OBJECTIVE COMPARISON OF TWO TO THREE DIMENSIONAL AVALANCHE MODEL OUTPUT AND FIELD DATA USING THE AIMEC APPROACH

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ABSTRACT: In recent years two to three dimensional avalanche simulation tools have gained importance to estimate the hazard. The models are optimized to determine run out distances of avalanches. However, technically dynamic models feature more information such as the spatiotemporal evolution of flow depth and velocity in the avalanche path that can be used to plan protection measures. In this work Doppler radar measurements from the Ryggfonn (N) test site are compared to the output of the two to three dimensional simulation model SamosAT applying the AIMEC (Automated Indicator based Model Evaluation and Comparison) approach. This approach allows an objective comparison and evaluation of the two dimensional output of geophysical flow models. A data transformation allows to compare the maximum velocities in the model to velocities obtained by Doppler radar measurements along the path. Mass balance recordings and mapped avalanche outlines are used to provide input scenarios. It is shown that the AIMEC approach is an ideal tool for the evaluation and comparison of complex model outputs and thus it can be used to improve the calibration procedure of two to three dimensional simulation software.

Key words: snow, avalanche, dynamics, modeling, doppler radar, velocity

1. INTRODUCTION

There are different approaches to obtain information of a avalanching snow moving down slope. On the one hand measurements are performed to directly determine avalanche characteristics of single events in the field. On the other hand computational software is used to simulate avalanches.

Radar measurements have been performed in order to measure avalanche velocities since the 1980-ies (Salm and Gubler, 1985). Over the years measurement techniques have been improved and pulsed radar systems have been used to measure the Doppler frequency of a moving avalanche (Schreiber et al., 2001). A detailed review can be found in Gauer et al. (2007b). Radar measurements are non-intrusive and provide information of the velocities of the avalanche body. Measurements have been performed at various test sites including Ryggfonn (Rgf), Norway (Gauer et al., 2007a,c; Rammer et al., 2007). Although measurements have been performed for some time now,

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the amount of available high quality data is still limited. The measured avalanche types range from small wet flow avalanches up to large powder snow avalanches.

Modern simulation software is based on flow models working in three dimensional terrain. A geographic information system (GIS) environment is used to handle data input, output and visualization providing an intuitive way of data handling. Here we use the snow avalanche simulation software SamosAT (**S**now **A**valanche **MO**delling and **S**imulation - **A**dvanced **T**echnology, Zwinger et al. (2003); Sampl and Zwinger (2004); Sampl and Granig (2009)). The underlying flow model describes the spatiotemporal evolution of the main flow variables, such as flow depth and slope parallel velocities in two space dimensions.

Evaluations of two dimensional computational results have mainly been done by back calculations for single events and have been performed manually (Sailer et al., 2002; Issler et al., 2005). Multidimensional simulation results along the avalanche path has mainly been evaluated in cross sections along a predefined path profile (Pirulli and Sorbino, 2008; Christen et al., 2010; Buehler et al., 2011; Mergili et al., 2012).

Simulation software results are available in a global Cartesian coordinate system. Unfortunately the Doppler radar data is provided in spherical coordinates with the origin at the radar antenna and only the velocity component in radar direction is measured. A comprehensive method, evaluating the two dimensional velocity results of multiple simulation runs with respect to the corresponding measurement coordinate system is lacking. For this purpose the **A**utomated **I**ndicator based **M**odel **E**valuation and **C**omparsion - **AIMEC** (Fischer, 2012) has been extended. With this approach we intend to evaluate the simulation software results by:

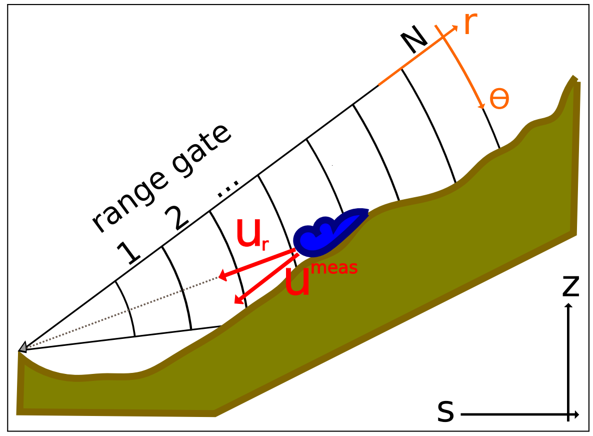

Figure 1: Vertical cross section of the radar coordinate system for fixed ϕ. The avalanche's velocity is measured in radar direction $u_r(s)$ and has to be processed to a bottom parallel velocity $u^{meas}(s)$.

- taking into account variations in the input,
- analyzing the simulation results with respect to the measurement coordinate system.

In this paper we describe a new method how to process both, measurement data and two dimensional simulation results such that they can technically be compared. One examples at the Rgf test site are utilized demonstrate the new method and highlight the limitations of comparing measurements to simulations. An offset indicator is introduced which reflects the ratio of simulated to measured velocities.

2. DOPPLER RADAR DATA

The Doppler radar is operating at a frequency of $5.8\,\mathrm{GHz}$ which allows to detect the motion of snow particles above $0.05\,\mathrm{m}$ diameter. In an avalanche, snow clods of this size usually constitute the so-called fluidized (saltation) layer as well as the dense flowing part (Gauer et al., 2008). Clods that are much smaller will not be detected. Hence, echo signals of the 5.8 GHz radar will meanly originate from within the fluidized layer or the upper surface of the dense flow (Gauer et al., 2007b).

The output of Doppler radar measurements is a time series of intensity spectra. Different types of velocities can be derived from this spectra, such as velocity of the maximum signal intensity, maximum velocity, mean velocity or front velocities. The velocity of maximum intensity is a measure for the bulk velocity which is computed in simulation software (Gauer et al., 2007b).

The measurements are performed with respect to the radar coordinate system. In figure 1 the vertical cross section of the radar measurement set up is shown. The spherical range gate shells intersect with the mountain profile $z(s)$. The radial r distance dependent measurements can be projected on the plane coordinate s.

The velocity component is measured in radar beam direction $u_r(s)$ while the avalanche moves with the bottom parallel *measurement* velocity component

$$u^{meas}(s) = u_r \cos\zeta(s), \tag{1}$$

where ζ is the deviation angle between $u_r(s)$ and $u^{meas}(s)$ in the range gate.

3. SIMULATION RESULTS

Avalanche simulations are performed with the simulation software SamosAT. It consists of two basic models, a dense flow avalanche (DFA) model and a powder snow avalanche (PSA) model in order to describe the descent of dry mixed snow avalanches (Sampl, 1999; Zwinger et al., 2003; Sampl and Zwinger, 2004; Sampl and Granig, 2009). In this study the SamosAT DFA model is used. The DFA is modeled as a shallow flow in two dimensions along the mountain surface. The depth averaged model equations for shallow flow include a modified

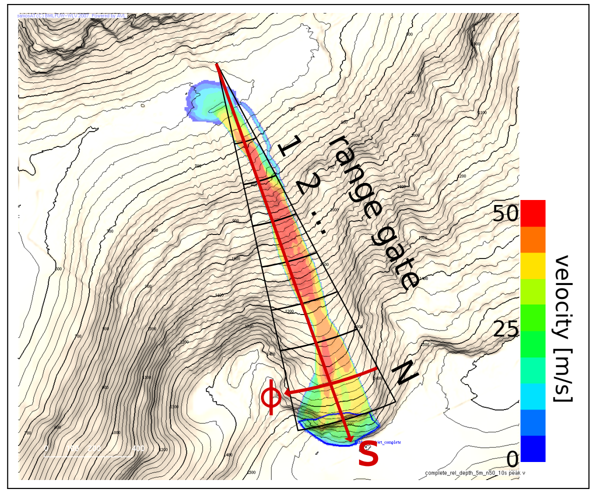

Figure 2: Peak velocity results of a reference simulation at Rgf (Colours indicate velocity values (blue=0 m/s to red=50 m/s)) superimposed by the radar measurement domain for an antenna opening angle of $30°$. 3 dB opening angles of commonly used radar antennas are in the range of $9-15°$.

bottom friction relation (Sampl and Granig, 2009). The standard calibration values (Granig and Oberndorfer, 2008), which are optimized for snow avalanches of a 150 year return period, are used.

The main outputs of the avalanche simulation are flow depth and slope parallel, depth averaged velocities $h(x, y, t)$, $\mathbf{u}(x, y, t)$ at a constant density ρ. x, y denote the two dimensional Cartesian coordinates, commonly used in GIS applications to determine locations on the surface of the Earth. The peak velocity corresponds to the maximum over time of the two dimensional velocity field,

$$u(x, y) = \max_t\{|\mathbf{u}(x, y, t)|\}. \tag{2}$$

The computational results are available in a discrete x, y Cartesian coordinate system (Fischer, 2012). However, the related Doppler radar measurements are provided in spherical coordinates with the origin at the radar antenna (figure 2).

Table 1: Release area and depth information for the investigated Ryggfonn avalanche.

number/data	A_{rel} $[10^3\ \mathrm{m}^2]$	d_{rel}^{range} [m]
17.04.1997	11.8	1-2.5

Input data for the simulation (DEM, release areas, release depth (range)) is obtained related field measurements. In table 1 the release conditions (inclined release area size A_{rel} and the release depth d_{rel} range normal to the surface) are summarized for the investigated avalanche event. In order to account for the uncertainty of the release depth we perform multiple simulation runs with a continuously increasing (5 cm release depth step size) for each example. For the comparison the average peak velocity $u^{sim}(x, y)$ over the performed simulation runs is taken.

To obtain velocities which are comparable to the field measurements $u^{meas}(s)$, the two dimensional peak velocity results $u^{sim}(x, y)$ need to be processed. Thus a transformation from the Cartesian simulation coordinate system to the polar radar coordinate system is performed. In figure 2 the Rgf top view with peak velocity simulation results superimposed with a coordinate system s, ϕ representing the measurement domain of a virtual radar at the actual radar measurement position is shown. In order to obtain the simulation results in a radar relevant framework a discrete data transformation to a coordinate with projected horizontal coordinate s in longitudinal direction and cross coordinate ϕ:

$$u^{sim}(x, y) \to \tilde{u}^{sim}(s, \phi) \tag{3}$$

is performed. For simplicity the ˜ are dropped in the following. Based on the peak velocity field (equation 2) the maximum in lateral direction ϕ of the peak velocity for each point s of the avalanche path is defined as

$$u^{sim}(s) = \max_{\phi}\{u^{sim}(s, \phi)\}. \tag{4}$$

With this the simulated velocities $u^{sim}(s)$ are available in the same spherical shells that are provided by the range gate volumes of the measurement data $u^{meas}(s)$. By taking the maximum over the lateral coordinate ϕ we achieve comparability to the Doppler radar data.

4. METHOD OF COMPARISON

After the pre-processing simulated and measured avalanche velocities ($u^{sim}(s)$ and $u^{meas}(s)$) are available with respect to the same coordinates and can be compared. To this end we assume that peak velocities of maximum intensity, measured by the Doppler radar correspond the peak velocities of the snow avalanche simulation.

In figure 3 the velocity comparison of the avalanche event is shown. The red line shows the velocities u^{meas} derived from the Doppler radar measurement data. The blue line shows the averaged simulation velocity u^{sim}. The velocity results of the single simulation runs with increasing release depth are displayed from green to yellow. The profile of the central radar measurement line $z(s)$ is shown for orientation on the right ordinate.

In order to have a scalar velocity comparison measure we define the offset indicators $\Delta_n = \frac{u_n^{sim}}{u_n^{meas}} - 1$ for each range gate $n = 1, \ldots, N$.

Its average

$$\Delta = \frac{1}{N} \sum_{n=1}^{N} \Delta_n, \tag{5}$$

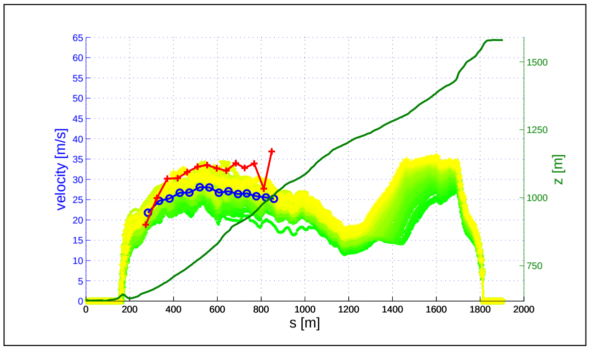

Figure 3: Velocities of processed radar measurement data $u^{meas}(s)$ (red), simulated velocities in radar coordinate system for increasing release depth (green to yellow), averaged simulation run results $u^{sim}(s)$ (blue) for the Rgf 1997 event. The profile of the central radar measurement line is shown for orientation on the right ordinate.

represents a offset indicator for area along the path where measurements exist. The value represents the velocity deviation when comparing the simulation to the measurement. $\Delta \times 100$ represents the percentage of underestimated velocities (negative signs) or overestimated velocities (positive signs).

Its standard deviation

$$\sigma_\Delta = \left(\frac{1}{N-1} \sum_{n=1}^{K} (\Delta_n - \Delta)^2 \right)^{1/2}, \; n = 1, \dots, N, \qquad (6)$$

is a measure how well the shape of the spatial evolution of peak velocities fits.

5. DISCUSSION AND CONCLUSIONS

A new method to compare measured Doppler radar data and two dimensional simulation results was introduced. The method was applied to an avalanche event at Ryggfonn. Numerous simulation runs were executed with variations of the input data. In figure 3 the analysis results are displayed. Table 2 shows the corresponding mean velocities and offset indicator values for each investigated avalanche events.

Table 2: Offset indicator table. $\bar{u}$ represents the average velocities.

number/data	$\bar{u}^{sim}$ [m/s]	$\bar{u}^{meas}$ [m/s]	$\Delta \pm \sigma_\Delta$
17.04.1997	26.04	30.95	-0.14 ± 0.111

The velocities of the simulation software were slightly lower than the ones derived by the Doppler radar measurements ($-14\,\%$ on average). The offset indicators standard deviation is a good representation for how well the form of the spatial velocity evolution fits.

Interpreting the results and offset estimates some limitations have to be considered. The computed offset indicator is the average value in the area were both, simulation results and radar measurements exist. In figure 3 it can be observed that the avalanches deceleration phase is initialized while the simulation results show rather continuous velocities. Furthermore the simulation runs are performed using physical parameters optimized to reproduce snow avalanches with a 150 year return period while the measurements include different types and return periods of avalanches. Additionally the velocity results of the simulation model represent a dry mixed depth averaged bulk velocity while the Doppler radar data represent velocities of a certain flow regime (top of dense part/fluidized layer).

Nevertheless, the offset indicator gives an valuable estimate of a comprehensive evaluation of simulation results. The extended AIMEC approach is a suitable tool to evaluate simulation results with field measurements in a technically comprehensive way and thus it can be used to improve the calibration procedure of two to three dimensional simulation software.

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