COMPARISON OF MEASURED AND SIMULATED SNOW AVALANCHE VELOCITIES

Philipp Jörg[1,2], Matthias Granig[2], Yves Bühler[3], Helmut Schreiber[4]

ABSTRACT

Velocity measurements by means of videogrammetry and pulsed Doppler radar at two selected snow avalanche events are analysed and compared with avalanche simulations. At the test site Vallée de la Sionne (Switzerland) an artificially triggered avalanche was filmed by two synchronised digital video cameras to obtain the front velocity of the avalanche. At the monitoring site Grimming/Multereck (Austria) a spontaneous avalanche was measured by the radar system of the Technical University Graz, which provides valuable velocity records along the avalanche path. The analysis showed that the peak velocity of the simulations within the avalanche track is about 5 m/s lower than observed. However, in the run out zone the measured and calculated values show good correspondence. For this study it was important to apply only the standard parameters to check the level of agreement with the practical application. The objective of this paper is to study the progression of avalanche velocities with the avalanche models SamosAT and ELBA+ in comparison to the field measurements.

Keywords: SamosAT, ELBA+, snow avalanche simulation, pulsed Doppler radar, avalanche velocity

INTRODUCTION

The destructive force of an avalanche is derived from the density and velocity of the flow regime. Since the flow density represents an uncertain parameter, the measurement of the avalanche speed on real-scale test sites has an increased significance. An overview of various velocity measurements in the past is given in Gauer et al. (2007). In contrast to photo or videogrammetry, a pulsed Doppler radar also works in poor weather conditions (fog, snowfall) or during the night. The radar has to be positioned in the endangered valley bottom such that it is in line with the moving direction of the avalanche. While pulsed Doppler radar only provides one-dimensional velocity information along a defined profile, the output of videogrammetry (georeferenced frontlines) provides the lateral spreading of the avalanche. Another advantage is its flexible usage and the straightforward setup of the cameras, located at a safe position on the opposite slope.

In the 1960's high speed stereophotogrammetry has been used to map dense flow avalanche run out and velocities (Kahn, 1966; Brioukhanov, 1968). With the development of affordable digital cameras with high frame rates, this technique was applied in avalanche research. Measurements of front velocities were carried out in Vallée de la Sionne (VdlS) using two or three synchronized photo or video cameras (Vallet et. al, 2001; Vallet et. al, 2004; Wicki and Laranjeiro, 2007; Thibert, 2011; Bartelt et. al, 2012).

The first usage of pulsed Doppler radar dates back to 1990, where the velocity of several avalanches has been analysed (Randeu et. al, 1990; Schaffhauser and Okorn, 1990). From that time on the technique has been optimised and the spatial resolution increased.

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In the framework of the EU-Project SAME (1996-1998) the use of an additional frequency enabled the discrimination of dense flow and powder part velocity (Schreiber et. al, 2001; Gauer et. al, 2007; Rammer et. al, 2007). For scientific purposes this dual frequency setup was used on several test sites.

PRINCIPLE OF VELOCITY MEASUREMENTS AND SIMULATION MODELS

Videogrammetry

The artificially triggered avalanche #917 in VdlS (see next section) was captured with two video cameras from the opposite slope. The position of the cameras was determined by differential global positioning system (DGNSS) measurements to an accuracy of 5 cm. The synchronisation of the cameras to an accuracy of 1/50 s was performed by a vocal signal, transmitted by a small VHF radio. After the artificial release the avalanche was filmed with a frame rate of 25 images/s. In intervals of 5s image pairs were extracted from the film footage, where the lines of the actual avalanche front were determined manually. The georeferenced frontlines plotted in Fig. 3 were provided by the avalanche dynamics group of the WSL Institute for Snow and Avalanche Research SLF. A detailed description of video processing, image orientation, etc. is reported in the following papers: Vallet et. al, 2001; Vallet et. al, 2004; Wicki and Laranjeiro, 2007; Bartelt et al., 2012.

Pulsed Doppler radar

At the monitoring site Grimming the pulsed Doppler radar runs with a single frequency at 5.82 GHz, using two antennas for capturing the lower and upper part of the steep slope. The major part of the signal, which corresponds to a wavelength of 5.2 cm, is reflected by the dense flow part of an avalanche. A short description of this technique is reported in Gauer et al. (2007):
“A pulsed Doppler radar emits short pulses of electromagnetic waves having a constant signal frequency and samples the echo in distinct time intervals corresponding to distance intervals (range gates). In the case of an avalanche, frequency analysis of the echo signals, exploiting the Doppler effect, i.e. the apparent frequency shift of the reflected radar signal due to the motion of the targets relative to the radar, yields a velocity distribution/spectrum within the width (volume) covered by a range gate (in the direction of the radar beam). The measured velocity, of a single target is directly proportional to the frequency shift of the radar signal.“ The range-gate principle is shown in Fig. 1.

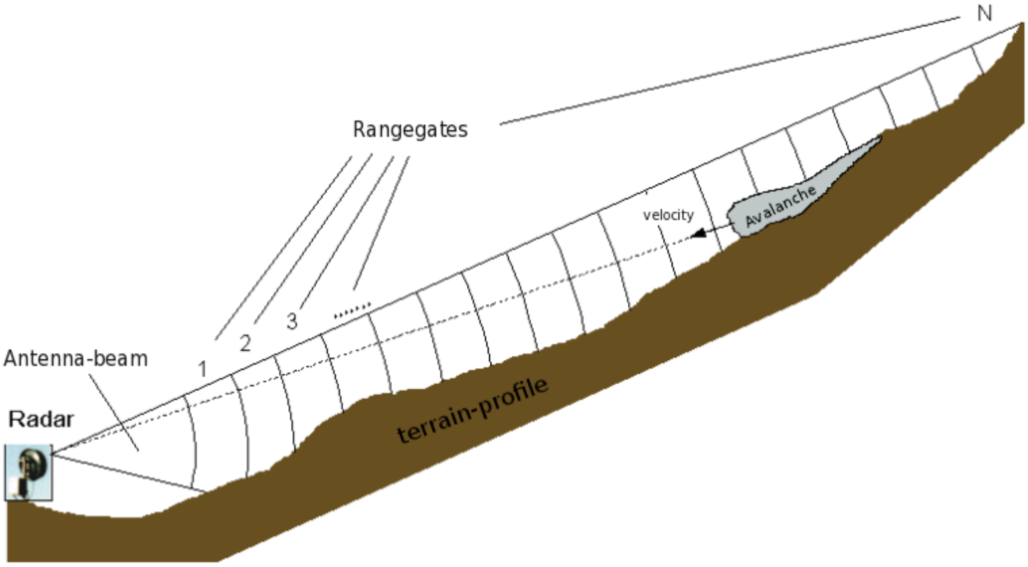

Fig. 1 The principle of range-gating (resolution=50 m) of a pulsed Doppler radar (© Schreiber).

The main purpose of the radar system in Grimming is the detection of moving snow mass exceeding a certain velocity-threshold in the release zone of the Grimming/Multereck avalanche. If this happens, the subjacent road is closed by a light signalling system. However, the avalanche radar also gives insight into the spatial and temporal evolution of the avalanche's velocity and dynamics, also making it a valuable tool for avalanche researchers. The velocity analysis of the avalanche event on 17 March 2010 was carried out by the Institute of Microwave and Photonic Engineering (Technical University Graz, Austria). Starting with the raw echo Doppler spectra a derivation of different display formats (dependency on time and/or range) was realised, using the INW avalanche software (Schreiber, 2011). Fig. 2 visualises the whole avalanche event in a time-range-diagram, where on x-axis the time [s] and on y-axis the distance from radar [m] is displayed. The colours belong to the avalanche speed [m/s] in the respective time and distance (range gate). In simple terms the avalanche reaches from the top left to bottom right, where the green tail marks the run out of the avalanche.

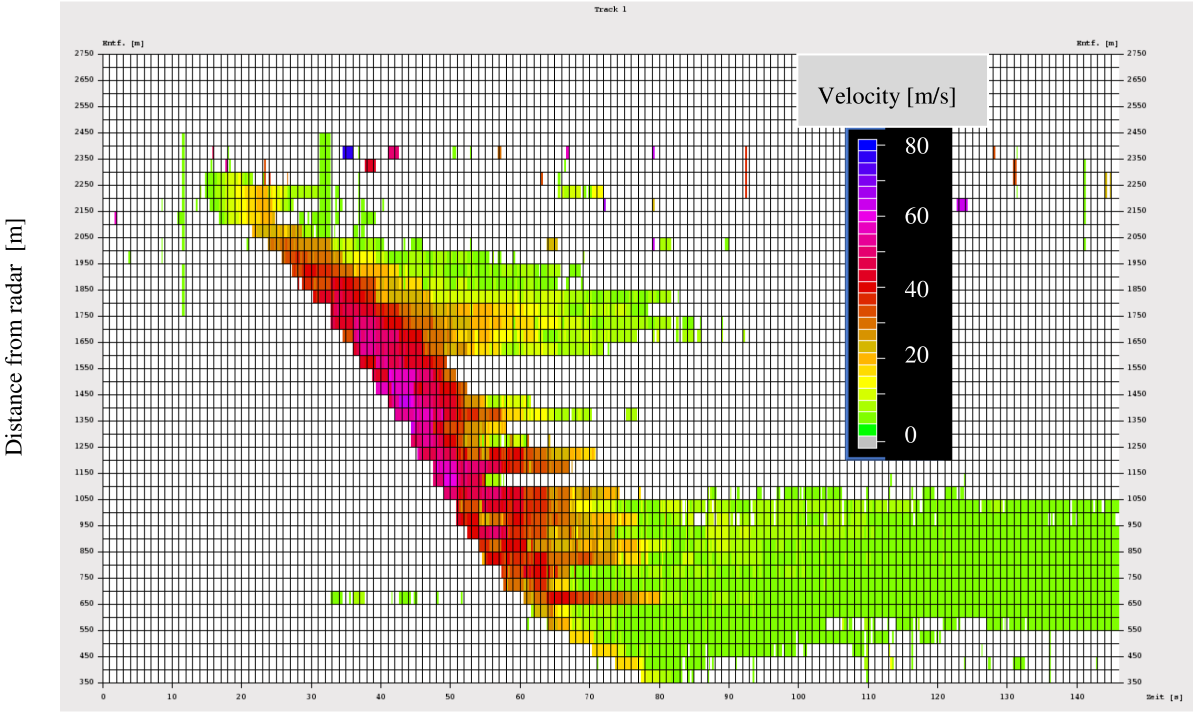

Fig. 2 Time-range-diagram of the Grimming/Multereck-avalanche on 17 March 2010 (© Schreiber).

Simulation models

In SamosAT and ELBA+ the dense flow layer is modelled as shallow flow in two dimensions on the terrain surface. The dense flow layer is divided into a large number of small mass elements, where the depth-averaged mass- and momentum-balances are solved for each of it. The bottom shear stress is based on a so-called Voellmy-fluid, i.e. a combination of Coulomb-friction and a turbulent friction term (Sampl, 2007; Volk, 2005).

In SamosAT numerical particles, moving with the flowing mass, are used for the numerical solution (Lagrangean formulation). A smoothed-particle hydrodynamics (SPH) method is used to calculate the flow depth at the numerical particles. For the SamosAT simulations in this work snow entrainment is considered along the dense flow layer front (Sampl and Granig, 2009).

In ELBA+ a non-moving (Eulerian) grid is used, where the model equations are solved with a finite difference scheme. The avalanche movement is divided in a starting, flowing and deposition phase, where different friction terms are considered (variable friction regime). In ELBA+ snow entrainment happens only if the normal stress at the terrain surface exeeds a certain threshold (Volk, 2005).

AVALANCHE EVENTS AND RESULTS

Vallée de la Sionne – Avalanche #917 on 26 March 2008 (12:45)

The real-scale test site in VdlS, Canton Valais, Switzerland has been operational since 1997/1998. Natural and artificially released avalanches are investigated at the test site with a vertical drop of approximately 1200 m and a horizontal distance of about 2250 m. Detailed descriptions of the VdlS test site and its various measurement devices is given in Issler (1999, 2003), Sovilla et al. (2006a,b), Gauer et al. (2007) Rammer et al. (2007) and Sovilla et al. (2008a,b). The following information concerning the weather conditions in the days before and the dimension of the release area of this artificially triggered avalanche are reported in Kern et al. (2010):

"A significant snowfall had accumulated about 0.8 m of new snow in the release zone of the avalanche track. This was followed by some minor snow accumulations, the most important in the late evening of 24 March which added 0.2 m of new snow. The week before the artificial release on 26 March, the temperature had been about -10 °C in the release zone (subject to diurnal fluctuations) and the speed of the westerly wind had been moderate, not exceeding 9 m/s. At the time of artificial release (12:45), the temperature in the release area was about -3 °C after a significant temperature rise from -12 °C in the morning. The weather was sunny and there were weak easterly winds with speeds below 2 m/s. The ~400 m long fracture was about 1 m high and was composed of two subsequent 0.5 m high fractures." Fig. 3 gives an overview of avalanche #917 on 26 March 2008. With the help of a photo, provided by WSL Institute for Snow and Avalanche Research SLF, the extent of the release area and the run out of the dense flow part were estimated. The position of the avalanche front at 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 64 s is plotted in Fig. 3 and a profile along the track was defined.

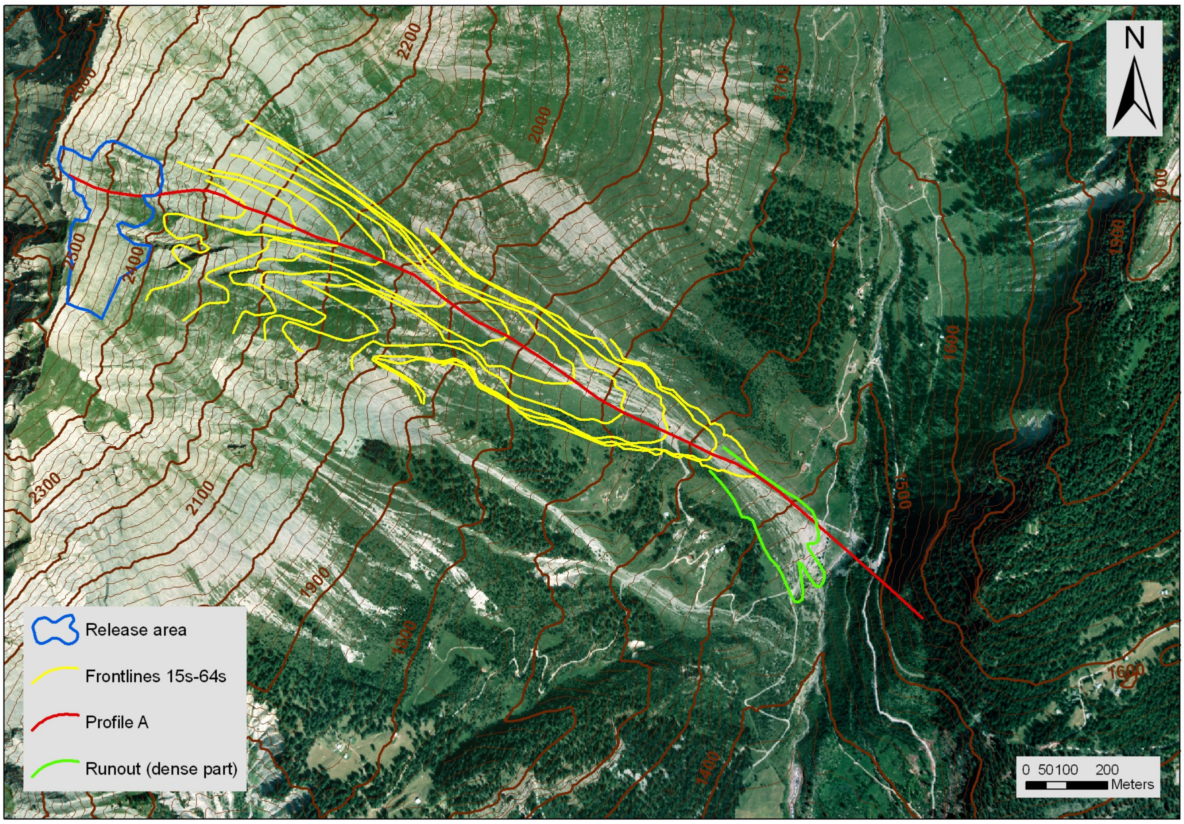

Fig. 3 Vallée de la Sionne: Avalanche #917 with release area, frontlines, profile and run out (Aerial imagery ©swisstopo - DV033492.2).

For analysis of the velocity the three-dimensional distance (between the frontlines) along profile A was calculated and divided by the corresponding time interval. The result is plotted in Fig. 4, where the error bars indicate an accuracy of +/- 5 m/s. The significant acceleration in the last time step is probably caused by the powder part of the avalanche, overrunning the dense flow regime.

Using the models SamosAT and ELBA+, simulations were carried out with a release depth of 1.0 m (Kern et. al, 2010), leading to a release cubature of 85.000 m³. The dense flow simulations were calculated with and without entrainment, in which the estimation of 0.2 m was taken from Bartelt et al. (2012). In this publication, a comparison of measured speeds of two avalanche events in VdlS versus the peak velocity modelled by the numerical simulation tool of the SLF, RAMMS (Christen et al., 2010) is given. Generally the peak velocity of the calculations without entrainment presents lower values (Fig. 4). Especially in the model ELBA+ using entrainment is a crucial point to achieve realistic velocities in the avalanche track. All in all the SamosAT calculation with entrainment shows the best agreement with the video measurements. The significance of snow entrainment in avalanche modelling is also discussed in the following papers: Sovilla and Bartelt, 2002; Gauer and Issler, 2004; Sovilla et al., 2006a,b.

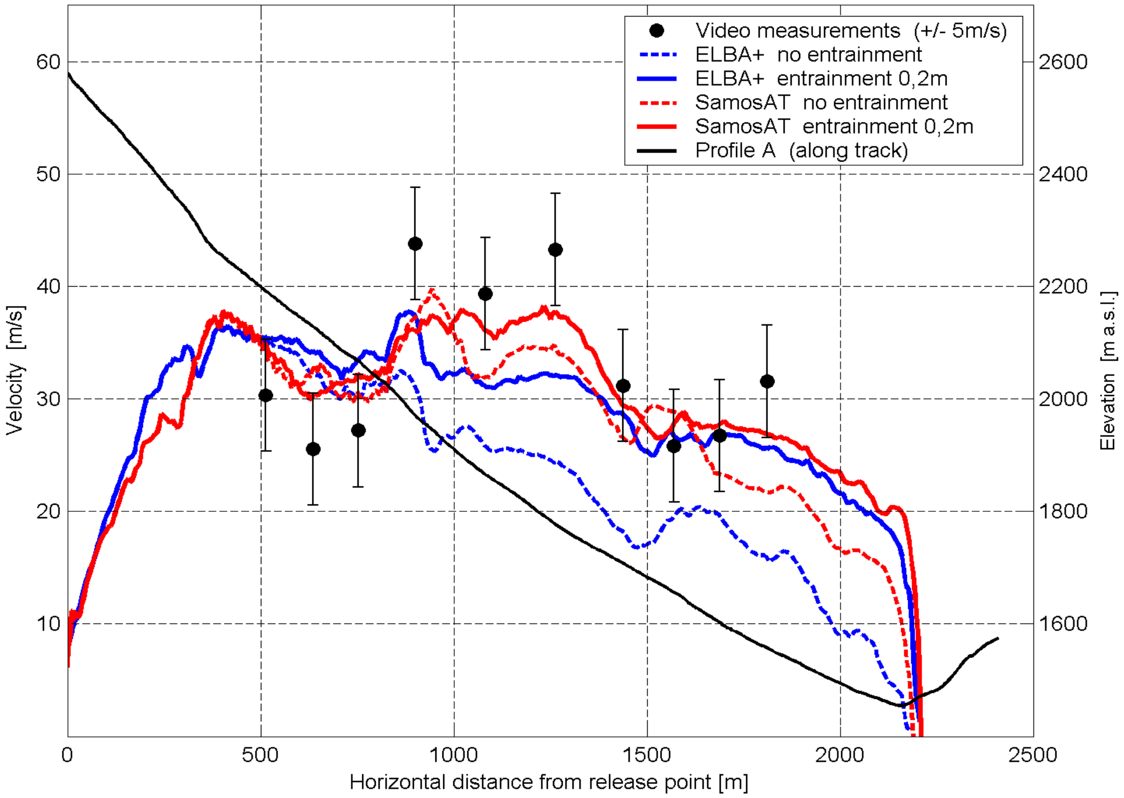

Fig. 4 VdlS -Aval.#917: Front velocity of video measurements vs. peak velocity in simulation models.

Grimming/Multereck-Avalanche on 17 March 2010 (07:13)

A snowfall during a 5-day period had accumulated about 1.1 m new snow at the automatic weather station Multereck (2159 m a.s.l.) in the vicinity of the avalanche path, accompanied by south-westerly winds with moderate speed up to 12 m/s. The temperature in this period was in the range of -8 to -4 °C at the nearby station Tauplitz (1762 m a.s.l.), showing a slight increase (data provided by ZAMG). In the morning of 17 March a spontaneous avalanche occurred on the steep north-eastern slope captured by the pulsed Doppler radar. Analysing the time-diagrams, the first signal of moving snow mass was detected in range gate 36-39, which corresponds to an elevation of 1740-1870 m. With the help of a photo and a mapping of the slope the width of the release areas were estimated.

In Fig. 5 the upper release areas 1 and 2 are displayed. A detailed analysis of radar-data reveals a second echo in the range gate 32-34 (1570-1700 m a.s.l.), indicating the triggering of a secondary release zone. More precisely in this range gates two clearly separated spectral components were observed, with different temporal development. While the velocity of the first remains constant, the second component exhibits acceleration. The secondary release area 3 was placed in the orographic left gully of the avalanche path (Fig. 5). The upper release mass is split on a ridge in 1600 m a.s.l., flowing together in a gully at 1200 m a.s.l. with a final run out on an alluvial cone. The "Salzkammergut-" federal road below is partly secured by means of a tunnel. At the southern end of the tunnel an unprotected bridge section exists. To reduce the remaining risk an avalanche monitoring and warning system has been developed by the Institute of Microwave and Photonic Engineering in (Technical University Graz, Austria), using a pulsed Doppler radar as its central element.

The analysis of the front velocity along profile B is fixed by the arrival time of the avalanche in each range gate. Within a range gate (length=50 m) the speed is calculated with high resolution using the INW avalanche software (Schreiber, 2011). Therefore the measured velocity is corrected by the deviation of the velocity-vector along the profile to the radar axis. The velocity analysis of the radar echo starts below release area 1 in an elevation of 1734 m (Fig. 6). A short peak at 1450 m a.s.l. is visible, due to a vertical drop of 50 m along the track. The highest velocity is reached at 1200 m a.s.l., where the orographic left and right avalanche meets like in a bottleneck. The model calculations SamosAT and ELBA+ were executed using the release areas 1,2 and 3 (Fig. 5), with an estimated release depth of 1.0 m, leading to a cubature of 51.000 m³. The dense flow simulations were calculated with and without snow entrainment along the track. The process of triggering a secondary release area, mentioned in the radar analysis above, was realised in the SamosAT model. In ELBA+ this possibility is not implemented, so the release areas 1,2 and 3 were triggered synchronously. In SamosAT the velocity maximum at the bottleneck at 1200 m a.s.l. is better represented, than in ELBA+. Whereas in the simulation model ELBA+ the lower release area runs ahead, the following release mass from release zone 1 and 2 collide at this point, leading to a strong deceleration of the avalanche. In the calculation of SamosAT the lower release area is triggered by the avalanche coming from above, resulting in a concentration of mass and high velocities in the orographic left avalanche track. All in all the correct simulation of this avalanche seems to be a “timing” problem. Generally the peak velocity of the simulations without entrainment displays lower values (Fig. 6). Especially in the model ELBA+ using entrainment is an important point to achieve reliable velocities in the avalanche track.

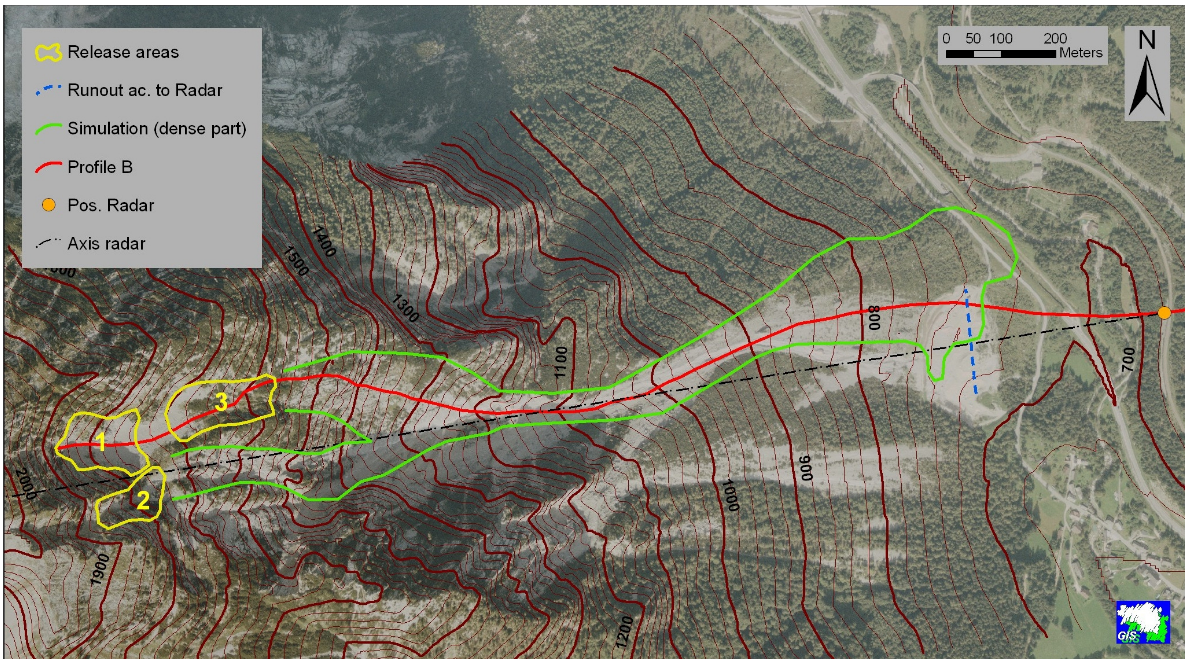

Fig. 5 Overview of the monitoring and warning test site Grimming/Multereck (© GIS Steiermark).

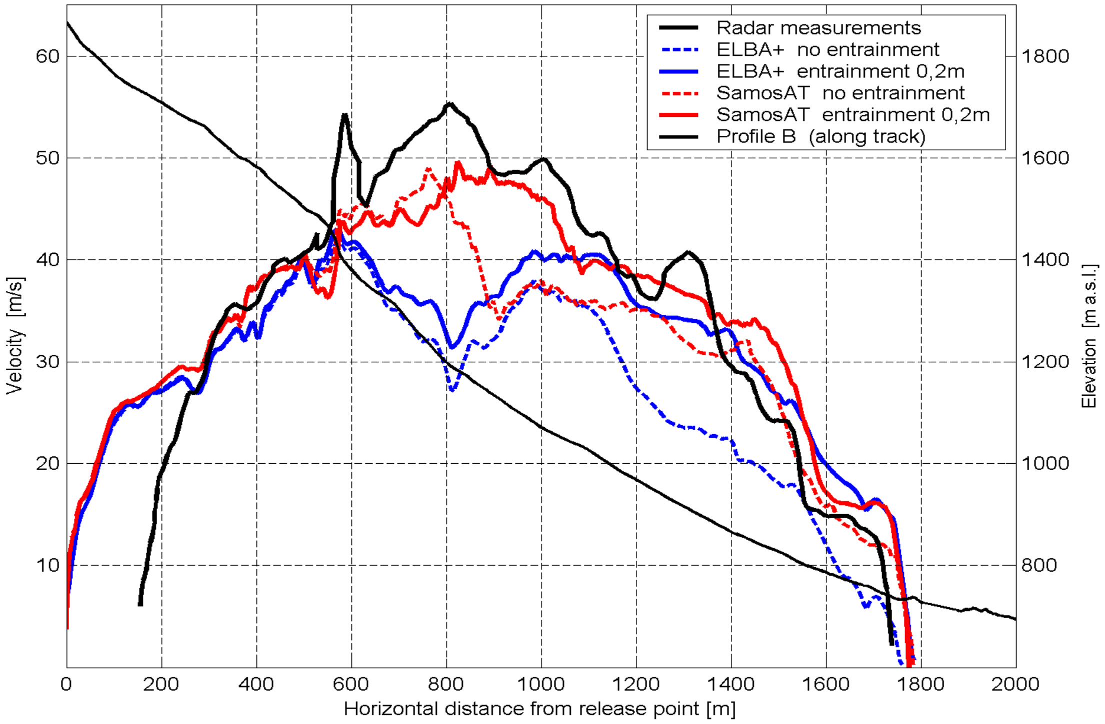

Fig. 6 Grimming/Multereck (17.03.2010): Avalanche speed of radar measurements versus peak velocity in simulation models.

DISCUSSION OF THE RESULTS

The comparison between measured and modelled avalanche velocities provides crucial feedback regarding the behaviour of the employed simulations. Besides the avalanche velocity the density is the main parameter for the determination of avalanche pressure, which is the deciding criterion in hazard zone mapping. The comparison of measured avalanche speed either with photogrammetric methods or with radar gives the possibility to analyse the simulation results along the surveyed avalanche tracks. Many papers have already been published describing the measurements in VdlS. For the first time within this research the models ELBA+ and SamosAT were checked with measured avalanche velocities. Sailer et al. (2002) has done a recalculation of avalanche velocities from VdlS and Ryggfon with the previous model Samos99, as well as a rough analysis with a prototype of the SamosAT software in 2006. However, since then the model was further developed (Sampl, 2009; Jörg and Granig, 2010), implying that a new evaluation became necessary. The ELBA+ model is checked for the first time with real avalanche velocities along the avalanche path.

An important point for this study was to use the standard model parameters and the usual calculation methods according to the program handbooks (Volk, 2005; Sampl, 2007) to compare the velocity of the measurement with the regular calculation as applied in the practical modelling for hazard mapping. The estimation of the total avalanche mass contains an uncertainty factor, but this could be minimised by checking snow height measurements from nearby weather stations, the use of the radar information regarding the extent and by checking the available documentations like photos or local expertise. Finally for both avalanche events 0.2 m of snow entrainment was applied, which is an usual value in the practical application.

For this paper the two avalanche events from VdlS #917 and Grimming/Multereck (17.03.2010) were reconstructed and analysed. In this approach it could be shown that the calculations provide a result, very similar to the measurements. The analysis of the VdlS path showed that to 2050 m a.s.l. the simulation was about 5 m/s higher than observed. In the track region between 2050 m and 1700 m the calculated avalanche does not accelerate as strongly as observed (see Fig. 4). The measurements further downhill correspond with the simulation results until the last measurement point at 1550 m a.s.l.. A possible explanation for the discrepancy in the upper track regions is that the avalanche entrains more than 0.2 m, slowing the avalanche down somewhat. At the elevation of 2000 m a.s.l. the avalanche reaches a gully, which leads to an increased speed (bottle neck effect). In contrast at the elevation of 1750 m a.s.l. the more flat terrain results in a deceleration of the speed (Fig. 4). These steps are less distinct in the simulations without entrainment. In general these simulations without additional snow showed a difference of about 3-8 m/s in lower avalanche speed.

The Grimming/Multereck avalanche event on 17 March 2010 was a medium size avalanche with 51.000 m³. The radar system from the Technical University Graz detected and surveyed the avalanche continuously along the whole path (Fig. 6). The measurement displayed certain peaks and troughs, which are explained above. Apart from these variations, the model calculations especially by SamosAT with entrainment correspond very well to the radar data. Between 1450 m a.s.l. and 980 m a.s.l. the ELBA+ model does not conform to the measurement, which can be explained by the missing secondary release area. Also without entrainment the simulated velocities are about 5-8 m/s lower. The definition and location of the avalanche profile is a crucial point in the interpretation of the radar measurement, which contains a certain level of error. Though these results give information about the reliability of the simulations along a certain avalanche path.

CONCLUSIONS

So far it was assumed that the ELBA+ model calculates lower avalanche velocities along the avalanche track. The two analysed avalanche events showed that the calculated velocities are in the order of magnitude of 3-6 m/s lower or fit well to the measurements depending on the location. In the run out zone it seems that the calculations tend to a better accordance with the measurements, which is important for the hazard mapping. This occurs, because most of the calibration data was derived from the run out zones, hence the models are more reliable in these areas.

In general the SamosAT model shows somewhat higher velocities than ELBA+. Though lower than the peak measurement of about 2-4 m/s, which is already within the error of the measurement itself. It can be shown that it is essential to include snow entrainment in the simulations; otherwise the results would differ up to 10 m/s, especially in the run out. This emphasises the need to optimise the application of the entrainment modules to achieve a higher accuracy for a certain avalanche event.

Both models worked properly only with additional snow entrainment of 0.2 m, which is usually applied in modelling for practical application. In general it is very difficult to estimate the total amount of potential entrainment mass along a certain avalanche track in advance (Sovilla et al., 2006a,b). Taking a mean average snow entrainment of 0.2-0.3 m is a discussible empirical approach. It appears that entrainment depths are not constant along the track and can influence the evolution of avalanche velocity as mass fluxes control the avalanche flow regime (Bartelt et al., 2012). Further evaluations of real scale measurements on different observation sites will improve the fundamental knowledge of avalanches, which enables a better modelling of this alpine hazard.

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