

Prototype for operational seismic detection of natural avalanches

B. LEPRETTRE,^{1,2} J.-P. NAVARRE,¹ J. M. PANEL,¹ F. TOUVIER,¹ A. TAILLEFER,¹ J. ROULLE¹

¹Centre d'Études de la Neige, Centre National de Recherches Météorologiques, Météo-France, 38406 Saint-Martin-d'Hères Cedex, France

²ADR / CEPHAG, ENSIEG, BP 46, 38402 Saint-Martin-d'Hères, France

ABSTRACT. A compact, operational prototype for automatic seismic detection of natural avalanches, named SARA, is proposed as a means to improve real-time estimation of natural avalanche activity. A software combining multi-component signal analysis and fuzzy logic has been set up to reject spurious signals automatically. The average success rate of our system, estimated from a set of previously identified signals, is somewhat over 90%. Two prototypes have been installed in the French Alps during the winter of 1996–97. The SARA system enables the user to follow up the evolution of natural avalanche activity with a high time resolution. Results obtained in 1997 are presented and compared with other data related to avalanche activity.

INTRODUCTION

The estimation of natural avalanche activity is currently based on visual observations. These are imprecise and are impossible at night or during poor visibility. On the other hand, a precise and objective, real-time estimate of the temporal evolution of avalanche activity would improve risk assessment. First, it would allow us to evaluate the influence of meteorological parameters such as precipitation volume and rate, temperature or wind speed and direction on natural avalanche activity. Secondly, avalanche forecasters could use this real-time information to obtain knowledge of the current avalanche situation before writing their reports.

Seismic Detection of Avalanches (SDA) is a means for estimating the natural avalanche activity more objectively. The principle and difficulties of SDA are first discussed in section 1. A brief chronological account of SDA studies at the Centre d'Études de la Neige (Snow Research Centre) is given in section 2. Section 3 describes the functions of our operational SDA prototype, two of which have been installed in the French Alps. Finally, the results obtained during the 1997 campaign are given in section 4.

1. PRINCIPLE AND DIFFICULTIES OF SEISMIC DETECTION OF AVALANCHES (SDA)

When an avalanche occurs, seismic waves are transmitted into the ground and propagate over several kilometres. These waves can be detected and recorded by a three-component seismic data logger. The technical feasibility of SDA was proven in the 1970s (St. Lawrence and Williams, 1976). However, unlike classical seismological studies, the Seismic Detection of Avalanches consists of detecting local events. In addition to earthquakes, any local seismic source (e.g. rolls of thunder, mining blasts, vehicle or helicopter sounds)

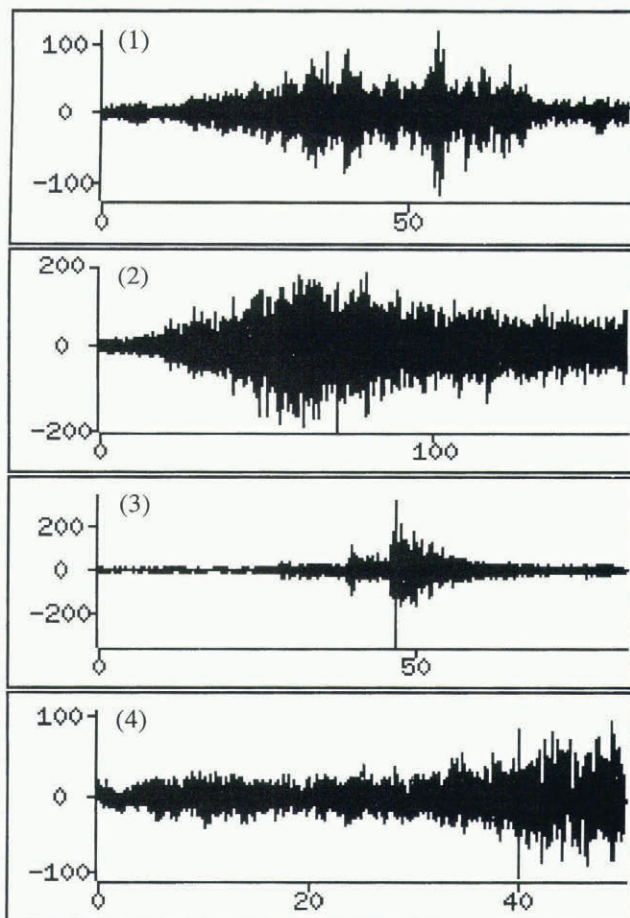


Fig. 1. Examples of avalanche signals: (1) Large avalanche near the sensor on moderately uneven ground; (2) Medium-size avalanche on smooth terrain; (3) Medium-size avalanche on a steep, uneven rocky slope; (4) Distant very large avalanche (12 km from the sensor).

is likely to produce signals that can be mistaken for avalanches. As a matter of fact, the signals associated with avalanches represent only about 5–10% of the recorded seismic signals. Therefore, more than 90% of the recorded events are extraneous and must be rejected. Many snow avalanches produce long signals (over 2 mn), with smooth, progressive amplitude variations. However, avalanche signals vary considerably from one event to another, depending mainly on the profile of the avalanche path and the quantity of snow in the flow, as well as on the distance and the geomorphological characteristics of the terrain between the avalanche and the sensor (Fig. 1). Therefore, we could not find a distinctive, simple criterion for discriminating avalanche signals reliably. On the other hand, most extraneous signals are associated with less-complex physical phenomena and hence produce less variable signals. However, some types of extraneous signals (e.g. rolls of thunder or some earthquakes) are likely to behave like avalanche signals.

Therefore, recognizing avalanche signals automatically is a difficult problem. Other SDA experiments have been carried out in the Spanish Pyrenees (Sabot and others, 1995), but these focus essentially on the extraction of physical features (speed and volume of snow) from the recorded signals: no general method for automatic recognition of avalanche signals has yet been proposed. In order to recognize avalanche signals automatically, it is necessary to undertake a detailed analysis of the signals obtained and to take into account the specific properties of each type of event.

2. SDA STUDIES AT THE CENTRE D'ÉTUDE DE LA NEIGE (CEN), 1984–96

2.1. Preliminary studies

Preliminary studies carried out at La Plagne, Savoie, France, in 1984 showed the feasibility of SDA: the number of recorded seismic signals proved to be highly correlated to natural avalanche activity (estimated by careful visual observations from the resort staff).

In 1991, the first experimental site was equipped at Saint-Christophe, Isère, France (Oisans massif). This site is on a slope at an altitude of 1700 m. The surrounding terrain is a steep, regular slope facing southwest with scree and grass. In addition to the three-component sensor and the seismic data logger, a PC computer and a modem were installed in order to allow direct monitoring of the instruments from the CEN and daily data transmission. A large number of seismic events of all types was recorded at this site from 1991 to 1994. About one event out of two could be identified from eye-witness accounts of local residents or earthquake reports. Using this system, a large number of unambiguously identified events was recorded, including about 20 avalanches.

2.2. The SARA system: software for automatic recognition of avalanche signals

At the same time, we began analysing these identified events in order to discover criteria for automatic signal recognition. We established that, by combining several complementary criteria, we could overcome the variety of signals and reach a satisfactory recognition rate. Thus, a prototype software, named SARA for “Système d'Analyse pour la Reconnaissance des Avalanches” (Analysis System for Avalanche

Recognition) was written. It can be visualized as a combination of three separate modules:

1. Multi-domain signal analysis.
2. Estimation of facts using fuzzy logic.
3. Decision-making using an expert system.

Three domains are involved in the analysis process:

Time domain. Events such as blasts or local earthquakes are recognized from their envelope shape. The envelope of the signal is compared to a typical model of an earthquake envelope.

Time–frequency domain. Some events (distant earthquakes, helicopter sounds, etc.) have a typical time–frequency behaviour. The time–frequency content of the signals is estimated using auto-regressive (AR) modelling and a minimum-variance power estimator (also known as Capon's estimator).

Polarization domain. The linearly polarized motions are detected in the time–frequency plane. This assists in recognizing extraneous signals produced by a fixed source as well as signals with typical polarization patterns (e.g. local earthquakes). For avalanche signals, the azimuth of the arriving linear waves is likely to help in estimating the location of the avalanche path.

About 20 parameters have been estimated from the results of the analysis and have been used in the second module. Using these parameters and the fuzzy-set theory (Zadeh, 1965), 25 so-called “facts” are given a truth value, i.e. a number ranging from 0 (totally false) to 1 (totally true). These facts sum up the characteristics of the signal in each domain. The use of fuzzy logic is a way of overcoming the imprecision of the recognition criteria (that is, the variety in the behaviour of the signals). The boundaries of the fuzzy sets were first estimated from theoretical considerations (e.g. seismic-wave propagation laws) and tuned using a set of 334 previously identified events, including 12 avalanches.

Finally, these facts are combined with the third module using a basic set of rules. The truth value associated with every possible class (avalanche, blast, earthquake, helicopter, vehicle and thunder) is estimated. Each value denotes how close the signal is to the associated class, according to the criteria that were set up from the analysis of identified events. Compared to other methods that are able to deal with imprecision and/or uncertainty, such as discriminant analysis or neural networks, fuzzy logic has the advantage of being more flexible: the constraints concerning the training set of events are fewer and the system is easy to modify according to the evolution of our knowledge.

The flow chart of our system for automatic recognition of avalanche signals is shown in Figure 2. Full details about the signal-processing methods have been given by Leprettre and others (1996, 1998). The SARA system was validated on 280 previously identified signals (different from those used for estimating the boundaries of the fuzzy sets), including 13 avalanches. The average success rate is about 90%. Most signals erroneously classified as avalanches are non-telesismic earthquakes that can easily be identified by using two distant SDA stations.

2.3. Pre-operational configuration

During the winters of 1995–96 and 1996–97, a pre-opera-

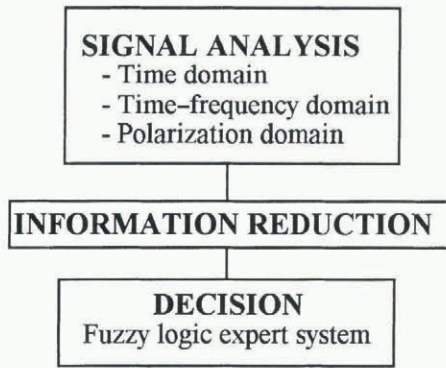


Fig. 2. Flow chart for the recognition process.

tional version of the SARA software was implemented in the PC computer at the Saint-Christophe site. The recorded signals were transferred from the seismic data logger to the PC twice each day and analysed by SARA. The results were then transmitted to the CEN by modem. Using this installation, we were able to obtain an estimated measure of the natural avalanche activity with a 12 hour step. These campaigns proved the efficiency of the SARA system as well as the value of SDA in an operational context. We therefore decided to build an operational autonomous prototype.

3. DESCRIPTION OF PROTOTYPE SDA STATION

3.1. Technical features

The key-element of the prototype is a LEAS SISMALP 3-PC seismic data logger. This instrument was originally dedicated to recording earthquakes. It has been modified to fit the particular needs of SDA: longer pre- and post-event, lower detection threshold. In addition, a PC-486DX card, including a 170 Mb PCMCIA hard disk, has been included within the data logger. This PC card can be switched on automatically by the logger at user-defined intervals in order to analyse the recorded signals. The purpose of the seismic data logger is therefore twofold: (1) Detection and storage of seismic events on a memory card; (2) File management and signal analysis on the PC card. The sampling frequency is 100 Hz to fit in with the characteristics of most avalanche signals (5–25 Hz frequency band, approximately).

The instruments installed together with the seismic data logger are:

Three-component seismic sensor. Mark Products L-22D geophone. Its transfer function is nearly constant in the 2–40 Hz frequency range.

BM18 MeteoSat emitter.

Synchronization device (GPS or Telecode).

Autonomous power supply. Batteries, solar cells and regulating device (15 days power reserve).

These instruments, apart from the sensor, are held by a 5 m pole (Fig. 3), so the whole system is compact, easy to install and easily removable. The cost of the whole SARA prototype is about 180 000 French francs.

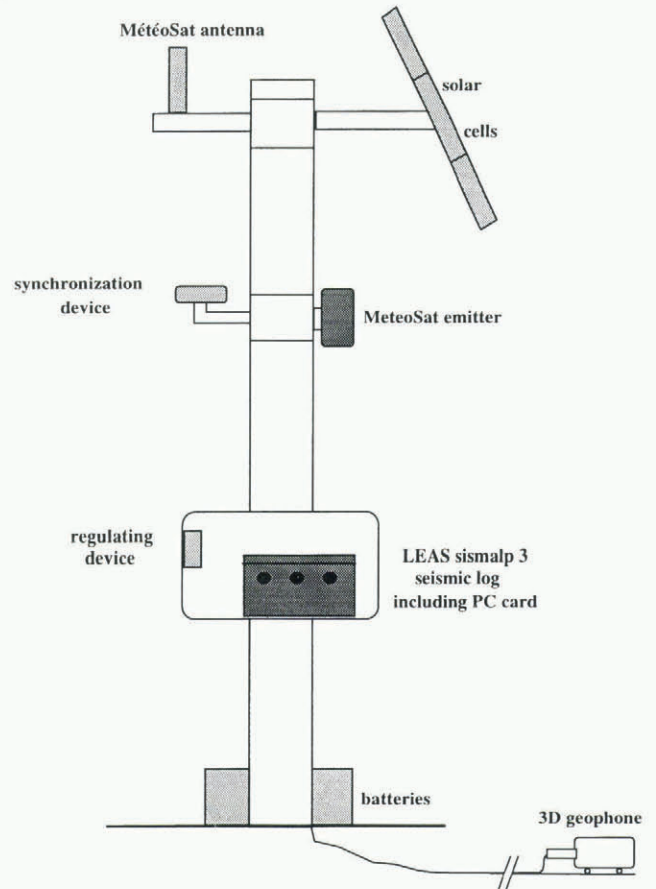


Fig. 3. Prototype of SDA station.

3.2. Operational functioning

Every hour, the PC card is switched on automatically and the following tasks are performed:

All the signals are transferred from the memory of the data logger to the hard disk and deleted from the memory.

Each signal is analysed by the SARA software and implemented on the hard disk. The results (i.e. the date and time of the signal, its characteristics and the decision made by SARA) are encoded in the form of a so-called “result line” of length 57 characters and stored in a separate file. The analysed signal is then archived in a special directory.

When all the signals are analysed, a 646 byte file is written, including a header and the last ten result lines. This file is loaded into the MeteoSat emitter and transmitted to the CEN a few minutes later. As the number of events recorded in a 1 hour interval is generally less than 10, the transmitted message is partly redundant compared with the previous one (transmitted 1 hour earlier). This is the first means of checking the quality of the message. Control characters are also included during the encoding process.

This configuration allows us to know the exact date and time when avalanches occurred with a delay not exceeding 1 hour. This remote estimation of natural avalanche activity is much more precise and objective than visual observations.

4. RESULTS FROM THE WINTER OF 1996–97

A first prototype was installed on 13 January 1997 at the Saint-Christophe site. The parameters of the SARA recognition software (as well as the detection parameters) are those used with the pre-operational system. As the seismic data logger installed with the prototype is very different from that used from 1992–96, the results presented in this section have therefore been obtained using a non-optimal configuration of the prototype.

Unfortunately, this winter was not very interesting for the experiment: the snow cover showed a marked deficit at a moderate altitude from late-February. From January to March, long periods of fine weather alternated with brief, moderate, very windy snowfalls.

4.1. Results obtained at the Saint-Christophe site

The most interesting period recorded extends from 15–31 January. Only one significant snowfall with high natural avalanche activity occurred during this period (19–23 January). Figure 4 shows the evolution of the global daily seismic activity (i.e. the number of events recorded each day) for this period (Fig. 4a). After automatic identification of the signals by the SARA system, only those signals in Figure 4b (black bars) remain. This shows the necessity of explicitly recognizing avalanche events: the days with a high global seismic activity are not necessarily associated with a peak of seismic avalanche activity. About 10–20 signals are recorded each day. The rate of “false alarms”, (i.e. signals erroneously classified as avalanches) is somewhat less than 10%.

Only one actual avalanche period can be seen in this graph (20–23 January). Visual avalanche observations reported daily by the Les Deux-Alpes ski resort (close to the

Saint-Christophe site) are plotted on the same graph (white bars). Unlike our measurements of seismic avalanche activity, visual observations are insufficient to estimate the start and intensity of the avalanche period. The forecast degree of risk of natural avalanche (Figure 4c), estimated by avalanche forecasters at the Saint-Martin-d’Hères weather station for the Oisans massif, is well correlated with seismic avalanche activity (high risk on 20–21 January).

Let us have a closer look at the 19–23 January period. The SARA seismic avalanche activity is plotted in Figure 5 with a 1 hour step over this period, together with the total depth of snow (measured at the nearby automatic *Nivôse* weather station of Les Ecrins). The evolution of the air temperature a-starting zones in the vicinity of the SDA station) is indicated in Figure 5b. It shows that this episode is characterized by a large rise in temperature. The first snowfall occurred from the morning of 19 January to 11.00 UTC, 20 January. The snow depth increased slowly until 00.00 UTC, 20 January. As soon as the fresh-snow layer reached about 45 cm, the natural avalanche activity started (first black bar). From 02.00 UTC, 20 January, the wind was rising and producing peaks in the snow-depth curve. The measured natural avalanche activity was moderate (only three signals from 00.00 to 18.00 UTC), probably due to wind erosion and to the slowness of snow accumulation. From 06.00 UTC, 20 January, a large rise in temperature was observed. During the night, the 0°C level climbed to an altitude of 3000 m. The air temperature reached positive or very slightly negative values. This large rise in temperature caused the natural avalanche activity to increase severely (15 avalanches detected from 23.00 UTC, 20 January to 14.00 UTC, 21 January). A small snowfall began again soon after that, accompanied by strong winds. The increase in the snow depth on 22 January essentially corresponded to

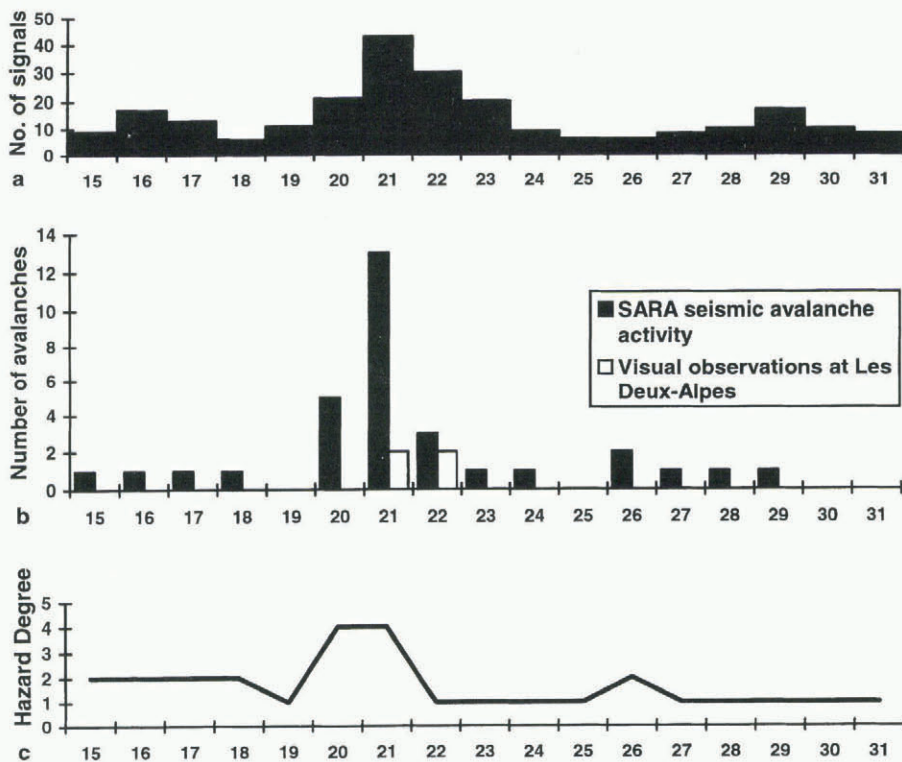


Fig. 4. Results provided by the SARA system for the period 15–31 January: (a) Global daily seismic activity, January 1997; (b) Daily seismic avalanche activity from automatic signal recognition (black bars) and from visual observations at Les Deux-Alpes ski resort (white bars); (c) Forecast degree of risk of natural avalanche according to the European Avalanche Hazard Scale.

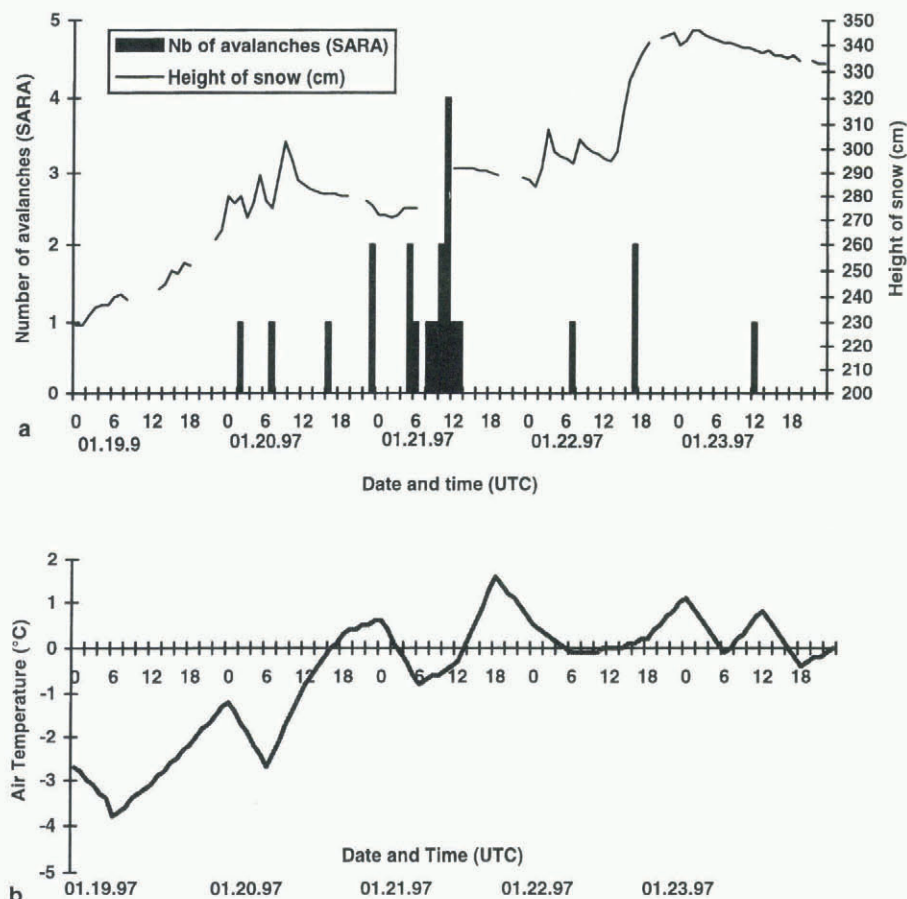


Fig. 5. Comparison between seismic avalanche activity and other data related to avalanche activity. (a) Hourly number of detected avalanches (black bars) and total depth of snow measured at Les Ecrins (elevation 3000 m) automatic weather station (black curve). (b) Air temperature estimated by the SAFRAN model for the Oisans massif (elevation 2400 m).

local snowdrifting near the *Nivôse* station (gusts from 4 to 8 m s^{-1}), not to a heavy snowfall. Only moderate avalanche activity was measured. The lack of precise wind data for this episode made it hard to evaluate the exact effects of wind on the avalanche activity.

Although the configuration of both the prototype and the SARA software was not optimal, the results obtained show the value of SDA as an operational tool for estimating natural avalanche activity. The semi-instantaneous transmission of detected activity is particularly interesting in an operational context: the estimated natural avalanche activity can be correlated in almost real time, with several measured and/or forecast parameters which influence avalanche activity (e.g. intensity of snowfall, accumulated depth of fresh snow, rain, temperature and wind), in order to improve short-term forecasting of the avalanche risk. Previous similar studies, carried out during less windy periods using a pre-operational configuration (Leprettre and others, 1997), showed that significant natural avalanche activity began as soon as the accumulated depth of fresh snow reached about 35–40 cm. Most avalanches seem to occur during snowfall, because the avalanche activity measured by our system decreased very rapidly soon after the snowfall stopped. However, this study of the influence of meteorological parameters on natural avalanche activity began only 1 year ago. Therefore, other investigations will be necessary before being able to reach a conclusion on this point.

4.2. Results from the Vaujany site

A second experimental site was installed on 12 February

1997 near the Vaujany ski resort, at the bottom of a small north–south oriented valley in the Grandes Rousses massif, Isère, France. The site is 3 km from the ski resort and 1 km from the water pipe lines of a hydroelectric power station. No significant natural avalanche period has occurred on this site in the present winter since 12 February. However, the main purpose of this site is to evaluate the possibility of installing SDA stations in a seismically noisy environment. Ski lifts seem to have a negligible influence on the recorded signals, given the relatively large distance. However, artificial avalanche releases made by the resort security staff, using a Gazex system, produce short, sharp, easily recognizable signals (blasts). On the other hand, any operation carried out on the water pipe lines (e.g. opening or closing one or several floodgates) produces smooth, slowly increasing and decreasing signals, which are similar to those produced by avalanches (even in the spectral domain). Studies are in progress to try to distinguish automatically these signals from avalanche signals. Finally, maintaining several sites is very useful for recognizing an earthquake erroneously classified as an avalanche by the SARA system (the signal is recorded by several SDA stations at the same time but with a brief delay).

5. CONCLUDING REMARKS

A prototype for the operational seismic detection of avalanches, named SARA, has been presented. It is based on a combination of a three-component seismic data logger and software for automatically recognizing avalanche signals.

Two prototypes have been installed in the French Alps. The reliability of the instrument seems satisfactory, because no major malfunction has been observed. Although there is still room for improving its performance, the SARA system allows us to follow the temporal evolution of natural avalanche activity objectively almost in real time.

The range of a SDA station depends mainly on the surrounding terrain (gentle slopes, steep rocky cliffs, etc.). At the Saint-Christophe site, large avalanches have been recorded as far as 12 km away from the site. On the other hand, small avalanches occurring on regular, gentle slopes 200 m from the sensor have not been recorded. The effective range of the system is about 3–6 km. To take the long-term view, only one such prototype might be installed at each massif. Hence, the recording site must be carefully chosen: it must be sufficiently quiet and representative of the avalanche activity of the whole massif.

The Centre d'Études de la Neige is currently investigating the possibility of pinpointing avalanches using a single SDA station. Preliminary studies have already shown that the azimuth of the linearly polarized waves (detected in the time–frequency plane) often gives a good estimate of the direction of the avalanche. However, the quality of this avalanche location strongly depends on the profile of the avalanche path: avalanches occurring on smooth, gentle slopes are generally difficult to locate, because they produce very few polarized waves. Other information can be used to help locate avalanches: we have noticed that avalanches in the same avalanche path often have similar temporal shapes, depending mainly on the avalanche-path profile. Therefore, a collection of avalanche “signatures” recorded from various well-known avalanche corridors could be used as a reference to facilitate avalanche location. Finally, we are attempting to determine whether physical parameters (e.g. type and quantity of snow in the flow, speed, length and profile of the avalanche path) can be derived from the recorded seismic signals. This study has been carried out by using artificially released avalanches and comparing the recorded seismic signal with other information: video, speed measurements, etc. Finally, the SDA system can be used to

determine the exact influence of several meteorological parameters on natural avalanche activity. This work requires a large number of avalanche periods to be recorded and compared with measurements of air temperature, humidity, precipitation, etc. Ideally, these meteorological parameters should be measured as close as possible to the avalanche-starting zones surrounding the SDA station but these are not always easily accessible. Therefore, we shall first need to define what are the most relevant parameters and how they should be estimated to take local effects into account.

ACKNOWLEDGEMENTS

This study on Seismic Detection of Avalanches was partly supported by the Direction de la Sécurité Civile and the Région Rhône-Alpes. Seismic Detection of Avalanches is currently a part of the CEN's contribution to the European SAME project, and receives financial support from the European Union.

REFERENCES

- Leprettre, B. J. P., J.-P. Navarre and A. Taillefer. 1996. First results of a pre-operational system for automatic detection and recognition of seismic signals associated with avalanches. *J. Glaciol.*, **42**(141), 352–363.
- Leprettre, B., J.-P. Navarre, A. Taillefer, Y. Daniélou, J. M. Panel and F. Touvier. 1997. Reliable estimation of avalanche activity using seismic detection. In *ISSW'96, International Snow Science Workshop, 6–10 October 1996, Banff, Alberta. Proceedings*. Revelstoke, B.C., Canadian Avalanche Association, 184–188.
- Leprettre, B., N. Martin, F. Glangeaud and J.-P. Navarre. 1998. Three-component signal recognition using time, time-frequency and polarisation information: application to seismic detection of avalanches. *IEEE Trans. Signal Process.*, **46**(1).
- Sabot, F., P. Martinez, E. Suriñach, C. Olivera and J. Gavalda. 1995. Détection sismique appliquée à la caractérisation des avalanches. In Sivardière, F., ed. *Les apports de la recherche scientifique à la sécurité neige, glace et avalanche. Actes de Colloque, Chamonix 30 mai–3 juin 1995*. Grenoble, Association Nationale pour l'Étude de la Neige et des Avalanches (ANENA), 19–24.
- St. Lawrence, W. and T. R. Williams. 1976. Seismic signals associated with avalanches. *J. Glaciol.*, **17**(77), 521–526.
- Zadeh, L. A. 1965. Fuzzy sets. *Inf. Control*, **8**, 338–353.