Continuous monitoring of the temporal evolution of the snowpack using upward-looking ground penetrating radar technology

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Summary

Snow stratigraphy and water percolation are key parameters in avalanche forecasting. It is, however, difficult to model or measure stratigraphy and water flow in a sloping snowpack. Numerical modeling results depend highly on the type and availability of input data and the parameterization of the physical processes. Furthermore, the sensors themselves may influence the snowpack or be destroyed due to snow gliding and avalanches. Radar technology allows non-destructive scanning of the snowpack and deducing internal snow properties. If the radar system is buried in the ground, it cannot be destroyed by avalanche impacts or snow creep. During the winter seasons 2010-2011 and 2011-2012 we recorded continuous data with upward-looking pulsed radar systems (upGPR) at two test sites. We demonstrate that it is possible to determine the snow height with an accuracy comparable to conventional snow depth measuring devices. We determined the bulk volumetric liquid water content and tracked the position of the first stable wetting front. Wet-snow avalanche activity increased, when melt water penetrated deeper into the snowpack.

1. Introduction

The seasonal snow cover is stratified; the layers result from a sequence of weather events (Colbeck, 1991). Layer discontinuities are a prerequisite for avalanche formation. Snow slab avalanches involve the failure of a weak layer below a cohesive slab. Snow stratigraphy, that is, the thickness and properties of the layers that form the seasonal snow cover, is therefore considered as one of the key parameters in avalanche forecasting (Schweizer et al., 2003). Until now, information on snow stratigraphy has been obtained from manual observations by digging snow pits. This method is laborious, provides low temporal resolution and is often not possible due to safety concerns. Moreover, the method is destructive so that the temporal evolution cannot be monitored due to spatial variations of the snow cover (Schweizer et al., 2008). Snow stratigraphy can be modeled for locations where high quality weather data are available (Brun et al., 1992; Bartelt and Lehning, 2002; Lehning et al., 2002a; Lehning et al., 2002b). However, to simulate snow stratigraphy in avalanche starting zones, input data need to be extrapolated. Even though this is possible (Lehning et al., 2006), the uncertainty of the result can be large due to snow accumulation and erosion by wind (Lehning and Fierz, 2008).

Percolating melt water interacting with snow stratigraphy is assumed to be the dominant driver for the formation of wet-snow avalanches. It is, however, problematic to model or measure water flow in a sloping snowpack. Some sensors have to be operated in open snow pits, and thus the stratigraphy will be destroyed (Denoth et al., 1984). Other types of sensors need to be placed within the snowpack and will influence the water flow.

Radar technology allows scanning the snowpack non-destructively and deducing internal snow properties from its signal response. If the radar is buried in the ground, it is protected against snow creep and avalanche impact. Here, we present the preliminary results of two upward looking ground penetrating radar (upGPR) experiments performed in the eastern Swiss Alps.

2. Study sites

The first study site is the study plot at Weissfluhjoch above Davos, Switzerland at an elevation of 2540 m a.s.l. It is well accessible by cable car and the instrument hut is connected to the public electricity grid and the internet. The test site is equipped with several high-end sensors recording meteorological and snow cover properties. They offer excellent opportunities for comparisons and calibrations with our upGPR system.

The second study site, Dorfberg, is located between Weissfluhjoch and Davos at an elevation of 2230 m a.s.l. It is situated on a gently inclined slope next to a well-known wet-snow avalanche path. The test site is not connected to the public electricity grid and internet. At this test site, the main focus is on obtaining physical properties relevant for wet-snow avalanche formation. For that purpose, wet-snow avalanche activity was monitored from the valley bottom using time-lapse photography.

At both test sites, conventional manual snow profiles were conducted bi-weekly following the procedures described by Fierz et al. (2009). In addition, snow density and dielectric permittivity were measured for each layer.

3. Radar setup and processing

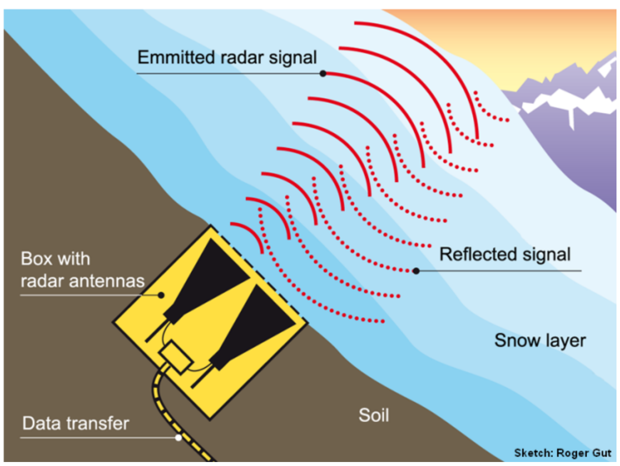

Figure 1: Measurement setup with upGPR buried in the ground and covered by snow.

An IDS (Ingeneria dei Sistemi) system with 600 MHz and 1.6 GHz antennas was used at the test site Weissfluhjoch and a 900 MHz system on Dorfberg. In order to protect the radar systems from avalanches and snow creep, they were installed in a wooden box buried in the ground. The antennas look upward and the radar pulses penetrate the snow from below (Figure 1). To distinguish reflection signals arising within the layered snowpack from coherent noise (system ringing), the antennas were vertically lifted and lowered during the measurements (Heilig et al., 2010). We conducted measurements every 3 hours in dry-snow conditions and every 30 minutes during snowmelt. The radar at the Dorfberg test site was powered by a 100 W solar system and three 12 V/38 Ah batteries.

We processed the radar data in a similar way to that described in Heilig et al. (2010). A dewow and a bandpass filter were applied. As the antennas were lifted and lowered during the measurements, all signals originating from the snowpack showed well-defined up-down curvatures in the radar sections, whereas noise signals, such as system ringing, remained constant, and could be eliminated by applying a background removal procedure. To compensate for divergence losses we used a gain correction that was linear with time. In the next step, a static correction to the signal reflection evoked by the wooden box/box-snow-transition above the antennas was applied, and subsequently all the signals from one measurement sequence were stacked to a single trace. Assuming a relative dielectric permittivity of $\varepsilon_r = 1.7$ allowed the two-way-travel time of the snow-air reflection to be converted to snow height.

4. Results

So far, we have operated our systems over two seasons (2010-2011 and 2011-2012). Figure 2 shows the results from Weissfluhjoch for the season 2011-2012. The root mean square error for snow height calculated with the radar compared with the snow height measured by a laser gauge was about 3.5 cm, as long as the snowpack was dry. Besides determining the snow height, the upGPR system also allows monitoring temporal changes in the internal dielectric permittivity. The settling behavior of old snow surfaces was compared to the height profiles measured by a combined settlement/temperature measurement system called MST (Weilenmann and Herzog, 1999). Our measurements showed that the signatures of former snow surfaces can be tracked up to four months after they were buried by subsequent snowfalls.

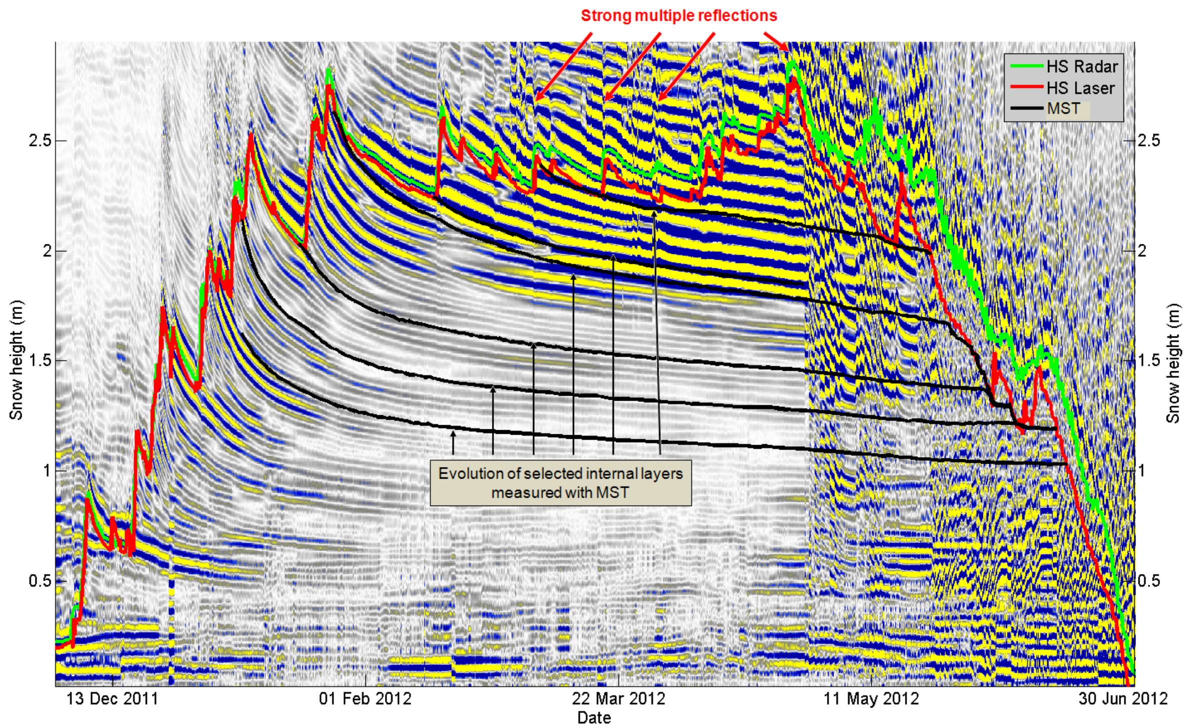

Figure 2: Processed radar data of the test site Weissfluhjoch for the winter season 2011-2012. Blue = negative and yellow = positive values of the reflected wave. Green line shows the snow height determined with the radar, red line represents the snow height recorded with a laser gauge. Black lines show the evolution of selected internal layers.

When snow is getting wet, the advance of stable wetting fronts can be detected. Strong multiple reflections relate to periods with water in the snowpack. When the liquid water content (θ_w) increases, ε_r increases and thus the snow height will be overestimated. At Weissfluhjoch this occurred in May (Figure 2). Even the diurnal variations in snow wetness are visible as the overestimation of the snow height changes during the day (ripples after 27 April). By comparing the radar signal to the snow height measured by a conventional gauge, the effective relative dielectric permittivity and the liquid water content can be calculated. The values agreed fairly well with the liquid-water content measured in snow pits and the outflow measured by a lysimeter.

Wet-snow avalanche activity at Dorfberg monitored by time-lapse photography was compared with the results from upGPR measurements. Avalanche activity was high when water penetrated into the snowpack. The largest avalanche, which had its starting zone at an elevation comparable to the radar location, occurred one day after the upGPR system had indicated that the melt water had fully percolated the snowpack.

5. Outlook

With the methods considered until now, it is not possible to derive detailed snow stratigraphy and snow properties for individual layers. Therefore, we seek to apply full-waveform inversions (FWI) to our upGPR data. Initial attempts look promising. Besides further development of our FWI schemes, it is planned to perform additional measurements using surface-based GPR and vertical radar profiles in snow pits. These data will provide further constraints for the characterization of the snowpack.

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