

Front and internal velocity distribution in powder snow avalanches

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ABSTRACT: Accurate velocity measurements of avalanches are essential for testing simulation tools and for performing risk mitigating studies. However, the flow of avalanches is complicated and not described by one unique velocity. In particular frontal approach velocities may not be representative for the internal flow dynamics. Furthermore measured velocities vary greatly not only with avalanche size and type but also with the instrument used. Optical methods, such as videogrammetry and photogrammetry can provide accurate measurements, but only of the outermost boundary and for large avalanches the inner core of the avalanche is nearly always concealed by a powder cloud. Radar of the appropriate wavelength can penetrate through the overlying cloud and directly measure this inner core, which is usually the most destructive part of the avalanche. In this work we investigate the velocity distribution of the inner avalanche core by combining radar data from two different systems, both installed at the Vallée de la Sionne avalanche test site, in Switzerland. Both systems operate at a frequency of 5-6 GHz which penetrates through the cloud and reflects of dense flow structures or lumps larger than around 50 mm. One radar is a phased array FMCW system, that can track fronts and internal surges with unprecedented spatial resolution but does not directly measure velocities. The other system is a pulsed Doppler system that directly measures velocity distributions in a coarse spatial resolution of around 50 m. By combining the data from both systems we can describe the velocity distribution along the length of the avalanche. Our measurements show that main material velocities in the avalanche head, can reach up to approximately two times the approach velocity.

Key words: avalanche dynamics, radar measurement, velocity, avalanche head dynamics

1. INTRODUCTION

Doppler radar measurements of avalanche velocities have been performed since the 1980s (Salm and Gubler, 1985). Over the years measurement techniques have been improved and pulsed Doppler radar systems have been used to measure the velocity of a moving avalanche along its track (Randeu et al., 1990; Schreiber et al., 2001). A detailed review can be found in Gauer et al. (2007b). Pulsed Doppler radar measurements are non-intrusive and provide information of the velocities of the avalanche body. Measurements have been performed at various test sites including Ryggfjonn (Rgf), Norway (Gauer et al., 2007b,a) and the Vallée de la Sionne (VdIS), Switzerland (Rammer et al., 2007, figure 1). Next generation radar measurement techniques such as phased array frequency modulated continuous wave (FMCW) radar systems provide unprecedented spatial resolution (Vriend



Figure 1: Set up at the Vallée de la Sionne test site with Doppler and GEODAR antennas on the outside of the bunker (l.t.r. Jim McElwaine, Anselm Köhler).

et al., 2013; Ash et al., 2014; Köhler et al., 2016). Measurements have been performed for different avalanche types ranging from small wet snow avalanches up to large powder snow avalanches.

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The goal of this paper is the joint data interpretation utilizing the advantages of two radar systems, creating a combined system, which allows the inves-

tigation of avalanche velocities from a new point of view. To achieve this we compare detailed measurements of frontal approach velocities obtained from GEODAR with Doppler velocity distributions in the avalanche head. The velocity distribution in the foremost part, i.e. the avalanche head, is of particular interest for the flow dynamics and to interpret impact scenarios of the avalanche with obstacles.

2. AVALANCHE PATH AND DATA

On the 3 February 2015 five avalanches were artificially triggered in Vallée de la Sionne (VdS) test site. During the five preceding days nearly 1 m of new snow had fallen on a 1.35 m thick snow-cover which consisted of weakly bonded faceted crystals at the surface and unstable layer of depth hoar on the ground (SLF, 2015).

The weather station “Donin du Jour” (VDS2) at 2390 masl in the close proximity north of the avalanche path showed the prevailing strong westerly winds with peak velocities higher than 40 km/h that loaded the release areas with wind packed snow. The air temperature stayed below -10°C , preventing the consolidation of the cold new snow and resulting in an unstable snow pack.

Avalanche “20150017” was released as the second avalanche that day at 11:45 from the left side of the release area Crête Besse 1 (CH1903: N593273 m, E127655 m, Z2574 m asl).

The avalanche descended through a channel, flowed over cavern B and hit the pylon (≈ 1250 m and 675 m distance to bunker) before stopping in the valley bottom (figure 2). The trajectory was relatively straight and channeled, the radar data is not much biased by laterally flowing structures or curves in the trajectory. The volume of the initial released slab was 15000 m^3 with a average release depth of 1.2 m. Successive entrainment resulted in a total volume of more than 78500 m^3 of flowing snow. The avalanche is classified as large. The head of the avalanche was characterized by several minor surges which consecutively overrun one after each other (Köhler et al., 2016).

3. RADAR DATA

3.1. GEODAR DATA

GEODAR measures the signal intensity $I_G(s, t)$ in terms of distance s and time t . The spatial resolution (0.75 m), coupled with a high temporal resolution (110 Hz) allows the tracking of the avalanche front flow features along the track in high detail (Vriend et al., 2013). The GEODAR intensity is high pass filtered to remove the background signal and then interpreted either as stationary background with low intensity, or moving snow with high intensity. With



Figure 2: VdS avalanche 20150017 impacting the pylon.

this approach the leading edge (fig. 3 green line) of the avalanche and the corresponding avalanche approach velocity v_{ap} (fig. 4 red line) can be determined.

3.2. DOPPLER RADAR DATA

This radar system measures signal intensities $I_D(v, s, t)$ for different velocities v in terms of distance s and time t . The Radar utilizes the Doppler effect to directly measure velocities in discrete range gates of 50 m. It is also possible to derive approach velocities by means of total signal intensities $I_D^{tot}(s, t) = \int I_D(v, s, t) dv$, similarly to the GEODAR. However the main advantage of this system is to evaluate the velocity distribution, representing the avalanche movement.

3.3. COMBINATION OF RADAR SYSTEMS

As a first step we investigate the velocity distribution in the avalanche head, i.e. the first 50 m of the avalanche. In this work this length will be considered constant and referred to as head length l_{head} . It is measured from the foremost tip of the flow towards the tail of the avalanche. To estimate the velocity distribution in the avalanche’s head $I_{head}(v)$ we employ the following tasks:

First a time synchronization is performed by minimizing the differences in arrival times t^* of Doppler and GEODAR for given distances s^* .

Then high accuracy approach velocities v_{ap} are determined in predefined sections (i.e. range gates) of the avalanche path. To do so, the high accuracy

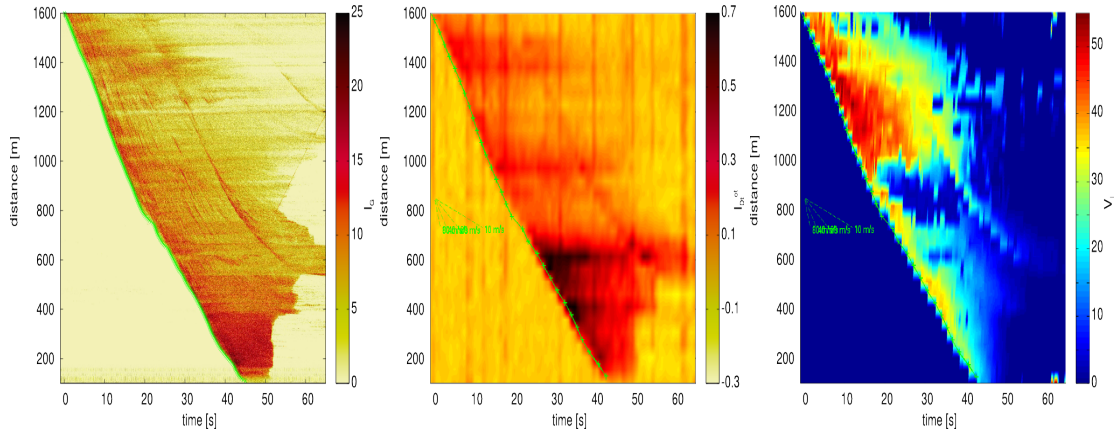


Figure 3: Combined radar data with 50 m Doppler resolution. Space-time radargram data l.t.r.: GEODAR intensity data $I_G(s, t)$, total Doppler intensity data $I_D^{tot}(s, t)$, Doppler velocity of maximum intensity $v_I(s, t)$.

GEODAR position data is utilized to employ the time distance relation $v_{ap} = \frac{s_{exit} - s_{entry}}{t_{exit} - t_{entry}}$, which is an approximation of the derivative of leading edge position with respect to time.

With this knowledge we can estimate the length of the avalanche's head. By utilizing the approach velocity relation $v_{ap} = \frac{l_{head}}{t_{head}}$, the head length (e.g. $l_{head} = 50$ m) can be transformed to the corresponding head time t_{head} , i.e. the time that the first 50 m need to flow past a certain point (e.g. through one range gate) in the avalanche path. With this we can finally determine the velocity distribution in the avalanche head:

$$I_{head}(v) = \int_{s_{entry}}^{s_{exit}} \int_{t_{entry}}^{t_{entry} + t_{head}} I_D(v, s, t) dt ds \quad (1)$$

The knowledge of the velocity distribution in the avalanche head $I_{head}(v)$ gives a definition of the velocity of maximum intensity v_I , i.e. the velocity most of the material is moving with in the first l_{head} m of the avalanche:

$$v_I = I_{head}^{-1}(\max_v(I_{head}(v))). \quad (2)$$

It is further possible to define maximum v_{max} and minimum velocities v_{min} from the distributions (i.e. 5 and 95 % quantiles, interpreting $I_{head}(v)$ in sense of a normalized distribution function). However these values encounter large variabilities due to the chaotic and turbulent nature of the avalanche flow and will not further be analyzed in this work.

The radar systems measure the avalanche velocity component in radar beam direction. Due to the outstanding measurement set up in the VdIS (fig. 1) this direction is mostly aligned with the main avalanche movement. However, for comparison with models it is necessary to convert the velocity to a slope parallel velocity. This can be done by scaling the velocities by $1/\cos \delta$, where δ is the

angle between the talweg and the radar beam. The correction factor for velocities in beam direction on topography following velocities (bottom parallel) ranges between 0.1 and 6.5% for the VdIS path (Fischer et al., 2014). Corrections due to lateral deviations between radar beam and avalanche approach direction are not taken into account in this work.

3.4. VELOCITY ANALYSIS

Figure 4 shows the velocity distribution in the avalanche head ($l_{head} = 50$ m) for VdIS avalanche 20150017. Generally the approach velocities v_{ap} values vary in the range of the material velocity distribution $I(v)$. The ratio of main material velocity v_I to approach velocities v_{ap} varies between -14 % up to +96 %, with an average of +10 %. Areas with a significant difference between main material velocity v_I and approach velocity v_{ap} are highlighted in figure 4 with circles.

Large velocity differences in avalanche 20150017 are found around $s = 500$ – 575 m and 1275 – 1450 m distance (pink areas in figure 4). These intermittent accelerating areas are characterized by high material velocities v_I compared to the corresponding approach velocities v_{ap} (v_I to $v_{ap} \approx 12$ – 31 % and 15 – 33 % larger). This velocity ratio can be interpreted as constant surging behavior in the avalanche head (Köhler et al., 2016). This behavior remains observable until the approach velocities reaches the maximum material velocity and a stopping process is initiated.

Additionally the 20150017 avalanche shows two major stopping surges at 650 – 700 m and 750 – 800 m, compare figure 3 and yellow areas in figure 4. In stopping surges the approach velocity v_{ap} drops drastically (i.e. the front of the avalanche almost

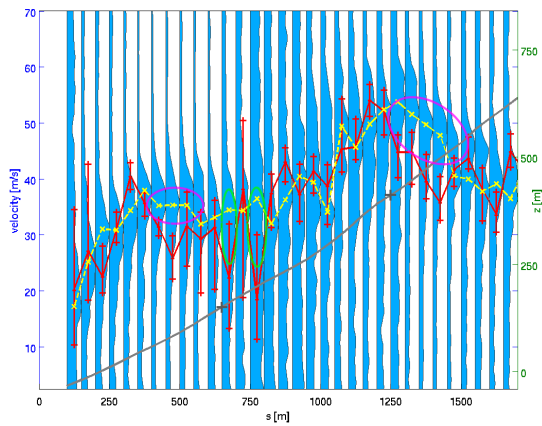


Figure 4: Combined radar data with 50 m Doppler resolution for VdIS avalanche 20150017. Displayed is the avalanche path for orientation with origin at the bunker, approach velocity v_{ap} and velocity distributions $I_{head}(v)$ ($I_{head} = 50$ m) with corresponding main material velocities v_I at different distances, including the correction factor for bottom parallel velocities. Areas where there is a significant difference between main material velocity v_I and approach velocity v_{ap} are marked: accelerating areas in pink and stopping surges in green.

stops), while the material velocities represented by v_I in the 50 m avalanche head stay rather consistent. This leads to material velocities v_I that exceed the avalanche approach velocity v_{ap} by $\approx 54\%$ and 97% respectively. Due to the high material velocities the avalanche does not stop and the stopping surge (accompanied by the drastic drop of the approach velocity) is followed by a relaxation of the approach velocity to the main material velocity, which was previously observed in the avalanche's head.

4. CONCLUSIONS

In this work we investigated the potential of combining different radar systems in order to gain a deeper understanding of avalanche flow dynamics and the respective velocities. A Doppler radar and the GEODAR system were combined and allowed to investigate the differences in approach velocity and the velocity distribution in the avalanche head.

Intermittent accelerating areas and stopping surges showed material velocities of up to two times of the material velocity. The knowledge of this difference is crucial when considering planning of mitigation structures or model testing especially along the avalanche track. Since this investigation represents a first step of the combination of different radar systems several limitations such as the accuracy of approach velocity determination or signal to noise levels at different distances have to be taken into account. Finally one has to note that the investigated velocity ratio represents the main material velocity and thus increases for maximum material velocities, which are significantly higher.

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References

- Ash, M., Brennan, P. V., Keylock, C. J., Vriend, N. M., McElwaine, J. N., and Sovilla, B. (2014). Two-dimensional radar imaging of flowing avalanches. *Cold Regions Science and Technology*, 102:41–51.
- Fischer, J. T., Fromm, R., Gauer, P., and Sovilla, B. (2014). Evaluation of probabilistic snow avalanche simulation ensembles with Doppler radar observations. *Cold Regions Science and Technology*, 97(0):151 – 158.
- Gauer, P., Issler, D., Lied, K., Kristensen, K., Iwe, H., Lied, E., Rammer, L., and Schreiber, H. (2007a). On full-scale avalanche measurements at the Ryggfjonn test site, Norway. *Cold Regions Science and Technology*, 49(1):39–53.
- Gauer, P., Kern, M., Kristensen, K., Lied, K., Rammer, L., and Schreiber, H. (2007b). On pulsed Doppler radar measurements of avalanches and their implication to avalanche dynamics. *Cold Regions Science and Technology*, 50(1):55–71.
- Köhler, A., McElwaine, J. N., and M. Ash, B. S., and Brennan, P. (2016). The dynamics of surges in the 3 February 2015 avalanches in Vallee de la Sionne. *Journal of Geophysical Research: Earth Surface*.
- Rammer, L., Kern, M., Gruber, U., and Tiefenbacher, F. (2007). Comparison of avalanche-velocity measurements by means of pulsed Doppler radar, continuous wave radar and optical methods. *Cold Regions Science and Technology*, 50(1-3):35–54.
- Randeu, W. L., Okorn, R., and Riedler, W. (1990). A pulsed Doppler radar for acquisition of avalanche dynamics. *Proceeding of Conference CIV'90 Avalanches and Planning of Mountain Territory*, 9th–10th October 1990, Arabba (BL), Italy:118–126.
- Salm, B. and Gubler, H. (1985). Measurement and analysis of the motion of dense flow avalanches. *Annals of Glaciology*, 6:26–34.
- Schreiber, H., Randeu, W. L., Schaffhauser, H., and Rammer, L. (2001). Avalanche dynamics measurement by pulsed Doppler radar. *Annals of Glaciology, Vol 32, 2001*, 32:275–280.
- SLF (2015). Weekly Snow and Avalanche Report: 30 January – 5 February 2015. Technical report, WSL Institute for snow and avalanche research SLF, CH–7260 Davos Dorf.
- Vriend, N. M., McElwaine, J. N., Sovilla, B., Keylock, C. J., Ash, M., and Brennan, P. V. (2013). High-resolution radar measurements of snow avalanches. *Geophysical Research Letters*, 40:727–731.