variations. By comparing the snow reflectance in the NIR and the SSA of the same snow samples I will empirically verify the close correlation between these two parameters. Based on this correlation function the SSA can be calculated for the NIR images, resulting in a 2D mapping of the SSA of a snow pit wall. Finally, I will verify the empirical results using the results of a 2D beam-tracing model, which simulates the interaction between radiation and snow based on natural snow structures.

Many grain size definitions refer to individual, granular snow particles, not taking into account the sintered structure of snow. Therefore, I chose the SSA to describe the mean size of the structural elements of snow. This parameter had also been suggested in earlier articles dealing with optical properties of snow (Giddings and LaChapelle, 1961; Warren, 1982; Grenfell and Warren, 1999).

In chapter 2 model-based stereology is introduced as a new stereological approach to measure the SSA on natural snow samples. Model-based stereology can be applied to all snow types. This makes the method much more applicable than prior stereological approaches, which had been restricted to rounded grains. In combi-
nation with a special preparation technique for the snow samples (Schneebeli and Smith, 2004) this method proves also to be an efficient alternative to chemical adsorption methods and calculations in the computer tomograph (micro-CT). In a first step, the SSA is stereologically estimated from slices of reconstructed micro-CT samples. The results agree very well with the micro-CT calculations. In a second step, a field sample is analysed stereologically as well as by computer tomography. In a third step I compare the SSA data, classified by snow type, to results from CH$_4$-adsorption-measurements by Legagneux et al. (2002). This comparison, too, shows a good correlation and confirms the results of our measurements.

(Manuscript submitted to the Journal of Microscopy: Matzl, M. and Schneebeli, M.: Stereological measurement of the specific surface area of snow.)

The next step on the way to a quantitative mapping of the snow stratification, is the 2D assessment of snow reflectance in the NIR spectrum.

Chapter 3 introduces and describes the method of the NIR photography and presents first results. I specify the used instruments and explain the method as well as the calibration of the camera in detail. The experimental results show that a homogeneous snow sample has a certain range of reflectance which is determined by grain size (defined as greatest grain extension) as well as grain shape. The NIR image of a profile wall is compared to the manual assessment of the profile characteristics and to a segmented photograph of a surface section. While some layers can be detected by all three approaches, other features, particularly very thin layers or layers with slightly changing grain sizes are not detectable in the manual profile assessment and other layers again are not clearly recognisable in the NIR image. Even the unprocessed NIR image gives an informative overview of the stratigraphy and the spatial variability of the layers. The quantitative analysis turns out to be more complicated, as the used grain size definition seems to be insufficiently representative for describing the reflectance of snow.

(Manuscript draft: Matzl, M. and Schneebeli, M.: Near infrared photography of snow stratigraphy.)

In the previous chapters I developed and applied methods to estimate the SSA of natural snow samples and to measure the NIR reflectance of snow pit walls. In the next chapter
these two parameters will be measured for the same snow samples and then be correlated.

In chapter 4 we empirically test the correlation between the SSA of snow and its reflectance. We introduce a measurement design to apply both methods, NIP and stereology, to the same snow samples. Such a comparison has been carried out for about fifty homogeneous layers. It shows that an increasing reflectance of snow in the NIR is caused by the exponentially increasing SSA. The results of the correlation are compared with values published by Warren and Wiscombe (1980); Dozier (1992); Sergent et al. (1993). The comparison shows similar results for SSA-values below 20 mm\(^{-1}\). For larger values the empirical data overestimate the reflectance compared to the values simulated with the theoretical models of Warren and Dozier (Warren and Wiscombe, 1980; Dozier, 1992).


The good correlation between reflectance and SSA makes it possible to use the SSA as a link between structural and optical snow properties. The SSA of the NIR images can be calculated based on the correlation function. These "SSA-mappings" document the snow stratigraphy in high detail based on its structural size, including fine features as infiltration channels as well as subtle changes of the snow structure.

In chapter 5 we will verify our findings by simulating the snow reflectance based on natural snow structures. Optical properties of snow are usually modelled using Mie-Theory and the delta-Eddington approximation, based on the analyses of Warren and Wiscombe (1980) and Wiscombe (1980). In their models snow grains are approximated as ice spheres. Leroux et al. (1998) simulated the single scattering properties of snow using a beam-tracing model (BTM) based on defined hexagonal geometries (plates and needles). Their results show that grain shape has a strong impact on reflectance in the NIR spectrum. Meirold-Mautner (2004) incorporates a similar approach into a radiative transfer model. However, both studies use defined artificial geometries to approximate the natural grain shapes.

In chapter 5 we test the applicability of a 2D beam-tracing model to simulate the reflectance of given natural snow structures. The model, which originally was designed for predicting the properties of soil materials (Bänninger et al., 2006) is adapted for the use with snow samples. The aim is to determine whether other parameters than the SSA influence the reflectance of snow in the NIR. The BTM
has been run for 10 surface sections which are also characterised according to the 
structural parameters SSA, density, Euler-Poincaré characteristic, shape factor 
and an isotropy factor. The results are consistent to the empirical measurements 
in chapter 4 and show increasing reflectance with exponentially increasing SSA 
values. While the results suggest that additional structural parameters than 
the SSA affect the reflectance of snow, none of the examined parameters has 
been identified to be the probable cause. This is the first approach to base 
radiative transfer modelling on natural snow structures. Further calculations 
will be conducted to produce a more representative number of samples and to 
quantify the influence of other structural parameters.

dependent reflectance of snow.)

In the last chapter the research results are summarised and the relevance of the findings is 
discussed. Finally I give an outlook on possible next steps and applications of the developed 
methods.

Bibliography


Tech. Rep. 70, CRREL, Hanover, USA.

cover crystals. In: *Davos Symposium, September 1986*, 162, IAHS, Davos, Switzerland, 
3–34.

Hanover, USA.

Colbeck, S. C., Akitaya, E., Armstrong, R., Gubler, H. U., Lafeuille, J., Lied, K., McClung,


Chapter 2

Stereological measurement of the specific surface area of snow

The specific surface area (SSA) of snow is a crucial parameter for the description of the microstructure of sintered materials (German, 1996), such as snow. The SSA had also been suggested to be a proper parameter to describe optical snow properties (Giddings and LaChapelle, 1961; Warren, 1982; Grenfell and Warren, 1999). In the following chapter I will introduce a stereological method to measure the specific surface area (SSA) of snow samples. In chapter 4 this method will be used to measure SSA and reflectance for the same snow samples in order to correlate the results and show that the SSA can be used as a link between structural and optical snow properties.

2.1 Summary

The specific surface area (SSA) of porous materials strongly influences the physical and chemical properties of these materials. Current methods for measuring the specific surface area of snow are gas-adsorption techniques and X-ray micro-tomography, which both require expensive and complex instrumentation. In this study the specific surface area of thirty snow samples covering major snow types and a wide density range of seasonal snow was analysed using micro-tomography and model-based stereology. The results show that the specific surface area of all snow types, even of those with very complex shape, can be determined with

\[1\text{Based on an article submitted to the Journal of Microscopy by M. Matzl and M. Schneebeli}\]
very high precision using model-based stereology. The SSA determined using gas-adsorption
and stereology correspond well. This suggests that the snow matrix has a microscopically
smooth surface, with no micro-structures smaller than 10 μm. It is therefore advisable to
measure the specific surface area of layered snow samples with the stereological method
because it provides relevant information at a higher spatial resolution compared with the
volume-averaged property of gas adsorption.

2.2 Introduction

The specific surface area (SSA) is an important geometrical measure for sintered materials
as it is strongly related to their physical (German, 1996), chemical (Dominé and Shepson,
2002), and electromagnetic (Grenfell and Warren, 1999) properties. Moreover, the SSA,
being the ratio of surface area to ice volume, considers the sintered structure and thus
describes snow as a genuinely sintered porous and not simply granular material. Therefore
the SSA is an important parameter for the description of snow structure. Information about
the SSA is also fundamental for all chemical processes concerning snow as it governs the
rate of exchange (Dominé and Shepson, 2002). The SSA can be converted into an effective
diameter (Mitchell, 2002; Thomsen et al., 2005), which is commonly used for estimating
radiation transfer.

Current methods for measuring the SSA of snow are X-ray tomography (Brzoska et al., 2001;
Flin et al., 2005) and chemical adsorption techniques (Legagneux et al., 2002). Dominé et al.
(2001) compared the adsorption technique with methods based on single grains (optical mi-
croscopey and scanning electron microscopy) and showed that systematic and large differences
in the SSA result from these different approaches. Grain based methods also face a practical
difficulty because of the fragile nature of snow. The analysis of single grains requires crushed
snow, which introduces new surfaces and thus biases the measurements.

Another aspect to be considered is the layered nature of natural snow packs (Colbeck, 1991).
New measurements at spatially high resolutions show that layering is often underestimated by
the traditional methods (Pielmeier and Schneebeli, 2003). The thin layers greatly influence
air permeability, vapor transport and ventilation, and thus also snow metamorphism and the
snow chemistry (Albert et al., 2002). Gas adsorption techniques, which require a relatively
large sample size, do not take into account layered structures, as the SSA is averaged over
the whole sample. Micro-tomography is limited to small samples and both methods require the transport of an undisturbed natural snow sample to a cold laboratory, which is often difficult. Furthermore both methods are technically rather demanding and require expensive instrumentation.

In this paper we describe an approach to estimate the SSA of snow using model-based stereology, which requires no assumptions to be made about particle shape. This approach enables the use of undisturbed natural snow samples. It also takes into account thin layers just a few millimetres in height. At the same time it is relatively fast, and cheaper and less complicated to apply, than the other two methods.

The purpose of stereology is to measure geometric properties in lower dimensional spaces. In this case this means deriving the SSA, a 3D property, from a 2D section. Stereological methods have been applied to well-rounded equilibrium snow before, but the uncertainties associated with the complex shape of many snow types, such as new snow, faceted snow or depth hoar, mean that these have never been investigated. This limitation has often been seen as a short-coming of stereological methods per se. Classical stereological approaches have, when applied to snow in the past, required strict assumptions about particle arrangements and shapes (Weibel, 1980). Because of these assumptions, Kry (1975), Good (1989), and Edens and Brown (1995) analyzed only round-grained snow types. Davis and Dozier (1989) developed a new method based on Miles (1985), using several parallel sections per sample to determine more precisely the optical diameter of snow, but they still required knowledge of snow crystal morphology.

Our approach to estimate the SSA using model-based stereology relies on vertical sections of samples analysed in an X-ray micro-tomograph (micro-CT). We stereologically estimated the SSA of 30 samples reconstructed in the micro-CT and compared the results with 3D calculations based on the triangulated ice surfaces of the virtual samples. The results agreed excellently. To test the use of this method for field samples, one sample was first reconstructed in the micro-CT and then casted, sectioned with a microtome and digitally photographed. The resolution, image quality and SSA of the reconstructed sample and the physically sectioned sample are comparable. Because casting micro-CT samples is very difficult, this comparison was not possible for all samples. The results were also compared with the SSA values measured by CH$_4$-adsorption published by Legagneux et al. (2002).
2.3 Theory

Classical stereological approaches require assumptions not only about the homogeneity of the sectioned material but often also about the geometrical properties of the particles. Model-based stereology still assumes spatial homogeneity of the material, but no further assumptions about the shape of the objects are required (Baddeley and Vedel Jensen, 2005). This stereological approach draws on stochastic geometry and relies on sampling theory. This allows a more precise definition of the assumed homogeneity of the material under study, which is treated as a realisation of a stationary and isotropic random process. Model-based stereology requires, in combination with a sampling method based on vertical sections, isotropy of the material only in the horizontal direction (Baddeley and Vedel Jensen, 2005). This condition is fulfilled in a seasonal snow cover, where the single layers are assumed to be spatially homogeneous in the horizontal direction on a scale of approximately 0.05 m or more. Using vertical sections to estimate the SSA in a design-based stereological approach is explained in Baddeley et al. (1986). The vertical section is defined with respect to a reference plane, which in our case is parallel to the layering of the snow. A test line with a sine-weighted orientation distribution is used. This compensates for the preselected vertical direction and ensures isotropic uniform random intersections between the structure and the test line. The test system meeting these requirements is composed of cycloids (Figure 2.1). Each cycloid has one point of origin $p$. If the line length of one cycloid ($l/p$), and the number of points ($P$) hitting the reference space and the number of the intersections between the test line and ice structure ($I$) are known, the SSA can be estimated using Saltykov’s formula:

\[
\text{SSA} = \frac{2\pi l}{P} \times \frac{I}{l}
\]
SSA_v = \frac{2 \cdot I}{P} \cdot \frac{1}{\rho_i}.

(2.1)

This results in the SSA estimated per unit volume (SSA_v) [mm^{-1}]. SSA_v is often normalised with respect to the volume fraction of the material of interest, which in our case, is ice. The specific surface area per ice volume is then:

SSA_i = SSA_v \cdot \frac{1}{(1 - \Phi)} \cdot \frac{1}{\rho_i},

(2.2)

where \Phi is the porosity of the snow, 1 - \Phi the volumetric density, and \rho_i = 0.917 g cm^{-3} the density of ice. The volumetric density is estimated by the ratio between the surface area of the ice phase and the total surface area of the section.

In the context of chemical measurements, SSA is expressed per mass (SSA_m) [cm^2 g^{-1}] (Dominé et al. (2001)) and we have:

SSA_m = \frac{1}{\rho_i} \cdot 10 \cdot SSA_i.

In radiation transfer modelling either the volume-to-area ratio is used for the structural characterisation of snow (Grenfell and Warren, 1999) or the effective diameter. The effective diameter relates to the SSA_i, defined by (Mitchell (2002), equation 9) as follows:

r_{eff} = \frac{\int r^3 N(r)dr}{\int r^2 N(r)dr},

r_{eff} = \frac{1}{SSA_i},

where N(r) is the size distribution with respect to radius.

2.4 Method

Micro-CT samples

Thirty snow samples at different stages of snow metamorphism were used for the verification of our stereological estimations. A wide range of structures and densities was covered. The densities of the different samples range from 68 to 343 kg m^{-3}. In this range, the density values are distributed more or less regularly. The mean density of all samples was 207 kg m^{-3}, which is typical for seasonal snow. The vertical axis of the samples was always chosen perpendicular to the snow layers. Each sample was classified according to the International
Classification of Snow (Colbeck et al., 1990), where 2a = partly decomposed precipitation particles, 3a = small rounded particles, 3b = large rounded particles, 4a = solid faceted particles and 5a = hollow or partly solid cup crystals.

All samples were measured in a Scanco micro-CT 80 with a voxel size between 10 and 36 µm. The scan resolution was adapted to the structural size of the samples so that the smallest structure was always 2 to 4 times larger than the size of the voxel (Kaempfer et al., 2005). The size of the volume data was at least $192^3$ voxels. The raw data from the micro-CT were filtered with a 3x3 median filter and segmented using a constant threshold. The SSA measured on the segmented volume data ($SSA^{uCT}_v$) was calculated from the triangulated surface of the ice matrix (Hildebrand et al., 1999).

**Applying model-based stereology to virtual vertical sections**

For the stereological analysis, twenty parallel vertical slices were cut from each reconstructed sample using a systematic uniform random sampling scheme (Howard and Reed, 1998). The size of the virtual sections varied between 192 x 192 up to 296 x 296 pixels. Typical examples are shown in Figure 2.2. A table of the complete data set is presented in Appendix A.

![Figure 2.2: Section images of reconstructed snow samples. Ice grains are displayed in black. The scale bars are 1 mm. The size of the displayed images corresponds to the section size used for the analysis. See also Table 2.8 for a detailed description.](image-url)

An algorithm to digitally draw the cycloids was developed using its parametric equation
\[ x = \theta - \sin \theta, \quad y = 1 - \cos \theta, \quad 0 \leq \theta \leq \pi, \] where \( \theta \) is the zenith angle (Baddeley et al., 1986).

To define an appropriate test system, the SSA was estimated using different cycloid widths (Figure 2.1). The representative cycloid size was determined using cycloid widths between 5 and 50 pixels and by determining the region where the mean SSA and the variance were constant. The test system is a compromise between the number of intersections and the cycloid size to avoid effects caused by an undersampling of the ice structures or the finite resolution of the test system.

An automated procedure to count the intersections between the ice structures and the test lines was developed: (i) The outlines of the ice structures were determined using a 3 x 3 pixel Sobel-filter. (ii) An AND-Operation was performed using the Sobel-filtered image and the computer-generated image with the test system of cycloids with known \( P \) and \( l/p \). The operation is true for the pixels where test lines and ice structures intersect. (iii) Adjacent intersection pixels, connected in terms of an 8-neighbourhood, were counted as one intersection. The probability that a touching point should be counted either as 2 intersections or as no intersection was assumed to be 50%. Touching points were therefore counted as one intersection (Figure 2.3). (iv) The SSA\(_v\) was calculated from the number of intersections and the known length of the test lines using equation 2.1. (v) The SSA\(_v^{stereo}\) was obtained by dividing the SSA\(_v\) by the volumetric density (equation 2.2).

When determining the representative cycloid size, we found that using cycloids wider than approximately 10 pixels led to stable values of a mean SSA for our snow sections. For
cycloids smaller than 10 pixels the SSA values increased with increasing cycloid width. For
cycloid widths larger than approximately 30 pixels, the variance around the mean SSA value
increased because there were too few intersections between the ice structure and the test
lines. In between these boundaries the size of the cycloid influenced the estimated SSA
values by 5.8% for a single section. The coefficient of variation of the sample-SSA is, in this
case, 5.8% divided by the square root of the 20 sections per sample, which results in 1.3%. For the following results cycloid widths between 12 and 17 pixels were used, according to
the resolution of the images.

**Comparison between a micro-CT sample and a physically sectioned sample**

A special advantage of stereological methods is that they can be combined with a practical
sampling method. The fragile nature and changeable surface of snow requires either very
fast measurements or a method to preserve the snow structure. Samples of natural snow can
be preserved by casting them with diethyl-phthalate (Good, 1989; Schneebeli and Smith,
2004) and freezing them with dry ice in the field. The method is relatively fast, and up
to 15 samples can be prepared per hour. The casted snow samples are sectioned in a cold
laboratory using a Leica Sliding Microtome. The resulting surface sections were digitally
photographed with a maximum resolution of approximately 5 \( \mu \text{m} \). The digital grey scale
images were segmented to binary images using adaptive histogram equalisation (Pizer et al.,
1987). Morphological opening and closing were applied as well as a median filter before
segmentation.

It is very difficult to apply this sampling procedure to a micro-CT sample which has a
maximum diameter of 36 mm. We performed this procedure for one snow sample to test
whether comparable results can be achieved from a virtual section of the reconstructed micro-
CT sample (resolution 18 \( \mu \text{m} \)) and from a physically cut surface section of the same casted
sample. The surface section was then photographed using resolutions varying between 6 \( \mu \text{m} \)
and 24 \( \mu \text{m} \) to investigate the resolution effects.

**Comparison between stereology and \( \text{CH}_4 \)-adsorption**

We used the data in Legagneux et al. (2002) to compare the SSA measured with stereology
and those measured with adsorption. Legagneux et al. (2002) measured the adsorption

---

\(^2\)With the term "surface section" we refer to a planar section of an intransparent medium. This term is
used to avoid confusion with the concept of transparent thin sections. "Surface section" describes both the
planar section and also its segmented photo.
isotherm of CH$_4$ on 176 snow samples at the temperature of liquid nitrogen (77.15 K at atmospheric pressure) and analysed the isotherm. The 176 samples were divided into 14 snow-type classes. We reclassified these snow types according to their description in the International Classification of Snow and compared them with our classified data set.

2.5 Results

Figure 2.4 shows the scatterplot of SSA$_i^{\text{stereo}}$ and SSA$_i^{\text{uCT}}$. The SSA$_i$ measured with the two methods were correlated with $r^2 = 0.99$ and $p < 0.001$. The correlation changed insignificantly if the zero point was not fixed. The coefficient of the correlation function shows that there was no systematic offset or deviation from a one-to-one slope: $SSA_i^{\text{stereo}} = 1.001 \cdot SSA_i^{\text{uCT}}$.

![Figure 2.4: Scatterplot of SSA$_i^{\text{stereo}}$ vs. SSA$_i^{\text{uCT}}$. The grey bars indicate the standard deviation of the different sections in one sample.](image)

Plotted against density, the SSA$_i$ tends to decrease with increasing densities (Figure 2.5).

Micro-tomography and the field method of casted snow samples were compared directly by first reconstructing a snow sample in the micro-CT and then sectioning it and photographing it in the microtome. Table 2.1 gives an overview of the SSA$_i^{\text{stereo}}$-values resulting from different sampling techniques and image resolutions. The corresponding images are displayed in
Figure 2.5: Scatterplot of SSA$_i^{stereo}$ and snow density. Four different snow types are distinguished.

Figure 2.6a to 2.6f. The mean SSA$_i^{stereo}$ of five virtual sections of the reconstructed sample was 13.2 mm$^{-1}$ and the standard deviation 0.7 mm$^{-1}$. The resolution of the reconstructed sample was 18 $\mu$m. The physically cut surface section was photographed at varying resolutions between 5.6 to 24.0 $\mu$m. With absolute values varying from 13.5 to 14.1 mm$^{-1}$, the mean SSA$_i^{stereo}$ was 13.8 mm$^{-1}$ and the standard deviation 0.2 mm$^{-1}$.

<table>
<thead>
<tr>
<th>Source</th>
<th>Resolution $[\mu m]$</th>
<th>SSA$_i^{stereo}$ [mm$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>microtome</td>
<td>5.7</td>
<td>14.1</td>
</tr>
<tr>
<td>microtome</td>
<td>7.1</td>
<td>13.9</td>
</tr>
<tr>
<td>microtome</td>
<td>9.7</td>
<td>13.5</td>
</tr>
<tr>
<td>microtome</td>
<td>17.0</td>
<td>13.9</td>
</tr>
<tr>
<td>microtome</td>
<td>24.0</td>
<td>13.7</td>
</tr>
<tr>
<td>micro-CT</td>
<td>18.0</td>
<td>13.2</td>
</tr>
</tbody>
</table>

Table 2.1: Comparison of a microtome section and the average over 5 virtual micro-CT sections of the same sample. The microtome section was processed at various resolutions.

The comparison between our stereological measurements and CH$_4$-adsorption data is shown in Figure 2.7. The re-classification of the snow types was not unambiguous. Nevertheless, the mean of the SSA values for the corresponding snow types compare well, and, although
the SSA_{stereo} seem to be slightly larger, a t-test applied to the means of the four snow classes shows that the difference is statistically significant only for faceted grains.

2.6 Discussion

Estimating the specific surface area of snow using model-based stereology produces reliable results without requiring any assumptions about the shape of the particles. We showed for a single sample that a resolution four times higher did not distinctly increase SSA_{stereo} (Table 2.1). The variance of the SSA_{stereo} due to varying image resolutions was found to be smaller than the variance between the five virtual sections within one sample.

Figure 2.7 shows that SSA_{stereo} is comparable to the SSA_{i} measured by the adsorption
Chapter 2. Stereological measurement of the specific surface area (SSA)

Figure 2.7: SSA values derived by stereology and CH$_4$-adsorption (Legagneux et al., 2002) for different snow types. The boxes cover the range between 25% and 75%. The small hyphen inside marks the mean, the large hyphen the median, and the x the maxima/minima.

The scatterplot in Figure 2.5 shows a trend for SSA to increase with decreasing density. At the same time our data show a characteristic SSA–density cluster for precipitation particles, rounded grains and a combined class of faceted crystals and depth hoar. We assume that this loose relationship is due to the fact that metamorphism and sintering often have an impact on both parameters, SSA and density, at the same time.

Figure 2.7 suggests that a rough estimation of the SSA is possible for a known snow type, at least for rounded and decomposed particles. However, according to Figure 2.5, a more
accurate prediction should be possible from a combination of snow type and density. To test whether snow types can be well classified according to snow density and SSA, more snow samples with a larger range of SSA and density values must be analysed.

2.7 Acknowledgments

We thank Matthew Sturm for many useful suggestions. Numerous helpful comments by two anonymous reviewers have greatly improved the paper and are gratefully acknowledged. This work was supported by the Swiss National Science Foundation (project no. 200021-101884).

Bibliography


### 2.8 Appendix

<table>
<thead>
<tr>
<th>Sample</th>
<th>Density [kg m$^{-3}$]</th>
<th>SSA$_i$\textsuperscript{stereo} [mm$^{-1}$]</th>
<th>SSA$_i$\textsuperscript{uCT} [mm$^{-1}$]</th>
<th>Mean structural length [mm]</th>
<th>Mean object distance [mm]</th>
<th>Snow type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>313</td>
<td>12.1</td>
<td>12.1</td>
<td>0.24</td>
<td>0.35</td>
<td>4a</td>
</tr>
<tr>
<td>2</td>
<td>334</td>
<td>10.4</td>
<td>10.3</td>
<td>0.24</td>
<td>0.44</td>
<td>4a</td>
</tr>
<tr>
<td>3</td>
<td>267</td>
<td>11.0</td>
<td>10.4</td>
<td>0.24</td>
<td>0.57</td>
<td>5a</td>
</tr>
<tr>
<td>4</td>
<td>343</td>
<td>9.4</td>
<td>9.2</td>
<td>0.28</td>
<td>0.42</td>
<td>5a</td>
</tr>
<tr>
<td>5</td>
<td>273</td>
<td>15.8</td>
<td>12.1</td>
<td>0.23</td>
<td>0.42</td>
<td>4a</td>
</tr>
<tr>
<td>6</td>
<td>173</td>
<td>27.0</td>
<td>26.2</td>
<td>0.14</td>
<td>0.39</td>
<td>3a</td>
</tr>
<tr>
<td>7</td>
<td>259</td>
<td>21.6</td>
<td>21.7</td>
<td>0.14</td>
<td>0.24</td>
<td>3b</td>
</tr>
<tr>
<td>8</td>
<td>261</td>
<td>14.6</td>
<td>13.4</td>
<td>0.20</td>
<td>0.42</td>
<td>5a</td>
</tr>
<tr>
<td>9</td>
<td>68</td>
<td>48.0</td>
<td>49.1</td>
<td>0.06</td>
<td>0.46</td>
<td>2a</td>
</tr>
<tr>
<td>10</td>
<td>240</td>
<td>29.5</td>
<td>29.1</td>
<td>0.10</td>
<td>0.19</td>
<td>3b</td>
</tr>
<tr>
<td>11</td>
<td>236</td>
<td>29.4</td>
<td>28.5</td>
<td>0.11</td>
<td>0.20</td>
<td>3b</td>
</tr>
<tr>
<td>12</td>
<td>242</td>
<td>27.3</td>
<td>26.8</td>
<td>0.11</td>
<td>0.21</td>
<td>3a</td>
</tr>
<tr>
<td>13</td>
<td>265</td>
<td>21.9</td>
<td>20.0</td>
<td>0.14</td>
<td>0.24</td>
<td>4a</td>
</tr>
<tr>
<td>14</td>
<td>138</td>
<td>54.5</td>
<td>56.7</td>
<td>0.05</td>
<td>0.21</td>
<td>2a</td>
</tr>
<tr>
<td>15</td>
<td>128</td>
<td>51.0</td>
<td>51.8</td>
<td>0.05</td>
<td>0.22</td>
<td>2a</td>
</tr>
<tr>
<td>16</td>
<td>109</td>
<td>49.7</td>
<td>51.5</td>
<td>0.05</td>
<td>0.30</td>
<td>2a</td>
</tr>
<tr>
<td>17</td>
<td>97</td>
<td>50.4</td>
<td>51.7</td>
<td>0.05</td>
<td>0.33</td>
<td>2a</td>
</tr>
<tr>
<td>18</td>
<td>156</td>
<td>38.5</td>
<td>41.9</td>
<td>0.07</td>
<td>0.21</td>
<td>3a</td>
</tr>
<tr>
<td>19</td>
<td>127</td>
<td>49.9</td>
<td>51.8</td>
<td>0.05</td>
<td>0.24</td>
<td>2a</td>
</tr>
<tr>
<td>20</td>
<td>307</td>
<td>20.9</td>
<td>22.5</td>
<td>0.13</td>
<td>0.30</td>
<td>4a</td>
</tr>
<tr>
<td>21</td>
<td>144</td>
<td>26.9</td>
<td>25.3</td>
<td>0.12</td>
<td>0.38</td>
<td>3a</td>
</tr>
<tr>
<td>22</td>
<td>108</td>
<td>40.5</td>
<td>37.1</td>
<td>0.08</td>
<td>0.36</td>
<td>2a</td>
</tr>
<tr>
<td>23</td>
<td>137</td>
<td>49.0</td>
<td>49.4</td>
<td>0.06</td>
<td>0.24</td>
<td>2a</td>
</tr>
<tr>
<td>24</td>
<td>313</td>
<td>19.6</td>
<td>19.0</td>
<td>0.17</td>
<td>0.21</td>
<td>4a</td>
</tr>
<tr>
<td>25</td>
<td>307</td>
<td>17.2</td>
<td>15.9</td>
<td>0.16</td>
<td>0.35</td>
<td>4a</td>
</tr>
<tr>
<td>26</td>
<td>301</td>
<td>16.3</td>
<td>14.8</td>
<td>0.18</td>
<td>0.37</td>
<td>4a</td>
</tr>
<tr>
<td>27</td>
<td>127</td>
<td>47.8</td>
<td>45.4</td>
<td>0.06</td>
<td>0.28</td>
<td>2a</td>
</tr>
<tr>
<td>28</td>
<td>135</td>
<td>43.0</td>
<td>42.4</td>
<td>0.07</td>
<td>0.29</td>
<td>2a</td>
</tr>
<tr>
<td>29</td>
<td>158</td>
<td>41.8</td>
<td>39.7</td>
<td>0.07</td>
<td>0.25</td>
<td>2a</td>
</tr>
<tr>
<td>30</td>
<td>169</td>
<td>38.2</td>
<td>36.3</td>
<td>0.08</td>
<td>0.27</td>
<td>2a</td>
</tr>
</tbody>
</table>

**Table 2.2:** Complete data set. SSA$_i$\textsuperscript{uCT}, mean structural length, and mean object distance were measured by the micro-CT. The snow types are categorised according to the International Classification (Colbeck et al. (1990)).
Chapter 3

Near infrared photography of snow stratigraphy

In this chapter, I explain the concept and the realisation of digital near infrared photography (NIP). I will show that NIP enables a two-dimensional (2D) assessment of the snow stratigraphy based on the snow reflectance. Compared to existing 2D approaches, this method is fast and easy to apply. Even uncorrected images include more stratigraphic information than usually can be assessed in a manual approach. Further calibration will additionally allow for a quantitative interpretation of the images (as will be shown in chapter 4).

3.1 Abstract

Objective documentation of snow profiles is difficult, because the characteristics are assessed by manual and visual inspection, and therefore depend on the interpretation skills of the observer. We propose to use digital near infrared photography (NIP) to objectively assess and document snow profiles. This method is based on the dependency of snow reflectance in the near infrared (NIR) range of the radiative spectrum on snow grain size. The NIR reflectance of the snow was calibrated against structurally well-defined snow samples. A photographic technique was developed and image processing algorithms applied to generate snow profile images classified according to grain size. The images were compared to surface sections from casted snow samples and to manually assessed profiles (hand profiles). A single

---

1Based on a manuscript draft by M. Matzl and M. Schneebele
image covers an area between 0.5 to 1 m², while larger areas can be covered with tessellated images. Subtle stratigraphic features can be quantified and recorded, and spatial variability of different layers measured. The method is easily applicable and allows a fast and detailed documentation of snow stratigraphy.

3.2 Introduction

Snow profile assessments are essential for the interpretation of perennial and seasonal snow covers (Sturm and Benson, 2004), and as a basis for avalanche forecasting (Schweizer and Jamieson, 2003). The objective assessment and documentation of snow profiles is a long standing problem, since the texture of snow cannot be easily discerned in the visible spectrum. The complex spatial patterns within a snow pack which develop during sedimentation, metamorphism and water flow are rarely accounted for in traditional snow profiles, which tacitly assumes that the properties do not vary laterally. Hand drawings of vertical snow profile cross sections have been made occasionally (Sturm and Benson, 2004; Pielmeier and Schneebeli, 2003), where horizons and layer boundaries are explicitly delineated. However, spatial variation and transitions of grain sizes cannot be extracted. The translucent snow profile is the best known attempt to map other than vertical features in a more quantitative way. The translucent profile delivers a clear delineation of boundaries between layers, but the transmitted light intensity cannot be interpreted in a unique fashion, because transmissivity depends not only on the grain size but also on the snow density (Good and Krüsi, 1992; Zhou et al., 2003) and on the section thickness. An indirect method is Frequency Modulated Continuous Wave radar (Marshall et al., 2004) which maps dielectric discontinuities. Discontinuities with a sufficiently large signal-to-noise ratio exist for seasonal alpine snow packs (Gubler and Weilenmann, 1986), but not necessarily for arctic snow packs (Holmgren et al., 1998) where no stratigraphic interpretation is possible.

We propose the use of NIP to quantitatively map the stratigraphy of snow packs. The reflectance of snow is sensitive to grain size in the NIR (800-1400 nm) spectrum (Warren, 1982). This property of snow is used in remote sensing (Dozier et al., 1981; Nolin and Dozier, 1993). First experiments comparing analogue NIR photographs and translucent profiles showed the feasibility of the approach (Haddon et al., 1997), but analogue NIR photographs are difficult to process quantitatively. Mätzler (2002) proposed a NIR scattering experiment
to objectively measure grain size at the snow surface. We applied a similar approach in which we digitally photographed snow profiles in the NIR and used image processing to calculate reflectance and the distribution of the visually observed grain size of snow.

The measurement of snow grain size is often a compromise between fast field determination (Grenfell et al., 1994) and elaborate and time-consuming laboratory methods (Lesaffre et al., 1998). The extension of the actual grain is often very difficult to determine, because the length of the principal axis can be very variable. Therefore, grain size expressed as a single diameter represents an incomplete physical measure for the optical properties of snow (Grenfell and Warren, 1999). An alternative is the use of the volume-to-surface-area ratio or the specific surface area (SSA), which can be determined from surface sections of samples taken from snow profiles. However, this would make it difficult to compare the grain size determined visually in the field with the grain size derived from photography in the NIR. For field measurements grain size is commonly defined as the “greatest extension” of a grain (Colbeck et al., 1990). This definition is also used throughout this work.

The relation between grain size and reflectance for the combination of camera and filter used in this study was calibrated with sieved, homogeneous snow samples. Natural snow profiles were photographed and compared to manual snow profile descriptions and to microstructural surface sections.

### 3.3 Instrumentation, image acquisition and processing

The digital camera used was a Kodak DCS420ir. The charge-coupled device (CCD) of this camera has a size of 1512 x 1024 pixels. The near infrared absorbing filter in front of the CCD was removed and replaced by a gelatine filter (Kodak Wratten 87c). This combination of filter and CCD limits the recorded light spectrum to 840 to 940 nm at the 1% transmission limit. The center wavelength is at 890 nm. The uneven illumination of the CCD caused by the Nikon Nikkor 20 mm lens by vignetting was corrected by subtracting a reference image taken in an Ulbricht sphere at different apertures and homogenous illumination.

The view angle for all images was approximately perpendicular to the vertically cut wall of the snow profile. A careful preparation of the vertical surface of the profile wall was crucial for the quality of the resulting images. We used a snow saw for the rough preparation and a soft brush for the final smoothing of the profile wall. Illumination of the profile was always
Figure 3.1: Photograph of a snow profile wall with targets (A) and sample containers (B).

diffuse, either by the presence of clouds or artificially achieved by shading with a white cloth. Variable illumination or shading of the profile wall was referenced using targets with a 2 cm diameter, made of barium sulphate photographic paper. These targets were attached to pins and inserted along the edges of the photographed profile wall (Figure 3.1). The reflectance of each image was calibrated with a Spectralon greyscale standard which is composed of 4 different fields: 12%, 25%, 50%, and 99% reflectance. The field part of the method took us between 10 and 20 minutes, not accounting for the excavation of the pit.

The preprocessing of the images included a geometrical transformation based on a least square fit to equalise geometrical deformations which occur by tilting or turning the camera not exactly perpendicularly to the profile wall. It further included the brightness correction of the vignetting and also of the unevenly illuminated snow profile. These preprocessed images were used for all further steps. The geometrical transformation was also required to compare the reference system of the traditional snow profile with that of the image.

Snow samples for the surface sections were extracted from the profile wall in small containers, filled with dyed liquid diethyl phthalate, frozen with dry ice, and subsequently analysed in the cold laboratory (Good, 1989; Schneebeli and Smith, 2004). The positions of the sample containers were recorded by taking a second image with the sample containers inserted into the profile wall (Figure 3.1).
The final classification of the images with respect to grain size is based on the calibration function (equation 3.1, below) obtained from snow measurements using sieved snow samples. The processing of one image, from importing the raw data file to the corrected and calibrated image takes approximately 10 minutes.

### 3.4 Reflectance of sieved snow

The reflectance of different crystal types of sieved snow samples was measured to determine the dependence on grain size and grain-type. To create calibration samples, the snow was sieved into white boxes of 100 mm depth. We used seven sieves with a size between 0.25 mm and 4.0 mm. The density of the sieved snow was above 300 kg m$^{-3}$. The reflection from the bottom of the box was insignificant (Bohren and Barkstrom, 1974). The samples were photographed under diffuse day light. The mean grain-shape and grain size (measured as the greatest grain extension) for each snow sample were determined by observing many grains (more than 50) under a stereomicroscope.

The experimentally determined relation between grain size and reflectance was linear with a significance of $p < 0.05$ (Figure 3.2). The grain size $d$ in mm is related to the dimensionless

**Figure 3.2:** Comparison of visually determined grain size and shape of disaggregated snow to NIR reflectance. The line is a least-square fit to the data.
reflectance $r$ by

$$d = \frac{r - (0.87 \pm 0.01)}{(0.067 \pm 0.008)}$$

(3.1)

In addition to its correlation with grain size, reflectance seems to be influenced by the shape of the grains. Rounded grains for example seem to have an approximately 10% lower reflectance than dendritic or fragmented particles.

### 3.5 Reflectance and stratigraphy of snow profiles

The field measurements were carried out during winter 2001-2002 in Davos, Switzerland at elevations between 2300 and 2800 m a.s.l. Most of the investigated snow profiles have been influenced by wind and some showed signs of small avalanches. To confirm the stratigraphic features, a manual profile was taken and samples were extracted from the wall and casted with diethyl phthalate. From the casted samples surface sections were cut and compared to the NIR image and the hand profile. The layers in the processed and grain size-classified image were visually identified. The discussed example profiles show a complex stratigraphy within 0.5 m$^2$. The profile locations were selected to best represent slope stability, and represent typical, not extreme profile variability.

![Figure 3.3: Classified NIR image of an undisturbed (a) and an adjacent disturbed (b) profile. Both images are taken parallel to the slope.](image-url)
The first example profile was located on a north exposed slope with 33 degree inclination, about 15 m below a rocky, steeper slope. Figure 3.3 displays two profiles, about 5 m horizontally apart from each other. The layers (numbered and indicated with black lines) visible in Figure 3.3a have deposited parallel to the slope and were fairly undisturbed, while most layers in Figure 3.3b are strongly disturbed. The disturbance is distinct in the NIR image, but was almost impossible to recognise by eye and only detected after brushing. The layers 3 and 4 were almost undisturbed and formed a weak layer. The weak layer is highlighted with an arrow in the hand profile (Figure 3.4). Alongside the weak layer, the hand profile shows manually and visually detected layers, distinguished by hardness, crystal-shape and crystal-size. Layers that correspond to the NIR image are indicated with black lines and numbered at the left image border. The black frame in Figure 3.3a indicates the location of a snow sample. The surface section of this sample is displayed in Figure 3.5. Distinct layers in the surface section are numbered in correspondence to the hand profile and the NIR image.

Figure 3.6 shows a 2 m long profile wall composed of 4 NIR images. The vertical patterns are artefacts of the profile preparation. Even without further quantitative information this image gives an informative overview of the stratigraphy and the horizontal variability of the snow cover.
3.6 Discussion

A method was developed to assess and document the stratigraphy of layered snow covers using a digital camera sensitive in the NIR spectrum. This method has been shown to objectively document the complex and laterally varying features of snow stratigraphy with an improved efficiency and at higher resolution than conventional methods. Even very thin layers and slight changes within layers can be detected. We observed that a homogeneous snow layer exhibits a certain range in reflectance as well as a characteristic texture. The displayed NIR images (Figures 3.3 and 3.6) show that both features are relevant for an analysis of the stratigraphy of the snow pack. The time required for the preparation of a
profile wall and the digital processing of the image is 20 to 30 minutes, while conventional methods with a comparable level of detail would take much longer.

The three methods NIP, hand profile, and surface section show similar relative changes in grain sizes between different layers. In particular, the surface section (Figure 3.5) shows the same sequence and similar grain size as the NIR image (Figure 3.3). The marked layers 2 to 4 in the hand profile (Figure 3.4) also coincide with the layers in the NIR image. The absolute grain size values vary between NIR image and hand profile. One reason for this difference might be a general problem in visually estimating grain size in the field, as shown by the surface section. The other much more fundamental problem is that the greatest extension of the grain is not optimally suited to explain the reflectance of snow. Our initial goal was to develop a simple tool to validate grain size in snow profiles. Therefore we chose a size definition compatible with traditional methods. But our results show that the correlation between reflectance and traditionally assessed grain sizes is additionally influenced by a shape parameter (Figure 3.2). Thus, for further quantitative NIR measurements another size definition must be found. We are now investigating whether specific surface area is more representative than grain size to characterize and explain geometrical and optical snow properties.

Fig 3.6 shows the value of NIP for a 2D documentation of snow stratigraphy or snow profiles, even without quantitative information. The linking of the adjacent images shows that normalising illumination is incomplete, but structural continuity in the lateral direction is very well visible. A definite quantitative interpretation will further increase the potential of this method.

### 3.7 Acknowledgments

We thank C. Fierz and K. Kronholm for the manual snow profiles, G. Krüsi for the preparation of the surface sections, C. Pielmeier for help in field measurements, and P. Blatter (Metrology and Accreditation Switzerland, METAS) for the calibration of the camera. This project was supported by the Swiss National Science Foundation project no. 2000-066643.01.
Bibliography


Chapter 4

Measuring specific surface area of snow by near infrared photography\textsuperscript{1}

In the chapters 2 and 3, I developed methods to measure the snow reflectance in the near infrared and the specific surface area of snow. In the following chapter, I will describe a measurement design which allows the assessment of both parameters for the same snow samples. The correlation of the results shows that the reflectance increases with exponentially increasing specific surface area. Based on this correlation function the near infrared mappings of the snow stratigraphy (see also chapter 3) can be transformed in specific surface area and thus two-dimensionally quantify the size of the snow structures.

4.1 Abstract

The specific surface area (SSA) is considered an essential microstructural parameter for the characterisation of snow. Photography in the near infrared spectrum (NIR) is sensitive to the SSA. We calculated the snow reflectance from calibrated NIR images of snow pit walls and measured the SSA on samples obtained at the same locations. The correlation between reflectance and SSA was found to be 90%. Calibrated near infrared photography (NIP) allows to determine quantitatively SSA and its spatial variation in a snow profile in 2D within an uncertainty of 15%. In an image covering between 0.5 m\textsuperscript{2} and 1 m\textsuperscript{2} even layers of 1 mm thickness can be documented and measured.

\textsuperscript{1}Based on an article submitted to the Journal of Glaciology by M. Matzl and M. Schneebeli
4.2 Introduction

The specific surface area (SSA) is, as the porosity, an essential microstructural parameter for
the characterisation of sintered materials such as snow (German, 1996). The SSA is changing
during isothermal and temperature-gradient metamorphism (Legagneux and Domine, 2005;
Schneebeli and Sokratov, 2004) and determines the radiative properties (Warren, 1982; Ler-
oux et al., 1998) and is highly relevant for the catalytic effect caused by photochemical
properties (Dominé and Shepson, 2002). It is likely that also the permeability of snow (Al-
bert and Perron, 2000) is determined by SSA, as German (1996) shows for other sintered
materials.

Natural snow packs consist of morphologically different layers (Colbeck, 1991). The com-
plexity of the stratigraphy (Sturm and Benson, 2004; Pielmeier and Schneebeli, 2003) usually
defies a detailed and exhaustive sampling of snow to determine SSA. Current methods, such
as adsorption (Legagneux et al., 2002), micro-tomography (Brzoska et al., 2001; Schneebeli
and Sokratov, 2004) and stereology (Matzl and Schneebeli, 2006) are restricted to relatively
small snow samples, require a cold laboratory, and are relatively time-consuming. These
methods are therefore confined to point measurements. Thus, a method which could deliver
spatial information on natural snow profiles while requiring only simple equipment would
make the measurement of SSA more accessible. Such a method could also be extremely
valuable to initialise and validate numerical simulations of snow pack metamorphism (Brun
et al., 1989; Lehning et al., 2002).

Warren and Wiscombe (1980b) used Mie-Theory to describe the optical properties of snow
in the NIR spectrum. Based on this theory the reflectance between between wavelengths
of 750 to 1400 nm is controlled by snow grain size. The authors also concluded that the
influence of snow density can be neglected, as the interparticle distances between the grains
are still large compared to the wavelength. According to Dozier (1992) no interferences
will be observed in the NIR spectrum as long as the snow density is less than 650 kg m$^{-3}$.
Impurities influence the reflectance of snow only in the visible spectrum, but not in the NIR
(Warren and Wiscombe, 1980a; Leroux et al., 1999). The dependence of snow reflectance
on grain size is used in remote sensing to map grain size in the surface snow layer (Dozier
et al., 1981; Nolin and Dozier, 2000).

Already Giddings and LaChapelle (1961) speculated that the most appropriate definition of
the optically relevant grain size of snow is deduced from the volume-to-surface ratio, which
is the inverse ratio of the SSA. However, this speculation has not yet been experimentally verified. Mitchell (2002) theoretically shows that the SSA can be directly converted to an effective optical diameter. This suggests that the SSA builds a link between optical and structural snow properties.

Few approaches were conducted to measure stratigraphy based on optical snow properties. The translucent snow profile (Benson, 1962; Good and Krüsi, 1992) is the best known attempt to map other than vertical features more quantitatively. The translucent profile delivers a clear delineation of boundaries between layers, but the transmitted light intensity cannot be interpreted in a unique fashion, because transmissivity depends not only on grain size but also on snow density (Zhou et al., 2003), and section thickness. First experiments comparing analog NIR photographs and translucent profiles show the feasibility of a photographic method (Haddon et al., 1997), but analog photographs are cumbersome to process quantitatively.

We developed a method based on digital photography to determine the snow reflectance in the NIR spectrum. The reflectance was compared to the SSA of precisely located snow samples. The correlation between the reflectance of the snow samples and their SSA is about 90% with an uncertainty between 3-15%, where the uncertainty increases with increasing SSA. Based on this correlation function we calculated the SSA for the NIR images. The SSA can be mapped with a spatial resolution of approximately 1 mm in an image covering a profile wall with a size up to 1 m². Even thin layers which can hardly be detected by traditional methods can thus be detected in the images.

4.3 Method

The correlation between SSA and snow reflectance required an experimental design which allowed measuring both parameters for the same snow samples. The reflectance of a snow profile wall was measured using digital photography in the NIR (section 4.3.1). Afterwards, snow samples containing specific layers were taken from the same snow wall. The SSA of the snow samples was determined using stereological methods (section 4.3.2) as shown in Matzl and Schneebeli (2006). The reflectance of these samples was calculated from the NIR images. Reflectance and SSA were correlated for well distinguishable and preferably homogeneous layers (section 4.3.3). Figure 4.1 illustrates the experimental design. The correlation function was then used to calculate the SSA for the whole NIR image of the profile wall.
Figure 4.1: A: NIR image of a profile wall with four calibration targets (a) in the corners. The locations of the sample containers are marked with a black frame. B: Magnification of the NIR image at one sample location. The vertical distribution of the reflectance signal for this sample is calculated based on the pixel intensity of the targets (a). C: Image covering the same profile wall with the inserted sample containers (b). The surface section of one sample is displayed (D) and also the corresponding vertical SSA signal.
4.3.1 Near infrared photography

The camera used for the digital photos was a Kodak DCS420ir with a 20 mm Nikkor lens. A gelatine filter (Kodak Wratten 87c) was placed over the CCD. The wavelength of the detected light is in the range of 840 to 940 nm.

The distance between camera and profile wall was around 1.5 to 2 m. The size of the photographed profile walls varies from 0.5 to 1 m$^2$. Before photographing, the profile wall was cut carefully with a saw and smoothed using the back side of a brush.

To compensate for tilting or turning of the camera with respect to the profile wall, a geometrical correction was performed on the digital image. The correction required at least 3 targets, inserted in the profile wall with a known distance to each other and a known geometry (Figure 4.1 A). The nearest neighbour method was used to transform the target coordinates in the digital image congruently with their original geometry and distance.

The calibration targets were manufactured of Spectralon greyscale standards with a NIR reflectance of 50 and 99%. Alongside the geometrical correction they were used to correct illumination variations by interpolation between the 50%-targets and subtracting the interpolation from the original image. The NIR reflectance $r$ of the snow was calibrated with regard to the pixel intensities of the targets:

$$r = a + b \cdot i,$$

where $i$ is the intensity of each pixel and $a$ and $b$ are determined by a linear regression on the pixel intensities of the greyscale standards. The coefficient of deviation of the reflectance from the calibrated image measured at the white targets is 2.6%.

After photographing the smoothed wall, a second image of the profile wall was taken including the inserted containers of the snow samples (Figure 4.1 C). The comparison of the two images allowed us to define the exact sample coordinates in the first image. The reflectance signal was calculated by averaging horizontally over the 65 mm of the image covering the sample location (Figure 4.1 B).

4.3.2 Achieving the SSA from surface sections

The samples with a volume of approximately 70 x 70 x 50 mm were cast with dyed diethylphthalate and frozen for the transport to the cold laboratory (Schneebeli and Smith, 2004). In the cold laboratory vertical surface sections were cut of the samples and photographed
using a Leica Sliding Microtome. The resulting images had a resolution of 10 µm, a width between 10 and 25 mm, and a height between 30 and 60 mm (Figure 4.1 D). The SSA from the vertical surface sections was measured using model-based stereology (Baddeley et al., 1986; Matzl and Schneebeli, 2006). In the following SSA [mm$^{-1}$] is the ratio between surface area and the volume of the ice-phase. Stereological estimations were also used to determine the volume density of the snow samples, which allowed the further calculation of snow density. The snow type of the surface sections was visually determined according to the International Classification of Snow (Colbeck et al., 1990).

### 4.3.3 Correlation of reflectance and SSA

For each sample we visually identified discrete layers. Apparent vertical homogeneity defines the extension of a particular layer (Figure 4.1). The mean SSA and the mean reflectance were calculated for each layer. These values were used for correlating SSA and reflectance. Samples with strongly inclined layers were excluded.

### 4.4 Results

Figure 4.2 gives an overview of all the measured parameters. Density and SSA are stereological estimates from the segmented surface section while the reflectance is calculated from the NIR image. Corresponding layers are marked for the SSA and the reflectance signal.

In total, twenty-nine samples were obtained from field measurements. For each sample we distinguished between one to three layers for which mean reflectance and SSA were measured. Figure 4.3 shows the scatterplot of reflectance and SSA for all layers. The data were classified according to the International Classification of Snow (Colbeck et al., 1990). For a comparison with existing data we choose values published by Warren and Wiscombe (1980b), Dozier (1992), and Sergent et al. (1993) (Figure 4.3). We transformed the sphere diameter $d$ used in these publications to SSA ($SSA_{sphere} = 6/d$).
Sample 1: Melt-freeze crust between layers of decomposed precipitation particles.

Sample 2: A sequence of decomposed precipitation particles, a melt-freeze crust, faceted crystals and rounded poly-crystals

**Figure 4.2:** Surface section and NIR image of two snow samples and the derived density, SSA, and reflectance signals. For the lower sample the absolute height of the surface section and the NIR image vary. The grey bands mark visually identified layers.
To avoid an over-weighting of the intermediate reflectance class we grouped our data in reflectance classes of 5%. Six measurements per each class were randomly selected. The regression was calculated based on these stratified samples. The scatterplot shows an exponentially growing relation between SSA and reflectance $r$:

$$SSA = Ae^{rt}$$

where $A = 0.017 \pm 0.009 \text{ mm}^{-1}$ and $t = 12.222 \pm 0.842$. The correlation coefficient $R^2$ is 90.8% at a significance level $p < 0.002$. The error increases with increasing SSA from 4% at a SSA of 5 mm$^{-1}$ to about 15% for SSA values of about 25 mm$^{-1}$.

The scatterplot of density and SSA for the same snow layers shows that we included snow types with a wide range of densities and SSA values (Figure 4.4). It can also be seen that low density snow covers the whole range of measured SSA and samples with a low SSA cover a wide range of densities.

Figures 4.5 to 4.6 show the quantitative 2D mapping based on equations 4.1 and 4.2. Figure 4.5 also shows a conventional hand profile. The photograph corresponds with the hand profile. Note, that the ice crust at a height of 73 cm and the boundary at 36 cm are well visible. Not only distinct layers are mapped but also gradual transitions, for example that between 57 and 60 cm height. The SSA varies between 1 mm$^{-1}$ for the lower profile parts...
and for the ice crust and 27 mm\(^{-1}\) for the upper parts of the profile.

Figure 4.6 shows a NIR image with inhomogeneous illumination. The upper left part of the profile is too bright. However, it is still possible to recognise features such as the melt crust in the upper third of the profile or the infiltration zone below.

### 4.5 Discussion

The SSA and the reflectance of a wide range of snow types were measured. An increasing reflectance is correlated to an exponentially increasing SSA. We did not observe any systematic difference between snow type and the fitted line. This result supports the assumption of Giddings and LaChapelle (1961) that SSA is the most important parameter determining snow reflectance in the NIR.

The comparison with data published by Warren and Wiscombe (1980b), Dozier (1992), and Sergent et al. (1993) agree well with our observations for SSA values below approximately 20 mm\(^{-1}\) (Figure 4.3). For higher SSA values our measurements seem to overestimate the snow reflectance. There are possibly two reasons for this difference: i) the calibration targets may have had a significantly lower reflectance than specified and ii) the measured light
intensity was not only reflectance but also light that passed the snow pack from the snow surface. Because the snow samples showing a large SSA value were mostly obtained close to the surface, such an influence cannot be excluded.

The correlation function between reflectance and SSA was used to calculate the SSA for the NIR images. The images of the snow profiles (Figures 4.5 and 4.6), especially when combined with a manual profile, show that variations in the SSA reflect the layering of a snow cover in high detail. The method visualises layers and also slight vertical and horizontal structural variations which are cumbersome to record by conventional field methods. Even very small local differences in the SSA are well visible, as for example an infiltration zone in Figure 4.6. This method could be improved in several respects. A homogeneous and diffuse illumination of the profile wall is essential, because the digital correction of an inhomogeneous illumination
is not possible without losing the context to absolute reflectance. We found that in the field such heterogeneities in the illumination are not detectable by eye. Figure 4.6 shows such uncontrolled reflections. The upper left part of the profile was too bright, which makes a quantitative interpretation of this part difficult. The shading for diffuse illumination must cover at least 0.5 m behind the profile wall, and must extend over the side walls of the pit. An additional improvement is the use of a flat field correction. A second image where a target of constant colour brightness covers the whole profile wall is subtracted from the first image. This method even corrects for very local illumination heterogeneities and may be used instead of the digital interpolation between the reference targets which has been used for our study.

We conclude that the current technique allows to visualise relative differences of SSA at a very high resolution. The SSA on a 2D image can be measured with an uncertainty of about 15%. The proposed improvements could significantly enhance this result.

The ability to measure SSA in 2D opens up the possibility to link micro- and macro-scale measurements of snow structure. SSA of individual layers as well as the stratigraphy of the snow cover is crucial for chemical models. Because of the widespread use of SSA to parametrise air permeability and thermal conductivity of sintered materials (German, 1996), it can be expected that this should also be possible for snow. Such an extension would be very useful to initialise and calibrate numerical models simulating the transport and transformation processes occurring in a snow cover.

4.6 Acknowledgments

We thank Matthew Sturm for his valuable comments and suggestions. The financial support of the Swiss National Science Foundation (project no. 200021-101884) is acknowledged.
Figure 4.6: SSA mapped for a profile wall with inhomogeneous illumination.
Chapter 4. Measuring SSA by NIP

Bibliography


Chapter 5

Structure dependent reflectance of snow in the near infrared

In the following, the empirical findings of chapter 4 will be compared to the results of a beam-tracing model. The model is implemented to simulate the optical snow properties based on natural snow samples. Previous models usually based optical simulations on geometrically defined particles such as spheres and hexagonal columns or plates. Our results confirm the empirical findings that snow reflectance in the near infrared depends mainly on its specific surface area.

5.1 Abstract

Approaches for modelling the reflectance of snow are currently based on spherical or hexagonal particles. The effect of different snow types on reflectance is yet not well understood. In this study, a beam-tracing model was applied to vertical surface sections of different snow types to investigate the effect of non-spherical and anisotropic shapes on the reflectance of snow. A wavelength of 890 nm was used, because in this spectral range (near infrared) the reflectance depends mainly on the grain size. The vertical surface sections covered various snow types with a specific surface area between 10 and 30 mm$^{-1}$. Modelled snow reflectance was found to mainly depend on the specific surface area, a parameter which corresponds to an effective optical diameter. We tested other structural parameters and found a potential

\footnotesize{1Based on a manuscript draft by D. Bänninger, M. Matzl, and M. Schneebeli}
correlation between reflectance and an isotropy factor.

5.2 Introduction

The albedo of snow varies strongly in the near infrared (NIR) spectrum. Thus, the radiative transfer properties of snow in this wavelength spectrum are highly relevant to its energy balance (Marks et al., 1992; Roesch et al., 2002), to remote sensing applications (Nolin and Dozier, 2000), and also to biological questions (Sturm et al., 2001). The variation in albedo from 0.9 to 0.4 depends on the microstructure of the snow. However, the effect of different snow types and irregular snow microstructures on reflectance is not well understood. Especially the effect of anisotropic shapes which are formed due to strong temperature gradients within the snow are poorly known (Painter and Dozier, 2004).

Radiative transfer models for snow are mainly based on spherical or hexagonal particles. The general radiative transfer equation derived by Chandrasekhar (1944) can not be solved analytically. Therefore, approximations such as the two-stream method (Bohren and Huffman, 1983) and the delta-Eddington method (Wiscombe, 1980) have to be used. These methods use the concept of equivalent sphere diameter (Wiscombe, 1979) and thus consider the influence of snow structure only roughly. More recent approaches aim at including this structural information. The grain is approximated by dielectric films (Mätzler, 2000) and by grains as plates, needles and hexagonal particles (Leroux et al., 1999; Meirold-Mautner, 2004).

Matzl and Schneebeli (2006b) empirically obtained the correlation between reflectance of snow in the NIR and the specific surface area (SSA), a structural parameter. Their results show increasing reflectance values with an exponentially increasing SSA. The measurements did not provide information whether values deviating from the fit are only due to measurement imprecisions or also conditioned by other structural parameters.

In this study we want to examine whether other structural parameters of snow are responsible for the variation of the reflectance \( r \) at a given SSA. To answer this question we applied a beam-tracing model (BTM) to explicitly account for the role of natural structures on radiative transfer in snow. The BTM was originally developed and implemented to describe reflectance of soil surfaces (Bänninger et al., 2006). The snow structures were defined as digital images of surface sections of tomographed natural snow samples. From these surface
sections we stereologically estimated the SSA and the density. The samples were also characterised by the structural parameters such as the Euler-Poincaré characteristic, a shape factor, and an isotropy factor. Finally we tested the possible correlation between the structural parameters and the reflectance and compared the modelled results with those of the empirical data set from Matzl and Schneebeli (2006b).

5.3 Theory

5.3.1 Structural parameter

In this study we consider different structural parameters to analyse the effect of snow structure on the reflectance of snow in the NIR. As first parameter we used the SSA which we estimated for vertical surface sections (Baddeley and Vedel Jensen, 2005) using model-based stereology. This approach has been explained in detail for snow samples in Matzl and Schneebeli (2006a). In the following the SSA is defined as surface-to-volume ratio [mm$^{-1}$]. The SSA has been used for several years as an optical equivalent sphere to describe optical properties of a general polydispersion (Dobbins and Jizmagia, 1966) and snow (Grenfell and Warren, 1999). This property has been used to parametrise structures for radiative transfer modeling of snow (Dozier et al., 1988). Alongside its use for the optical description of snow, the SSA is an important parameter for describing the structural size and the geometry of sintered media.

For the same surface sections we calculated also the Euler-Poincaré characteristic (EPC), a shape factor, and an isotropy factor. The Euler-Poincaré characteristic is defined as $X = F - E + V$ where $F$, $E$ and $V$ are the numbers of faces, edges and vertices respectively (Ohser and Mucklich, 2000). The EPC determined for a 3D sample differs from that determined for a 2D cross section from the same sample, whereas the SSA does not depend on the dimensionality of the sample. The shape factor is defined as the ice particle perimeter squared divided by the particle area as observed in the image. The isotropy factor is calculated as the ratio from the vertical and horizontal mean intercept lengths in the ice phase. Isotropy values smaller than one indicate predominantly horizontal structures and values larger than one predominantly vertical structures.
5.3.2 The beam-tracing model

The beam-tracing model, presented in Bänninger et al. (2006), requires an explicit description of the geometry of the scattering medium. Hence, it traces the path of light beams in a medium with a given structure of phases with given attenuation properties. We used 2D images which represent sections through the snow samples. The BTM is designed to process the radiative transfer in the 2D space. Reducing dimensionality from 3D to 2D causes some loss of information but makes the BTM computationally feasible. According to the analysis of Vokov and Remizovich (1998), the differences between radiative transfer calculations for the 2D and 3D case are of minor importance. In this paper we do not discuss the simplification caused by dimensional reduction because the 3D connectivity of the air-phase has hardly an influence on the radiative transfer, since snow particles are highly transparent.

The image describing the structure of the scattering medium is a black and white image representing the ice (black) and air (white). Each of the two phases is characterised with a complex refractive index. The optical path of a beam is defined by its position and propagation direction and the subsequent scattering events, calculated based on Snell’s Law and using the Fresnel equations at the optical interfaces. To obtain the orientation of the particle boundaries in space we preprocessed the images: We filtered the image with an x- and an y-gradient filter for each contour line pixel at the ice-air interface. A contour line pixel is an ice pixel having at least one of its eight neighbour pixels being an air pixel. Using the law of Pythagoras the direction of the contour line pixels is found.

The BTM models the illumination by defining the direction, position, and intensity of the incident beams. The model tracks these beams pixel-by-pixel through the image. Reflectance is calculated by summing-up the intensities of the light beams leaving the sample at the upper surface. When the intensity of a light beam within the sample drops below a defined threshold, the beam is assumed to be completely absorbed. This assumption is required because light absorption decreases exponentially and thus never reaches a value of zero. We assigned the left, right, and bottom edge of the sample to be completely reflective. Using mirror constraints at the boundaries of the sample simulates an infinitely broad sample. The height of the sample image was chosen in such a way that light beams reflected at the bottom did not reach the top surface again.
5.4 Experiment

We realised a first model run using artificially generated snow sections. With this experiment we tested the contribution of density and SSA to snow reflectance. We generated media by distributing discs in an image. The discs were distributed on a regular triangular grid to fulfill the mass density constraint defined by the user. Additionally, the discs were randomly displaced from the grid nodes. Allowing some irregularity mimicks natural unstructured media better. The displacement was sufficient small that discs did not overlap. Figure 5.1 shows a cutout of media generated accordingly.

In a second model run we used images of natural snow sections to calculate the reflectance using the BTM (Figure 5.2). The images were derived from field samples which were cut and photographed using a Leica Sliding Microtome. We selected snow samples varying in density and SSA. For a further discussion about the influence of structure on reflectance we calculated also shape factor, EPC, and isotropy for these samples. We calculated an empirical reflectance by fitting about fifty values measured on snow samples by Matzl and Schneebeli (2006b). The images we used had a width between 10 and 20 mm and a length
of approximately 360 mm. The image resolution was 69 pixel mm\(^{-1}\). The model was run for a wavelength of 890 nm. The complex refractive index for snow at this wavelength is \(\hat{n} = 1.303 + i4.348e^{-7}\) (Warren, 1984).

![Figure 5.2: Surface sections of natural snow samples. In the following we refer to these samples with the indicated capital letters (A–J). The images shown here are magnified cutouts of the images used for the simulation.](image)

5.5 Results

5.5.1 Description of snow structure

By using the SSA we parametrise the surface-to-volume ratio of the snow. But the SSA does not contain information about the grain shape nor the isotropy of the structure. Therefore, we calculated the EPC, shape factor, and isotropy factor to test their influence on snow reflectance. Table 5.5.1 lists the parameters we used to describe the structure of the snow samples.
Table 5.1: Structural properties of the natural snow samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Density [kg m(^{-3})]</th>
<th>SSA [mm(^{-1})]</th>
<th>EPC</th>
<th>Shape factor</th>
<th>Isotropy factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>343.0</td>
<td>15.2</td>
<td>0.38</td>
<td>36.8</td>
<td>0.91</td>
</tr>
<tr>
<td>B</td>
<td>312.6</td>
<td>15.9</td>
<td>0.95</td>
<td>29.1</td>
<td>0.92</td>
</tr>
<tr>
<td>C</td>
<td>258.6</td>
<td>19.2</td>
<td>0.89</td>
<td>27.6</td>
<td>1.06</td>
</tr>
<tr>
<td>D</td>
<td>256.8</td>
<td>16.0</td>
<td>0.89</td>
<td>28.6</td>
<td>1.04</td>
</tr>
<tr>
<td>E</td>
<td>252.1</td>
<td>28.9</td>
<td>0.93</td>
<td>25.8</td>
<td>0.89</td>
</tr>
<tr>
<td>F</td>
<td>226.5</td>
<td>31.7</td>
<td>0.94</td>
<td>29.5</td>
<td>0.94</td>
</tr>
<tr>
<td>G</td>
<td>214.3</td>
<td>24.8</td>
<td>0.79</td>
<td>27.6</td>
<td>0.83</td>
</tr>
<tr>
<td>H</td>
<td>326.4</td>
<td>12.4</td>
<td>0.43</td>
<td>38.8</td>
<td>1.11</td>
</tr>
<tr>
<td>I</td>
<td>270.9</td>
<td>25.0</td>
<td>0.96</td>
<td>28.5</td>
<td>1.04</td>
</tr>
<tr>
<td>J</td>
<td>204.9</td>
<td>15.3</td>
<td>0.62</td>
<td>39.5</td>
<td>1.08</td>
</tr>
</tbody>
</table>

5.5.2 Modelled reflectance for the computationally generated snow sections

With the first model run, i.e. the run using the computationally generated sections, we found that reflectance depends significantly on the SSA, but not on the density of snow. The modelling results are summarised in Table 5.5.2.

Table 5.2: Modelled reflectances of the artificial generated snow samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Density [kg m(^{-3})]</th>
<th>SSA [mm(^{-1})]</th>
<th>Modelled r [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>458.5</td>
<td>3.0</td>
<td>46.3</td>
</tr>
<tr>
<td>b</td>
<td>458.5</td>
<td>26.1</td>
<td>60.3</td>
</tr>
<tr>
<td>c</td>
<td>321.0</td>
<td>3.0</td>
<td>44.0</td>
</tr>
<tr>
<td>d</td>
<td>321.0</td>
<td>26.3</td>
<td>66.2</td>
</tr>
<tr>
<td>e</td>
<td>183.4</td>
<td>3.0</td>
<td>45.0</td>
</tr>
<tr>
<td>f</td>
<td>183.4</td>
<td>26.4</td>
<td>65.0</td>
</tr>
</tbody>
</table>

5.5.3 Modelled reflectance for the natural snow structures

For the calculations presented in Table 5.5.2 we used the BTM as it was implemented originally to model the reflectance of soil samples. A key assumption in this approach is
that we defined a light intensity threshold. Scattered light beams with an intensity below this threshold are neglected. The choice of this threshold has two consequences: (i) The smaller the value for this threshold the more scattered beams have to be followed and thus the computational time increases drastically. (ii) The higher the value for the threshold the more light is neglected in the final result. Soil is a very strong light absorber. Neglecting some light intensity has almost no effect on the result. This is completely different for snow: Snow is a very weak light absorber. Thus, neglecting some light intensity has a significant influence on the result. As a consequence, the definition of the threshold within the BTM has to be considered in some way to obtain less biased results.

To address this fact for the snow samples, we modelled the raw reflectance $r_{\text{raw}}$ and recorded the light intensity depth distribution $I = [I_1, I_2, ..., I_K]$ when discretising the sample into $K$ layers at depth $Z_1$ to $Z_K$. Simultaneously we recorded the amount of neglected light intensity at the various depths of the sample, $N = [N_1, N_2, ..., N_K]$. After finishing the simulation run we had in some way to re-allocate and redistribute the neglected radiation flux. The neglected radiation re-appearing at the surface is proportional to the extinction curve. Thus, the redistribution of the neglected light was done by multiplying the neglectance depth distribution with the extinction curve derived from the simulation run. Summing-up this depth distribution and adding it to the raw reflectance yields the corrected reflectance:

$$ r = r_{\text{raw}} + \sum_{k=1}^{K} I_k N_k $$

(5.1)

The corrected reflectances for samples A to J are listed in Table 5.5.3. Therein, the modelled reflectances are compared with reflectances we calculated from a fit derived from a measurement series (Figure 5.3) from Matzl and Schneebeli (2006b).

### 5.5.4 Merging reflectance and structure information

The scatterplot of SSA and reflectance is shown in Figure 5.3 combined with the measured values from Matzl and Schneebeli (2006b). In Figure 5.4a – 5.4d we plotted the modelled reflectance against the structural parameters shape, EPC, isotropy and density.
Table 5.3: Modelled reflectances of natural snow samples and reflectances calculated using the empirical fit.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Modelled $r$ [%]</th>
<th>Calculated $r$ from fit [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>81.8</td>
<td>83.8</td>
</tr>
<tr>
<td>B</td>
<td>82.4</td>
<td>84.3</td>
</tr>
<tr>
<td>C</td>
<td>81.8</td>
<td>86.6</td>
</tr>
<tr>
<td>D</td>
<td>81.7</td>
<td>84.4</td>
</tr>
<tr>
<td>E</td>
<td>85.4</td>
<td>91.5</td>
</tr>
<tr>
<td>F</td>
<td>84.8</td>
<td>92.6</td>
</tr>
<tr>
<td>G</td>
<td>85.3</td>
<td>89.7</td>
</tr>
<tr>
<td>H</td>
<td>77.0</td>
<td>81.3</td>
</tr>
<tr>
<td>I</td>
<td>83.5</td>
<td>89.8</td>
</tr>
<tr>
<td>J</td>
<td>72.8</td>
<td>83.9</td>
</tr>
</tbody>
</table>

Figure 5.3: A-J: SSA and modelled reflectance of natural snow samples. The line shows the fit based on measurements (black dots) by Matzl and Schneebeli (2006b).
Figure 5.4: Dependence of the simulated reflectance on structural parameters: (a) Shape, (b) EPC, (c) Isotropy, and (d) Density
5.6 Discussion

5.6.1 Application of the beam-tracing model to snow

The beam-tracing model was originally designed to model the radiative transfer in soil samples (Bänninger et al., 2006). Here, we adapt and apply this particular beam-tracing model to simulate the effect of snow structure on reflectance. Hence, we relate structure information with radiative transfer properties.

To reduce the computational time and to make the model more applicable to this particular medium a threshold criterion is implemented. We account for the light lost due to the threshold criterion by redistributing equivalent intensities according to the modelled extinction curve. For example, decreasing the light intensity threshold by order of magnitude increases the calculation time from 4 to 30 hours, while the modelled reflectance values change only in the order of 0.2%.

For the simulations presented in this study we used collimated instead of diffuse incident light as was used in the experimental setup of Matzl and Schneebeli (2006b). For reasons of computational time we run the simulation only with 100 incident beams. A random occurrence of extrem incident angles in such a small ensemble might influence the result significantly. Using collimated incidence with normal direction to the sample surface prevents such errors.

5.6.2 Comparison between modelled and empirical reflectance

From the model runs based on the computationally generated samples (Table 5.5.2) we found no influence of the density on the reflectance, but the reflectance increases substantially with an increasing SSA. This is consistent to the measurements of Matzl and Schneebeli (2006b) who found that reflectance depends mainly on SSA. A comparison of the modelled values of the artificial samples (Table 5.5.2) to the measured data (Figure 5.3) shows that the absolute value of the reflectance is approximately 25% lower. The large difference between modelled and empirical reflectance values is caused by not accounting for the neglected light intensities, as explained in section 5.5.3.

Using the extended implementation of the BTM, i.e. redistributing the neglected light intensities, the modelled and empirical reflectances agree well (Figure 5.3): The reflectance
increases with an exponentially increasing SSA. The absolute modelled reflectance is smaller than the measured reflectance, with an increasing difference for larger SSA values. A possible reason for this difference could be an inaccuracy in the measurement design which was mentioned by Matzl and Schneebeli (2006b). It seems that neglecting the light which penetrates through the snow overestimates reflectance for SSA values above 20 mm$^{-1}$.

### 5.6.3 Influence by the structure

In Figure 5.3 it is shown that the scatter between the modelled reflectance and the SSA is similar to the scatter in the empirical data set. The cause for this variation probably originates from structures which are not parameterised by the SSA.

Plotting the reflectance against EPC, density, and shape factor (Figure 5.4a, 5.4b and 5.4d) does not show either clear trends. A possible reason could be that the chosen parameters do not capture the features pertinent for the radiative transfer. Analysing the isotropy factor we find a trend which results in increased modelled reflectance in presence of predominantly horizontal features (Figure 5.4c). To verify this finding we need more values for a statistical verification.

The scatterplots (Figure 5.4) show that the samples A, H, and J deviate from the structural properties of the other samples. We assume that this deviation originates from the different snow types of the samples. The samples A, H and J consist of large faceted crystals and depth hoar, while the other samples consist of decomposed or rather rounded particles (Figure 5.2).

### 5.7 Conclusion

We implemented a beam-tracing model to simulate the radiative transfer in vertical surface sections of snow samples taken at natural profile walls. The simulations showed an increase of reflectance with exponentially increasing SSA and correspond well with the empirical data set used for comparison and with prior modelled results (Warren, 1982). At the same time the results showed that no one-to-one relation exists between SSA and snow reflectance in the NIR. The scatter could not be explained by the examined structural parameters EPC, density, and shape factor. Isotropy could be a significant parameter, but the samples were too few to validate this assumption.
We conclude that: (i) beam-tracing models is an important tool to solve the problem of structure dependent snow reflectance; (ii) more precise measurement series of well defined snow types are necessary to test structural influences on the reflectance and to compare different models; and (iii) additional structural parameters have to be examined, which describe the structural elements which are relevant to the radiative transfer in snow.

Bibliography


Chapter 6

Conclusions and outlook

It was the aim of this project to develop a field method for quantitative and two-dimensional (2D) assessments of the snow stratigraphy. In my thesis, I show the development and the practical realisation of near infrared photography (NIP). The inexpensive and fast method allows the mapping of the snow stratigraphy at high spatial resolution. Even small features, which are nearly not observable by conventional methods can be detected in the digital images. The near infrared (NIR) reflectance of snow has empirically been shown to depend on its specific surface area (SSA). This allows to calculate the SSA from the reflectance of the NIR images. The resulting images quantify the snow stratigraphy based on the size of the snow structures.

In the following sections I summarise the research results. The relevance of the findings as well as the encountered difficulties are discussed and an outlook on possible next steps and applications is given.

6.1 Model-based stereology

The development of a stereological approach to estimate the SSA from snow samples was a necessary step for calibrating NIR images. At the same time the finding that stereological methods can be successfully applied without any restrictions concerning the snow type makes this approach very attractive for the microstructural analysis of snow samples. In snow science, stereological methods have been critically discussed for a long time due to the formerly unavoidable assumption about the shape of the tested particles (Kry, 1975; Good,
In this study I applied a model-based stereological approach which only assumes a material that is horizontally homogeneous on the scale of the sample size. The accuracy of this method was verified based on computer tomograph (micro-CT) scans. The micro-CT calculations and the stereological estimations of the SSA correlated very well with $R^2 = 0.99$ and $p < 0.001$. An important benefit of this method is that it can be combined with the analyses on casted and frozen field samples. This combination allows the measurement of SSA from undisturbed natural field samples, even from remote locations. Furthermore, the stereological method can resolve fine layers and subtle changes of the ice structure.

**Outlook**

- The successful implementation of this method makes it feasible to derive other snow parameters than SSA (for example curvature of ice-air interfaces or connectivity of ice and air phase) by using model-based stereology. These additional parameters could also be calculated from casted 3D samples and samples scanned in a micro-CT, but the effort for these methods is much higher and the sample size in the micro-CT is restricted to a diameter of maximum 36 mm.

- The described stereological approach will in a next step be used for a comparison with the penetration resistance recorded with the Snow Micro Pen (SMP). Mätzler (2002) showed a close relationship between SSA and correlation length of distances between particles in snow. Future tests will evaluate whether this correlation could be also verified for SSA and the correlation length of the force signal of the SMP. A successful correlation would allow us to use the SMP for hardness measurements as well as for measurements of the snow microstructure. This would be very useful and efficient, especially for investigations focusing on the vertical stratigraphy. It could open the way for 3D mapping of microstructural snow pack features.

### 6.2 Near infrared photography

In chapter 4 we empirically proved the dependence of snow reflectance on the SSA. The correlation shows an exponentially increasing SSA with increasing reflectance. Based on this correlation the SSA is calculated for the calibrated and processed NIR image. The resulting image is a 2D map of the SSA for the profile wall.
This work shows that NIP is an inexpensive and fast method to quantitatively measure the snow stratigraphy in 2D. In the following section I give an outlook on possible, intended and scheduled next steps and applications.

**Outlook**

- A major point in the calibration of the images is the correction of inhomogeneous illumination. For this study we used standard targets of a known reflectance to correct illumination errors. This method does not account for irregularities on a small scale, as for example local reflections originating from other equipment in the snow profile. To overcome this problem more work is necessary to develop a flat field correction for field use. A second image, where a target (flat field) of constant colour brightness covers the profile, could be subtracted from the first image and correct for non-uniformity, as applied in case of dye tracing in soils (Forrer et al., 2000). The method has proved successful in first tests. It remains to find an evenly reflecting material which is crease-resistant and applicable for field work.

- Alongside the methodical improvement, some suggestions concerning the weight and the size of the equipment could make NIP a field tool more attractive to snow scientists and practitioners. The current camera (Kodak DCS420ir) should be replaced by a calibrated smaller camera. Today, commercial NIR cameras are available at a relatively lower price (below 1000 US$). It is also possible to use a regular camera converted to a NIR camera (url: www.maxmax.com). With an appropriate filter such cameras can be used in visible as well as in NIR wavelengths. By the use of a smaller camera and an adapted tripod the weight of the equipment could be reduced by approximately 4 kg to a weight of 2 kg. With the use of a wide angle, the size of the snow pit and thus time and effort in the field could further be reduced.

- Even an unprocessed NIR image of a snow profile wall gives a detailed, 2D overview of the snow stratigraphy. The image shows layers, disturbances, and horizontal features not detectable in the visible wavelength spectrum. The only important condition is a carefully smoothed profile wall. Thus, it would be very helpful if NIR images were already available on-site, for example to check whether the location of the hand profile is representative for a wider horizontal range, or to focus on specific features invisible to the human eye. In addition to a NIR camera, this would require the use of a small
laptop in the field.

- Being able to measure the SSA of natural snow covers in the field we now have a proxy parameter to link analyses carried out in the cold laboratory to field investigations. For example, the relationship of thermal conductivity to the SSA and to other structural parameters is currently investigated using the micro-CT. Such results can be readily adopted to assess the actual conditions of the snow cover. They can also be used for the verification and initialisation of snow cover models which simulate this parameter.

- Another application is the observation of temporal and spatial changes in the snow cover. The spatial variability of the snow cover has been the object of recent investigations (Kronholm et al., 2004). The basic techniques used are hand profiles including stability tests and SMP-profiles, which are restricted to horizontal spacing of approximately 0.5 m in the field. NIP, with a minimum horizontal resolution of 1 mm, can complement these measurements and provide sound rules for an interpolation between the local measurements of the SMP.

- Single NIR images and also overlapping adjacent images can be used to quantify the spatial variability on scales from millimetres to metres. Strata for geostatistical calculations can be defined by means of digital image analysis. This spatial analysis can be further extended to 3D by photographing a series of closely spaced snow stratigraphies.

- Distinct layers in the NIR images can be discriminated based on pixel intensities as well as on texture. This suggests that more information, possibly about the snow type, can be extracted from the NIR images by also considering the texture. To test this hypothesis the texture in the NIR images can be analysed using pattern recognition techniques. Repeating patterns can then be compared to the snow type information from the corresponding hand profiles.

- NIP is recently applied to document the periodic snow profiles at the test site of the Swiss Federal Institute for Snow and Avalanche Research (SLF), Weissfluhjoch, Switzerland. NIP will also be applied to produce a catalogue of characteristic snow cover stratigraphies and weak layers. The snow stratigraphy will be quantified on the basis of characteristic properties, such as mechanical stability, density, structural properties, and the order of the layers. For this project, NIP can be used in both ways, for a qualitative visual documentation of the stratigraphy and for quantitatively
6.3 Modeling beam traces in real snow structures

In chapter 5 we applied a 2D beam-tracing model to describe the radiative transfer in snow. The intention was to determine the reasons for the deviations from the empirical fit between SSA and snow reflectance (chapter 4). We addressed the question whether these deviations were exclusively caused by measurement inaccuracies or whether additional structural parameters besides the SSA affect the NIR reflectance of snow.

To my knowledge, this is the first time that a spatially highly resolved beam-tracing model was applied to natural snow structures. The modelled results are consistent with the findings from chapter 4 and show an exponentially increasing SSA with increasing reflectance. The modelled results also show that snow reflectance in the NIR cannot be completely explained by the SSA of snow. While the observed scatter could not be explained by the examined structural parameters Euler-Poincaré characteristic, density, and shape factor, there seems to exist a correlation between the isotropy factor and reflectance. Still, more values are needed to validate this finding.

Outlook

- The next step will be to broaden the statistical basis of the simulated data set.
- Another step will be the comparison between a model based on Mie-scattering and this beam-tracing model. The variations between the two approaches could give us an indication whether the information loss by assuming optical equivalent spheres is relevant and whether more and other structural information is needed for radiative transfer modelling.

Bibliography


Good, W. (1989): Laboratory techniques for the characterization of snow structures. In: *Pro-


Curriculum vitae

Margret Matzl
Born on February 29, 1976, in Ebersberg, Germany.

Education

1982-1986 Primary School, Vaterstetten, Germany.
1995-1996 Student of musicology, Ludwig-Maximilians-Universität, Munich, Germany.
1996-1998 Student of geography, Ludwig-Maximilians-Universität, Munich, Germany.
1999-2003 Student of geography, Humboldt-Universität zu Berlin, Germany.
2003-2006 Dissertation on "Quantifying the stratigraphy of snow profiles" at the Institute of Terrestrial Ecology, Soil Physics, ETH Zurich and the Swiss Federal Institute for Snow and Avalanche Research (SLF), Davos, Switzerland.