Reliable Estimation of Avalanche Activity Using Seismic Methods

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ABSTRACT

In order to improve natural avalanches forecast, Météo-France has developed an operational system for automatic, quasi real-time estimation of the avalanche activity. It is based on the detection of the seismic signal associated with avalanches. Avalanches represent only about 10% of the recorded seismic signals, all the others being unwelcome signals that must be eliminated. This task requires a complete analysis of the signal. We have developed a system (named SARA) which uses time-frequency analysis and fuzzy logic to recognize avalanche signals. The average success rate of our system is about 90%. The results provided by the SARA system are compared with other parameters related to avalanche activity. SARA proves able to follow the evolution of avalanche activity in almost real time. Concrete applications, such as surveillance of avalanche prone zones, are considered.

INTRODUCTION

The estimation of natural avalanche activity is mainly based on the visual observation of avalanche deposits. These require good visibility conditions (i.e. daylight and clear weather) as well as significant observation staff. A time lag of several days is likely between the occurence of an avalanche and its report. Furthermore, airborne powder avalanches often produce almost invisible deposits that will not be observed when the weather clears. Thus, the estimation of natural avalanche activity is biased in both terms of time and intensity. A reliable measurement of the avalanche activity would nevertheless help nivologists to forecast the short-term avalanche hazard. It could also lead to concrete applications, such as surveillance of avalanche prone areas, and legitimate decisions concerning the closing or reopening of roads threatened by avalanches. The presented system uses seismic detection in order to get rid of the constraints of visual observations.

1. PRINCIPLE AND DIFFICULTIES OF THE SEISMIC DETECTION OF AVALANCHES (S.D.A.)

When an avalanche occurs, the descending snow packets generate seismic waves into the ground. These waves travel in the ground and can thus be detected and recorded by a seismic station. The effective range of SDA is typically 5-6 km, although big avalanches have been detected up to 11 km. The feasibility of SDA has been proved by previous studies (Saint Lawrence and Williams, 1976) (Navarre et al., 1991). These studies have also highlighted the main difficulty of SDA: in addition to avalanche signals, many unwelcome signals are recorded: earthquakes, truck or helicopter sounds, thunder, mining blasts, animal or human footsteps,... As a matter of fact, avalanche signals represent only about 10% of the recorded signals. To get a reliable estimation of the avalanche activity, it is thus necessary to separate avalanche signals from the others.

2. TRAINING PHASE

The obtained avalanche seismic signals are highly dependent on several factors: quantity and type of moving snow, nature and profile of the slip surface, distance and nature of the ground between the avalanche and the seismic sensor. Consequently, avalanche signals are not typical: they vary a lot from one event to another. The automatic recognition of avalanche signals can therefore prove difficult. We thus had to learn how to discriminate avalanche signals.

The first phase of our experiment has therefore been devoted to obtaining a set of unambiguously identified seismic signals. The signals are three-component seismic signals recorded in Saint-Christophe-en-Oisans, Isère (French Alps, Oisans massif) in Winters '91, '92 and '93. A methodology for *a posteriori* identification of the recorded signals has been developed. For example, earthquakes are identified by comparing the date and time of our recorded signals to that of earthquakes listed in a bulletin published by the Laboratoire de Geophysique. For helicopter and truck sounds, information is gained from local councils, companies or local residents. Avalanches are identified according to testimonies of local residents, skiers or climbers as well as national park wardens. After a two-year practice, we finally got about 200 identified events, including about 15 avalanches.

↗	AV	non AV
AV 13 signals	12	1
non AV 267 signals	9	258

Table 1 Results of the SARA identification system on a population of previously identified seismic signals.

At the same time, all the identified signals have been analyzed in order to find recognition criteria. We rapidly realized that this problem was rather complex and that a detailed analysis of the signals, involving several description domains, was necessary to get a reliable identification of the signals.

3. AN AUTOMATIC SYSTEM FOR SEISMIC SIGNAL IDENTIFICATION USING FUZZY LOGIC

The system we have set up for automatic identification of the recorded three-component seismic signals proceeds in three steps (figure 1): signal analysis, information reduction and decision. We will not discuss here the technical details concerning each step. These are fully described in (Leprettre, 1996) and (Leprettre et al., 1996) as well as in a paper submitted in June 1995 to *IEEE Transactions on Signal Processing* by B. Leprettre, N. Martin, F. Glangeaud and J.P. Navarre.

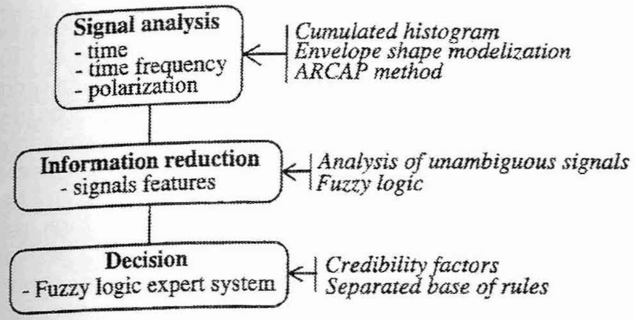

Figure 1 Structure of the proposed system for automatic seismic signal identification.

3.1. STRUCTURE OF THE ANALYSIS / DECISION SYSTEM

The first programme performs a time-frequency-polarization analysis of the input three-component seismic signal:

Time domain: The histogram of the signal modulus is used to discriminate very sharp signals, such as mining blasts or footsteps. A comparison between the smoothed signal modulus and a typical earthquake model allows to recognize short-range earthquakes.

Time-frequency domain: The ARCAP method, a combination of Auto Regressive modelization and Capon estimator (Dubesset et al., 1987), is used on a gliding window to select the dominant frequencies and estimate the associated power. We thus obtain a cloud of points representing the power distribution of the signal as a function of time and frequency. The time-frequency content of the signal allows to discriminate events with typical frequency behavior (e.g. teleseismic or mid-range earthquakes, thunder).

Polarization domain: Capon's method is used to filter each signal channel at the dominant frequencies. A linearity criterion is estimated on the filtered three-component signals in order to locate linear ground motions in the time-frequency plane. If a linear motion is detected in a given signal window, its duration and azimuth are estimated. We expect that this polarization study will allow us, in a near future, to locate avalanche events in addition to recognizing them.

The results of this signal analysis are the input of a second programme, which estimates about 25 features summing up the characteristics of the signal in each domain. These features are derived from both the analysis results and fuzzy sets (Zadeh, 1965). The fuzzy sets have been set up according to the knowledge we have obtained from the analysis of previously identified signals (cf part 2). Each feature is given a so-called *truth value*, that is, a number between 0 (totally false) and 1 (totally true).

Finally, the features are combined according to decision rules by a third data fusion programme. These rules derive from physical knowledge of both seismic waves generating phenomena and propagation rules, as well as more empirical knowledge resulting from the observation

FILE earthquake: 8116 3C-samples

CRITERIA :			**truth value**
Short signal			: 0.0
Steep ampl. hist.	Z: 0.0	EW: 0.0	NS: 0.0
Earthquake shape	Z: 0.0	EW: 0.0	NS: 0.0
P-S frequency decrease			: 1.0
Global frequency decrease			: 1.0
Low mean amplitude			: 1.0
One component below 6Hz			: 1.0
One High Freq. component			: 0.0
Lowest comp. is Low Freq.			: 0.0
Helicopter frequency			: 0.0
Spaced-out points			: 0.0
Broadband signal			: 0.0
Gentle ampl. hist.	Z: 1.0	EW: 1.0	NS: 1.0
Far earthq. shape	Z: 1.0	EW: 1.0	NS: 1.0
Band-limited signal			: 1.0
Grouped points			: 0.6
CONCLUSION: Midrange earthquake			: 0.9
Avalanche			: 0.4
All others			: 0.0

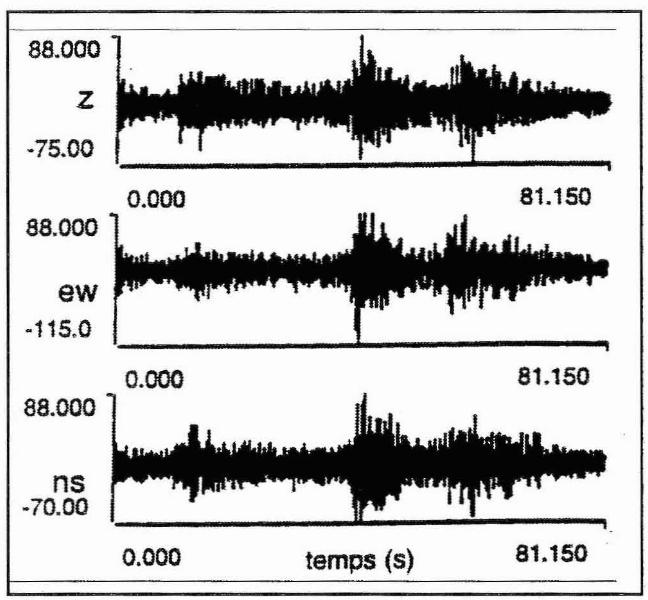

Figure 2 Example of signal identification using the proposed system.

of the identified signals. We thus obtain, as an output, the truth value associated to every possible signal origin. The truth value of the "avalanche" class indicates how much the signal is related to an avalanche signal according to our knowledge. If this value is greater than those associated with the other classes, we can conclude that the signal is an avalanche.

An example of signal identification is proposed in figure 2. The input signal is a mid-range earthquake. The signal features are listed together with their truth value. The right signal origin is found by our system. However, due to the complexity of the signal, the "avalanche" conclusion is proposed with a lower (but non-zero) truth value, indicating that the signal partially ressembles an avalanche according to the recognition criteria we have set up.

3.2. PERFORMANCE OF THE SARA SYSTEM

The described signal recognition system, named SARA for "Systeme d'Analyse pour la Reconnaissance des Avalanches" (analysis system for avalanche recognition), has been tested on a population of 280 unambiguously identified signals of various origin, including 13 avalanche signals. This population is of course different from the set of signals used during the training phase of the experiment. The results of automatic avalanche discrimination, considering only two classes (avalanche and non-avalanche), are presented in Table 1. Only one avalanche signal out of 13 has not been recognized, and only 9 non-avalanche signals out of 267 have been erroneously recognized as avalanches. Therefore, the global success rate of the SARA system is between 90% and 95%. More precisely, teleseismic earthquakes, mining blasts and helicopter sounds are almost perfectly rejected by SARA. However, about 10% of short- and mid-range earthquake signals as well as thunder sounds are not rejected.

4. DEVELOPMENT OF A PRE-OPERATIONAL SDA PROTOTYPE

Given the satisfactory performance of the SARA system, we have developed a pre-operational version in order to evaluate the interest of SDA for concrete applications. During Winters 1995 and 1996, the SARA system was implemented on a PC computer in the Saint-Christophe recording site. The recorded signals (the number of which gives the daily *global seismic activity*) were analyzed every 24 hours on the PC and the decision concerning each signal was transmitted to the laboratory. The number of recorded signals which have been recognized as avalanches by the SARA system gives the so-called *SARA seismic avalanche activity*. Using this pre-operational configuration, we have been able to follow up the evolution versus time of the seismic avalanche activity.

4.1. COMPARISON BETWEEN THE SARA SEISMIC AVALANCHE ACTIVITY AND OTHER DATA

We have compared, day by day, the information provided by the SARA s ystem with other data related to avalanche activity in order to check its consistency. The comparison parameters are:

Number of avalanches observed each day in the Les Deux-Alpes ski resort (close to the Saint-Christophe site).

Degree of natural avalanche risk for the Oisans massif on the European Avalanche Hazard Scale (EAHS), ranging from 1 (very low) to 5 (very high). It is estimated daily by the weather station at Saint Martin d'Hères, Isère. When the risk is larger than 2, significant natural avalanches are likely.

Degree of natural avalanche risk estimated by the SAFRAN-CROCUS-MEPRA expert system. This is based on a deterministic simulation of the snow mantle evolution (Giraud et al., 1994).

Figure 3 shows the evolution of these parameters for March 1996. The comparison between graphs (a) and (b) highlights the need to sort the recorded signals, in order to retain only these associated with avalanches. The global seismic activity can be high although the avalanche activity is low (see March, 12). The correlation between the estimated SARA seismic avalanche activity and the degrees of risk is fair. That is, the periods with high avalanche seismic activity generally correspond to periods when either the forecast (c) or the simulated (d) hazard degree is 3 or higher. However, the days with non-zero

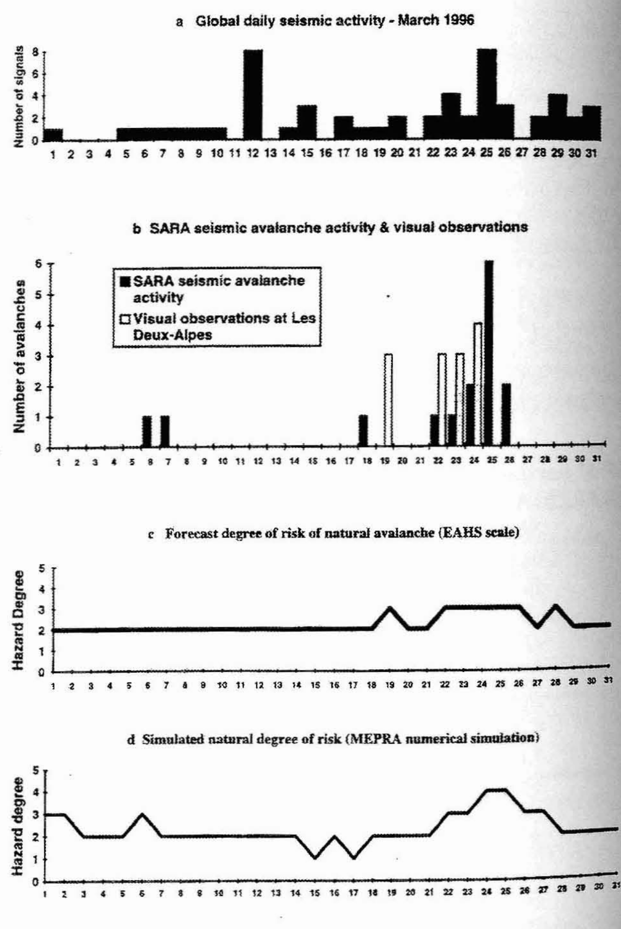

Figure 3 Results of the pre-operational version of the SARA system for March 1996: (a) Global seismic activity, (b) SARA seismic avalanche activity (black bars) and visual observations at the Les Deux-Alpes ski resort (grey bars), (c) forecast natural avalanche hazard on EAHS scale, (d) natural avalanche risk estimated from numerical simulation by the SAFRAN-CROCUS-MEPRA system.

seismic avalanche activity are not necessarily associated with visual observations. This can be accounted for by local effects, as the observations are not made in the recording site but in a nearby ski resort.

4.2. EVOLUTION OF THE SEISMIC AVALANCHE ACTIVITY DURING A SNOWFALL

As the date and time of each recorded event is known, we can follow up the evolution of the seismic avalanche activity provided by the SARA system during a snowfall. This allows to estimate the moments when the avalanche crisis starts and stops. The global height of snow, measured at hourly intervals by the nearby automatic *Nivôse* weather station of Les Ecrins, will be used as a comparison parameter.

The evolution of both data during the January 21-24, 1995 period is represented on figure 4. This shows that a significant avalanche activity starts as soon as the cumulated fresh snow layer reaches about 40 cm at 3:00pm on January 22. This avalanche activity stops rapidly three hours later as the snowfall stops too. When the snowfall starts again at 3:00am on January 23, the avalanche activity increases immediately and becomes very high (7 signals detected as avalanches on January 23). It definitely stops soon after the snowfall has eventually stopped at 11:00pm on January 23.

Thus, the SDA system we have set up proves able to follow up the natural avalanche activity in almost real time.

CONCLUSION AND FUTURE PROSPECTS

We have investigated the interest of Seismic Detection of Avalanches (SDA) as a means to estimate natural avalanche activity more objectively and reliably than with visual objections. The key point of the experiment is the automatic recognition of avalanche signals, which represent only about 10% of the recorded signals. We have briefly described a method for performing this selection automatically with a global success rate of 90%. The described system for Seismic Detection of Avalanches (named SARA) has been working in pre-operational conditions since January 1995. The SARA system is actually able to follow the evolution of the avalanche activity in almost real time. It could allow to:

- Supply an objective estimation of the current avalanche activity to help short-term forecast of the avalanche hazard,
- Supply a reliable data for analogous prediction methods,
- Improve the calibration of deterministic models for avalanche prediction, such as the SAFRAN-CROCUS-MEPRA system developed at Météo-France,
- Perform surveillance of roads or resorts threatened by avalanches. The objectivity of the information provided by a SDA station could officially legitimate decisions to evacuate local population or to close roads.
- Given these promising results, we have developed an operational, self-controlling prototype. The rejection of non-avalanche signals is performed *in situ* by the SARA software implemented on a PC 486DX card inside a LEAS FRANCE seismic station. Only the results in terms of seismic avalanche activity are transmitted to the laboratory at hourly intervals. This prototype is currently being tested on the Saint-Christophe site. Two such prototypes will be installed for Winter 96/97 on two different sites.

At the same time, further studies will be carried out to improve the performance of the SARA recognition system. We will investigate the possibility of locating the detected avalanche events automatically from the time-frequency localization of the linear motions of the signal. We will also try to determine whether a given avalanche corridor has a proper "seismic signature" and whether physical parameters of the avalanche (speed, quantity and type of snow, etc.) could be extracted from the recorded seismic signal. This part of the study will be conducted using artificially released avalanches.

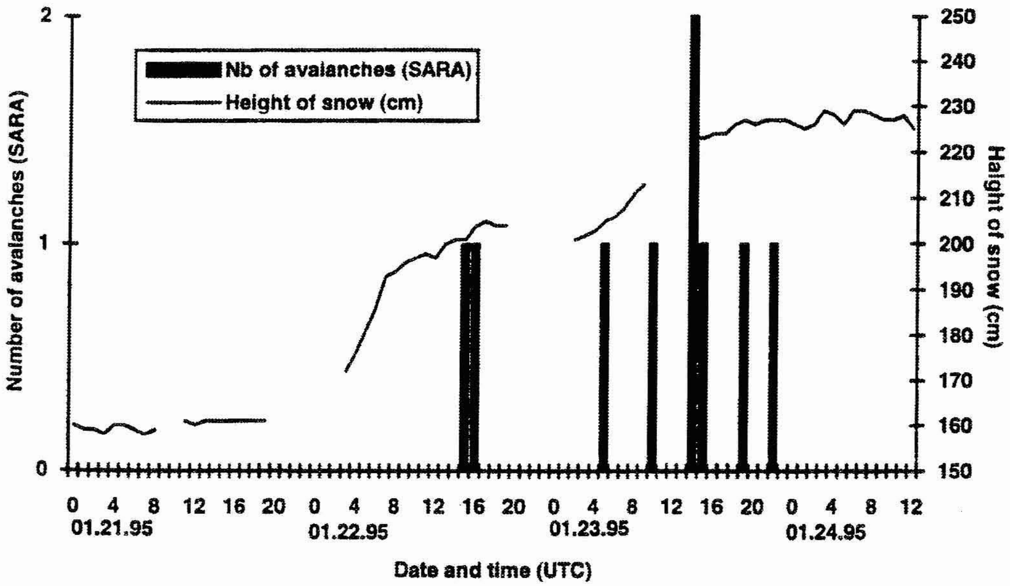

Figure 4 Comparison between SARA seismic avalanche activity (bars) and global height of snow (line) during a snowfall (January 21-24, 1995).

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