EU Programme SAME

Draft Proposal for a Co-ordinated European Full-Scale Avalanche Experiment

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For the Norwegian Geotechnical Institute

Project Manager:

Karstein Lied

Report prepared by:

Carl B. Harbitz

Carl B. Harbitz (NGI)
Dieter Issler (SFISAR)

Reviewed by:

Karstein Lied

Karstein Lied

Work also carried out by:

G. Brugnot (Cemagref)
U. Gruber (SFISAR)
C.J. Keylock (Univ. of Cambridge/IMO)
H. Schaffhauser (FBVA/AIATR)

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SAME

SNOW AVALANCHE MODELLING, MAPPING, AND WARNING IN EUROPE

Deliverable n°6*: Draft Proposal for a Co-ordinated European Full-Scale Avalanche Experiment*
Also in: *Norwegian Geotechnical Institute* report no. **581220-2**

Authors: Carl B. Harbitz (NGI) and Dieter Issler (SFISAR)
Work also carried out by: G. Brugnot (Cemagref), U. Gruber (SFISAR),
Horst Schaffhauser (FBVA/AIATR), and C.J. Keylock (Univ. of Cambridge, previously Icelandic Meteorological Office)

Summary

The scope of this proposal is to describe the conclusions made in the EU programme SAME (Avalanche Mapping, Model Validation and Warning Systems) for a future co-ordinated European full-scale avalanche experiment. It is not meant to be a completed and final application for financial support in its present stage. A final application will hopefully come into being when the real participants in a potential co-ordinated experiment are singled out.

There are both practical and modelling objectives of such an experiment, and it is believed that they can all be reached by combining the existing techniques in one small and one large experimental site. Gathering the necessary know-how for all the required experimental techniques and the projected costs of comprehensive experimentation underline the benefits of co-ordination.

The typical questions that arise in practical applications are linked to the maximum runout of extreme events, impact pressure distributions over an area as a function of the return period, and run-up heights. To apply an avalanche model in practice, it is necessary to have well-established rules to define both the input as well as the model parameters. Considering the range of information required in practical studies there is not — and probably never will be — a single model that is able to answer all the questions. Therefore the comparison between the results of different types of models is important to make the estimation of the hazard more reliable.

Model development and verification require comprehensive measurements on real avalanches for improved understanding of the underlying physics, validation of the modelling approach, and calibration of the parameters. The remaining key problems—description of different flow-regimes and flow-regime transitions, modelling of snow entrainment and deposition, and choice of the initial and boundary conditions for each application of the models—are directly connected to the scarcity of comprehensive, reliable experimental data and the concomitant lack of model validation. Related research programmes to overcome some of these problems are described. Modellers' needs in terms of physical quantities to be measured, the priority and ease of each measurement, and the level of precision required, are discussed.

The proposal further details the measurement techniques to be used. The potential and limitations of available techniques are outlined. It is emphasised that both large (10^{4-5} m^3) and small (10^{3-4} m^3) avalanches need to be studied. Both for the small and the large sites minimum equipment to comply with modellers' needs (above) is determined to comprise three locations (preferably, upper track, lower track, run-out zone) heavily instrumented with capacitance probes, load cells, and FMCW radar for entrainment and flow depths for detailed measurements of variables that reveal the main mechanisms at work in avalanche flows. In addition to these spatially localised but temporally extended measurements, spatial information is needed for the initial and final conditions, i.e., the released and the deposited volume and mass. For the small site, snow stakes in the starting zone should be provided; for the large site, aerial photogrammetry is presently the only viable method. Finally, spatio-temporal measurements (trajectory, front velocity along the path, evolution of spatial distribution of internal velocity, etc.) are needed. Video observation is an obvious and simple tool for use in all avalanche sites. Additions for larger sites include Doppler radar for velocity measurements. Capacitance probes provide density and velocity information, but are expensive and may be problematic for measurements in wet snow. Consequently, light-emitting diodes may need to be substituted in some places (with a consequent loss of density information). Capacitance probes provide unique information for powder-snow avalanche modelling.

A proposed set-up of an experimental site is sketched, and the main requirements on the data acquisition systems and proper construction of the instrument supports in terms of dimensioning and minimum flow disturbance, are described.

The site selection process should be based on the potential of the sites rather than on their current equipment. The general equipment-independent characteristics of the avalanche path such as size, altitude, and topography, its relevance to practical problems and to the scientific objectives of the programme, the frequency of events, the accessibility of the site, safety, infrastructure, and the question of building and artificial release permits are chief among the criteria to be applied. It must not be expected that a site can be found that fulfils all the requirements. The final site selection process will also have to include political aspects. Under any circumstances, however, the final selection has to be postponed until mutual agreement on the scope, participants, and organisation of the collaboration has been established.

Two large sites, Ryggfonn (Norway) and Vallée de la Sionne (Switzerland), and two small sites, Col du Lautaret (France) and Monte Pizzac (Italy) were finally left to compare and contrast for co-ordinated experiments. Ryggfonn (Norway) and Vallée de la Sionne (Switzerland) will both keep running regardless of their status concerning co-ordinated experiments, it is rather a question of extension and complexity of experiments.

The proposal summarises information compiled in the SAME programme on the existing avalanche test sites. An overview of the strong and weak points of each of the four candidate sites reveals that

- none of the sites is easily accessible for all the prospective partners, with Ryggfonn being very distant for almost all partners;
- the two small sites fulfil all the relevant criteria and differ mainly in the complexity of their path geometries;
- the two large sites are quite comparable in most respects. The proven avalanche record is a strong point in favour of Ryggfonn until more experience has been gained at Vallée de la Sionne, which is far more accessible, however.

In the final decision, the advantages and disadvantages of the various combinations of a large and a small site will be decisive. In this respect, the following conclusions can be drawn:

- The combination Vallée de la Sionne / Col du Lautaret is the least favourable because path characteristics do not clearly complement each other, campaigns may often coincide in time, the access distances are not so well balanced among the prospective partners, and the avalanche frequency at Vallée de la Sionne is not known yet.
- The path characteristics of Monte Pizzac complement those of either large site in an interesting way, favouring Monte Pizzac somewhat over Col du Lautaret.
- The final decision will have to take into account the contributions of each partner institute to the joint experiments at the small and the large site because access time can be critical.

Instrumentation and construction costs according to the outlined standards are estimated to amount to more than one million ECU for a new large site. Completing the equipment of one of the existing large sites like Vallée de la Sionne or Ryggfonn reduces the costs to 240–550 kECU. Completing the equipment of one of the existing small sites like Monte Pizzac or Col du Lautaret will cost 50–350 kECU. It is strongly recommended that the present level of instrumentation of the four sites not be used as a main criterion in the site selection process. Reducing the degree of instrumentation would provide significantly less information on the internal dynamics of avalanches and thus make validation of new, advanced models less conclusive.

A time schedule for a probable next phase following a positive answer to a potential proposal and a delay for site selection is presented. This phase then includes planning, sensor development, installation, and testing.

Finally, visions for future joint programmes are elaborated based on the experience gained in the SAME programme. The problems related to exchange of experimental data and computational models will hopefully be solved within a proposed permanent European network of avalanche institutions.

Contents

Review and reference document

1 INTRODUCTION

1.1 Introductory remarks

(C.B. Harbitz)

The scope of this proposal is to describe the main recommendations made in the EU programme SAME for a future co-ordinated European full-scale avalanche experiment in terms of practical needs and scientific aspects. The projected costs of comprehensive experimentation underline the benefits of co-ordination.

The proposal is based on the three SAME reports on existing computational models for snow avalanche motion (Harbitz, 1998), European avalanche test sites (Issler, 1998), and existing experimental techniques (Schaffhauser, 1998), as well as discussions between the SAME partners (cf. Sec. 1.3). The importance of including more experts on various relevant experimental techniques not involved in SAME in a potential second programme is emphasised.

The dynamics of avalanches are complex, and no universal avalanche model exists. The limited amount of data available from real events makes it hard to evaluate or calibrate even the existing models.

Further model development and verification require comprehensive measurements on real avalanches for improved understanding of the underlying physics, validation of the modelling approach, and calibration of the model parameters. The remaining key problems — description of different flow-regimes and flow-regime transitions, modelling of snow entrainment and deposition, and choice of the initial and boundary conditions for each application of the models — are directly connected to the scarcity of comprehensive, reliable experimental data and the concomitant lack of model validation.

1.2 Objectives

(C.B. Harbitz, D. Issler, and C.J. Keylock)

The objectives of co-ordinated experiments can be divided into practical and modelling objectives, Table 1.1.

Table 1.1: The objectives of co-ordinated experiments

Practical Objectives	**Modelling Objectives**
Impact pressure on obstacles: • Dependence of pressure upon avalanche properties and structural configuration. • Spatial and temporal distribution of pressure on an obstacle. • Long-term remnant static pressure after impact. • Shear forces on snow sheds. • Improved design of defence structures. Hazard zoning: • Improved trajectory modelling. • Improved runout distance prediction. • Mapping of pressures. • Effect of obstacles on flow path trajectory and energy. • Dependence of fracture area and depth on topographical and meteorological parameters. Tests of monitoring systems (warning, alarming): • Acoustic and seismic systems. • Radar-based systems. • Mechanical systems.	Validation of existing models through measurements of: • released mass, • trajectory, flow depths and velocities, • run-out distance and deposit distribution, • pressures Guidance for future model development in addition requires: • Mass balance (global, local, and time-resolved). • Determination of flow regime (velocity fluctuations and profiles, density fluctuations and profiles, and pressure measurements (particle size distributions)). • Suspension rates from dense to powder component • Granulometry of deposits. Seismic and acoustic studies aiming at: • Identification of different sources of seismic and acoustic signals. • Correlation of signal variations to avalanche properties. • Determination of signal variability over different avalanches in the same path. • Estimation of avalanche size and mass from catalogue of seismic signals for different avalanches in different paths.

1.3 September 1997 Davos meeting

(C.B. Harbitz)

A full meeting of all SAME participants involved in avalanche dynamics (experimentation and modelling) was held September 15-19, 1997 in Davos, Switzerland. The purpose of the meeting was to discuss in depth the requirements of avalanche model development on the type and quality of full-scale avalanche experiments, the available experimental techniques, the relative virtues and disadvantages of existing experimental sites, and to outline the content of the present proposal.

Also the needs in each country in terms of avalanche type and protection were sketched. The needs mirrored the priorities made when establishing/developing the existing experimental sites.

The following institutions and persons were represented and contributed with information that made it possible to write the present proposal: AVL—Austria (Peter Sampl), CEMAGREF—France (Pierre-Henri Dodane, François Rapin, Philippe Revol), CEN—France (Yves Durand, Gilbert Guyomarc'h, Jean-Pierre Navarre), CSVDI—Italy (Francesco Sommavilla, Betty Sovilla), FBVA/AIATR—Austria (Lambert Rammer, Horst Schaffhauser), ICC—Spain (Glòria Martí), IMO—Iceland (Chris Keylock), NGI—Norway (Carl Harbitz), SFISAR—Switzerland (Perry Bartelt, Urs Gruber, Dieter Issler), TU Graz—Austria (Helmut Schreiber), University of Barcelona—Spain (Françoise Sabot, Emma Suriñach), and University of Pavia—Italy (Massimiliano Barbolini).

2 PRACTICAL NEEDS IN AVALANCHE HAZARD MAPPING/ZONING

(U. Gruber)

The aim of avalanche modelling in practice is to determine the hazard at a given location in order that protective measures against this danger can be undertaken. The modelling requirements of the practitioners depend basically on the defence strategies they want or can apply.

2.1 Basic needs

2.1.1 Maximum reach of an avalanche

The simplest strategy is to avoid the presence of any human being or building in the endangered area. In this case, the only need of the practitioners is the *maximum reach of an avalanche* (the run out area/distance).

2.1.2 Impact pressure

Due to the increase of the population and the infrastructure in mountainous regions it is becoming increasingly difficult to avoid human presence in endangered terrain. This is especially the case where avalanche occurrence is not obvious and infrequent. Under these circumstances the practical needs are not a simple «Yes-No» decision, but a more sophisticated estimation of the hazard of an avalanche. The main requirement of the practitioners is the *impact pressure* of an avalanche event at a given location. Due to economic and risk management considerations, the impact pressure must be related to a *frequency*. Therefore the main question to be answered in practice is: »What impact pressure is caused by an avalanche at a given location every year / every ten years / every hundred years?". By answering this question it is possible to choose a specific *defence strategy* for a given *damage potential*.

At a minimum, an averaged impact pressure must be estimated in order to be able to roughly decide how buildings in endangered areas have to be reinforced. It is also necessary to know if a powder snow cloud can accompany the flowing avalanche, causing pressure at high elevations on the buildings. The knowledge of such an averaged impact pressure allows delineating zones of small impact pressures where it is possible to protect buildings in an endangered area by reinforcement measures.

2.1.3 Interaction with obstacles and planned buildings

A rough estimation of the dense and powder snow avalanche part also indicates how more specialised defence structures like catching or deflecting dams and galleries (snow sheds) should be dimensioned. But for reliable and economic dimensioning of those protection measures, more detailed information is necessary about the *interaction of the avalanche with defence constructions*:

- Impact pressure depending on the width and height of the construction (small, large obstacles)
- Duration of the impact pressure
- Shear forces at the bottom of the avalanche (especially important for the snow sheds)
- Run-up height at a deflecting or a catching dam, respectively
- Effect of an obstacle on the flow path trajectory and the energy of the avalanche

2.2 "Intermediate" needs

The knowledge about the impact pressures, the frequency of an avalanche and the interaction with defence structures are the basic needs in practice. However, these needs are difficult to reach immediately. Therefore some «intermediate» needs for the practice should also be stated.

2.2.1 Historical event registration

The mapping and the registration of the important characteristics (release area, fracture depth, perimeter, deposition depth and observed impact pressures) of *historical events* is a must. It helps both to judge the frequency of an avalanche in a certain area as well as to verify and subsequently to improve the reliability of avalanche models.

2.2.2 Improved knowledge about release zone area and fracture depth

To be able to determine the frequency of an avalanche of a given size it is important to have more precise knowledge about the *release zone area* and *fracture depth*. The practical need is to have rules for the delineation of a release area, which are based mainly on the local precipitation rate, the terrain configuration (slope, aspect, ridge, gully), the expected snow type and the snow transport by wind. Again, those rules have to be related to the frequency. Questions of the following type have to be answered: »What is the typical size of a 5-year avalanche release area and fracture depth in a 35° slope, that has a confined shape and is near a ridge, where snow transport by wind is possible?", or »what is the size of an avalanche that is expected only every hundred year in the same location?", or »what is the frequency of an avalanche at all in a 30°-slope that is unconfined and where only minor wind transport is expected».

2.2.3 Improved knowledge about the avalanche dynamics

To be able to achieve a better reliability to define the impact pressures at a given location (basic need) it is important to improve the understanding of the flow regime. Based on this general statement the following «intermediate» practical needs can be derived:

- Rules for the application of friction parameters depending on the terrain roughness, the terrain confinement, the snow type and the avalanche size.
- Rules for the occurrence of dense, mixed or powder snow avalanches.
- A model that correctly calculates the path trajectory and the lateral spreading of an avalanche.
- A model that includes the interaction of the flowing snow with the snow cover.

2.3 Context of the practical needs for avalanche hazard mapping and the planning of defence strategies

Fig. 1 illustrates the dependencies of the practical needs in a wider context and should help to understand the above stated practical needs. In the lower part of Fig. 1, the direct practical needs and defence strategies are mentioned. In the upper part, the methods to solve the practical needs and to get also the intermediate results are shown.

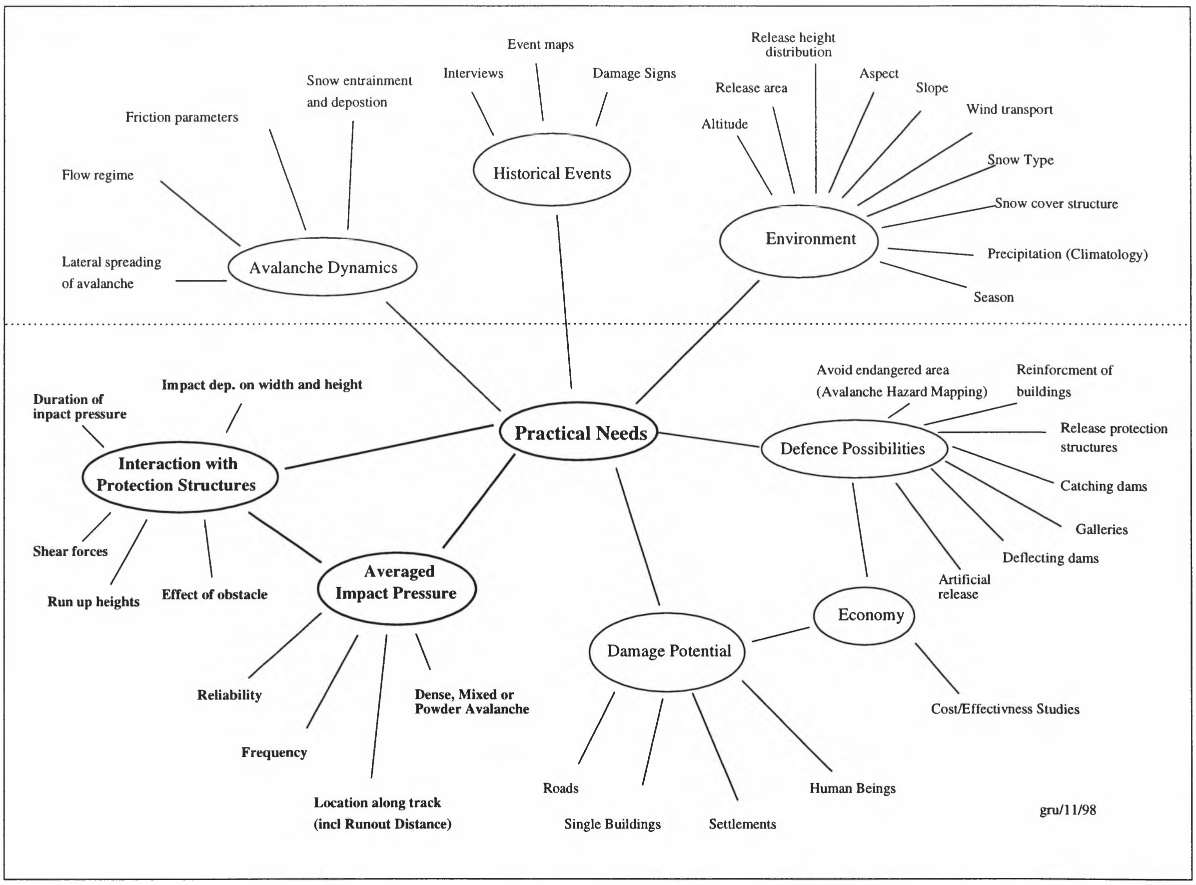

Figure 1: Mind Map: Context of practical needs for avalanche hazard mapping and defence planning.

3 FUTURE MODEL DEVELOPMENT

3.1 Directions for future model development

(C. Harbitz, D. Issler, and C.J. Keylock)

To meet the practical needs in hazard mapping and the theoretical needs for better understanding of the underlying physics in avalanche dynamics, a substantial effort in computational model development is desirable. The cruder the knowledge of initial and boundary conditions, the more one should favour relatively simple and robust models at the expense of detail in the predictions. Nevertheless, very often great detail is required and thus rather sophisticated models are needed, too.

Determination of realistic initial conditions is a serious problem in practical applications that has not received sufficient attention in the past. Typically, both the initial avalanche mass (fracture area and depth) and the flow behaviour (friction coefficients, snow entrainment and deposition rates, fraction of suspended snow) non-linearly depend on the return period. On the one hand, very simple models do not adequately reflect this non-linearity and may give strongly distorted results; on the other hand, determination of the effect of uncertainties in the initial conditions on the results requires a large number of simulations that are not currently possible with the more demanding advanced models.

We suggest that combining simple models allowing rapid scanning of the relevant parameter space with more advanced models for detailed simulations of selected scenarios could help bridge this gap. The simple models will not disappear, but acquire new meaning when combined with the more sophisticated ones.

For such combined analyses to yield meaningful results, the simple and advanced models must be properly matched. The following are among the relevant criteria:

- The input and output parameters of the simple model must be among those of the advanced model.
- The physical processes described by the simple model should also be contained in the matching advanced model so that parameter dependencies found with the simple model will also be reflected by the advanced one. E.g., a one-dimensional model with a simple snow entrainment mechanism explores dimensions of the parameter space that are inaccessible to two- or three-dimensional models without snow entrainment.
- Before practical applications are considered, the two models should be compared in situations that can reasonably be described with the simple model. In this way, a set of parameter values for one model can be approximately related to a set of values for the other model (e.g., friction or entrainment coefficients).

In order to account for the extraordinary variability of avalanche motion in response to initial and boundary conditions, flow-regime transitions and snow mass balance should be properly described. The vast majority of models in use today completely neglect these phenomena.

In simple models, flow-regime transitions may be captured »manually” by choosing different sets of parameter values in different sections of the path. It is obvious that only very few experts will be able to correct for model deficiencies in this way, and a high degree of subjectivity is thereby introduced. What appears to be missing at present is a dynamical determination of the effective constitutive law of avalanching snow in response to the local flow parameters.

Simulations of powder snow avalanches have already illustrated that the mass may grow enormously if sufficient erodible snow is available in the track. While the avalanche without entrainment already begins to decelerate in the track, in the presence of entrainment, maximum speed is reached only at the beginning of the run-out zone. It is highly probable that such a result is also valid for dense snow avalanches. On long avalanche paths, initial snow avalanche mass appears to be much less important than snow entrainment for a wide range of initial conditions.

Furthermore, density variations are represented in very few models, and then simply, while the resultant effects on other physical parameter values such as viscosity, are not represented in any of the dynamics models. Other aspects of the moving media (e.g. particle size distributions, particle concentration and rotation, temperature changes, and energy dissipation) are not adequately described in any of the dynamics models.

3.2 Related research programmes

We believe that international collaboration could produce high-quality models covering all essential practical needs. Below we refer to projects already proposed for a first step in this direction.

3.2.1 Erosion and deposition processes in dense snow avalanche dynamics

(D. Issler)

Mass change by snow entrainment or deposition sometimes has a negligible influence on the dynamics of dense-flow avalanches, but often it becomes the determining factor. The entrainment rate is expected to depend strongly on snow properties, terrain roughness, avalanche flow depth and flow regime.

The goal of this project, jointly proposed by members of SFISAR (Switzerland), the Avalanche Center of Arabba and the University of Pavia (Italy), is to develop mathematical models of snow entrainment and deposition that can be used in various numerical continuum models of avalanche motion.

A heuristic approach does not appear adequate in this context. Instead, experiments both at the laboratory and natural scale need to be combined with theoretical investigations of different conceivable entrainment and deposition mechanisms. The material properties of snow are believed to play a decisive role, so even the laboratory experiments should use snow. The mechanical analysis will have to reflect the fact that some of the relevant processes take place at the snow-particle scale; averaging procedures will be applied to obtain continuum formulations suitable for practical use.

It is proposed to study the basic processes in detail in chute experiments with natural snow, varying key parameters such as flow depth, terrain roughness, density and cohesion. At a small avalanche test site, detailed local mass balance measurements will be combined with tracer experiments and the usual velocity, flow-depth and pressure measurements. Much larger scales will be explored at a large test site where velocity profiles and entrainment / deposition rates can be measured directly.

3.2.2 Joint programme on avalanche modelling

(C.B. Harbitz)

A joint programme on numerical avalanche modelling has been recently initiated. The programme is meant to involve NGI, NTNU (Norwegian University of Science and Technology), MSU (Moscow State University), SFISAR, and University of Pavia. The intention is to avoid parallel and independent development of numerical models, and promote co-ordinated avalanche research efforts for optimal results with reduced costs. At present, all the invited participants have reacted positively to the initiative.

In addition to model extension into two horizontal dimensions and comparison of certain existing models, the programme will focus on an improved understanding of avalanche dynamics including flow-regime transitions, validation of the modelling approach (including stability and accuracy of the applied numerical methods) and calibration of the parameters.

Explicit studies of erosion and deposition processes will hopefully be satisfactorily examined by the programme described above. We believe that both these projects can benefit from each other. We also hope that the latter project can be adapted to, or form a subproject of, a possible continuation of the EU program SAME.

4 MODELLERS' NEEDS

(C.B. Harbitz)

In each experiment, the following parameters are to be supplied or measured for the purpose of model development and validation: Digital terrain data at sufficient resolution, release zone boundary and height, (longitudinal) velocity distribution/frontal velocity, deposition zone boundary and height, density values for release and deposition zones, snow cover profiles, velocity and density profiles (perpendicular to the ground), velocity fluctuations, flow height and extension, suspension rates from dense to powder component, entrainment and mass balance, basal roughness (for ground avalanches), impact pressures on large obstacles and small objects (for stagnation pressure), (thermodynamic) temperature, debris distribution in deposition zone (granulometry), seismic signals, acoustic signals.

Much of the specified data can be used for validation, not just for future model development.

The required parameter precision for model verification is listed in Table 5.2. For further details the reader is referred to the SAME report on European avalanche test sites (Issler, 1998). Priority and ease of each measurement is described in Table 4.1.

Table 4.1: Priority and ease of measurements. Measurement easy (A) to hard (D). Priority high (1)to low (3), Ø: measurement not required. Types of models explained in Harbitz (1998).

	Experiments																	
Type of model	Initial flow height	Release zone boundary	Frontal velocity	Dynamic flow height	Deposit mapping and volume	Flow width	Long. Velocity distrib.	Velocity profiles	Density profiles	Entrainment	Velocity fluctuations	Particle size distrib.	Dynamic stagn. Pressure	Density distrib.	Vertical mass flux	Snow pack properties	Dynamic stresses	Seismic/ Acoustic signals
	B	A	B	A-B	B	A	B	B-C	B-C	B-C	C	A	B	C	D	B[1]	B	A
2D depth av. dense flow[2]	1	1 area	1	1-2	1	1	1-2	1	3	1	Ø	3	2	2-3	Ø	1	2-1	Ø
1D depth av. dense flow	1	1 length	1	1	1	Ø	2	1	3	1	Ø	3	2	2-3	Ø	1	1	Ø
3D dense flow model[3]																		Ø
Sliding block model VS	1	1	1	Ø	1 distance	1	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø	1	1	Ø
Sliding block model PCM	Ø	1	1	Ø	1 distance	Ø	Ø	Ø	Ø	3	Ø	Ø	Ø	Ø	Ø	1	1	Ø
3D Powder	1 suspension	1	Ø	2	1	1	1	1-2	1-2	1	2	3	2	1-2		1	1 if separate Ø otherwise	Ø
1D powder	1	1	3	1	1	Ø	1	1-2	1-2	1	2	3	2	1-2	1	1	1 if separate Ø otherwise	Ø
Coupled models	1	1	Ø	1	1	1	1	1-2	1-2	1	2	3	2	1-2	1	1	1	Ø
2D granular models	1	2	1	1	1	Ø	1	1	1	Ø	1	1	2	1	Ø 1 if input to gran. models	1	1	Ø
3D granular models	1	1	1	1	1	1	1	1	1	Ø	1	1	2	1	Ø 1 if input to gran. models	1	1	Ø
Seismic/ acoustic studies	1	1	1	2	1	1	1	2	1	2	Ø	Ø	1	2	1	2	1	1

1) Characterisation of properties useful in a qualitative sense to guide parameterisation.
2) Future development of depth averaged models will introduce layering.
3) Information on French 3D dense flow model needed from M. Naaim, CEMAGREF

5 EXPERIMENTAL TECHNIQUES AND PROPOSAL FOR SET-UP

(H. Schaffhauser, D. Issler and C.B. Harbitz)

Both for the small (Monte Pizzac, Col du Lautaret) and the large sites (Ryggfonn, Vallée de la Sionne), minimum equipment to comply with modellers' needs (above) is determined to comprise three locations (preferably, upper track, lower track, run-out zone) heavily instrumented for detailed measurements of variables that reveal the main mechanisms at work in avalanche flows. These locations should be chosen so as to capture significant changes in the flow regime, e.g., break-up of the original slab and transition to a partly fluidised regime, later on the formation of a significant saltation and suspension layer, and finally the transition to a quasi-block-flow mode.

In addition to these spatially localised but temporally extended measurements, spatial information is needed for the initial and final conditions, i.e., the released and the deposited volume and mass. Finally, spatio-temporal measurements (trajectory, front velocity along the path, evolution of spatial distribution of internal velocity, etc.) are needed and require still other experimental techniques.

Tab. 5.1 summarises by which experimental techniques each physical quantity can be measured. Before presenting the proposal for equipping the small and large experimental site, the potential and limitations of available techniques are outlined. For more information, the reader is referred to the SAME report on experimental techniques (Schaffhauser, 1998).

5.1 Comparison of measurement techniques

Snow properties: Density, strength, layering and texture, temperature etc. are best determined by manual surveys. An automatic weather station in the release zone is useful for choosing the best moment for artificial release, but is not absolutely necessary. If the decision whether or not to launch a campaign is based on data from a distant observation point extrapolated to the release zone, critical assessment is needed so as neither to loose potential events nor to spend too many resources on unsuccessful release attempts.

Release parameters: Manual surveys after the release are required for determining the snow density, but incomplete information on the released snow depth is obtained, leading to large margins of error in estimating the released mass. For small, accessible release zones, snow stakes distributed over the potential release zone yield good information (±10–20%) if properly fixed. In large release zones, aerial photogrammetry is presently the only effective technique, but others may become competitive in a few years (terrestrial laser scanners, airborne laser scanners combined with high-precision Global Positioning System). Tests showed that total released mass in a large avalanche may be measured to about ±20–30% with aerial photogrammetry in good weather conditions. When aerial photogrammetry is not possible, terrestrial photogrammetry may be used to accurately determine the height of the fracture crown; the achievable precision for the release mass then drops to about ±50 %.

Deposit volume and properties: Photogrammetry is useful for large avalanche deposits (better precision than in release zone), but manual surveys are equally necessary for learning about the flow regime in the late phase of the avalanche and for studying particle-sorting effects. Photographing and then post-processing is the most obvious and time-efficient method for studying debris distribution.

Avalanche trajectory and front velocity: Video filming and terrestrial photos are adequate if a sufficient number of well-measured reference points are visible. The precision of the methods has not been evaluated quantitatively yet, but is believed to suffice for model validation.

Methods based on time lag between arrivals at fixed locations only give a quite limited number of front velocity values. The obtainable precision is proportional to the measurement or sampling frequency and depends inversely on the distance between the measurement points. This also holds for measurements with pulsed Doppler radars if signal appearance in different range gates is exploited. Doppler radar data and topographical information can be combined to obtain a typical avalanche velocity as a function of time or path length; however, ambiguities exist in the procedure and experience is needed for obtaining meaningful results. Based on experience from SFISAR's measurements at Val Medel, a precision of 5–10% of the maximum velocity may be expected for the front velocity; the localisation of the avalanche front from Doppler radar data alone should be within ±50 m, maybe better.

Longitudinal velocity distribution: A remote-sensing technique based on electromagnetic waves is needed. Doppler radar is the only currently available technique that can survey substantial portions or all of an avalanche. Information from pulsed Doppler radars with several range gates is more easily interpreted than data from continuous-wave Doppler radar where distance information is largely missing. *Ka*-band Doppler radars should be capable of measuring internal velocities in powder-snow avalanches. It was determined that such measurements are desirable, but not absolutely necessary in a small site.

Currently available systems in the SAME collaboration:

- SFISAR's continuous-wave Doppler radar system dates from the early 1980s and is now in use at the Vallée de la Sionne site. It consists of 3 emitters/receivers and 1 emitter with 2 receivers. The system works in the *X* and *Ka*-bands; typically 3 parabolic antennas and 2 wide-angle antennas are used. The useful range of the antennas varies from 0.5 to about 2–2.5 km.
- FBVA–AIATR uses a modern mobile pulsed Doppler radar system built at TU Graz–INW. The original *C*-band system has been enlarged by a *Ka*-band antenna. The maximum range is of the order of 2–2.5 km. The minimum length of the range gates is 50 m.

The location of a Doppler radar system has to be chosen carefully. The main requirements are (i) Visibility of the entire path, without obstruction from potentially moving objects like branches of trees, etc. (ii) Distance large enough for the entire path to be visible within the useful angle of aperture of the antenna, yet within maximum range of radar (typically 2–2.5 km). (iii) Angle between flow direction of avalanche and line-of-sight as small as possible. (iv) Adequate protection from powder-snow avalanches or other avalanche paths.

Table 5.1. Overview of the physical quantities that can be measured by the available experimental techniques.

	Flow variables																
Exp. technique	Snow pack properties	Release height	Release area	Deposit mapping / volume	Flow width	Dynamic flow height	Frontal velocity	Long. Velocity distrib	Velocity profiles	Velocity fluctuations	Density distribution	Dynamic stagn. pressure	Dynamic stresses	Entrainment	Vertical mass flux	Particle size distribution	Seismic/ acoustic signals
Manual survey	Yes	point-wise		large effort	max. width only									local balance before/after			
Weather station	partial information																
Snow stakes		small sites															
Photogrammetry.		±20-30 cm	yes	yes	max. width									local balance before/after			
Video / photo			yes	area only	yes		yes										
Doppler radar							pulsed radars only	Yes			In PSAs?						
FMCW radar	Layering (crude)					Yes	locally (pairs)		yes (if pairs)	< 1 Hz only				local entrainment rate	indications from Doppler mode		
Load cells						very crude				Partial information		yes	yes			partial information	
Strain gauges										Partial information		indirectly	partial information				
Switch array						Yes											
LED array						crude information			yes	Yes				indication of rate			
Capacitance probes						crude information	marginal		yes	Yes	yes	indirectly		crude information		partial information	
Geophones							epicentre velocity										yes

Velocity profiles: All presently available techniques for velocity profiles are based on cross-correlation techniques for two or more sensors arranged some distance apart in the flow direction: The average time lag of characteristic signals (from single snow particles or blocks) between two detectors at the same height determines the average velocity in that layer. The methods based on opto-electronics and capacitance probes use vertical arrays of 5–10 pairs of sensors whereas the frequency-modulated continuous-wave (FMCW) radar method only needs two radars entrenched perpendicular to the surface. It is proposed to install at least 3 pairs of such devices, depending on the length and topography of the path.

The opto-electronic method is based on light-emitting diodes (LEDs) and photo cells receiving the reflected light. It detects the motion of small structures ($O(1\text{ cm})$) over short distances ($O(10\text{ cm})$). Such devices can be installed at low cost, but the precision of th efront speed detection suffers from the narrow spacing in the flow direction. Capacitance probes can be built in various sizes; for application in avalanche dynamics, sensor sizes $O(10\text{ cm})$ and spacing $O(1\text{ m})$ in flow direction will be preferred. (The main use of capacitance probes is in measuring densities, see below.). Both methods require a support structure protruding into the flow. They have been successfully applied by Dent et al. (1998) in the U.S. The accuracy of such density measurements is not known for moving snow but is expected in the range ±20%.

FMCW radars detect the (electromagnetic) distance to layers where the index of refraction changes. These distances are proportional to the signal travel time and thus to the frequency difference between the received signal and the presently emitted signal. Selecting narrow ranges of frequency differences, specific layers in the snow pack (10–20 cm) can be singled out and used for cross-correlation between two radars located 5–10 m apart in the flow direction. The detected structures are $O(0.1\text{–}1\text{ m})$. SFISAR successfully applied the method at its Val Medel site and has now installed three pairs of FMCW radars at Vallée de la Sionne. Further information obtainable from FMCW radars is discussed below.

Velocity fluctuations: The *distribution* of the vertical velocity, integrated over the flow depth, can be measured by alternately running an entrenched radar in FMCW and Doppler mode. However, noise problems reduce the sensitivity for small velocities. Alternative data analysis techniques for pure FMCW radars are being developed. Horizontal velocity fluctuations are best measured with LED sensor arrays or capacitance probe arrays where available, but FMCW radar may also be used for low-frequency fluctuations.

Flow height: Crude values (±50 cm) can be obtained from vertically arranged arrays of sensors, e.g., load cells or LED sensors. Arrays of electro-mechanical switches have been successfully used at Monte Pizzac and give more precise information (±5 cm under ideal circumstances). With estimated density values, entrenched FMCW radars also yield the time evolution of flow depth in the dense-flow layer (±10 cm). The height of a powder-snow cloud can be obtained from video recordings; however, more research is needed into the precision of video measurements.

Dynamic pressure: A large body of experience is available for pressure measurements in avalanches. Electro-mechanical load cells are adequate at not too high frequencies. For resolving impacts of single snow blocks (studies of internal structure of avalanche, impact pressure fluctuations), piezo-electric load cells sampled at $\geq$ 10 kHz are preferred. Commercially available piezo-electric load cells are expensive; piezo-electric plastics (PVDF) may lower the cost in the future. Poorly damped high-frequency vibrations of the load cell mounting can seriously perturb measurement accuracy.

In powder-snow avalanches, stagnation pressure as well as ambient-air pressure should be measured at several heights above ground. Pitot tubes have been installed in Austria and Japan, but clogging is an open problem. Load cells are suitable for measuring stagnation pressure (up to a correction factor), while ambient-air pressure can be determined for example with membrane-based manometers. Approximate density profiles can then be obtained by combining these pressure measurements.

Density: Snow-cover density is measured manually along the path. Capacitance probes tested by Louge *et al.* (1997) presently appear as the most promising way of directly measuring the density of flowing snow, despite their high price. Approximate densities can also be obtained by combining impact-pressure measurements on load cells with velocity-profile measurements at the same location; difficulties related to the particle-size dependence of impact pressures and the strong fluctuations need to be solved, however.

Stratification and vertical mass flux: FMCW radar pairs in combination with load cells to 20 m should suffice for separating the dense-flow, saltation and suspension layers and to study the flow patterns in mixed avalanches. No methods for directly measuring vertical mass fluxes between layers are currently available. Density profile measurements at several locations and at least some indications of vertical fluctuation velocities will allow more indirect validation of multi-layer models, however.

Thermodynamic temperature: At present, thermodynamic temperature during or immediately after an event is not measured at any site. Serious difficulties arise from the long reaction times of temperature probes. Infrared thermometers are expected to measure the temperature of the liquid layer on snow grain surfaces. Hence, it is very difficult to estimate flowing temperature. Measuring the temperature in the deposits rapidly after the event is desired. A probe with several temperature sensors (±1°C) may be useful for field work, perhaps a ”fork-like” type of construction.

Basal roughness: At present not measured at any site. Best determined by taking photographs during survey after event.

Snow entrainment/deposition: A consistency check for the overall mass balance of the event can be obtained from manual measurements of eroded and deposited snow depths and densities along the entire path, as already carried out at Monte Pizzac in 1997/98. Photogrammetric surveys are not believed to give good results in the track because the entrained and deposited snow usually have widely differing densities.

Series of simple snow pits along the path reveal important information on the local mass balance (before/after the event) and give hints on the topographical dependence of snow entrainment. Application of suitable tracers at carefully chosen locations will help distinguish the undisturbed snow cover from the deposits of dry-snow avalanches and give information on the trajectories of single snow particles. However, such procedures can be carried out in small sites only. For the interpretation of the results, additional measurements near the snow pits—in particular, velocity profiles and flow depths—are extremely useful.

Rough estimates of the entrainment *rate* can be obtained from LED (±50%) or capacitance-probe arrays by comparing the time of onset or end of movement at different layers; the vertical distance between sensors must be small, however. By far the best instrument for this purpose is FMCW radar because layers at rest can easily be distinguished from moving snow in bitmap representations of time series of radar spectra. The entrainment or deposition rate can be directly read off suitable plots to about ±20%. It is best to use the radars in pairs so that velocity profiles can be obtained at the same location.

Particle-size distribution: Manual investigation of the deposits is the simplest method for studying segregation effects and the like, but information is obtained only on the final phase of the flow. Video recordings allow estimates of the particle sizes at the flow surface, provided no powder-snow cloud forms. A more indirect method combines velocity profile measurements with high-frequency impact pressure profiles: A large number of single impacts have to be identified and analysed in the high-frequency pressure recordings.

Assuming that particle velocities do not differ too much from the average values obtained from the velocity profile, the momentum transfer during the impact divided by the velocity gives the particle mass. Corrections for break-up of blocks much larger than load cells should be made.

Seismic or acoustic signals: Geophones or special low-frequency microphones have been tested at many sites. Although they give less precisely interpretable information than most other measurement techniques, it is recommended to install them in the track and somewhere outside, e.g., at the observation point. Geophones have been successfully used for triggering measurements on spontaneous avalanches; acoustic goniometry allows to investigate the avalanche activity in an extended region. Combining these measurements with other techniques will lead to improved understanding of the processes leading to seismic and acoustic signals and will help to develop these systems to reliable monitoring devices.

5.2 Instrumented structures

Many of the practical problems in avalanche dynamics concern the interaction of avalanches with man-made structures, as discussed in Section 2.1. An in-depth study of shock phenomena in moving snow, combining theoretical analysis and laboratory experiments, will be needed to fully understand the problem. Meanwhile, avalanche test sites offer the opportunity to study typical situations and to obtain order-of-magnitude values even if the details of the interaction are not well understood or their complexity defies calculation from first principles. A number of such experiments have been carried out at NGI's Ryggfonn site, and several structures were constructed and instrumented at SFISAR's Vallée de la Sionne site.

In view of this situation, there appears no need to specify which structures should be installed at the future large European test site. Since both candidate sites are well equipped in this respect and will continue operation, useful data will be collected in any case.

There are several reasons why it is less desirable to have large man-made structures at a small test site:

1. The flow is significantly perturbed by obstacles of similar width as the avalanche itself, so measurements beyond the large obstacles are not likely to be meaningful with respect to the flow regimes in the late phase of avalanches.
2. The cost of the structures is somewhat lower than at a large site but still very high. Given that such measurements are carried out at two large sites, the extra data to be expected does not appear to justify the high cost of the necessary equipment.

5.3 Proposed set-up of experimental site

Based on the assessment of Section 5.1, both the small and large test sites should feature three or more locations (comprising the upper track, lower track and run-out zone) well equipped for detailed measurements of internal flow variables. In addition, surveying techniques for determining snow-pack properties, released and deposited mass, and the flow trajectory have to be set up.

A wide array of sensor types is needed to perform all the necessary measurements. Chief among them are manual measurements after an avalanche release, video observations, capacitance probes (replaceable by LED sensors at the expense of losing important density information), (high-frequency) load cells, and FMCW and Doppler radar. Obstacles will mainly be instrumented with resistance strain gauges. At the large site, photogrammetry, Doppler radar and capacitance probes should be installed at any rate. Table 5.2 summarises the proposed standard of equipment.

FMCW radar and capacitance probes both allow measurement of important quantities that cannot be directly obtained in comparable quality by other, less expensive methods. Doppler radar is another measurement technique that also contributes significant and unique information. The availability of mobile Doppler systems (TU Graz–INW) makes it possible to use an existing system at more than one site, albeit with some uncertainties related to the transport of the system.

Attention has to be paid to the proper construction of the *instrument supports* at the three or more locations where detailed measurements are performed. The main requirements are the following:

- Dimensioning to avalanche impact pressures on the order of 0.5–1 MPa, on the basis of experiences from earlier experiments.
- The flow should be disturbed as little as possible, thus the width of the support structure must be minimised.
- The front can be instrumented with load cells whereas arrays of electro-mechanical switches, LED sensors and capacitance probes can be installed on the sides of the instrument support. To this end, the support should be at least 1–2 m long (in the flow direction).
- At sites with powder-snow avalanches, pressure and density measurements should be carried out to about 10 m in the upper track and to about 20 m in the run-out zone, if possible. Above the dense avalanche core, pressures diminish rapidly.
- High-frequency vibrations of the supporting structure can induce spurious pressure measurements and need to be taken into account.

It should be noted that the pressure measurements need to be compared to velocity (profile) measurements; thus the support structure is best constructed a little downstream (about 10 m) of the entrenched FMCW radar pair.

Table 5.2. Recommended equipment of small and large European avalanche test sites with comparison of achievable vs. desired measurement precision

	Experimental technique			Precision required by modellers
Parameter	In small site	In large site	Estimated precision	
Digital terrain model (DTM)	From good map or else by photogrammetry		Precision depends on quality of maps or photos	Dense snow: 10 m in open slope, 25 m if channelled. Powder-snow avalanches: 25 m Wet-snow avalanches: 2–5 m
Snow pack properties	Manual measurements	Manual measurements; automatic weather station in release zone desirable		Qualitative measurements presently sufficient
Release height, area and volume	Snow stakes	Photogrammetry	Crown line ±20 cm, release height ±20–30 cm	Sampling points every 5 m. Height: ± 30%, ± 30 cm (the more stringent), area: ± 5% , released mass: ± 30%
Deposit mapping	Manual measurements	Manual measurements and photogrammetry	Boundary to ±10 cm, deposit height ±10–20 cm	Sampling points every 5 m. Form: ± 2%, height: ± 30%, ± 30 cm (the more stringent). Granulometry of deposits.
Flow trajectory	Video		± 5 m (estimated)	A few percent of avalanche width
Dynamic flow height	Switch arrays at ≥ 3 locations	Switch arrays or FMCW radar at ≥ 3 locations; video for powder-snow avalanches	Switch arrays: ±5 cm; FMCW radar: ±10 cm	Time series to ± 10%
Frontal velocity	Video; (pulsed) Doppler radar desirable	Video and pulsed Doppler radar	Video ± 5–10% (estimated), time-of-passage ± 1%	± 5% at 5-10 points with precision of position 100 % of DTM
Longitudinal velocity distribution	(Pulsed) Doppler radar desirable	(Pulsed) Doppler radar	± 2 m/s	Velocity distribution of powder-snow cloud along path to ± 5%
Velocity profiles	Pairs of FMCW radars or arrays of LED sensors or capacitance probes at ≥ 3 locations		FMCW radar: Vert. resol. 10–20 cm, vel. to ± 5–50%. LEDs/capacitance probes: Vert. resol. 0.1–1 m, vel. to ± 5%.	± 10%, include transition to powder snow if possible, focus on bottom of flow. 7-10 measurements with a log spacing vertically
Velocity fluctuations	LED arrays at ≥ 3 locations	LED or capacitance-probe arrays at ≥ 3 locations	To be determined	± 20% (components of granular temperature), temporal resolution of 10 kHz
Density profiles	Capacitance-probe arrays desirable at ≥ 3 locations	Capacitance-probe arrays at ≥ 3 locations	± 10–30% expected, depending on density	± 20% , temporal resolution of 10 kHz
Stagnation pressure	Load cells at ≥ 3 locations		± 5% if vibrations of support structure accounted for	± 10%, at each site, 5-10 sensors at 15 kHz. Information combined with velocity for characterising granular temperature
Dynamic stresses	Load cells and manometers at ≥ 3 locations, strain gauges flush with ground		± 5% (typically)	Shear stresses at ground near measurement points of velocity and density profiles
Snow entrainment and deposition	LED arrays or FMCW radars and manual measurements at ≥ 3 locations	FMCW radars and manual measurements at ≥ 3 locations	Erosion rate: ± 50%. (LED arrays), ± 20% (FMCW radar): Global mass balance to ±10% of initial mass.	Mass balance at representative points. Erosion rate at locations with velocity profiles, normal/shear stresses and flow-depth measurements
Particle-size distribution	Manual measurements in deposits, photographed profiles	High-frequency load cells, FMCW radars and capacitance probes, photographed profiles in deposits	Qualitative results; further development of technique required for more detailed results.	Qualitative results only at present stage of model development
Seismic signals	Geophones at 3 locations		Explosion point to ± 10 m from video	Position of explosive charge ± 10 m. Include explosion in video
Acoustic signals	Microphone array at 1 or 2 locations			
Basal roughness	Field measurements and photos		Qualitative results	Useful for ground avalanches
Thermodynamic temperature			Question on possibility	Desirable

The *data acquisition system* has to fulfil rather demanding requirements:

- Large number of data channels with high sampling rates (30–50 kHz for radars, 20–30 kHz for LED sensors and capacitance probes, 10–20 kHz for high-frequency pressure measurements).
- 100–300 Mbytes of data per avalanche to be stored in a short time, in order to be ready for next event.
- Analogue/digital conversion should be made near the sensors at the large site due to long distance from uppermost sensors to observation point.
- Reliable and efficient communication between sensors and master computer at observation point.
- Adequate protection against lightning and mechanical damage to data or power cables.

Experience at Vallée de la Sionne shows that these requirements can be met by appropriately combining commercially available hardware with a custom-made data acquisition and command program. However, the required cost and effort must not be underestimated.
T The proposed general set-up of the European avalanche test site is schematically represented in Fig. 5.1. It should be noted that some simplifications will be possible for a small site since the distances are short enough to allow transmission of analogue signals; thus computers or powerful loggers in well-protected caverns near the sensors are not required for small sites.

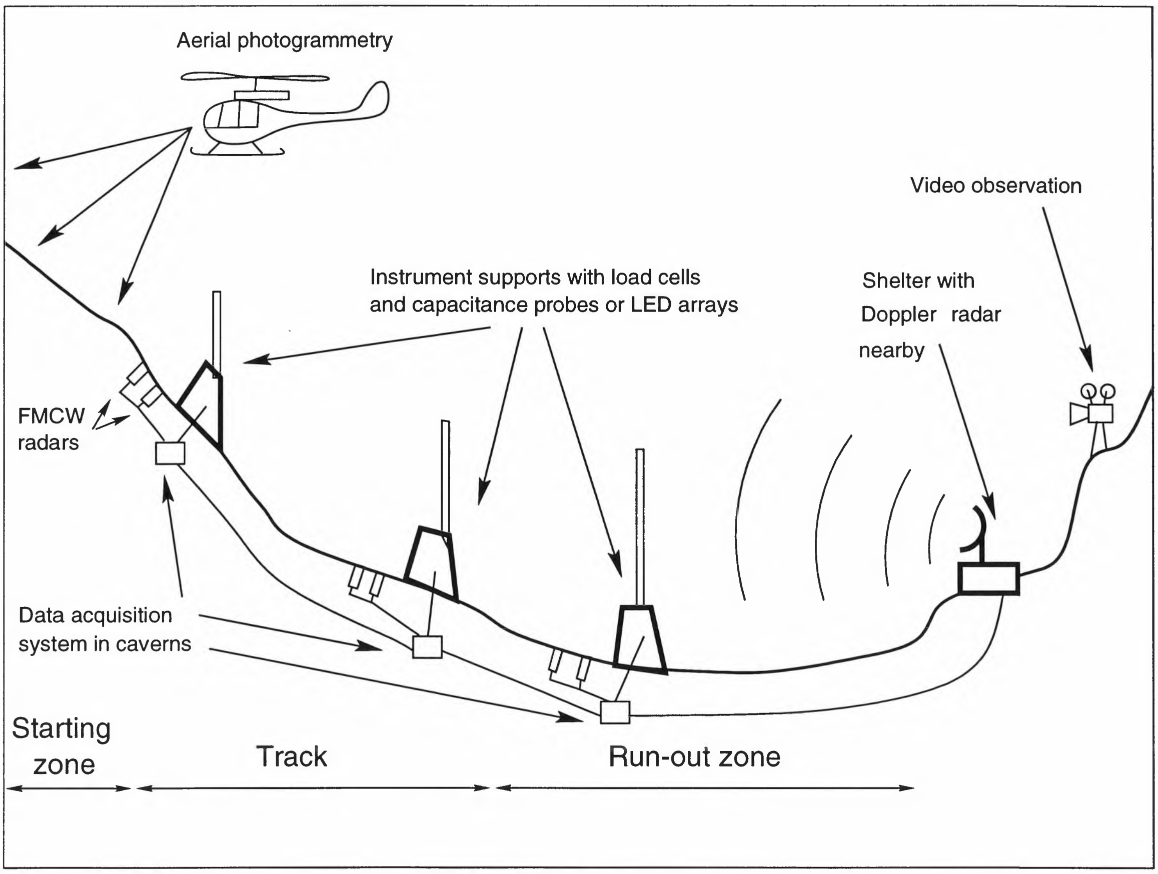

Figure 5. 1. Schematic view of the set-up of large experimental site with 3 instrument support structures in different sectors of the path and a shelter at the foot of the opposite slope.

6 SITE REQUIREMENTS

(D. Issler and H. Schaffhauser)

Requirements on equipment-independent site properties may be formulated as follows:

- Test path representative of typical “problem paths” with respect to size, altitude, topography, terrain roughness, wind exposition, etc.
- Frequent occurrence of all relevant flow types (dry and wet avalanches, at large sites also mixed avalanches).
- Avalanches observable from beginning to end.
- Safe and quick access to observation points in avalanche situations.
- Reliable securing of path and surroundings achievable so that manual measurements can safely be made in the field after a successful release.
- Highly effective techniques of artificial release applicable.
- Possibility of building sensor supports and representative obstacles in the path, shelter for experimental crew near path.
- Adequate infrastructure (transportation, lodging, working space, communication lines) for extended campaigns with participants from several institutions.
- Frequent surveys of site assured during wintertime.

An important question is whether a test site should present a simple topography (e.g., an open slope with smooth slope-angle changes) or a more demanding one. The first case can be handled by all models and allows studying the basic effects such as friction, lateral spreading, etc. without the interference of channelling or curvature effects. In the second case, we might have, e.g., a large, funnel-like starting zone, a confined track with bends, and an open run-out slope. The most simple-minded models cannot be subject to a meaningful parameter fitting or test at such a site. Simultaneous detailed measurements of several variables would be needed to unravel the reason for discrepancies between model predictions and experimental results.

The present level of model development favours moderately complicated topographies: For dense-flow avalanches, there are several quasi-three-dimensional models and models based on more sophisticated rheological laws awaiting in-depth validation; the same holds for the three-dimensional powder-snow avalanche models available today. Moreover, practical problems often involve moderate topographical complications. A test path containing some interesting topographical features would therefore be ideal. For the validation of powder-snow avalanche models, a run-out zone with an opposing slope would be useful (verification of run-up prediction). Extreme situations like a high vertical cliff or a gorge virtually blocking the avalanche should be avoided, however. Furthermore, the analysis becomes unduly complicated if topographical influences like bends or channelling coincide.

At most sites (at sufficiently high elevation) avalanches are dry in mid-winter and wet in the spring, thus different flow behaviour of dense-flow avalanches can be studied. Mixed avalanches with a substantial fraction of suspended snow occur more frequently at high altitudes where the snow is dry and light. Steep terrain also favours the suspension of snow. Typically, a long track is required for frequent formation of powder-snow avalanches.

With respect to the nivo-meteorological properties of the site, certain compromises are likely to be necessary. In particular, in the Alps the most frequent snow storms are brought about by north-westerly winds from the North Sea. The highest accumulation rates are thus encountered in south to east facing slopes due to strong snow drift effects. The pronounced short-wave radiation intake of such slopes reduces the time window for successful artificial release of large avalanches, however. In the Southern Alps, leeward slopes are typically exposed to the north, but snow storms are somewhat less frequent (albeit often very strong) and the climate is generally more maritime at higher temperatures, favouring wet-snow avalanches. For any proposed site, long-term records of avalanche occurrence would be extremely useful, and the climatic conditions and the local wind system should be studied. It is suggested to consult weather-radar records of precipitation intensity in winter to gain a clearer picture of the release depths to be expected. In addition field studies of the snow-cover evolution in the potential starting zones (or equivalent nearby slopes) would be very useful.

Several aspects determine the accessibility of a site in avalanche situations: First, there must be good, rapid connections by train, car or aeroplane to a settlement near the site so that all partners in the joint experiments arrive in time. Second, the experimental crew must be able to reach the observation point (shelter, etc.) within a short time even under conditions of high avalanche risk. Third, safe access to the entire path for in-situ measurements of avalanche deposits etc. after an event is important; this means that the risk of later avalanches in the same path can either be excluded for topographical and snow-mechanical reasons, or else effective methods for clearing secondary branches and critical spots on the way to the path must be available. For a large site, helicopter assistance is likely to be needed for surveying, artificial release, photogrammetry before and after the release, and transport of the field crews to the track and release zone; the considerable cost of this service is significantly reduced if there is a heliport nearby.

Regular surveys of the site by an experienced person and tests of the instruments are required for assessing the chances of success of a campaign and to guarantee the proper functioning of the experimental equipment.

It must not be expected that a site can be found that fulfils all these requirements perfectly. In particular, there is no location that can be reached with moderate effort by all partner institutes. Many otherwise promising sites cannot be considered because artificial release is not allowed due to legal restrictions or potential damage to forests or roads. Construction of instrumented structures for studying avalanche impacts is strongly restricted in many places.

7 SELECTION OF SITE

(D. Issler and C.B. Harbitz)

In all partner countries, large avalanches (order of 100 000 m^3) are a serious threat that requires attention due to their enormous destructive potential. Smaller avalanches (order of 10000 m^3) are much more frequent in all countries. In Italy, Spain and France, they are considered more important overall than large avalanches.

It was determined that both large (10^{4-5} m^3) and small (10^{3-4} m^3) avalanches need to be studied. The advantages of working at a small site are ease of (safe) observation, rapidity of surveying, the possibility of performing many types of experiments that are too time-consuming on large sites, cheaper site development and possibly a larger number of observed events. A large site is necessary for studying fully developed powder snow avalanches. Besides, the combination of large and small sites makes it possible to study the scale effects. Hence, it is proposed that both a large and a small site will be equipped.

Other strong arguments for equipping more than one site are a very restricted number of avalanches to be expected in each site every season, the uncertain time of occurrence that makes it difficult to be at the spot on time without long periods of waiting, the differences in climate, weather, snow conditions, and consequently flow regimes from one place to the other, and finally the differences in topography, protective measures, etc. in each site.

Two large sites, Ryggfonn (Norway) and Vallée de la Sionne (Switzerland), and two small sites, Col du Lautaret (France) and Monte Pizzac (Italy) were finally left to compare and contrast for co-ordinated experiments. In Núria (Spain), where the avalanches are released in the ski resort, it is not possible to install additional equipment and the snow is unreliable. The avalanche occurrence in the Austrian test site is too infrequent and no explosive release is allowed. Ryggfonn (Norway) and Vallée de la Sionne (Switzerland) will both keep running regardless of their status concerning co-ordinated experiments, it is rather a question of extension and complexity of experiments.

It was agreed to write a purely scientific proposal, weighing the advantages, disadvantages and cost of equipping the candidate sites. These have to be key elements in the final site selection process, which will, however, also have to include political aspects. Under any circumstances, the final selection has to be postponed until mutual agreement on the scope, participants and organisation of the collaboration has been established.

The selection process should be based on the *potential* of the sites rather than on their current equipment. The general characteristics of the avalanche path, its relevance to practical problems and to the scientific objectives of the programme, the frequency of events, the accessibility of the site, and the question of building and artificial release permits are chief among the criteria to be applied.

The following Tables 7.1–7.4 summarise information compiled in the SAME report on existing avalanche test sites (Issler, 1998). Table 7.1 follows the criteria established above and shows that

- none of the sites is easily accessible for all the prospective partners, with Ryggfonn being very distant for almost all partners;
- the two small sites fulfil all the relevant criteria and differ mainly in the complexity of their path geometries;
- the two large sites are quite comparable in most respects. The proven avalanche record is a strong point in favour of Ryggfonn until more experience has been gained at Vallée de la Sionne, which is far more accessible, however.

Table 7.2 gives an overview of the strong and weak points of each of the four sites. In the final decision, however, the advantages and disadvantages of *combinations of a large and a small site* will be decisive. Table 7.3 lists our assessment. The following conclusions can be drawn from that table:

1□The combination Vallée de la Sionne / Col du Lautaret is the least favourable because path characteristics do not clearly complement each other, campaigns may often coincide in time, the access distances are not so well balanced among the prospective partners, and the avalanche frequency at Vallée de la Sionne is not known yet.
2□The path characteristics of Monte Pizzac complement those of either large site in an interesting way, favouring Monte Pizzac somewhat over Col du Lautaret.
3□The final decision will have to take into account the contributions of each partner institute to the joint experiments at the small and the large site because access time can be critical.

Finally, Table 7.4 shows to which degree the four sites are equipped at present. It is strongly recommended that this not be used as a main criterion in the site selection process: As will be seen in Section 8, the cost differences for equipping to the established standards are significant but not overwhelming.

Table 7.1: *Comparison of four avalanche test sites with respect to their potential on the basis of geographical location, topography and land-use restrictions*

	Col du Lautaret	**Monte Pizzac**	**Vallée de la Sionne**	**Ryggfonn**
Representativeness				
• Path characteristics	Small to medium avalanche, moderately channelled	Small to medium avalanche, strongly channelled	Large avalanche, partly channelled	Large avalanche, partly channelled
• Path typical of:	Many high-elevation avalanches	Many moderate-elevation avalanches	Large Alpine avalanches	Large Nordic and many Alpine avalanches
Avalanche types and frequency	Dry and wet DFAs, early stages of PSAs; high frequency	Dry and wet DFAs; weak powder-snow part possible	Dry and wet DFAs, large PSAs; frequency not known yet	Dry and wet DFAs, mixed avalanches; high frequency
Surveyability of path	Very good	Good except for small segment	Good except late run-out near river	Good except parts of starting and run-out zones
Accessibility	Rapid, safe access from Grenoble, some problems with access to shelter	Immediate, excellent access from CVA; Arabba may be difficult to reach for other partners	Rapid access from Sion, but far from Davos. Helicopter required. Big effort required for safe access to slope.	Far from Oslo, very far from other partners. Access to release zone questionable.
Release techniques	Effective (Gaz.Ex)	Effective (Cat.Ex) but not controlled by CVA	Effective in good weather (helicopter), questionable in bad weather (mortar)	Effective (preinstalled explosives)
Upgrade possibilities	Negotiable	Strongly restricted	Additional sensors and structures	Additional sensors and structures

Table 7.2: Advantages and disadvantages of the candidate sites for co-ordinated European avalanche experiments

	Advantages	**Disadvantages**
Col du Lautaret	+ All types of avalanches + Sufficient avalanche frequency + Very good view onto path + Good accessibility, infrastructure and safety	– Very simple path geometry – Long distance from other research centres
Monte Pizzac	+ Strongly channelled path with turns and slope changes, interesting for detailed studies + Good avalanche frequency + Excellent conditions for field work (tracer experiments) + Excellent accessibility from Arabba, infrastructure and safety	– No well-developed powder-snow avalanches – Timing of release attempts not controlled by CVA – Access from outside may be difficult in avalanche situations – Long distance from other research centres
Vallée de la Sionne	+ Large and interesting path typical of the Alps + All types of avalanches + Large range of avalanche sizes + Excellent possibility for studying impact on structures	– Avalanche frequency unknown. – Helicopter required for access to shelter, artificial release and field measurements – Long distance from other research centres – Tracer experiments difficult – Extreme run-out zone hidden from shelter
Ryggfonn	+ Large path typical of nordic avalanches + Long-time record of good avalanche frequency + All types of avalanches + Large range of avalanche sizes + Excellent possibility for studying impact on structures	– Safety problems during field investigations – Very long distance from other research centres – Tracer experiments difficult – Significant fraction of path hidden from (radar) observation point – Unnatural run-out behaviour due to retaining dam

Table 7.3: Advantages and disadvantages of combinations of a small and a large site for co-ordinated European avalanche experiments

Sites	Advantages	Disadvantages
Col du Lautaret / Vallée de la Sionne	+ All types of avalanches on both sites + Sufficient avalanche frequency at Col du Lautaret + Rapid access to both sites from Grenoble	– Somewhat similar topgraphies – Similar climatic situation (simultaneous campaigns!) – Avalanche frequency at Vallée de la Sionne unknown – Helicopter required at Vallée de la Sionne
Col du Lautaret / Ryggfonn	+ All types of avalanches on both sites + Good overall avalanche frequency, effective artificial triggering at both sites + Sites complement each other with respect to climatic conditions	– Quite similar topographies – Ryggfonn very far from other research centres – Unnatural run-out behaviour due to retaining dam at Ryggfonn
Monte Pizzac / Vallée de la Sionne	+ Complementary topographies + Complementary climatic conditions + Reasonably balanced access times for most partners	– Avalanche frequency at Vallée de la Sionne unknown – Helicopter required at Vallée de la Sionne
Monte Pizzac / Ryggfonn	+ Complementary topographies + Complementary climatic conditions + Long-time record of good avalanche frequency	– Very long distance from other research centres – Unnatural run-out behaviour due to retaining dam at Ryggfonn

Table 7.4: *Needs for additional equipment at the four candidate test sites. The requirements are based on the recommended standards elaborated at the SAME workshop in Davos. CPA: capacitance-probe array; LED: light-emitting diode*

<table>
<tr><th></th><th>Col du Lautaret</th><th>Monte Pizzac</th><th>Vallée de la Sionne</th><th>Ryggfonn</th></tr>
<tr><td colspan="5">*Initial and final conditions*</td></tr>
<tr><td>• Digital terrain model</td><td colspan="2">2—5 m resolution</td><td colspan="2">10 m resolution</td></tr>
<tr><td>• Release and deposit area / mass</td><td>Photogrammetry or establish manual methods</td><td>Additional snow stakes, consider photogrammetry</td><td>Refine methods</td><td>Establish photogrammetric methods</td></tr>
<tr><td>• Snow properties</td><td colspan="4">Establish standard methodology</td></tr>
<tr><td>• Shape, trajectory</td><td>O.K.</td><td colspan="3">Consider use of image processing techniques</td></tr>
<tr><td colspan="5">*Depth-averaged flow variables*</td></tr>
<tr><td>• Front velocity</td><td>O.K.</td><td colspan="3">O.K., consider use of image processing techniques</td></tr>
<tr><td>• Velocity distribution</td><td>Doppler radar</td><td>Use ILWF Doppler radar</td><td>O.K.</td><td>Use ILWF Doppler radar</td></tr>
<tr><td>• Flow depth</td><td>Georadar or switch arrays</td><td>O.K.</td><td>O.K.</td><td>Georadar or switch arrays</td></tr>
<tr><td>• Ground shear stress</td><td colspan="4">Install (additional) shear/normal force near velocity profile points</td></tr>
<tr><td>• Seismic signals</td><td>O.K.</td><td>(Install geophones)</td><td>O.K.</td><td>O.K.</td></tr>
<tr><td colspan="5">*Internal flow variables*</td></tr>
<tr><td>• Velocity profiles and fluctuations</td><td colspan="2">LED arrays or CPAs or FMCW radar pairs</td><td>O.K.</td><td>LED arrays or CPAs or georadar pairs</td></tr>
<tr><td>• Flow density profiles</td><td colspan="2">Install 3 CPAs if possible</td><td colspan="2">Install 3 CPAs</td></tr>
<tr><td>• Pressure profiles and fluctuations</td><td>Install additional pressure sensors in upper path</td><td>O.K.</td><td colspan="2">Install additional pressure sensors in upper path</td></tr>
<tr><td>• Granulometry</td><td colspan="4">Establish methodology</td></tr>
<tr><td colspan="5">*Snow entrainment / deposition*</td></tr>
<tr><td>• Manual measurements</td><td>Establish methodology</td><td>O.K.</td><td>O.K.</td><td>Establish methodology</td></tr>
<tr><td>• Tracer experiments</td><td>Difficult to implement</td><td>O.K.</td><td colspan="2">Difficult to implement</td></tr>
<tr><td>• Erosion rate</td><td colspan="2">Install FMCW radars</td><td>O.K.</td><td>Install georadars</td></tr>
<tr><td>*Data acquisition*</td><td>Increase capacity?</td><td>O.K.</td><td>O.K</td><td>Additional cables</td></tr>
</table>

8 COST ESTIMATES

(D. Issler and C.B. Harbitz)

The projected costs of comprehensive experimentation underline the benefits of co-ordination. Instrumentation and construction costs according to the standards outlined above are estimated to amount to more than one million ECU for a new large site. This estimate is confirmed by the costs incurred by SFISAR in equipping the Vallée de la Sionne site. Reducing the degree of instrumentation would provide significantly less information on the internal dynamics of avalanches and thus make validation of new, advanced models less conclusive.

A concept based on mobile equipment used at several sites for maximising the number of observed events was also discussed. It had to be abandoned because it allows only a very limited number of variables to be measured. In particular, most instruments probing the processes in the interior of the avalanche (FMCW radar, high-frequency pressure sensors, capacitance probes, etc.) as well as instrumented obstacles require heavy permanent infrastructure. Instead, the artificial release techniques need to be optimised. Use of a mobile Doppler radar system is a viable option if the access time is short enough.

Table 8.1 gives rough estimates of the cost of installing various types of sensors and structures in an avalanche path. Actual costs will depend on accessibility of the construction site, stability of terrain (foundations!), local labour costs, etc.

Table 8.1: Rough estimates of the cost (in ECU) of installing various types of sensors and structures in an avalanche path

Item	No. Of sensors	Cost per sensor	Sensor support	# sensor supports	Cost per support	Data acquisition	Total cost
Snow stakes (small site)	20	100	(installation)	20	200	—	6000
Markers for photogrammetry	20	100	(installation)	20	200	—	6000
Camera for photogrammetry	1	30000					30000
Video cameras	4	1000	masts etc.	4	1000	5000	13000
Pulsed Doppler radar	1	200000	shelter	1	100000	(included)	300000
FMCW radars	6	25000	Containers in ground	6	2500	15000	180000
Pressure sensors	24	2500	wedge or pillar	01.mai	15000	15000	98000
Capacitance probes	48	3000	wedge or pillar	01.mai	15000	20000	188000
LED arrays	60	15	wedge or pillar	01.mai	15000	20000	43000
Geophones	3	1000	containers in ground	3	1000	5000	11000
Shear/load cells in ground	9	1000	foundation	3	3000	3000	21000
Instrumented tower	20	1000	20 m tower	1	70000	10000	100000
Impact wall	15	1000	wall	1	70000	10000	95000
Data transmission, large site			caverns, trench	3	30000	60000	150000
Data transmission, small site					5000	25000	30000
Engineering, software, etc.							100000

Based on the equipment each institution could provide in their own site and the equipment they could bring to other sites (video recorders; Continuous Wave Doppler radar (IMO); Pulse-Doppler radar (AIATR, TU-Graz); seismic sensors (University of Barcelona and CEN); acoustic sensors (EPFL-LEMA?); meteorological stations (CEN, IMO?)), it is possible to estimate the costs to equip each site to the required standards. These results are detailed in the site report by Issler (1998). A rough summary is presented in Table 8.2. The higher figures correspond to full equipment with a modern pulsed Doppler radar for each site and a full complement of capacitance sensors. The lower figures are obtained if AIATR's mobile Doppler radar is used and light-emitting diode sensor arrays substituted for the more costly capacitance probes at the small sites.

Table 8.2: Rough estimates of the cost to equip each site to the required standards

Site	Cost (kECU)
Col du Lautaret	153-573
Monte Pizzac	50-470
Vallée de la Sionne	240-440
Ryggfonn	350-550

In planning the site equipment, the priorities established in Table 4.1 have to be followed. For any given level of funding, different schemes of allocating funds to the large and small site are possible. The list below shows the established preferences for funding allocation at different funding levels:

- *Little money (150–200 kECU):*
  1. One fully equipped small site (no or fewer capacitance probes, only mobile Doppler radar). Large sites are relatively well equipped anyway.
  2. Improved equipment of large site (e.g., georadar for Ryggfonn or capacitance probes for Vallée de la Sionne).

  Full equipment of a small site is preferred if this is substantially less costly than full equipment of the large site.
- *Medium amount of money (about 500 kECU):*
  1. Full equipment of small site (mobile Doppler radar), additional equipment for large site (capacitance probes preferred).
  2. Full (Vallée de la Sionne) or nearly full (Ryggfonn) equipment for large site.
  3. Partial equipment of large and small site (LED arrays substituted for capacitance probes).

  Full equipment of two small sites is not considered a viable alternative.
- *Nearly full funding (about 800 kECU):*
  1. Fully equip large site and partly equip small site.
  2. Fully equip small site and partly equip large site.
- *Full funding (1000–1300 kECU):*
  Fully equip large and small site.

An additional requirement to note is the personnel for maintenance of additional equipment and logistics. Also planning and preparation costs must be charged to the project. After completion of the joint experimental programme, instrumentation costs are borne by the institute, i.e. cost sharing or additional program funding is needed.

9 TIME SCHEDULE

(C.B. Harbitz)

After a positive answer to a potential proposal there will probably be a delay of about 6 months for site selection, if this has not been done already. A schedule for planning, sensor development, installation and testing the integral system in the respective sites is presented in Table 9.1. In short 1-2 years are needed for these introductory topics, followed by experimental season(s). Planning and preparation costs must be charged to the project.

Table 9.1: Time schedule for planning, sensor development, installation and testing

	Small site Mt. Pizzac / Col du Lautaret	Ryggfonn	Vallée de la Sionne
Planning	1 year	6-8 months	3 months
Sensor development	6-18 months	6-18 months	6-18 months
Installation/testing	1 summer	1 summer	1 summer

Even though Monte Pizzac will have no problems to get a building permit, the application for this should come up for discussion long before a positive answer to the proposal exists, to avoid 6-9 months of waiting for the official papers.

10 GENERAL THOUGHTS ON FUTURE CO-OPERATION

(C.B. Harbitz)

10.1 Visions for future joint programmes

Collaborations, and international ones in particular, cannot be commanded but need time and goodwill to grow. Based on the experience of SAME, future joint efforts can only develop if the participating institutions establish new positions related to the programme to prevent the work being added to the already heavy workloads of the employees. The proposal must also detail the breakdown of labour allocation, including administrative work, to obtain a better sharing of workload between institutions according to funding. Detailed contracts on tasks to be accomplished by each partner must be established, and the fulfilment of each task must be an indispensable condition for disbursement. An improved cost statement is needed in projects where individual institutions incur 50% of the cost, and EU provides the other 50%. All partners must be aware of the consequences of accepting a project with inadequate EU funding.

10.2 Data exchange

Efficient and mutual exchange of experimental data, results, maps, and events files is a precondition for joint experimental activity. However, this topic is hampered with severe difficulties. Also, issues relating to the maintenance and future updating of such databases have to be solved.

A thorough investigation of existing avalanche experimental data should be accomplished initially as an obvious guidance for future experimental studies. An external contribution to the SAME program has been received from Pavel Chernouss (Kirovsk, Russia), providing a catalogue of 45 Russian experiments in the period 1965-1978.

Within meteorology and seismology there is a long tradition for international data exchange. However, institutions involved in these scientific disciplines are absolutely dependent on such exchange across borders for their operational use, as opposed to avalanche institutions using their data mainly for research and local/national forecasting.

In North America, avalanche data is also available to everyone, while in Europe the data is more a part of the livelihood of the given institution.

A solution may be that the data is free for research, and invoiced for commercial use. Hence, the data will be open also for the universities and educational programmes. However, a potential conflict may arise in the large difference in the amount of data produced by the various institutions. The institutions that produce more data may not want to release these (even for research) until they have analysed the data themselves. On the other hand, it is hard to see how effective data analysis can be performed without involving all the institutions involved in data acquisition.

Exchange of data between the SAME partners was discussed at the November 1998 SAME Managerial Board meeting in Venice, cf. Appendix. The problems related to data exchange will hopefully be solved within the permanent European network of avalanche institutions proposed at the November 1998 SAME Managerial Board meeting in Venice. A proposal for such a network including data sharing procedures will be produced by Dr. Walter Ammann (SFISAR) and Dr. Gérard Brugnot (CEMAGREF).

10.3 Model exchange

Most institutions have a more restrictive policy on the exchange of computational models. Mutual exchange between the avalanche research institutions is normally acknowledged to promote co-ordinated research efforts. However, the institutions could probably be met with major problems with respect to safety, liability, national regulations, and loss of competitive advantage, if the models are freely distributed to consultants who cannot be considered to be avalanche experts.

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APPENDIX

Statement

Exchanges of data related to snow avalanches between the SAME partners

(G. Brugnot)

Representatives of the organisations engaged in the EU funded programme SAME - Avalanche mapping, model validation and warning systems - met in Venice on September 12 and 13, 1998, for the final meeting of this programme.
As a result of their discussions about the future of their joint efforts, they are committed to share the data collected by the undersigning organisations according to these provisions:

INFORMATION GATHERED DURING, AND WITH FINANCIAL CONTRIBUTION OF SAME PROGRAMME

This information will be made available on a server. This server will provide access to the results shaped up along deliverables plus summaries. The deliverables will provide a description of all proprietary information the undersigning partners are willing to share and also to set at the disposal of the European scientific community.

OTHER INFORMATION PROPRIETARY TO THE UNDERSIGNING PARTNERS

This information and its availability conditions are defined as follows:

Content of the information concerned

The information concerned is twofold:

- Historical information, structured along textual databases and maps
- Data obtained through experimental activities

Obligation related to this information (meta-information)

The undersigning parties are committed to describe all their proprietary data as metadata. A possibility offered them is to verify that the deliverables available on the SAME server provides enough information about their proprietary metadata and, if necessary add complementary information. :

Conditions of availability of this information

The information will be delivered under these conditions:

Undersigning partners: free under the condition that a common research project is submitted. The other undersigning partners are informed of this request, including the research project started under these conditions.

Research and education organisations: under the condition that a research[1] or education[2] programme is submitted, the information will be given out with a cost that should not be in excess of the marginal cost exposed in supplying the information..

All other organisations: the information will be available under the conditions decided by the undersigning partner. The cost will cover the average cost exposed in collecting the information plus the marginal cost exposed in supplying the information. The request will have to describe what will be the use of the data.
In all cases the information will not under any condition be transferred to a third organisation. Neither will it in any case be used for a purpose that is not described in the request.

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[1] Is considered as a research activity which may benefit from these conditions: any project organised by a university, a scientific institute or similar (private or institutional), for non-commercial research purposes only. A necessary condition for the recognition of non-commercial purposes is that all the results obtained are openly available at delivery costs only, without any delay linked to commercial objectives, and that the research itself is submitted for open publication.

[2] Is considered as an educational activity which may benefit from these conditions: any project using these data and products, solely for educational purposes, without transmission or redistribution of these data and products to any further third party, nor use of them to generate a meteorological value-added service

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