Measurements and modelling of snow avalanche speeds

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ABSTRACT Particle speed distributions in artificially released dense flow avalanches from start to stop have been measured using oversnow vehicle based X-band microwave doppler radars. Frequency-modulated continuous-wave X-band radars buried in the avalanche tracks provide localized flow height and slope-perpendicular particle speed profile recordings. So far, measurements on 20 avalanches have been performed. Avalanche sizes varied from a few hundred to several tens of thousand cubic meters of snow, total drop height from release to runout from 150 m to 1000 m. Most avalanches were channeled at least in their middle part. The results show the following trends: The frontal speed of an avalanche increases with increasing size of the avalanche body. Transfer of avalanche snow from the avalanche body to the avalanche tail portion is highly effected by track roughness. If the body portion disappears, the avalanche front speed decreases rapidly and avalanches stop even at high slope angles. The relative velocities of particles in the flow increase with flow speed. The slope rectangular particle speed profile is roughly exponential. Computer modeling has been started, based on Haff’s concepts for granular flows. An attempt is made to clearly separate material parameters from topographic and track roughness parameters.

Mesures et modélisation des vitesses d’avalanches

l'avalance s'arrête, même sur des pentes raides. Les vitesses relatives des particules augmentent avec la vitesse de l'écoulement. Le profil de vitesse perpendiculaire à la pente est exponentiel. On a commencé des modélisations par ordinateur sur la base des idées de Haff concernant des écoulements granulaires. On cherche à séparer clairement les paramètres de la neige de ceux qui sont influencés par la topographie et la rugosité du terrain.

INTRODUCTION

The modeling of dense flow avalanches has to be improved to meet the requirements of hazard mapping for land use purposes. Detailed measurements in natural avalanches have been started several years ago in Canada (McClung, 1983), in Norway (Bakkehol, 1983), in France (Eybert-Bénard 1978), in Switzerland (Salm and Gubler, 1983) and are planned in Japan. These experiments measure frontal speeds, pressures, and seismic signals of avalanches with fixed installations in given tracks. To further refine our knowledge of the physics of flowing snow, nonlocalized flow velocity measurements as well as at least localized flow depth and slope-perpendicular flow velocity profile measurements are needed. The oversnow vehicle-based microwave doppler radars allow records of flow velocities in the front, the body and the tail portion of the avalanche, even if a snow dust cloud inhibits the optical view on the flowing portion of the avalanche. To be able to distinguish between the influence of snow quality from the influence of track geometry on the flow mechanism, the measuring system can quickly be relocated from one track to another, to take measurements on the same day, of similar snow conditions but different track geometries. The results are used to test and calibrate traditional models and to develop new models.

MEASUREMENT AND ANALYSES OF FLOW SPEED

The microwave reflectivity of dry snow (1 - 30 GHz) is dominated by specular reflection for nearly perpendicular incidence and by volume scattering for incidence angles deviating more than some 10° from perpendicular incidence. Volume scattering in homogeneous dry snow is very low penetrability equals hundreds of wavelengths. Avalanche snow consists of a mixture of snow chunks and fine grained snow. Debris size and surface roughness often have characteristic lengths comparable to the wave length of X-band radars (0.03 m). The refractive index of dry snow is about 1.3 ($\rho$= 350 kg/m$^3$). For wet snow the real part of the refractive index may be significantly higher depending on wetness, but also absorption increases drastically with increasing wetness. Targets of this type (Mie to optical scattering range) have reflectivities which are roughly constant for a wide range of incidence angles with backscatter coefficients of the order of -10dB to +10dB. Backscatter from snowparticles suspended in air (dust cloud) is smaller because of the much smaller particle radii and the low particle number-density.
Continuous-wave doppler radar allows to measure the distribution of the velocity components of the snow chunks in direction to the radar antennas within the microwave illuminated part of the avalanche. The range of illumination is restricted by the footprint of the radar (footprint is the area covered by the radar beam) and the microwave penetration depth in granular snow. The penetration depth in granular snow depends on grain or block size and grain number-density as well as grain density, and is limited to a few tens of wavelengths in dry snow and a few wavelengths in wet snow. For the five doppler systems in use, the radar beam-perpendicular footprint diameters at a distance of 1 km vary between 30 m and 130 m (-3dB limit). The doppler coefficient for X-band radars is roughly 70 Hz/m*s. The basic time period between independent samples is 125 ms, but is increased by an averaging process to reduce noise to 500 ms. A more detailed description of the doppler measuring technique is given in Salm and Gubler (1985).

Depth of the avalanche flow is measured locally by FMCW X-band radars buried in the ground under the avalanche track, looking upward rectangular to the flow direction through the static part of the snow cover below the sliding plane and through the moving avalanche snow above the sliding surface. The radars measure electromagnetic distances between the ground surface, the sliding layer and moving snow particles with a basic time resolution of 25 ms. The distance resolution is limited to about 0.1 m. More information on the use of FMCW radars in snow and avalanche research is given in Gubler (1984).

A combination of two synchronized FMCW radars, buried about 10 m apart in flow direction, is used to measure a mean particle speed profile perpendicular to the flow. By cross-correlating time series of reflected power from a given height in the flow measured by the two radars, the time of flow of particles between the two radars can be calculated. The estimated error in the speed determination is 2 - 5 m/s. This type of measurement is based on the assumption that the internal structure of the avalanche does not significantly change within the distance of the two radars, which is equivalent to the assumption that the fluctuation speed of the larger particles in the flow (particles with diameters at least comparable with the wavelength) is much smaller than the corresponding flow speed.

TEST SITES

The test sites are on the Lukmanier Pass (1600 m.a.s.l.). This north-south connection is closed during winter time because the road is endangered by many large avalanches with drop heights of 600 to 1200 m and track lengths up to 2.2 km. Some of these avalanches run several times per winter. Many are channeled at least in their middle part. For the measurements, the avalanches are released artificially, using mortars.

RESULTS

The basic results of doppler measurements are speed spectra. Each radar channel produces a time series of spectra. The interpretation
FIG. 1 Part of a time series for speed spectra measured with a high resolution radar, and corresponding characteristic speeds as a function of time for a small avalanche.

FIG. 2 Part of time series of speed spectra of a very large avalanche measured with a wide beam-angle radar.
of the spectra depends on the footprint and on the penetration depth of the radar. Narrow-beam radars deliver time series of speed distributions of an avalanche moving through a given location defined by the relatively small footprint. The variation of the flow speeds from the front to the tail are recorded as the avalanche moves through the location. The shape of the spectra depend on the type of avalanche. Small slab avalanches (consisting mainly of block flow), low speed sliding avalanches and sheet flows in runouts produce fairly narrow, almost symmetric spectral lines. High speed avalanches are characterized by wider spectra which often show a sharp cutoff at the high speed end followed by a wide asymmetric peak toward lower speeds and long tails often reaching down to zero speeds. These spectra correspond roughly to what is expected if a flow with an exponential flow speed profile is probed at a low incidence angle with a radar having a penetration depth which is of the same order of magnitude as the characteristic length of the speed profile and flowdepth. Comparison of direct front speed measurements (time of front flow between two footprints) with corresponding particle speed distributions show that the avalanche front speed corresponds to some 30 to 100 % amplitude value of the spectral high speed cutoff (characteristic speed). Because this high frequency cutoff is steep, the inaccuracy for the front flow speed determination is less than 10 %. As long as a significant section immediately behind the front moves at about front speed (existence of an avalanche body), the highest particle speeds of the avalanche are measured near the front. In the tail portion of the avalanche, speed decreases almost linearly with time. Some typical speed spectra and time series plots of characteristic speeds are shown in Fig.1. It can clearly be seen from time series analyses in all avalanches that snow is transferred from the body to the tail portion, decreasing body length and very likely flow height at a rate depending on track roughness. As soon as the body disappears completely, the avalanche front speed starts to decrease significantly and the avalanche often stops at slope angles above 25°. Wide angle antennas deliver a combination of target speeds occurring in a large fraction of the track. As long as the avalanche front does not deaccelerate significantly the characteristic speed of these spectra still corresponds to the front speed. A typical example of spectra as given in Fig.2.

Fig.3 shows that there is a significant trend for smaller avalanches to move at lower speeds. So far we have only one reliable slope perpendicular speed profile measurement. Even in this case the avalanche was small. The size of the dry avalanche is estimated to a few hundred cubic meters, total drop height was about 600 m. The speed profile was measured in the lower part of the channeled track. The avalanche width is only about 10 m. The flow height at the measuring site was between 0.4 m and 1 m. We were able to calculate cross-correlations at 5 levels (in 0.15 m steps) in the flow. The result is shown in Fig.4 and has to be compared with the doppler particle speed and stop watch front speed measurements:

- slope angle at measuring site: 35°
- distance between radars: 16.8 m
- front speed (dust cloud!): 20 m/s measured with stop watch.
FIG. 3 Maximum speed of dense flowing dry snow avalanches as a function of size, for channeled avalanches at comparable slope angles.

FIG. 4 Flow speed profile measured with localized FMCW-radar.
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max. particle speed measured with doppler radar 25 - 26 m/s
characteristic speed 20 - 23 m/s
surface speed measured in profile 23 m/s
mean speed from profile 20 m/s

The characteristic length of the exponential fit of the speed profile is 0.1 m. The time series for the top two levels showed a very low number density of targets. It looks as if a few clods of snow were ejected from the flow by a small step in the track just above the upper radar. The upper radar also showed a significantly higher flow height for the beginning part of the avalanche.

In several other cases we were able to perform only 1 to 2 cross correlations over the whole flow depth. In all cases we found good correspondence between profile and doppler speed evaluation.

SUMMARY OF CONCLUSIONS FROM THE MEASUREMENTS

- The front velocity of dense flow avalanches depends on the size of the avalanche body (section of avalanche with constant flow velocity and flow height immediately behind the front).
- The amount of transfer of avalanche snow from the avalanche head and body to the avalanche tail is important for the development of the flow.
- The front flow velocity starts to decrease rapidly if the avalanche body disappears completely. This effect may stop an avalanche even in steep terrain (slope angles above 25°).
- High track roughness increases the snow transfer from body to tail.
- The highest particle velocities are found immediately behind the front in the avalanche head.
- In the avalanche tail, the characteristic particle speed in a fixed cross section decreases almost linearly with time.
- The relative velocities of particles (width of velocity spectral line) in the avalanche head and body increase with increasing characteristic speed and avalanche size. This is interpreted as an increase of fluctuation speed of larger clods of snow.
- In almost all cases we measured very high particle accelerations in the starting phase. There are indications that the acceleration is higher or the acceleration phase is longer for medium hard slabs than for soft slabs.
- At least for small avalanches, snow temperatures near the melting point result in lower flow speeds, lower particle relative velocities and very long avalanches without typical head and body structures.
FIG. 5 Friction coefficients for Voellmy type models, as a function of avalanche size.
- At high snow temperatures larger avalanches tend to solidify in the runout and to move as flexible bodies pushed by the snow behind.

CALIBRATION OF TRADITIONAL VOELLMY-TYPE MODELS

Because we continuously record flow speeds from start to stop of dense flow avalanches, a direct calibration of three-parameter models (2 friction coefficients, 1 size parameter) is possible for each avalanche occurrence. The traditionally used friction coefficients (Buser and Frutiger 1980) tend to predict speeds slower than measured, for large avalanches. We found that the dry friction and the turbulent friction coefficient depend on avalanche size, both decreasing with increasing size. To stop high speed avalanches within the measured runout distance, dry friction coefficients have to be drastically increased in the runout zone ($\mu = 0.3 - 0.5$ compared to $0.15 - 0.3$ for the track). The results are given in Fig.5.

MODELING DENSE FLOW AVALANCHES AS GRANULAR FLOWS

Basic assumptions

The idea of modeling flowing snow as a granular material was introduced by Scheiwiller (1982) and Salm and Gubler (1985). We follow here Haff’s (1983) concept. For a more detailed presentation refer to the above mentioned literature. The constituent grains have each to be dispersed from their neighbors that transmission of energy and momentum is mediated principally through binary collisions. To analyze viscous stresses and pressure, two quantities are introduced; the fluctuation velocity \( v \), which is the rms velocity that would be measured in a reference frame traveling along with the flow, and the mean free path \( s \). The mean free path is assumed to be small compared to the mean grain diameter \( d \), so that the grain number density remains approximately constant throughout the flow. The dissipative loss of kinetic energy \( E \) per inelastic binary collision, \( \Delta E/E \propto (1-e^2) \) (\( e \): coefficient of restitution) should remain small, or the typical decay length \( \lambda \) for the fluctuation velocity has to be large compared to \( d \).

\[
\frac{\lambda}{d} = (1-e^2)^{-1/2} > 1
\]

The following relationships can be deduced from Haff’s theory

\[
\frac{du}{dy} \approx \frac{\sigma_s}{p_s} \frac{1}{d} \frac{1}{v} \quad u(y): \text{flow velocity at height } y \text{ in the flow}
\]

\( p_s \): fluctuation pressure
\( \sigma_s \): shear stress in fluidized material
Collisional energy dissipation is

\[ I \propto (1-e^{-2}) \rho \frac{v^2}{s} \]  

(2)

The fluctuation speed profile is assumed to be exponential with its maximum at the sliding interface

\[ v(y) = v_0 e^{-y/\lambda} \]  

(3)

Similarly, in agreement with measurements, an exponential flow speed profile is assumed:

\[ u(y) = u_0 (1-\exp(-y_{pf}/\lambda))^{-1} (1-\exp(-y/\lambda)) \quad \text{for } y \leq y_{pf} \]

and \[ u(y) = u_0 \quad \text{for } y > y_{pf} \]

(4)

\( u_0 \): surface flow speed; 
\( y_{pf} \): lower boundary of plug flow region

For small grains (single ice particles) it is assumed that \( \lambda \gg d \), \( e=1 \). For larger clods of snow consisting of many ice grains in the upper part of the flow, \( \lambda \) is assumed to be of the order of the clod diameter \( d \), the dissipation per binary collision being significant.

Model

The movement of the avalanche body is modeled by calculating the most important types of energy losses. In the release zone the slab is sliding and gradually breaking up into clods of snow and fine grained material. The energy dissipated in the increase of the specific grain and clod surface (breaking of ice bonds between snow grains) is supplied to the grain system as fluctuation energy. The fluctuation energy for the larger clods ( \( \propto v_{OC}^2 \) ) is assumed to be generated by collisions of the clods with the macroscopic terrain roughness characterized by a mean amplitude \( A_R \) and a mean wavenumber \( K_R \).

\[ v_{OC} = A_R K_R U(A_R) \]  

(5)

This increase of fluctuation energy with flowspeed is in good agreement with the observed broadening of the particle speed distribution at increasing characteristic speed. The granulation model is based on the assumption that the probability \( P \) to break a clod into parts is proportional to the exponential

\[ P \propto \exp\left( \frac{\text{effective surface energy increase of particle}}{\text{fluctuation energy of particle}} \right) \]  

(6)
The corresponding rate of increase of surface energy in a volume $L^3$ equals
\[
\dot{\varepsilon}(r) = 4\pi r^2 \frac{(L/2r)^3}{1} \exp\left(-12\sigma/\rho_s r \frac{v_{0C}^2}{v_0}\right) \frac{u(A_R)}{u(0)} \frac{K_s}{2\pi} 
\]

\[\rho_s: \text{snow density} \]
\[\sigma: \text{effective surface free energy, depending on slab hardness:} \]
\[r: \text{mean clod radius} \]
\[1: \text{surface energy increase} \]
\[2: \text{number of fractures} \]
\[3: \text{collision rate at interface} \]

From Mellor's (1977) data on specific disaggregation energies for snow, $\sigma$ can be estimated to be in the range of 0.1 - 10 J/m$^2$. The actual mean clod radius is calculated from the total effective surface energy increase
\[
r(x) = \frac{(2\pi\sigma(L/2)^3)}{\int \varepsilon'(x) \, dx} \]  \quad (8)

$\varepsilon'(x) = \frac{d\varepsilon}{dx}$ is limited to the actual fluctuation energy generated in $x$.

Equating the rate of kinetic energy decrease in the flow with the dissipation rate of the granulation process results in a reduction of flow speed:
\[
u'_1 = \frac{\partial u}{\partial x} = \frac{\sigma}{r(x)} \frac{1}{4} \exp(2\sigma/r(x) \frac{v_{0C}^2}{v_0}) \frac{K_s}{\rho_s} \frac{1}{u_0} F(y_{PF}, A_K, \lambda) \]  \quad (9)

The actual upper boundary of granulation is approximated by
\[
y_{PF} = A_R + \lambda \cdot C_{PF} \frac{v_{0C}^2}{2gh \cos(\alpha)} \]  \quad (10)

$\alpha$: slope angle
$C_{PF}$: coefficient of order 1

The fluidization height for the coarse-grained material increases with increasing fluctuation speed induced at the flow base, and decreases with increasing flow height.

Field observations support the assumption that there is a fine-grained boundary layer at the avalanche bed surface. At the interface we may rewrite equation (1)
\[
\frac{du}{dy} \bigg|_0 = \left(\frac{u(\lambda)}{u_0}\right)^n \frac{u_0}{\lambda} = \frac{\sigma}{p_g} \frac{1}{d} \frac{v_0}{v_0} = \frac{\mu}{d} \frac{v_0}{v_0} \]  \quad (11)

$p_g$: pressure of overburden load
In the model, the following equation is used

\[ v_0 = C \ u_0^n(\lambda) \]  

(12)

\( v_0 \): reference velocity [m/s]
\( C \): \([(m/s)^{1-n}] \), coefficient of order 1 depending on \( \lambda \)

There are indications (Salm, pers. communication) that \( n \) is less than the theoretical value of 1. In model calculations \( n = 0.65 \) proved to be a reasonable choice.

If shear occurs in this boundary layer, the corresponding dissipation retards the flow. The resulting shear friction stress per unit density (Haff, 1983) is

\[ f_s \propto C_s \ v_0 \ u_0 \]  

(13)

\( f_s \): shear friction stress
\( C_s \): coefficient of order 0.005 - 0.01 for snow avalanches

Shear is enabled as soon as the fluctuation pressure of the fine-grained boundary layer material supports the overburden flow. This condition is approximated by weighting \( f_s \) with the ratio of fluctuation pressure to gravitational pressure,

\[ f_s = C_s \ v_0 \ u_0 \ \text{MAX}(1, \frac{0.5 \times v^2}{g \times h \times \cos(\alpha)}) \]  

(14)

In addition, fluctuation energy of the large snow clods in the upper part of the flow is dissipated in binary collisions (eqn. 2). The corresponding flow retardation is

\[ u_2' = \frac{\Delta u}{\Delta x} = \Theta \ \frac{1}{h} \ \frac{1}{\lambda} \ A_R^3 \ R \ u_0 \ F^*(\lambda, A_R, F_P) \]  

(15)

\( \Theta \): [m] equals approx. snow clod diameter
\( d = (0.01 - 0.1) \) m
\( F^* \): Normalizing and conversion coefficient

As long as the flow is partially fluidized, it is assumed that the discharge \( Q \) stays constant. The actual flow height \( h \) is calculated from

\[ h \ B(x) \ u = Q \]  

(16)

\( u \): mean flow velocity
\( B(x) \): avalanche width

Two additional mechanism are included in the model: (1) entrainment of loose snow from the track at the avalanche front, increasing the avalanche volume and flow depth and its corresponding retardation term.
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\[ u'_5 = 0.5 \frac{\rho e}{\rho} \frac{B h}{V} u_0 \]  

(17)

\( \rho \): density of entrained snow  
\( V \): avalanche volume

(2) loss of snow of the avalanche body by transfer of part of the snow of the coarse and fine grained shear layer in the avalanche body to the avalanche tail, reducing the avalanche volume and flow height. This loss depends on the actual flow speed profile and is modeled to be proportional to the roughness height of the track. Small avalanches may lose enough material by this mechanism to be stopped in relatively steep terrain, as observed in nature.

The equation of motion (Salm, 1985), ready for computer iteration, may be written as

\[ \frac{\Delta u}{\Delta x} = \sum_{i=1}^{5} u'_i \]  

(18)

\( u_1 \): eqn. (9)  
\( u_2 \): eqn. (15)  
\( u_5 \): eqn. (17)  
\( u_3 \): acceleration by gravity and retardation by dry friction

\[ u'_3 = \frac{g(\sin(\alpha) - \mu \cos(\alpha))}{u_0} \]  

(19)

\( u_4 \): retardation by shear losses in fine grained boundary layer if fluidization occurs

\[ u'_4 = f_s \frac{1}{u_0} \frac{1}{R} \]  

(20)

\( R \): hydraulic radius of flow

In the runout, two sliding regimes are modeled: (1) at low snow temperatures the sliding movement of the front element is modeled; collisional dissipation is still possible. (2) at snow temperatures near the melting point the flow is modeled as a flexible solid body; dissipation by collision is disregarded.

The model has been used to fit measured avalanches. The input parameters can be strictly classified in material parameters \( (C_\mu, \mu, \lambda, \Theta, \sigma) \), topographic parameters \( (A_R, K_R, \alpha(x), B(x)) \) and avalanche size parameters (flow height, width and volume at start).

It turns out that the material parameters need not be changed as long as one deals with the same class of avalanches (dry or wet). Typical values are \( C_\mu = 0.008, \mu = 0.2, \lambda = 0.1-0.3 m, \Theta = 0.05, \sigma = 1J/m^2, A_R K_R = 0.05 \). Examples are given in Fig.6.
FIG. 6 Comparison of measured and modeled avalanche flows: (a) small avalanche, (b) large avalanche. In (c) the influence of avalanche volume and entrainment are shown: curve 1: avalanche volume = 20'000 m³, fracture height = 1 m, no entrainment, curve 2: volume = 2000 m³, fracture height = 0.5 m, no entrainment. Curve 3: volume = 2000 m³, fracture height = 0.5 m, height of loose snow in the track = 0.25 m. The unbroken curves show avalanche speed, the broken curves, flow height (1 m/s corresponds to 0.1 m of flow height).
CONCLUSION

It follows from the above outlined granular model that the most sensitive parameter is track roughness. The friction force depending on the third power of track roughness is proportional to actual flow speed squared, comparable to the turbulent friction force in the original Voellmy model and in the rigid body (PCM-) model. Entrainment forces have a similar dependence on speed. The granulation term, which is only effective during the starting phase of the avalanche, behaves like a slightly increased dry friction. The shear friction losses (eqn. 20) correspond to a friction force proportional to $u^n$ where $n = 1$ to 2 for variable discharge or $n = 2$ to 3 for constant discharge during partial fluidization (eqn. 13). The main differences with traditional models are: the flow has two regimes, sliding and partial fluidization. The measurements support this two regime flow because, in almost all cases, a transition between an initial high acceleration phase and a steady state phase can be observed. In addition, the computer code allows for the modeling of entrainment at the front and snow loss from the avalanche body. Both mechanism seem to significantly influence the development of avalanches (Fig.6).

More measurements and theoretical work are needed to prove or disprove the suitability of granular flow concepts for flowing snow.

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REFERENCES


DISCUSSION

H. Norem
In our own full scale experiments we have found that the snow cloud and the dense flow have a common front when entering the runout zone. Have you measured the velocity of the snow cloud and eventually, do your experiments confirm our findings?

H. Gubler
Our observations confirm your findings. A high frequency radar will be available next winter to perform separate measurements of the snow cloud.

T. Nakamura
Could you tell me the lowest snow density of moving avalanches, which your radar system could detail?

H. Gubler
The radar detects specular reflections from surfaces of snow down to densities of a few ten kg/m$^3$. For snow particles suspended in air backscatter depends mainly on particle size and particle number density. Moving snow dust clouds of densities of a few kg/m$^3$ can be seen by the radars at frequencies above 20 GHz.