TRACKING WETTING FRONT ADAVANCE WITH UPWARD-LOOKING GROUND-PENETRATING RADAR

Lino Schmid[1]*, Christoph Mitterer[1], Achim Heilig[2,3], Jürg Schweizer[1], Olaf Eisen[3,4]

[1] WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland
[2] Department of Geosciences CGISS, Boise State University, Boise, ID, USA
[3] Institute of Environmental Physics, University of Heidelberg, Heidelberg, Germany
[4] Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

ABSTRACT: Percolating melt water combined with snow stratigraphy are thought to be the dominating drivers for the formation of wet-snow avalanches. It is, however, difficult to model or measure water flow in a sloping snowpack. For modeling, results highly depend on the type and availability of input data and the parameterization of the physical processes; in the case of sensor deployment, problems with snow gliding and avalanches will arise. In addition, if sensors are placed within the snowpack they will influence the flow of water. Radar technology allows scanning the snowpack non-destructively and deducing internal snow properties from its signal response. During the winter seasons 2011-2012 we recorded continuous data with an upward-looking pulsed radar system (upGPR) operating at a frequency of 900 MHz which was placed next to a well-known wet-snow avalanche path. We determined the bulk volumetric liquid water content and tracked the position of the first stable wetting front. All recorded wet-snow avalanches failed as full-depth avalanches. Wetting advance recorded with the radar corresponded with observed avalanche activity.

1. INTRODUCTION

When percolating water interacts with snow stratigraphy the strength of snow and thus snowpack stability is changing. Increasing water content (> 3% by volume) implies a strong decrease in strength (Bhutiyani, 1996) and therefore knowing the water content is the key to determine wet-snow instability. Measuring water content with conventional methods such as time-domain reflectometry (Schneebeli et al., 1998) or plate-like capacity sensors (Denoth, 1994) proofed to provide reliable results, but its application is hampered by several facts: The sensor is always inserted into the snow cover and water may preferentially drain towards the disturbed surroundings of the sensor. Often the sensor has to be inserted into a snow pit wall which again may lead to drainage effects along the open pit wall. In addition, the sample support of the sensors is often rather small. Modeling attempts for representing the flow behavior in snow provided good results for snow hydrological research questions (e.g. Illangasekare et al., 1990). However, during the beginning of the melt season the interaction of liquid water with the snowpack is highly non-linear resulting in a complex feedback system which is difficult to mimic with a model.

Radar technology offers the opportunity to overcome shortcomings of sensors deployed within the snowpack. Upward looking radar systems have been used to monitor snowpack evolution (Gubler and Weilenmann, 1987; Heilig et al., 2009).

We installed an upward-looking ground penetrating radar system next to a well-known wet-snow avalanche path in order to record wet-snow properties and obtain information on water flow related to wet-snow avalanche activity.

Corresponding author address: Lino Schmid
WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11,
CH-7260 Davos Dorf, Switzerland;
tel: +41 81 4170175; fax: +41 81 4170110;
email: schmidl@slf.ch

2. METHODS

2.1 Study site

The upward-looking radar (upGPR) measurements were performed at the study site Dorfberg above Davos (Switzerland) at an elevation of 2230 m a.s.l. The location of the upGPR is next to a well-known wet-snow avalanche path on a gently inclined (22°), southeast-facing slope. There is neither a connection to the public electricity grid nor a possibility for data transfer via internet. An automatic weather station 90 vertical meters below the position of the radar provides information on several weather and snowpack properties. Conventional manual snow pit profiles according to Fierz et al. (2009) were conducted on a bi-

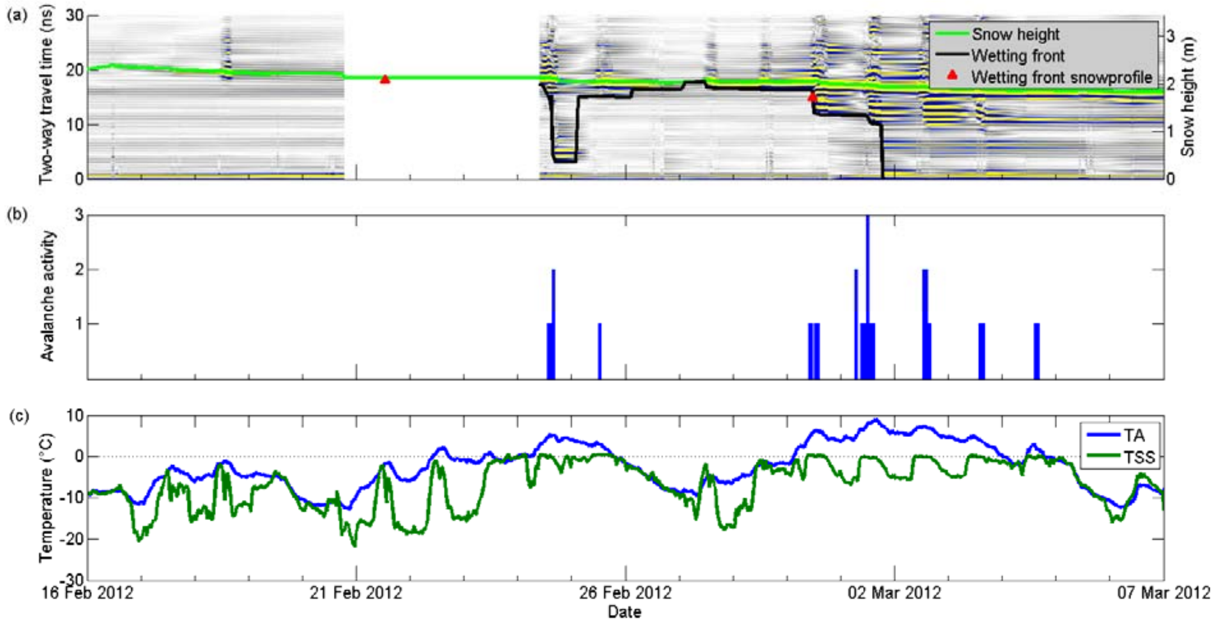

Figure 1: Measurements taken between 16 February and 7 March 2012. (a) Processed upGPR data. Blue = negative and yellow = positive values of the reflected wave. Green line shows the snow height and black line represents the transition of dry to wet snow determined with the radar. The red triangles show the dry to wet transition measured in snow pits. (b) Number of avalanches per 15 minutes. (c) Air (TA) and snow surface (TSS) temperature.

weekly basis within a few meters from the radar location. The profiles included layer-by-layer snow density and liquid water content measurements using a plate-like capacity probe (Denoth, 1994). Avalanche activity was monitored from the valley bottom with time-lapse photography (Feick et al., 2012).

2.2 The upGPR system

Commercially available 900 MHz radar antennas were buried in the ground to scan the evolving snowpack from below. The radar antennas were placed in a wooden box so that the system was protected against snow creep and/or avalanche impact. The power supply and control cables were placed in the soil and lead to the control box mounted on an avalanche defense structure. The box contained a power-efficient PC, the radar control unit and power management devices. The instruments were powered by a 100 W solar system and three 12 V/38 Ah batteries.

Since the signal response from the layered snowpack cannot be distinguished from coherent noise, the antennas were vertically lifted and lowered with an electrical motor during the measurements (Heilig et al., 2010). In order to have a high temporal resolution during the day, but also to safe electrical power, measurements were conducted every 30 minutes from 9:30 h to 18:30 h.

2.3 Processing of the radar signal

We processed the data in a similar way as suggested by Heilig et al. (2010). In contrast to their setup, the system is now installed beneath the level of the soil surface and not in a snow cave. We applied a dewow filter for removal of low-frequencies, a band pass filter to reduce clutter and noise and a linear gain increasing with travel time to compensate for divergence losses of the radar signal. As described above, antennas were lifted and lowered two times during each measurement. All signals originating from the snowpack show a distinctive step whereas system-immanent signals resulting from, e.g. antenna ringing, are constant over the whole measurement and can be eliminated by applying filter algorithms and lifting correction. After performing a static correction to the first reflection (which is in our case the wooden plate that covers the radar box), all reflections parallel to the wooden plate became horizontally planar, whereas multiple reflections and other interfering signals appear in an inverse oscillation to the vertical movement. The resulting radargram was

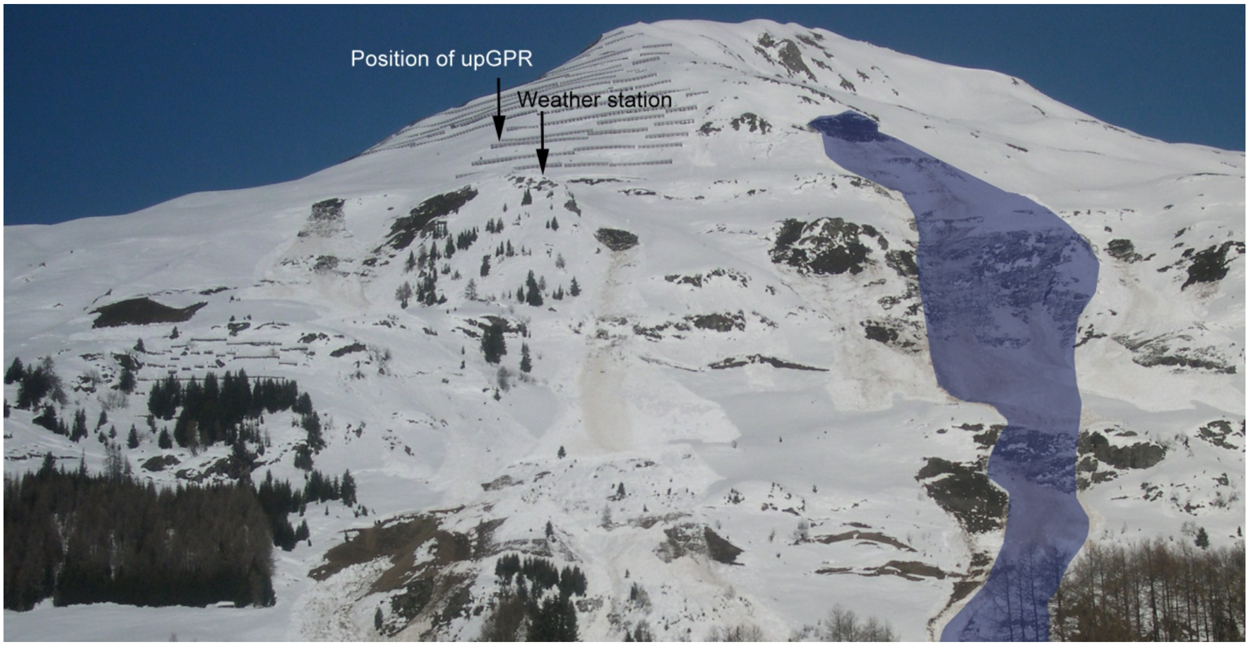

Figure 2: Study site at Dorfberg above Davos, Switzerland. upGPR and automatic weather station are located on top of the observed avalanche slope. The largest avalanche is marked in blue. Photo taken on 3 March 2012.

stacked over the number of all traces. Finally, all measurements were merged into one radargram.

3. RESULTS

The most prominent wet-snow avalanche cycle took place between 24 February 2012 and 4 March 2012. The first avalanches were recorded in the afternoon of 24 and 25 February; afterwards activity decreased due to cooling (Fig. 1c). With the next warm period, avalanche activity increased steadily and finished on 4 March 2012. The largest wet-snow avalanche was recorded on 2 March at 17:00 h (Fig. 2).

The top graph in Figure 1 shows the processed radar signals in a radargram. Blue represents negative and yellow positive values of the reflected wave. High amplitudes are thus given by more saturated colors. Assuming a mean relative dielectric permittivity of the snowpack of $\varepsilon_r = 1.7$ (Heilig et al., 2009) and knowing the two-way travel time to the snow surface, allows deriving the snow height above the radar (green line in Fig. 1a). Since measurements are only taken from 9:30 h to 18:30 h, the night values are interpolated from the last measurement and corresponding first measurement of the next day. The gap between 21 and 23 February is due to technical problems.

Infiltrating water causes strong reflection signatures and the highest amplitudes within the radar signal hint to the transition of dry to wet snow. Based on these signal signatures, we can follow the advance of percolating water (black line in Fig. 1a). A first wetting of the snowpack down to 0.4 m occurred on 24 February. Afterwards, the snow cooled down and only the upper 0.2 m were slightly wet. On 29 February the snow became wet again. The radar signal of 1 March suggests that melt water had percolated through the entire snowpack. The recorded wetting advance is in good agreement with measurements taken in the snow pit on 29 February (Fig. 1a).

The advance of the wetting within the radar signal corresponds fairly well with the wet-snow avalanche activity. It seems that the avalanches always release slightly before the wetting of the snow can be detected in the radargram. This is mainly because the upGPR is located within a slope that is higher and less steep than most avalanche release zones. Only the largest avalanche had its starting zone at a comparable elevation (Fig. 2). This avalanche released on 2 March at 17:00 h – one day after the radar had indicated full penetration of melt water.

4. CONCLUSIONS

We installed an upward-looking ground-penetrating radar system (upGPR) in the vicinity of a well-known wet-snow avalanche path. At the same time, we recorded the avalanche activity by observing the avalanche path with time-lapse photography. We showed that it is possible to operate a solar-powered radar system in a remote site under harsh conditions. The system is protected against avalanche impact and snow creep.

Following the signature representing the transition from dry to wet snow, we successfully monitored the advance of percolating water. Concurrent wet-snow avalanche activity tended to be high when the water penetrated deeper into the snowpack. Avalanches released when the wetting of the snow reached the bottom of the snowpack. This correspondence suggests that improving the prediction of wet-snow avalanche activity with the help of remotely operating upGPR systems buried in representative starting zones might be feasible.

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