

## AVALANCHE DOPPLER RADAR MONITORING - LONG TERM VELOCITY MEASUREMENTS AT THE VALLÉE DE LA SIONNE

Michael Neuhauser<sup>1,\*</sup>, Andreas Kofler<sup>1</sup>, Anselm Köhler<sup>2</sup>, Helmut Schreiber<sup>3</sup>, Thomas Gigele<sup>1</sup>, Betty Sovilla<sup>2</sup>, Lambert Rammer<sup>1</sup>, Jan-Thomas Fischer<sup>1</sup>

<sup>1</sup>Austrian Research Center for Forest (BFW), Innsbruck, Austria

<sup>2</sup>WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland

<sup>3</sup>Institute of Microwave and Photonic Engineering - University of Technology, Graz, Austria

**ABSTRACT:** In this contribution we present Doppler radar data obtained over multiple years in terms of total radar intensities and material velocities. These give an overview of the avalanche movement and allow characterizing typical avalanche velocities for various avalanche flow regimes. In the data analysis we survey the ratio of frontal approach to material velocities for the observed natural and artificially released avalanches. Measurements from over 40 avalanches, without distinguishing between various types of flow regimes, show that the maximum along the entire path of the main material velocity is on average approximately 5 m/s higher than the maximum frontal approach velocity. Local peak velocities may exceed the maximum of the main material velocity. The knowledge of the different avalanche velocities and their ratio is of major importance for practitioners and engineers since the material velocity, rather than the front velocity, determines the resulting impact pressure on buildings and structures. The presented data are the base for a future online repository. This open source material can be used for the calibration, parameter optimization and further development of avalanche simulation tools and their underlying process models.

**Keywords:** avalanche dynamics, radar measurement, velocity, avalanche head dynamics

### 1. RADAR MEASUREMENTS

Radar measurements have various applications in snow and avalanche research (Gauer et al., 2007a; Rammer et al., 2007; Vriend et al., 2013) and recently developed radar systems, like GEO-DAR (GEOphysical flow dynamics using pulsed Doppler radAR), allow an unprecedented insight in avalanche dynamics (Köhler et al., 2016). They are used as avalanche detection systems and from a scientific point of view they are essential to investigate the dynamics of avalanches from release to deposition (Salm and Gubler, 1985; Ash et al., 2014; Fischer et al., 2014). Radar measurements are particularly important to gather information on powder snow avalanches, which inner denser core is concealed by a powder cloud (Fischer et al., 2016). More specifically, Doppler radar systems measure dynamic characteristics of distributed targets, i.e. spatially and temporally resolved velocities. The major part of the 5-10 GHz radar pulse are caused by the dense flow part of an avalanche with particles larger than 50 mm. Most of the existing avalanche velocity estimates rely on approach velocities by radar or optical methods.

The Doppler radar allows to deduce various velocity measures, which in turn have different potential applications (Ranadu et al., 1990; Schreiber et al., 2001). Most importantly, the **main material velocities**  $v_{max}$ , i.e. the velocity of highest signal intensity, at which most of the avalanching snow moves, can be assessed. This velocity is of highest priority to estimate avalanche impact pressures and potential damages. Furthermore the **frontal approach velocity**  $v_{ap}$  of the avalanche front can be determined, which allows to deduce arrival times of potential avalanches.

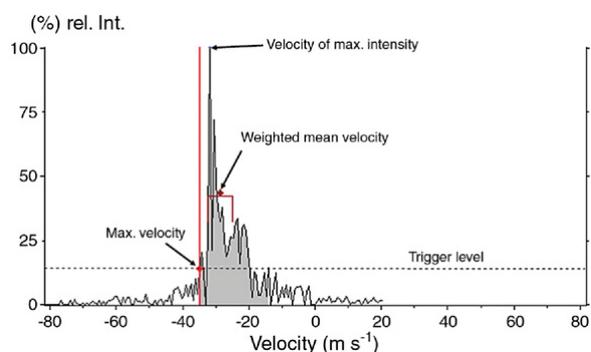


Figure 1: Example of a velocity spectrum (from Gauer et al., 2007b).

\*Corresponding author address:  
Michael Johannes Neuhauser,  
Austrian Research Center for Forest,  
Rennweg 1, 6020 Innsbruck, Austria;  
tel: +43 (0)512-573933-5123  
email: Michael.Neuhauser@bfw.gv.at

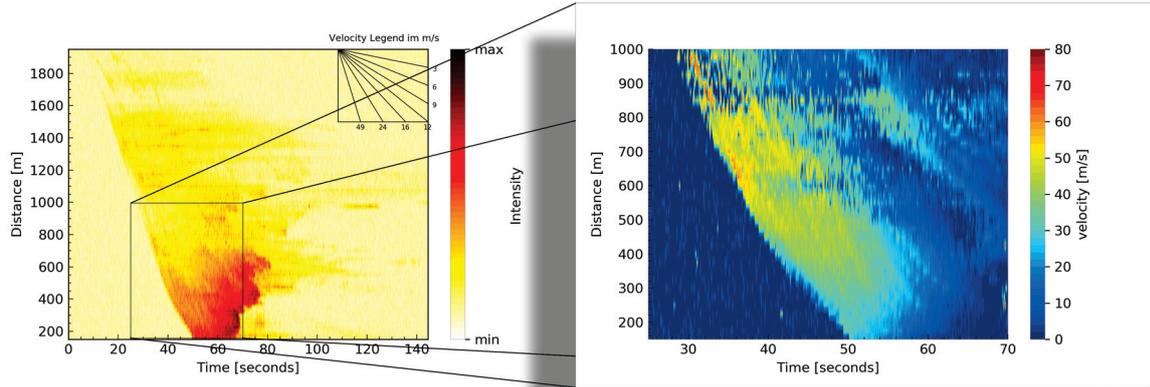


Figure 2: Avalanche 20163017. The left panel shows the avalanche Intensity  $I_{ava}$  over time and distance, with clear difference between avalanche signal (reddish colours) and noise (yellow). The right panel shows a close up of Doppler velocity of maximum intensity, with a maximum velocity of 60 m/s.

## 2. TEST SITE

We present Doppler radar measurements performed at the Vallée de la Sionne test site in Switzerland. From 1999 to 2010, a Doppler radar with a spatial resolution of 50 m was used to detect artificially released avalanches during field measurement campaigns. Since 2010, a triggering system ensures that the radar and later on a Doppler radar, with an improved spatial resolution of 25 m, continuously monitor the avalanche activity at the site. With these radars 79 natural and artificially released avalanches have been measured. The destructive sizes of the avalanches range from d2 to d4 (CAA, 2016).

## 3. MTI PLOTS

The Doppler radar system measures signal intensities  $I_D(v, s, t)$  for different velocities in terms of distance  $s$  and time  $t$ . The radar utilizes the Doppler effect to directly measure velocities in discrete range gates of 25 m or 50 m, depending on the used radar system.

Figure (1) shows an example of such a velocity distribution. According to Gauer et al. (2007b) there are three important velocities that can be deduced from the velocity distribution for each time step and range gate: the velocity of maximum intensity, the maximum velocity and the weighted mean velocity. In this paper we focus on the maximum intensity velocity as a measure for the main material velocity.

The signal intensity decreases with distance. To compare intensities over distance they are normalized, by dividing them through the maximum intensity of the respective distribution.

From the intensity distribution we determine the total signal intensities,  $I_D^{tot} = \int I_D(v, s, t) dv$  (Fischer

et al., 2016). With a first normalization by the maximum intensity the total normalized signal intensities  $\tilde{I}$  are low for distributions with clear velocity peaks and high for noisy signals, that include a broad variety of velocities, e.g. the background scatter.

$$\tilde{I} = \int \frac{I_D(v, s, t)}{I_{D,max}(v, s, t)} dv$$

To maximize the signal contrast for each individual avalanche we introduce the avalanche intensity  $I_{ava}$ . Which is the total signal in Mfgtensity normalized to the range of intensities for this particular avalanche, in the range from 0 to 1.

$$I_{ava} = \frac{\tilde{I}(t, s) - \tilde{I}_{min}(t, s)}{\tilde{I}_{max}(t, s) - \tilde{I}_{min}(t, s)}$$

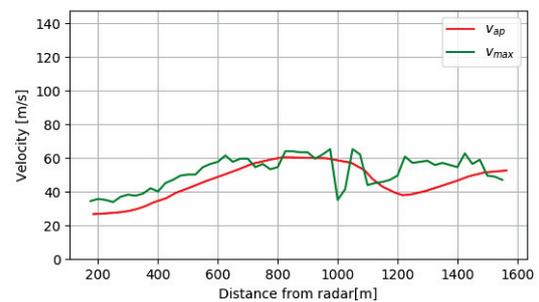


Figure 3: Velocity distribution in the head of avalanche 20163017. The main material velocity  $v_{max}$  reaches the maximum at 1050 m and the approach velocity  $v_{ap}$  at 780 m distance from the radar.

The disadvantage of this procedure is the loss of signal clearness over distance on the basis of the smaller difference between signal and background scatter. Plotting the total intensities over time and

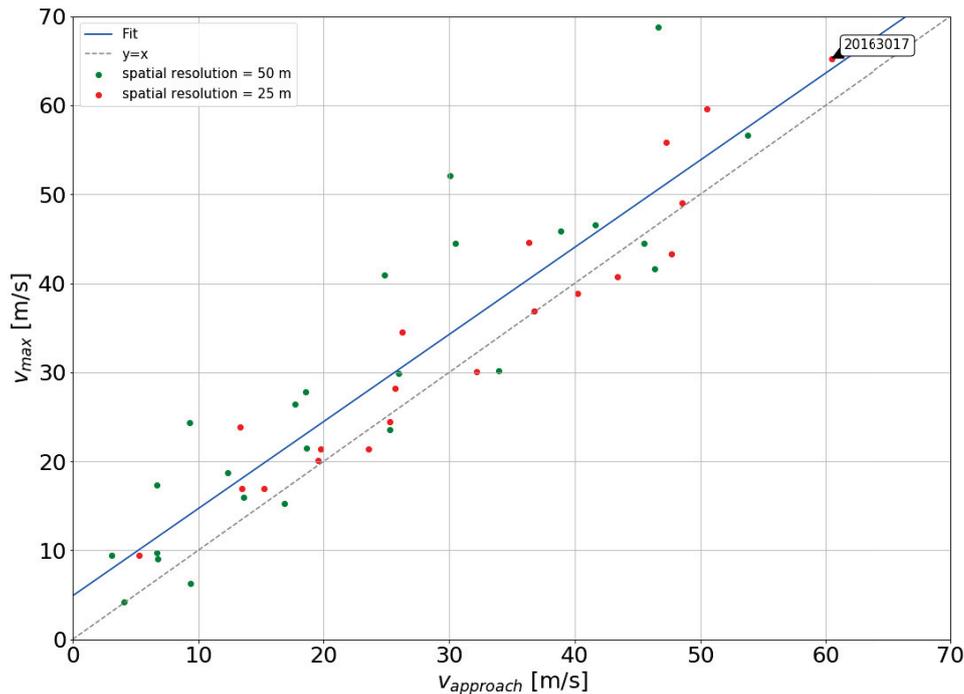


Figure 4: Comparison of the maximum values of frontal approach velocity  $v_{ap}$  and main material velocity  $v_{max}$  along the entire avalanche, for 45 avalanches from 1999 to 2018. Avalanche 20163017 is marked and fits well into the linear regression, relating frontal approach and material velocities with  $v_{max} \approx v_{ap} * 1 + 5$  m/s. Measurements with a spatial resolution of 50 m and 25 m are marked in green and in red.

distance leads to a similar result as the MTI Geodard plots (moving target indication, Köhler et al. 2016). Figure (2) shows total signal intensities for avalanche 20163017. Detailed information on this particular avalanche<sup>1</sup> is available in (Köhler et al., 2016). In the left part of fig. (2) one can clearly identify the front of the avalanche, approaching through time and space. The space time plot allows to estimate approach velocities as the gradient of the front:  $v_{ap} = \frac{s_{t_0} - s_{t_1}}{t_1 - t_0}$  (compare velocity legend in fig. (2)).

An identifiable avalanche front signal can be observed 16 seconds after the trigger, with a distance of 1600 m from the radar and it flows till 150 m corresponding to a time of 50 s.

The radar measures velocity components in radar beam direction. To correct them to a slope parallel velocities, they have to be scaled with  $1/\cos \delta$ , where  $\delta$  is the angle between the talweg and the radar beam. For the Vallée de la Sionne path and measurement setup this correction factor is between 0.1 and 6.5% (Fischer et al., 2014).

#### 4. HEAD VELOCITIES

The avalanche head is the region behind the front, where the highest velocities are located. For simplicity here we assume the length of this region to be  $l_{head} = 100$  m. By utilizing the approach velocity relation  $v_{ap} = \frac{l_{head}}{t_{head}}$ , the head length can be transformed to the corresponding head time  $t_{head}$ , which is the time the head needs to flow through a certain region in the avalanche path (Fischer et al., 2016). To determine the maximal, main material velocity, we survey this time range behind the front.

The velocities for avalanche 20163017, are presented in fig. (3). Between 1500 and 1100 m the main material velocity is much higher than the approach velocity and reaches the maximum at 1050 m. As a result the fast material behind the front is overtaking the front. As a result the approach velocity increases from 1200 to 900 m and reaches the maximum of around 60 m/s at 780 m from the radar.

#### 5. RESULTS & CONCLUSION

The intensity and velocity distributions allow a detailed but also complex analysis of the avalanche dynamic behaviour. For this work we concentrate on

<sup>1</sup><https://www.youtube.com/watch?v=ZCFQP60AHFk>

two relevant quantities: the maximum of the frontal approach and the main material velocity in the head, over the entire avalanche.

From the 79 detected avalanches 45 have high intensity signals that allow a detailed signal processing. Figure (4) shows 45 avalanches from Vallée de la Sionne, including maximum approach and material velocities from 1999 to 2018.

Over the years two different radar systems were used, with different spatial resolutions, marked in red and green. The frontal approach velocities  $v_{ap}$  are in the range between 3.0 - 53.8 m/s and the associated main material velocities  $v_{max}$  in a range between 4.0 - 68.7 m/s.

It is important to note, that the radar recognizes all material velocities in a certain range gate, while the frontal approach velocity is a mean value over the spatial resolution of the radar. Thus, there is always material moving faster than the main material velocity. For the investigated Vallée de la Sionne avalanches the mean difference between  $v_{max}$  and  $v_{ap}$  is  $\approx 5$  m/s. However local peaks of material velocities may exceed the corresponding main material and frontal approach velocity by 100 % (Fischer et al., 2016). The main limitation of this analysis is that the data includes various flow regimes with different flowing behaviour and stopping signatures (Köhler et al., 2018). To better understand the differences of these regimes a clustered analysis for flow regime and avalanche size would be desirable.

However, as most of the existing velocity estimates rely on front velocities, it is of major importance to know the correlation and deviations of frontal approach and the main material velocities. These are of major importance for to estimate impact pressures and to supply data for model validation.

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## 6. APPENDIX - DATA & REPOSITORY

For every detected avalanche a MTI Plot and a HDF5 file is available. Also the velocity of the maximum intensity, the front and the mask (= region of interest) are stored in this file. These files are the base for a future online repository. This open source material can be used for the calibration, parameter optimization and further development of avalanche simulation tools and their underlying process models.

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