Non-destructive quantification of snowpack properties

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Abstract

A temporal observation of the stratigraphy of seasonal snowpacks is only possible with non-invasive methods. Electromagnetic waves, specifically radar waves, proved to be the most appropriate technique to estimate internal snow parameters and media transitions non-destructively. Thereby, it is possible to estimate quantitatively snowpack stratigraphy and observe the snowpack evolution with time. Radar systems work as an active wave transmitter, which records reflection intensities with travel-time. Either the system modulates the signal on a defined frequency range as frequency modulated continuous wave systems (FMCW) or a short impulse is radiated at a center frequency and bandwidth. The stratigraphic resolution and the penetration depth of both systems depends on the system parameters. The frequency determines the penetration depth and sensitivity and the bandwidth determines the vertical resolution. In previous studies FMCW X- and Ku-band frequencies failed to penetrate a moist snowpack, but provided convincing results in resolving the snowpack stratigraphy. Pulsed 900 MHz antennas, as well as L- and C-band FMCW systems penetrated a wet snowpack up to one meter and measured adequate gradients in snow density. Current research in pulsed and modulated systems show that electromagnetic wave systems are convincing methods to quantitatively measure snow stratigraphy non-destructively.

1 INTRODUCTION

The determination of snowpack properties, such as stratigraphy and snow height, and changes thereof are essential features for compiling avalanche warning bulletins, preferably on a daily basis. For data assimilation in snowpack models the accuracy and spatial resolution depends on the input data. To date, the spatial resolution of these models is dependent on the spatial distribution of automatic snow height stations (Bavay et al., 2009). Schneebeli and Laternser (2004) noticed, that large daily new snow events are often unobserved by automatic snow height stations. Concerning the manual data acquisition, especially in slope and ridge regions, the data volume is limited by accessability and men-power. For avalanche warning services further spatio-temporal snowpack data on both plain and slope areas, are an important support for the regional risk and hazard management.

A spatio-temporal observation of snowpack properties is only possible if the method is quickly applicable and non-destructive. Furthermore, temporal observations of internal snowpack conditions is

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constrained to non-invasive measurements. For spatial observations of properties, time consuming methods like probing or digging snow pits are not sufficient. In-situ observing and remotely operated radar systems seem most promising for operational implementation. To date, two different system types were successfully applied in snow and avalanche research, namely impulse radar, such as ground-penetrating radar (GPR), or frequency modulated continuous wave (FMCW) systems (Marshall et al., 2005).

In this study we compare two possibilities to measure snowpack conditions with radar systems and discuss their applicability in the quantification of specific parameters as snow depth and layer determination.

2 METHODOLOGY

GPR-system

The use of impulse radars with high frequencies (2-7 GHz) to measure snow stratigraphy in an mountain snowpack was firstly described more than 35 years ago by Vickers and Rose (1973). Recent works in Scandinavia and in alpine regions used impulse radar systems such as ground-penetrating radar to determine the snow-water equivalent (SWE) (Marchand et al., 2001), snow depth and snow accumulation variability (Harper and Bradford, 2003; Machguth et al., 2006) as well as to detect avalanche victims (Heilig et al., 2008).

Here, we used a GPR instrument with shielded antennas with a nominal frequency of about 800 – 900 MHz. Further processing and interpretation steps focus on distinguishing between snow stratigraphic reflections and noise or static signals caused by the test arrangement and antenna design. If the antennas are stationary, all signals appear in horizontally constant responses. Therefore, the antenna noise in pulsed radar systems partly masks the reflections caused by the snow stratigraphy, which makes it difficult to detect the snow signals. In order to remove this effect, the antennas are moved vertically, which result in a signal pattern in which instrumentally caused signals are recorded horizontally constant and reflections generated by stratigraphic parameter correspond to the vertical movement.

FMCW-system

The example results from an FMCW radar system shown below are based on measurements made and reported in Marshall et al. (2007). This system operates in the X- and Ku-band frequencies, specifically 8-18 GHz. Since the snowpack was dry, the highest frequency and largest bandwidth was used for this study to maximize vertical resolution and sensitivity to stratigraphy, since penetration was not an issue. One advantage of FMCW radar is that a very large bandwidth can be used; in contrast, impulse radar systems typically are limited to a bandwith that is close to the center frequency. In a wet snowpack, L- and C-band FMCW systems are typically used (e.g. Yankielun et al., 2004; Koh and Jordan, 1995).

Like impulse radar, FMCW radar systems have instrumental noise, which must be removed before analysis. As with the impulse system, the antennas are typically moved vertically to differentiate the snowpack signals from instrumental noise (Fig. 2, Marshall et al., 2007). FMCW radar systems allow horn antennas to be used, which can have significantly more directionality than dipole antennas. This makes it possible to point the antennas at the sky, and use this signal to accurately remove instrumentation-related signals with a filtering algorithm (Fig. 3, Marshall et al., 2007). The instrumentation noise can change with temperature, therefore these "sky calibration" measurements are typically made periodically to do the best possible job of removing unwanted noise.

2.1 *Test arrangement*

The radar data of the present study conducted with GPR systems were recorded from beneath the snowpack. In order to enable a measurement system applicable in slopes with a predominant avalanche hazard, we constructed a sensor system, which is not prone to avalanche destruction. For the interpretability of the gathered GPR records, we arranged an experimental set-up with vertically moved antennas. Fixed GPR antennas were installed from January 2009 until the beginning of April 2009 at a test site in the Bavarian Alps at 1420 m a.s.l.. The antennas were remotely lifted by a hydraulic hoist system and completely buried in the snowpack. Conventional snowpack measurements in a snow pit were performed about 5 – 7 m away from the place of the radar records in a flat field to leave the snow above the antennas undisturbed.

The test site of the FMCW measurements was located in the Swiss alps slightly higher in elevation at 1560 m a.s.l.. The test arrangement for the FMCW measurements consisted of vertical moved antennas as well. Contrary to the GPR measurements, these records were conducted from above the snow surface, and covered a distance of 10 meters. After the FMCW profile was recorded, the standard snowpit measurements and Near Infrared photography was used to record in-situ snow properties at one location which the radar measured, and at 5 different locations profiles were made with the SMP.

2.2 *Theoretical basics*

In dry snow conditions, as recorded in the here presented examples, the sole snowpack parameter to cause reflections of the emitted electromagnetic waves is a change in density (Kovacs et al., 1995; Mätzler, 1996). The responses of the emitted signals are recorded in two-way travel time. Radar systems measure the time of an emitted electromagnetic wave travelling to a position, which causes reflection and back to the receiver. An reflection with a larger travel time is further away of the signal source, the transmitter. In dry snow conditions respective average wave-speed values were determined for both pulsed and continuous wave signals using a mean density value $\bar{\rho}$ of the snow pits and equation 1 for low loss medias

$$v = \frac{c}{\sqrt{\varepsilon_r}}. \quad (1)$$

ε_r is the relative dielectric permittivity, which is for dry snow conditions only a function of density and calculated by

$$\varepsilon_r = (1 + 0.845\rho)^2,$$

the approximation by Kovacs et al. (1995) with ρ given in cm³/g. The accuracies using eq. 1 for the determination of the snow height of the penetrated snow cover with a mean value of the density were between 2 – 10 % for both applied radar techniques (Marshall et al., 2005; Heilig et al., submitted).

3 RESULTS

Example radar profiles with both pulsed systems and frequency modulated systems are presented with the corresponding snowpack properties in Figure 1. The left side of the Figure shows the GPR profile and the right side the FMCW profile. The snow-pit data and the SMP profile are each related to the recorded radar signals. It is important to note that the radargram on the left side in Figure 1 consist of recorded and processed reflections and on the right side are only displayed the propability density function (PDF) of the location of major peaks recorded with the FMCW system during a measurement when the system was moved vertically. These peaks correspond to persistant high reflection values and are therefore comparable to the bright reflections recorded with the GPR system. Nevertheless, we measured two different snowpacks and do not compare the capabilities of each system directly.

The conditions of both observed snowpacks are comparable. While the thickness of the scanned snow covers was almost double for the GPR measurement, the mean density, the density distribution and the layer thicknesses were very similar between both measurements (Figure 1). Both radar systems showed a clear reflection response at the snow surface. Furthermore various internal layers are recorded by the two radar systems. The GPR radargram (Figure 1;left side) shows three remarkable separable reflections (B, C, D). The first reflection in radar wave direction occurs at the density increase at a snow height of 73 cm (D), the second reflection consits of an interference of the density decrease at 115 cm and the strong increase at 127 cm (C) and the third reflection is again another interference of two single signal responses at very varying snow layers. The strong crust at 154 cm in the profile likely caused the first bright reflection peak and the following strong decrease in

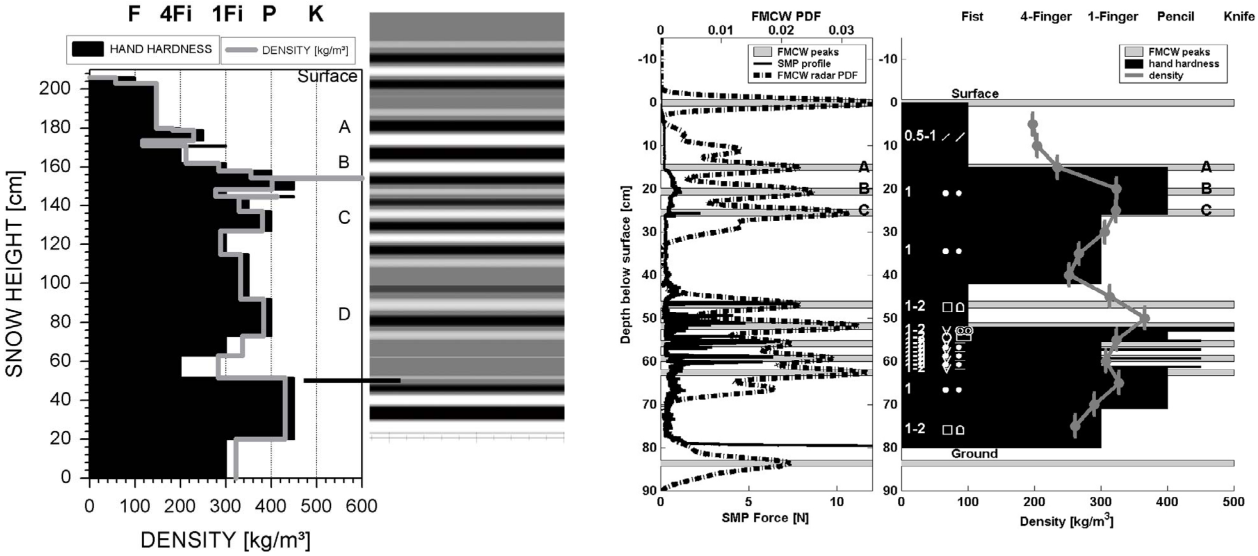

Fig. 1: Snowpack conditions recorded with radar systems in comparison to measurements of the density and hand hardness. Left the relation of GPR records to density and hand hardness is displayed and right visualizes the relation of the calculated probability density function (PDF) of FMCW measured reflections to density and hand hardness as well. Furthermore, recorded SMP signals are compared to the location of major radar reflections. Both figures show snow depth relative to the location of the antennas - on the right it is a distance in snow above the antennas, and on the left it is the depth below the snow surface.

combination with another increase at the second crust interfered to reflections A and B. This varying snow stratigraphy is below the vertical resolution limit and therefore can not be recorded as single reflections.

The FMCW system produced a reflection at the snow surface, and at the first layer transition recorded in the snowpit (A) (Figure 1). Reflection B is not related to a manually identified layer boundary, however the much higher resolution SMP shows an increase and subsequent decrease at this location. Reflection C occurs at the second major stratigraphic boundary identified in the snowpit and SMP. Several persistent ice layers were found deep in the snowpack which were detected by all 3 methods.

4 DISCUSSION & CONCLUSION

This study shows, that with ground-pentrating radar systems as well as with continuous wave systems relevant dry snowpack conditions are recordable in a non-invasive way. The determination of the snow height is adequately accurate with both systems. Additionally, internal layers could be recorded and related to changes in density and peaks in penetration resistance. This enables two different applications. First, radar systems are capable to determine the spatial variability in occurrence, persistence and location of specific layers of a slope much faster than previously by snow pits. Second, while utilizing radar systems from beneath the snowpack, it is possible to quantify the temporal evolution of the snow cover at one point and determine compaction and accumulation rates. As these measurements can be conducted at large ranges of slope angles and in avalanche endangered slopes, such kind of information can be very supportive for avalanche warning centers.

Whether to use GPR or FMCW systems has to be decided according to the intended operation. The ability to distinguish between two adjacent layers is distinctly higher by the use of FMCW systems with such a large bandwidth. This can be a decisive argument for the application to determine the spatial variability. Moreover, there is no commercial manufacturer of FMCW-systems in the frequency range suitable for applications from beneath the snowpack. If it is intended to place several radar antennas on different slopes to determine the snowpack evolution, the application of commercially available GPR systems is probably more reasonable, while the layer resolution is still accurate. Commercial GPR systems are made in large quantity by manufacturers for many different applications, therefore user support is provided, while FMCW radars currently must be built by researchers as they are not currently available for purchase.

Electromagnetic waves penetrate the snow cover non-destructively, which enables a much faster investigation of larger areas concerning the temporal observation of the evolution of specific layers and the snow height at specific locations. This gain of knowledge can be used to improve the spatial representativeness of measurements and for validating the calculated temporal changes of snowpack simulation models. Furthermore, more data for a better understanding of the spatial variability in large slopes can be achieved by the fast and non-invasive scan of a whole slope.

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