LISTENING TO SNOW – AVALANCHE DETECTION USING A SEISMIC SENSOR ARRAY

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ABSTRACT: Data on avalanche activity are of vital importance for avalanche forecasting. Avalanche activity is usually estimated based on visual observations, which are imprecise and impossible at night or when visibility is limited. In recent years various researchers have developed automatic avalanche detection systems to overcome these shortcomings. Over the last three winters we have developed a seismic sensor array to continuously monitor elastic waves in the snow cover on an avalanche slope near Davos (Eastern Swiss Alps). Due to the low frequency and high sensitivity of the sensors considerable background noise originating from the nearby town and ski hills was also recorded. Additional observations methods, such as cameras and a microphone, were installed to characterize sources of background noise. Since the deployment of the first prototype system in the winter of 2008, numerous avalanches have released on slopes nearby the sensor array, and on the instrumented slope itself. This enabled us to determine specific characteristics in the time-frequency representation of seismic signals generated by avalanches. Using this information we developed a preliminary method to detect and characterize the recorded signals, which is of vital importance to remove any signal not related to avalanches. Furthermore, we are also able to distinguish loose snow avalanches from slab avalanches. The seismic sensor array therefore provides objective avalanche activity data for a limited area (i.e. about 1 km^2). The development of the sensor array, the signal processing methods as well as a comparison of avalanche activity data with meteorological data from a nearby automatic weather station are presented.

1. INTRODUCTION

Avalanche forecasting relies on weather and snowpack data as well as avalanche observations (McClung and Schaerer, 2006). Avalanche activity is usually estimated based on visual observations, which are imprecise and impossible at night or when visibility is limited. This often leads to uncertainties in the number and exact timing of avalanches resulting in an underestimation of avalanche activity (e.g. Schweizer et al., 2003).

To overcome these shortcomings, over the last decade, two different types of avalanche detection systems have been developed. First, with infrasound avalanche monitoring low frequency (below 20 Hz) sound waves generated by avalanches are detected using special microphones (e.g. Scott et al., 2004). Second, with seismic avalanche detection ground movement (i.e. elastic waves) generated by the down-slope movement of avalanches is recorded using geophones (e.g. Navarre et al., 2009).

Such avalanche monitoring systems hold the potential to provide valuable information on avalanche activity. Avalanches that occur up to several kilometers away from the sensors can be detected, depending on the size of the event (e.g. Valt and Pesaresi, 2009). However, thus far such monitoring systems are not widely used. This is in part due to difficulties in automatically discriminating signals associated with avalanches from background noise signals.

Over the last three winters we have developed a seismic sensor array to continuously monitor elastic waves in the snow cover on an avalanche start zone near Davos (Eastern Swiss Alps). The goal of this project was to identify precursor signals to avalanche release (van Herwijnen and Schweizer, submitted). However, due to amount of background noise, so far we have not been able to conclusively identify any precursor signals. On the other hand, thanks to the high sensitivity of the system, avalanches are very well detected. In this paper the development of the sensor array and the signal processing methods to identify avalanches are presented. Avalanche activity data from the winter of 2009-2010 are compared to meteorological data from a nearby automatic weather station.

2. SENSOR ARRAY

2.1 Field site

The slope where the seismic sensors were deployed is a steep NE facing slope on the lee side of a ridge at 2475 m a.s.l. (Figure 1). The slope has consistently produced avalanches in the past. The

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site is very close to an automatic weather station at the top of the ridge and two additional automatic weather stations are within 200 m of the site. The site is easily and safely accessible from the town of Davos within two hours on foot, even when avalanche conditions are critical.

2.2 Development of the sensor array

The harsh alpine environment and severe power restrictions were the two main factors which influenced the design and development of the sensor array. The choice of sensor was constrained by the fact that snow is a very porous material and high frequency signals are rapidly attenuated. We therefore decided to use seismic sensors (geophones). Geophones are small, robust and sensitive vibration sensors which generally have a flat frequency response above their natural frequency. Furthermore, geophones are passive sensors, i.e. they do not require power for operation. We used 1D vertical geophones with a natural frequency of 14 Hz.

During the winter of 2007-2008 a prototype low power single sensor system was developed and deployed for testing. This system performed very well and provided continuous acoustic data for over 40 days. Preliminary analysis of these data showed that additional observation methods were necessary to identify sources of background noise. We therefore decided to develop an expanded system consisting of an array of seven sensors, two automatic cameras and a microphone. The main features of the system are:

- Six geophones directly inserted in the snow. To improve the coupling between the sensor and the snow, these geophones were mounted in a foam housing with a density close to that of snow.
- One geophone inserted in the ground. This geophone was used as a ‘reference’ sensor.

Figure 1: Photo of the slope where the sensor array was deployed. The location of the sensors on the slope is indicated with the ellipse.

- Amplification and digitalization of the sensor output performed at the sensor to minimize signal degradation.
- Continuous data collection for all seven sensors at a sampling rate of 500 Hz.
- Single Board Computer (SBC) mounted in the weather station at the top of the ridge to store the data. Data from the sensor array were received through the Ethernet port and stored on a 32 Gb SD card, allowing for up to 30 days of continuous recording.
- A microphone was installed to continuously record environmental acoustic signals. The microphone was connected to the SBC using a USB sound card and the data were stored on a 4 Gb USB memory stick.
- Two autonomous 7 Mpixel digital cameras were used to record images at 5 minute intervals.

The developed sensor array is a low power, high precision system. It is a rather ‘low-tech’ system since the sensors are directly connected to the data logger through cables. We had no interest in developing a more advanced wireless system, nor did we attempt to develop a system which could be monitored in real time. This would have complicated the design and imposed further restrictions on the power consumption.

2.3 Deployment of the sensor array

The coupling between the snow cover and the underlying ground is extremely bad, since both materials have large differences in acoustical properties. The geophones were therefore directly inserted within the snow cover, in order to optimize signal transmission. During the winter of 2009-2010, the deployment of the sensor array was carried out in two phases.

During the first phase the cables of the data acquisition system and one sensor were fixed to the ground before the first major snowfall. Wooden posts were inserted in the ground at the location of the six sensors to be placed in the snow cover. This enabled us to easily connect the sensors to the cables during the second phase of the deployment. Once the cable was covered by at least one meter of snow, by mid-December, the wooden posts were removed and the remaining six sensors were connected to the cable and placed on the snow surface. The sensors were placed in a rectangular configuration (Figure 2) with the sensor inserted in the ground in the middle and the slope was left undisturbed for the remainder of the season. Once the sensors were sufficiently covered by

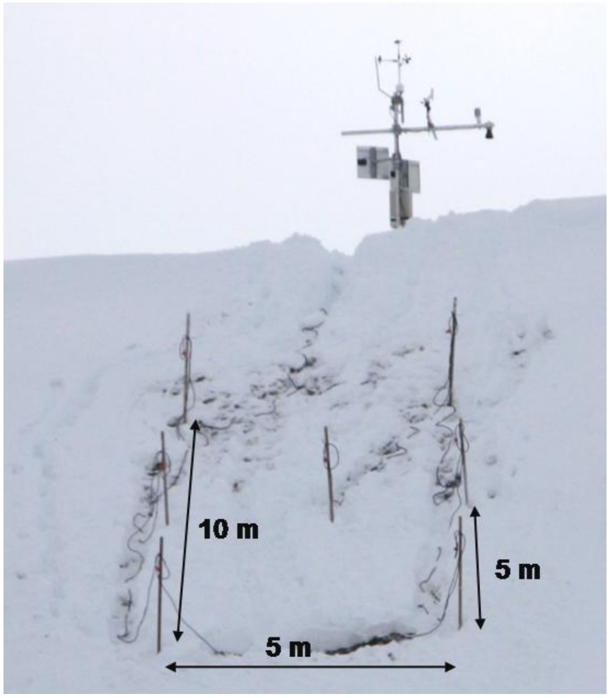

Figure 2: Photo of the deployment configuration for the winter of 2009-2010. The cables of the data acquisition system were fixed to the ground early in the season. Wooden posts were fixed in the ground in order to be able to connect the sensors once the cables were buried by snow.

snow, by mid-January, the data acquisition was started.

3. SIGNAL PROCESSING

Due to the low frequency of the geophones and the high sensitivity of the data acquisition system, there was considerable background noise in the data. Sources of background noise were identified using three methods. First, signals recorded with the geophones were compared to those recorded with the microphone. Second, when possible, sources of background noise and avalanches were identified on the images from the automatic cameras. Third, background noise was recorded manually in a field book while in the field. This enabled us to identify the main sources of background noise.

Since the amplitude of the recorded signals is dependent on the proximity and intensity of the source, discriminating signals from different sources could not be achieved using a simple amplitude threshold. For example, a helicopter flying very close to the instrumented slope generates signals which are much larger than those from a distant avalanche. It was therefore imperative to analyze the signals in the time-frequency domain, as was outlined in previous studies (e.g. Navarre et al., 2009). By displaying the running spectrum of the data, i.e. the change in the frequency content of the signal over time, one can clearly distinguish signals originating from different sources.

3.1 Backgrounds noise

In total eight major sources of background noise were identified: walking, airplane, explosives, unknown, helicopter, wind, snowcat and ski lifts. In Figure 3 typical background noise signals associated with a helicopter and wind are shown. Helicopters, as well as propeller airplanes, generate signals with very distinct harmonic frequencies (Figure 3a). On the other hand, the main frequency content of noise generated by wind is more broadband and contained within the 30 to 110 Hz range (Figure 3b). For a more detailed description of the different sources of background noise, the reader is referred to van Herwijnen and Schweizer (submitted).

3.2 Avalanche signals

Signals associated with numerous avalanches were identified using images from the automatic cameras. Below, two typical examples of a snow slab avalanche (Figure 4a) and a loose snow avalanche (Figure 4b) are shown.

Signals associated with both types of avalanches show very similar characteristics. As previously reported in several studies (e.g. Surinach et al., 2000), both loose snow and slab avalanches exhibit a typical 'spindle' shape associated with the flowing of the avalanche. The observed triangular shape in the running spectrum of the signals is also typical for flowing snow masses. It is attributed to the attenuation of seismic waves with distance, since high frequency signals attenuate more rapidly than low frequency signals (Biescas et al., 2003). Identifying signals associated with avalanches is therefore possible since the running spectrum is different from that associated with background noise (Figure 3).

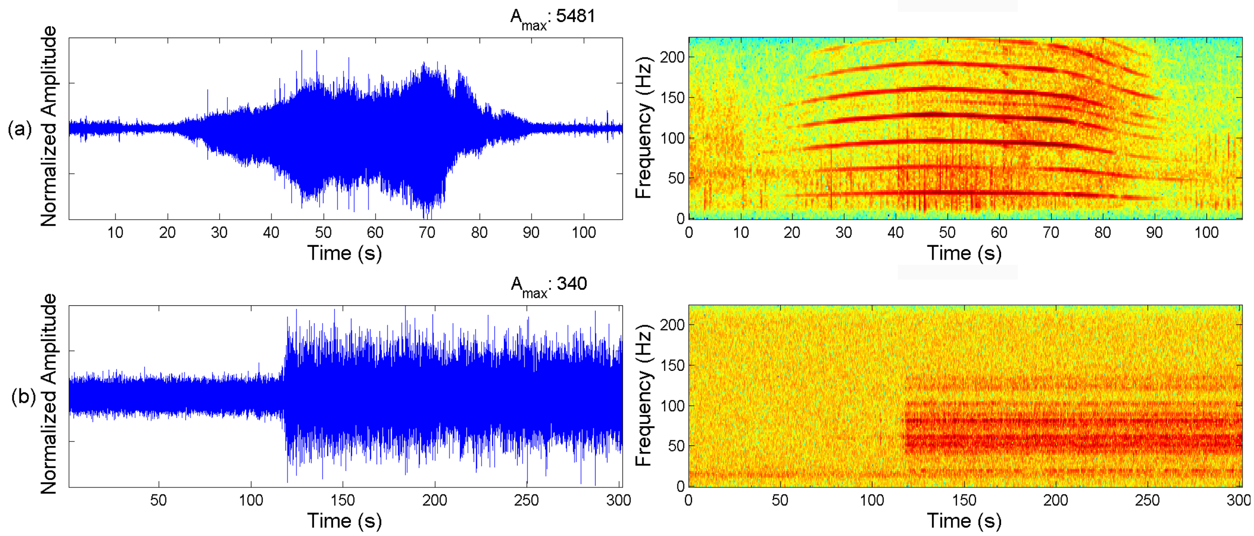

Figure 3: Two examples of background noise. (a) Helicopter. (b) Wind. Left panels: waveform. Right panels: running spectrum of the data. The colors indicate intensity, from dark blue (low) to red (high).

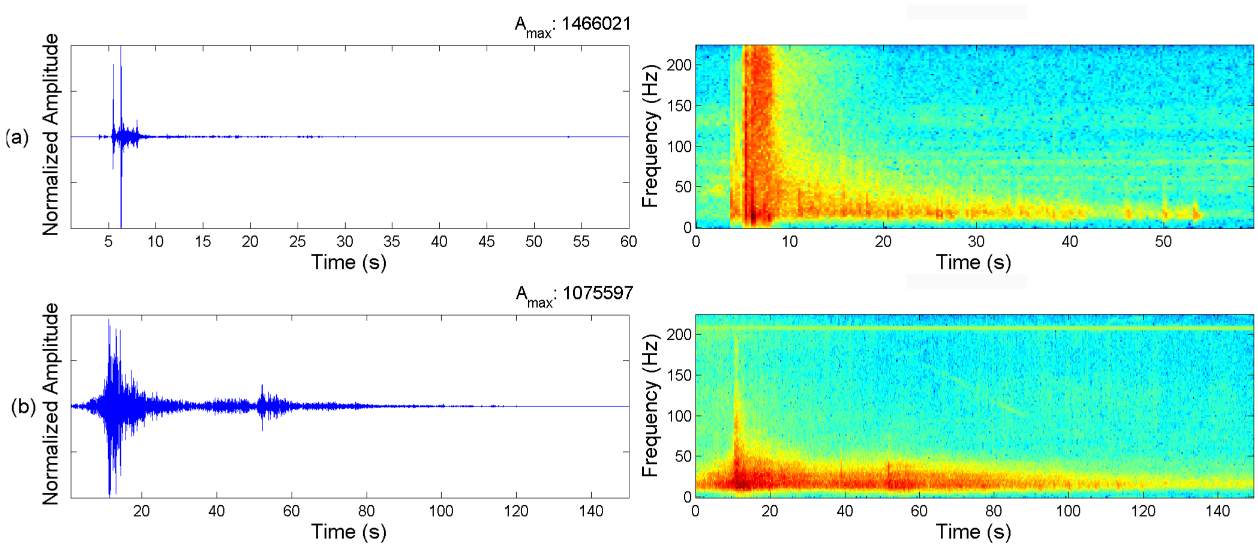

Figure 4: Two examples of signals generated by avalanches. (a) Slab avalanche. (b) Loose snow avalanche. Left panels: waveform. Right panels: running spectrum of the data. The colors indicate intensity, from dark blue (low) to red (high)

3.3 _Avalanche activity and meteorological data_

In order to determine the avalanche activity throughout the winter, signals associated with avalanches were manually identified. This was achieved by visual inspection of the data by an experienced observer, specifically by looking at the running spectrum as well as the waveform of the data. The time and date of any signal which exhibited characteristics typical for avalanches (see Figure 4) were recorded. Sensor data from 12 January 2010 to 30 April 2010 were analyzed.

Meteorological data were obtained from the automatic weather stations in the immediate vicinity of the sensor array. The air temperature, relative humidity, maximum wind speed and snow height were recorded for ten minute intervals.

4. RESULTS

In total 422 avalanche signals were identified. These include loose snow and slab avalanches of all sizes. Using information from the automatic cameras as well as from field observations, we determined that avalanches within a 700 m radius of the sensor array were detected, corresponding to an area of roughly 1.5 km^2.

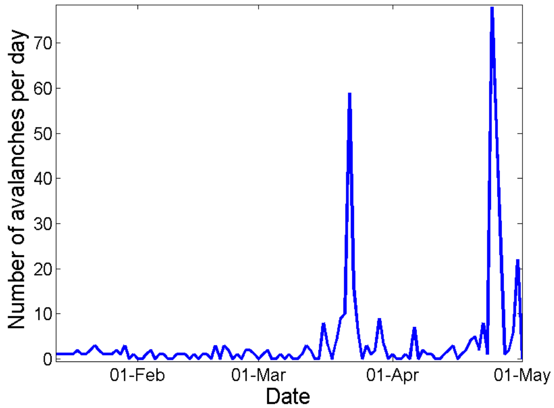

Figure 5: Number of recorded avalanches per day from 12 January to 30 April 2010.

In Figure 5 the avalanche activity from January to the end of April 2010 is shown. There were 32 days with no recorded avalanches. Two distinct peaks in the avalanche activity stand out; around 20 March and at the end of April. Both avalanche cycles were wet snow avalanche cycles and more than 50 avalanches per day were observed. The overwhelming majority of these avalanches were loose wet snow avalanches.

How the avalanche activity depended on meteorological conditions, namely air temperature, changes in snow height and average wind speed, is shown in Figure 6. Four avalanche cycles are highlighted: a dry snow slab avalanche cycle in February and wet snow avalanche cycles in the third week of March, the first week of April and at the end of April.

In the top panel (Figure 6a) the daily average air temperature is shown (red line) as well as the air temperature at the time of each recorded avalanche (blue dots). It comes as no surprise that the air temperature during the wet snow avalanche cycles was consistently above zero.

In the middle panel the change in mean daily snow height is shown (red line) as well as the 12, 24, 48 and 72 hour change in snow height prior to each avalanche (colored dots). During the entire season every snowfall was followed by some avalanche activity. Avalanches occurred either during

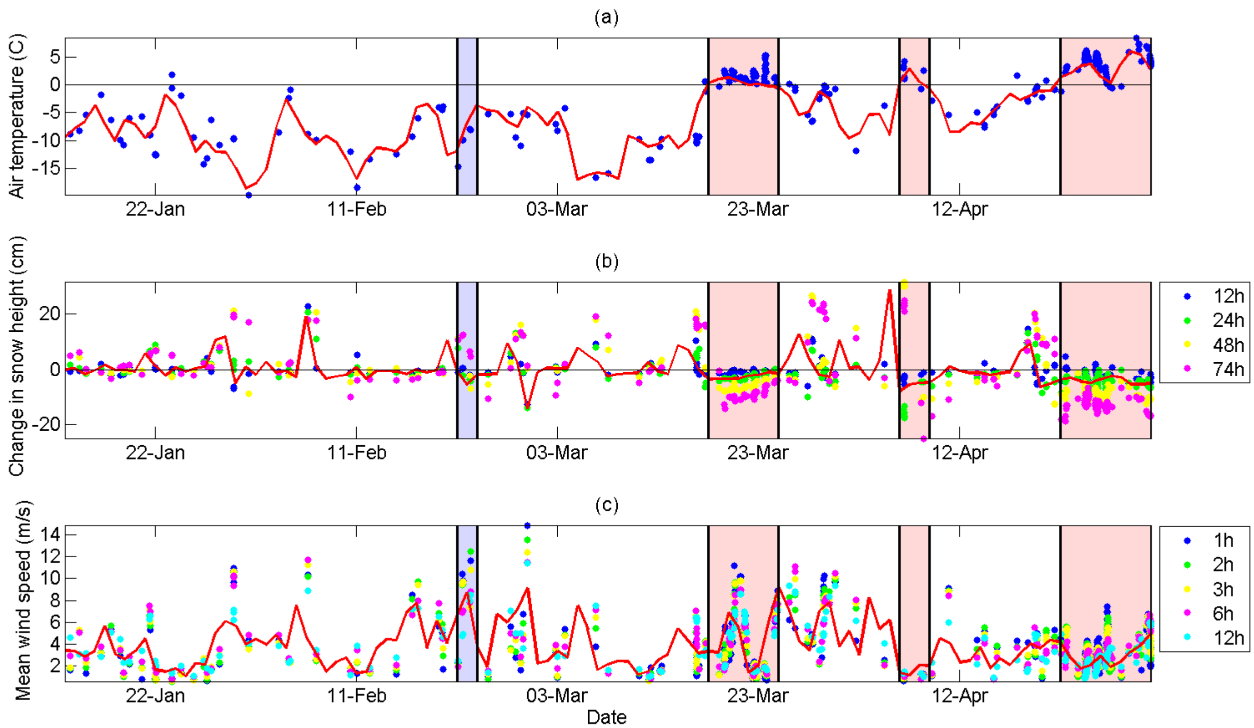

Figure 6: Avalanche activity and meteorological conditions. (a) Daily mean air temperature (red line) as well as the air temperature at the time of the avalanche (blue dots). (b) Change in mean daily snow height (red line) as well as the daily changes in snow height prior to each avalanche (coloured dots); see legend for colours. (c) Mean daily wind speed (red line) as well as mean hourly wind speeds prior to each avalanche (coloured dots); see legend for colours. Four avalanche cycles are highlighted: a dry snow slab avalanche cycle in February (blue area) and three wet snow avalanche cycles (red areas).

the snowfall or up to two days after the snowfall, as was the case for the February avalanche cycle. However, there were also many avalanches without any prior snowfall. Most notably, the wet snow avalanche cycles were associated with snow settlement, as evidenced by negative changes in snow height. This observation is consistent with results from a study on wet snow avalanche formation (Baggi and Schweizer, 2009).

Finally, in the bottom panel (Figure 6c) the mean daily wind speed (red line) as well as the mean 1, 2, 3, 6 and 12 hour wind speed prior to each avalanche (coloured dots) are shown. Interpretation of these data is not straightforward as wind direction is not included. Nevertheless, during the first half of the season, roughly up to 3 March, each peak in daily wind speed was associated with avalanche activity either on the same day or the next. This was the case for the February avalanche cycle. During the second half of the season this was not always the case, possibly because less soft snow was available on the snow surface for wind transport.

5. DISCUSSION AND CONCLUSIONS

We reported on the development and the deployment of a seismic sensor array for an avalanche start zone. Although the system was developed to investigate precursor signals to avalanche release, thanks to the high sensitivity it could also be used as a tool for objective avalanche detection.

By visually inspecting the data an experienced observer recorded over 400 avalanches. In combination with meteorological data from automatic weather stations in the immediate vicinity of the sensor array, this constitutes a unique record of avalanche activity for an entire winter season.

Analysis of avalanche activity in combination with meteorological data showed that each snowfall resulted in avalanche activity either during the snowfall or up to two days after. The delay between wind events and avalanche activity was generally shorter. However, these trends were less obvious since wind direction was not taken into account.

Overall, the work presented here shows the tremendous potential of a system to objectively record avalanche activity. However, for operational use the signal processing needs to be automated. While it is clear that avalanche signals exhibit distinct characteristics (Figures 3 and 4), automatic detection is far from straightforward. A pattern recognition method, such as a neural network, would be very well suited for this, as has been proposed for other seismic applications.

An automatic seismic avalanche detection system would undoubtedly provide reliable and accurate avalanche activity data for avalanche forecasting. Combined with meteorological data it could also provide new insight into avalanche formation.

ACKNOWLEDGEMENTS

For their help with field work, we would like to thank Sascha Bellaire, Susanne Hoinkes, Christoph Mitterer, Fabiano Monti, Benjamin Reuter and Walter Steinkogler. Funding for this research was in part provided by the FP6 project TRIGS (European Commission contract NEST-2005-PATH-COM-043386), the CCES project TRAMM (ETH Board) and the FP7 project HYDROSYS (European Commission grant 224416, DG INFSO)

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