Radar measurements of snow avalanche full scale experiment in Ryggfonn

Lambert Rammer
Forstliche Bundesversuchsanstalt, Inst. f. Lawinen- und Wildbachforschung
Hofburg-Rennweg 1, A-6020 Innsbruck, Austria

K. Kristensen and K. Lied
Norwegian Geotechnical Institute, P.O Box 3930 Ullevaal Hageby N-0801 Oslo, Norway

Helmut Schreiber and Walter L. Randeu
Institut für Nachrichtentechnik und Wellenausbreitung (INW)
Technical University Graz, Inffeldgasse 12, A-8010 Graz, Austria

ABSTRACT. At the full scale experiment site of NGI in Ryggfonn, avalanche velocities and forces have been measured through 15 years. In April 1997 an Austrian developed INW pulsed Doppler radar was used to measure avalanche velocities simultaneously at 15 segments in the avalanche track. Each of the 15 segments had a length of 50m, with a total length of the radar measurements of 700 m. Avalanche velocities of the flowing part were recorded for about 4 minutes in each segment. The recordings show the distribution of the avalanche velocity with time, simultaneously in each segment.

In addition to the radar measurements, avalanche forces were recorded continuously at two locations in the track.

The recordings show interesting results concerning the internal distribution of velocities in snow avalanches in relation to measurements of avalanche forces.

THE RYGGFONN PROJECT

The Ryggfonn project is a full scale experiment carried out to investigate forces of avalanches of different types and magnitudes on fixed structures, and the effects of a retaining dam in the avalanche path. The experiment site is the Ryggfonn avalanche path close to NGI's research station Fonnbu, Grasdalen, Western Norway.

The Ryggfonn avalanche usually starts from a north-facing cirque at around 1530 m a.s.l. and runs down a slightly channelled path into the valley floor below. The vertical drop from the starting zone to the runout area is around 900 m.

A joint experiment was carried out in April 1997 by NGI and FBVA/AIATR to measure avalanche forces and velocities at the full scale experiment site of NGI in Ryggfonn.

OBSERVATION METHODS

Fixed installations

- A 15 m high and 75 m wide retaining dam in the avalanche runout zone. On top of the dam is a 6.5 m high steel mast that is instrumented with strain gauges.
- A 4.5 m high concrete structure fitted with three load cells, each with an area of 0.72 m², situated 230 m up-slope from the dam.
- An 8.5 high tubular steel tower situated 320 m up-slope from the dam. The tower consists of four sections, each having a diameter of 1335 mm and plate thickness 15 mm.

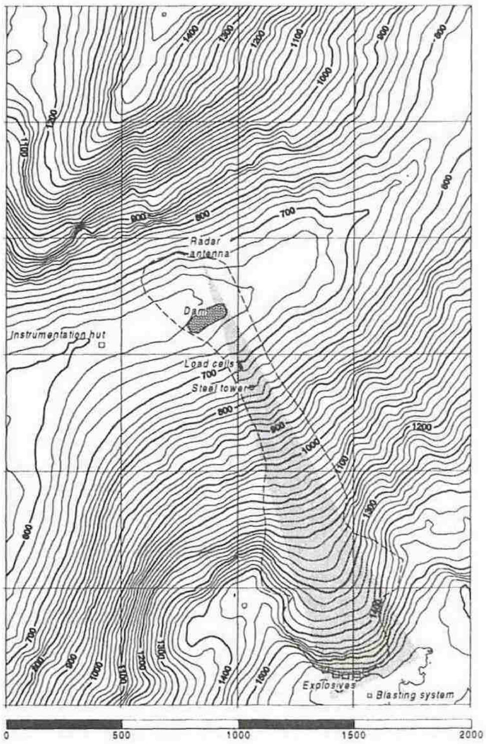


Figure 1. Map of the Ryggfonn avalanche path and experimental set-up in April 1997. The radar beam coverage is shaded.

The tower is instrumented with strain gauges for measuring shear and moment strains at two sections and a geophone for detecting the avalanches and triggering the recording system.

- An instrument shelter near the runout area with recording equipment. The equipment converts the analogue signals to digital signals and records them on a digital tape recorder.

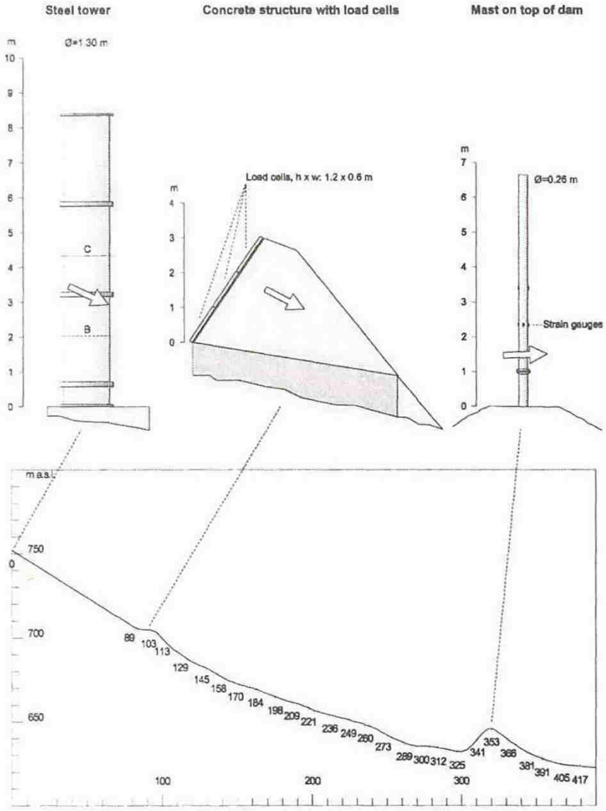


Figure 2. Fixed constructions in lower part of the avalanche path

The avalanches studied are both natural and artificially released. In the case of natural avalanches, the recording system is started when the signal from a geophone on the uppermost construction (the steel tower) exceeds a pre-set triggering level.

Artificial avalanches are released by detonating up till five preplaced charges in the starting zone by means of a radio controlled detonating system. Typically, each charge consists of 75 to 100 kg of dynamite. Artificial avalanches are usually videotaped and photographed with at time-lapse camera. In some cases, filming is done from the opposite mountain ridge.

If possible, all avalanches are mapped and sometimes surveyed for area and volume calculations. The weather parameters were measured at NGI's field station further up the valley at 930 m a.s.l.

Mobile radar equipment

A Pulsed Doppler Radar in a mobile version is used by the Austrian Institute of Avalanche and Torrent Research (AIATR) for the measurement of avalanche dynamics [6]. This radar, a development of the INW (Institute of Communications and Wave Propagation of the Technical University Graz), transmits short pulses of microwave energy, and analyses the received echoes reflected from the target objects hit by the antenna beam, with the purpose of measuring their velocities. In the case of the avalanche radar, the reflecting object is the ground covered with steady or moving snow. In addition to a continuous wave (CW) radar it also provides information from where (what distance) individual echo components originate, and thereby offers a more reliable detection and verification and the possibility of spatially resolved dynamic analysis of snow and ice avalanches. This is accomplished by a quasi-simultaneous acquisition of Doppler frequencies from a number of adjacent sections along an avalanche track (see Fig. C). This process is called range gating and allows the spatial discrimination of echo intensity, velocity and turbulence parameters in the top-down direction.

The three major components of the radar are :

- antenna: parabolic reflector with a diameter of 0.7 m
- RF-unit: a box containing the transmitter generating the microwave pulses and the receiver.
- Indoor control unit: a personal computer which controls all the functions of the radar. It does the digital signal processing, archives the measured data on a harddisk and displays them on the screen.

Each component can be lifted by a single person.

The measurement and control software has a graphical user interface. All the necessary status information of the radar, like measurement mode or components status are displayed in a window and can be changed or activated by mouse-click. The data measured by the radar are Doppler-velocity spectra for each rangegate at different time instants. One measurement cycle delivers simultaneously *n* spectra where *n* is the number of installed rangegates. The time-difference between the measurement cycles is normally about 100-200 ms. For off-line data processing after the measurement, additional software has been developed. Beside the above described raw data display it allows the calculation of the velocity, dependent on time for each rangegate, and the velocity of the avalanche front. There are several possibilities to determine the speed:

- Velocity of maximum intensity : the velocity of the spectrum-line with the highest echo intensity.
- Maximum velocity : the highest velocity at an echo intensity above a specified level (normally a multiple of the noise level) .

The results are 2D-timediagrams for each rangegate (see Figure 7) where the x-axis shows the time from the start of the measurement, and the y-axis the measured velocity in the rangegate, or 3D-diagrams where the velocity is drawn above the distance from the antenna and the time.

From the 2D-timediagrams the moment when the avalanche enters a rangegate can be determined. Since the velocity is known, the distance covered by the avalanche till the next measurement cycle can be calculated. With the avalanche track profile the next front position is determined by moving the distance along the assumed path. This calculation must be repeated until the avalanche enters the adjacent lower rangegate. It is very likely that the sum of the distances is not exactly equal to the length of the avalanche path in the rangegate (as given by the topographical data). Therefore the algorithm has to be applied iteratively with slightly changed velocity values. For these calculations a profile of the avalanche track is necessary since the radar measures the velocity component towards the antenna and not the actual velocity along the avalanche track (see Fig. 3). Therefore the velocity has to be corrected to the real value.

By doing this calculation, the front position can be determined with a resolution much better than the length of a rangegate (min = 50m). The actual precision depends on the time interval between the measurement cycles, the velocity and the accuracy and resolution of the track data.

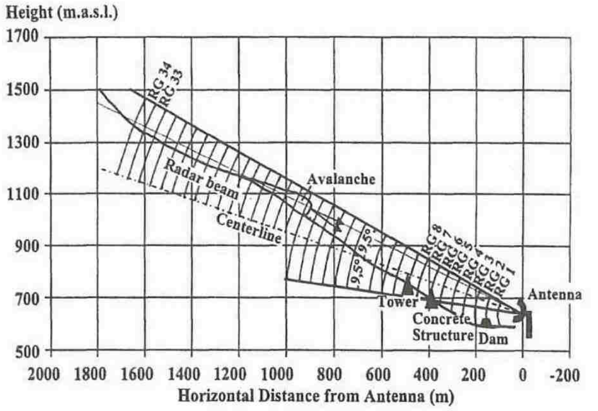


Figure 3. Profile of the avalanche track with radar set-up

Figure 8 shows a screen shot of the front velocity diagram calculated from the data of the Ryggfonn measurement. The diagram consists of two graphs where the first represents the front velocity in dependence on the horizontal distance from the antenna (x-axis) and the second one shows the profile of the avalanche track. Below is a table with the rangegate number in the first line (RG). The second row lists the assumed length of the avalanche path in this rangegate (l) while the third one shows the calculated runlength ($\sum s$). The difference between can be found in the last line.

AVALANCHE MEASUREMENTS

An avalanche was successfully released on the 17 of April 1997 by blasting 100 kg dynamite at the top cornice.

The week before the avalanche release there was a new snow accumulation of about 15 cm. The air temperature rose to above freezing in the runout zone below 1200 m a.s.l. during the day before the avalanche. At the time of the avalanche on the 17 the 0°C isotherm was at about 1000 m a.s.l. The blasting resulted in an initially dry slab release which entrained gradually moister surface snow on its way down the track. The avalanche deposit consisted of partly wet snow blocks. The average density of the uppermost 150 cm in a sample pit in the debris was 540 kg/m³ and the estimated volume of the avalanche was approx. 40.000 m³. The avalanche code (UNESCO/IAHS 1980) is: A2, B2, C1, D2, E7, F3, G7, H1, J4.

Avalanche runout

The avalanche passed the steel tower and the load cells, but stopped in the catchment area in front of the dam. The debris was split and diverted by the deposits from previous avalanches (Figure 4). The maximum height of the deposit in the runout area in front of the dam was about 3 m.

Measurements from the fixed installations

The average avalanche velocity in the runout zone can be roughly estimated from the times of impact on the constructions, although the sensitivity of the sensors on the constructions vary. From the steel tower to the load cells, a stretch of 103 m, the time difference between impacts is 2.9 seconds, suggesting an average velocity of 35.5 m/s (128 km/h).

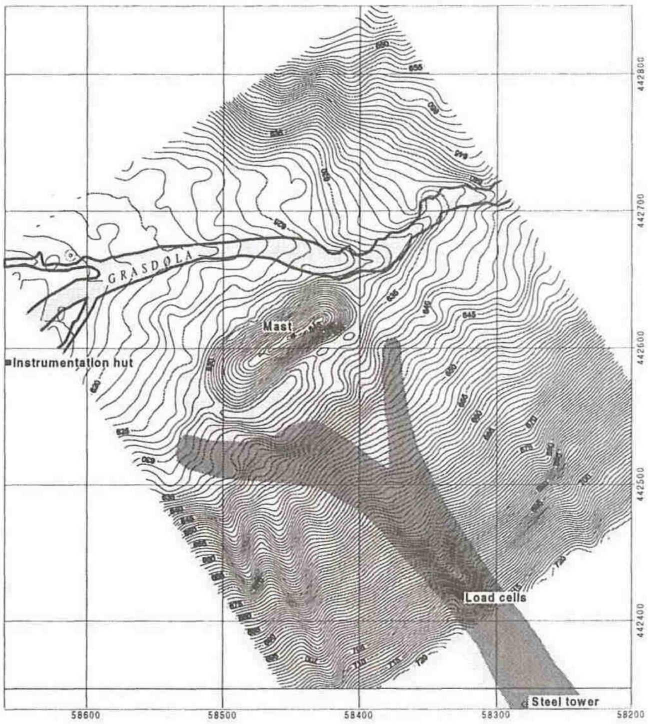


Figure 4. Map of avalanche deposit 17 April 1997 (dark shading)

The maximum moment stress at the tubular steel tower was at the middle section B. The moment caused a deformation of the steel of 200 µS (Figure 5). Because avalanches earlier in the winter had caused a build-up of avalanche debris of about 3 m around the tower, the main load was applied fairly high up on the construction.

Because of a damaged load cell there were no data from the uppermost load cell. Of the two lower cells it is the middle one that receives the highest load (maximum value 110 kPa) (Figure 6). The reason for this also being deposition of avalanche debris around the concrete structure from previous avalanches.

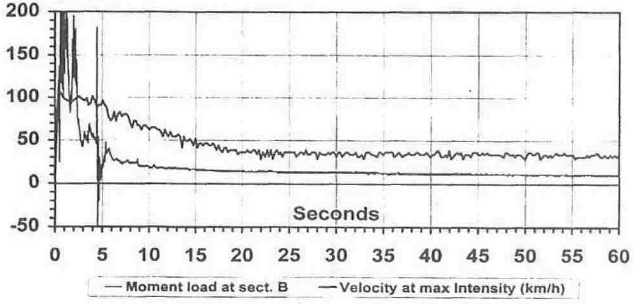


Figure 5. Moment load at section B and velocity at the steel tower

Radar measurements

The antenna was set up on the slope opposite to the avalanche track at an elevation of 30 m above the bottom of the valley, at a distance of 160 m from the crest of the dam. The control system and the operator were situated about 50 m upwards in the slope for higher safety. The centre line of the radar beam pointed to an area in the avalanche track approximately 200 m above the steel tower. The angle at which the effect of the microwaves is half of the effect at the centre line is 9,5° on both sides of the centre line in the vertical, and 5,5° in the horizontal direction. The avalanche in the upper part of the track at a distance of about 1200 m from the antenna could not be covered by the radar beam because it is hidden by a convexity in the terrain profile (Figure 3).

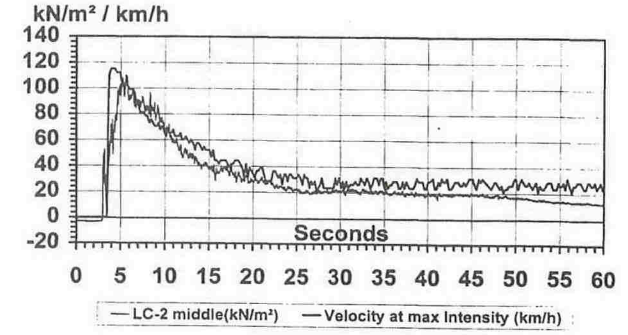


Figure 6. Impact pressure and velocity at the middle load cell

The software was set-up with 34 rangegates (RG) with a distance between the RGs of 50 m in each case, beginning at a distance of 100 m from the antenna (Fig. 3).

The trigger value was defined for the intensity of the radar signal with three times the noise level, for the velocity with 2,5 km/h.

Because of some problems with pinpointing the best position in the avalanche track by the centre of the radar beam, but also with insufficient power at large distances, the measurements could be evaluated only from a distance of 900 m or shorter from the antenna position. The timediagrams could be plotted, beginning at rangegate 15 (800 – 850 m from the antenna) and ending at RG 1 (100 – 150 m). 110 sec of avalanche running time are shown in each diagram. There are two types of diagrams, one for the velocity at the maximal intensity over time, (Figure 7), the other for the maximal velocity over time.

A peak velocity can be observed when the avalanche head is entering the RG, decreasing to an almost constant level for the avalanche tail after about 30 sec in the upper part of the measured track, and 20 sec in the lower part.

The end of the runout zone is shown in RG 3 between 200 – 250 m from the antenna. Normally the time can be observed, which an avalanche takes to pass the rangegate. In the present case, the avalanche consisted of wet snow, with a long, slow moving tail behind the front.

The steel tower is located at the beginning of RG 8, the concrete structure is located at the beginning of RG 6. In RG 9 and RG 8 a significant decrease of the velocity, especially of the avalanche tail can be shown, depending on the smaller slope angle in this region, increasing downslope in RG 7, where the slope profile becomes steeper again, to the maximum.

Figure 7 shows the corrected front velocity along the slope profile. The plot starts at the beginning of RG 15 with about 110 km/h, has a decrease in RG 13 and RG 12 with a minimum of about 75 km/h. The velocity increases till RG 9 to about 112km/h, where it begins to slow down to 95 km/h in RG 8 because of the smaller slope angle in this region.

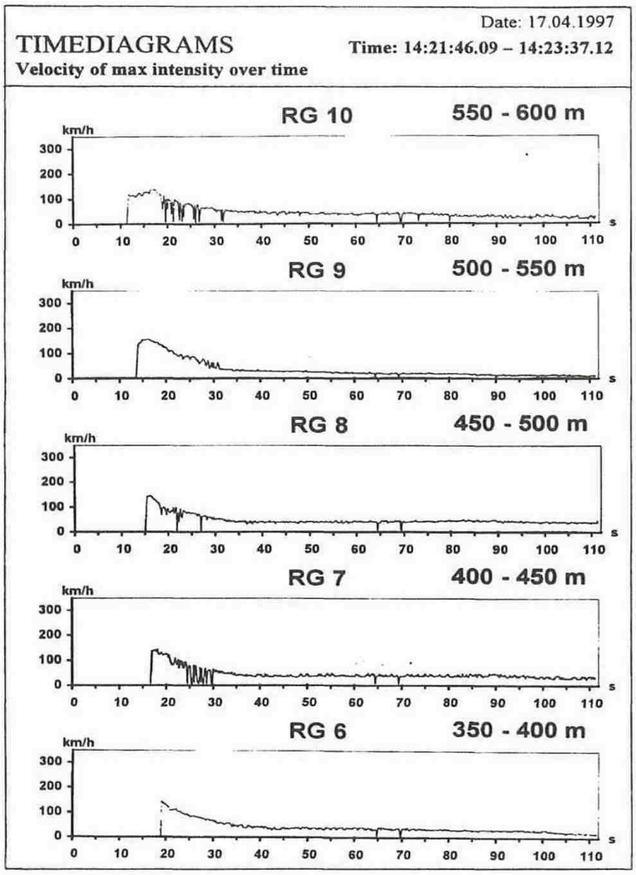


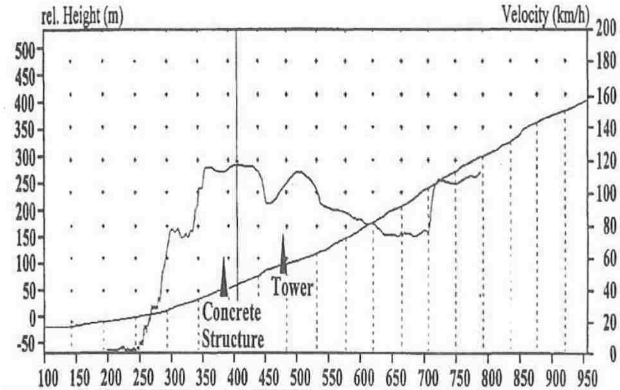
Figure 7. Timediagram of the velocity at the maximum intensity from RG 10 to RG 6

Between the tower in RG 8 and the concrete structure in RG6 the velocity has a maximum of 117km/h because of the more channelled avalanche track, decreases because of sharp bends between RG 6 and RG 5 down to about 80 km/h. In RG 4 the avalanche runs out and stops before the end of RG 3 close to the dam.

COMPARISON OF VELOCITY AND PRESSURE MEASUREMENTS

The average avalanche velocity between the tower and the load cells calculated from the time difference between the impacts of 2,9 seconds is 35.5 m/s (128 km/h).

The average front velocity calculated from the front velocity diagram (Fig. 8) from the radar measurements by integration over the distance between the tower and the load cells is 108 km/h. In diagram Fig. 6 the first impact can be observed at 2.9 seconds with a smaller peak of 52 kPa and a second impact at 3.47 seconds with the maximum peak. Calculating the load cell pressure with $\rho v^2/2$ we get a density of 83 kg/m³ for the first peak with a velocity of 35.5



RG	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
l			51,1	51,9	53,3	52,6	52,9	52,8	50,9	53,4	53,4	52,6	55,2	52,0	51,0				
∑s			47,1	51,2	53,5	52,4	50,1	53,7	46,0	57,0	54,3	57,0	59,3	54,1	47,2				
∑s-l			----	-0,7	0,2	-0,2	-2,8	0,9	-4,9	3,6	0,9	4,4	4,1	1,4	----				

Figure 8. Front velocity along the track.

m/s. On photos of the avalanche front we can see, that in front of the avalanche a cloud of powder and flying snow balls is running, which will be the part with the low density. Since the radar only can record the dense flow part of an avalanche, the cloud could not be recorded. So the start of the radar measurement at the load cells will be at 3.47 seconds and the calculated average speed for the distance of 103m is 29.7 m/s = 107 km/h which corresponds with the speed calculated from the front velocity diagram. At the tower where the velocity of the avalanche was decreasing along a stretch of 25 m, the cloud was also moving in close contact with the frontr of the avalanche body.

The peak pressure at the load cells with 110 kPa leads to a density of 175kg/m³ with 35.5 m/s, but 250 kg/m³ with 29.7 m/s, which is a little closer to the average density of 540 kg/m³ observed in the debris. The peak pressure at the load cells with 110 kPa leads to a density of 175kg/m³ with 35.5 m/s, but 250 kg/m³ with 29.7m/s, which is closer to the average density of 540 kg/m³ observed in the debris.

In Figure 9 a 3D-diagram: Time-Velocity-Distance, is displayed for the maximum velocities.

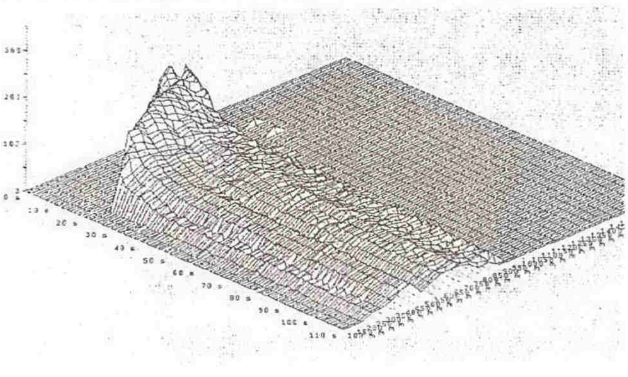


Fig. 9 3-D diagram of Time-Velocity-Distance

The measurement starts at 900 m at the time 0 seconds, with high velocities, the avalanche front reaches the stopping position after 25 seconds. After 110 seconds, low velocities along the whole recording stretch is still displayed. The overall recording time was about 4 minutes for the whole avalanche. A distribution of the velocities along the track depending on the terrain surface can be seen, with peaks between 700 m and 800 m, and between 400 m and 500 m.

CONCLUSIONS

The measurement of avalanche velocities by means of a pulsed Doppler radar gives a good idea about the distribution of the velocities along the avalanche track. A variation of the velocity caused by decrease or increase of the slope angle, but also by widening or channelling of the avalanche track can be recorded.

Regarding the speed/pressure relationship special attention has to be paid to the question of what part of the avalanche is measured by the two different devices at the moment of recording. Since only the dense flow part of an avalanche can be observed by the INW Radar, different starting points of the measurements are possible. Therefore the results have to be thoroughly analyzed.

Logistic problems for AIATR have been solved, and it is possible to start a measurement within three days in Ryggfonn. For future measurements in Ryggfonn the set-up of the antenna should be changed. The radar beam has to be pinpointed more to the upper part of the avalanche track in order to have a measurement also of the upper part of the track.. The maximum power is in the centre of the radar beam, therefore this distant region would not be covered by the part of the beam, where the attenuation is already close to 3 dB. Otherwise in the area close to the antenna the attenuation is not so important because the targets are nearer.

REFERENCES

Gubler H., Hiller M. und Suter U., (1986) Messungen an Fliesslawinen: Zwischenbericht 1986. *Mitteilungen des Eidgenössischen Institutes für Schnee- und Lawinenforschung*, Nr. 41, Aug. 1986

Kristensen, K., Larsen, J.O. (1996). The Ryggfonn Avalanche Dynamics Project. *Proceedings of the International Snow Science Project ISSW '96*, Banff, Canada

Kristensen, K. (1996) The Ryggfonn project. Avalanche Data from the Winters 1991/92, 1992/93 and 1993/94. *June 1996. NGI report 581200-31*

Lied, K. (1984) Earth dams for protection against snow avalanches. *NGI report 581200-4*

Riedler W., Randeu W. L. und Okorn R., (1990): Endbericht zum Projekt "Straßenforschung No. 730: Lawinenradar für die Straßensicherung" *Forschungsauftrag des österreichischen Bundesministeriums für wirtschaftliche Angelegenheiten*, INW/TU – Graz, Band 1 – 6, März 1990

Randeu W. L., Okorn R., (1992) :Endbericht "Meßbereichserweiterung für das Lawinenradar Alpe Rauz", *Straßenforschung Nr. 3.064* INW/TU - Graz, Aug. 1992

Randeu W. L., Okorn R R. and Riedler W., (1990) A pulsed Doppler radar for the acquisition of avalanche dynamics. *Proceedings of conference "Avalanches and planning of mountain territory"* (CIV´90), Arabba.