DETECTING AVALANCHES USING SEISMIC MONITORING SYSTEMS

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ABSTRACT: Meteorological, snowpack and avalanche activity data provide the essential building blocks for avalanche forecasting. While in recent decades the availability and coverage of meteorological data has dramatically improved, the same has not happened for avalanche activity data. The reason is that data on avalanche activity are generally obtained through visual observations, which are imprecise and impossible when visibility is limited. This leads to large uncertainties in the number and exact timing of avalanches, resulting in rather poor correlations between avalanche activity, meteorological parameters and estimated avalanche danger. To improve avalanche forecasting, remote detection of avalanches is therefore required to obtain accurate and near real-time avalanche activity data. Seismic monitoring systems are very well suited for this task and typically rely on one or several sensors in an avalanche track or at valley bottom to detect avalanches. We employ a different approach, consisting of continuously recording seismic signals in an alpine start zone. Avalanches can then visually be identified in the seismic data to obtain an avalanche database. Based on measurements from our field sites above Davos (Switzerland), we show how seismic monitoring can provide high resolution avalanche activity data, and how these data can provide new insights into avalanche formation processes. While for large-scale operational avalanche forecasting automatic avalanche detection still has to be developed, we will further show that seismic monitoring can already effectively be used to remotely detect artificially triggered avalanches below fixed avalanche control installations.

KEYWORDS: avalanche monitoring, avalanche forecasting, seismic instrumentation, avalanche formation.

1. INTRODUCTION

Seismic monitoring systems are well suited for the remote detection of hazardous mass movements such as rockfall, landslides and snow avalanches (e.g. Deparis et al., 2008; Surinach et al., 2005). Such systems consist of one or several seismic sensors, also called geophones or seismometers, inserted in the ground or bolted to rocks and connected through cables to a data recording system, or data logger. Ives et al (1973) were the first to show that seismic monitoring equipment can be used to remotely detect avalanches. It quickly became evident that such avalanche monitoring systems could potentially provide valuable information for avalanche forecasting, since data on avalanche activity represent the most direct instability data (McClung and Schaerer, 2006). As noted by Harrison (1976): 'a network of a few sensors which remotely could detect and locate avalanches during storm conditions over an area of a few square miles would have important application'. Since then, numerous studies have shown that, depending on the size, avalanches that occur up to several kilometers away from the sensors can be detected (e.g. Valt and Pesaresi, 2009). Nevertheless, thus far seismic monitoring systems are not widely used, in part due to the non-trivial task of automatically discriminating signals associated with avalanches from background noise signals (e.g. Bessason et al., 2007).

Since 2008, we have been developing a seismic monitoring system to continuously monitor avalanche activity in an alpine start zone above Davos, Switzerland. During the initial stages of the project, we mainly focused on developing robust and reliable instrumentation and on signal interpretation (van Herwijnen and Schweizer, 2011b; van Herwijnen et al., 2010). Since then, our focus has shifted towards the formulation of algorithm for the automatic detection of avalanches (Rubin et al., 2012) and assessing how accurate avalanche activity data can be utilized for avalanche forecasting (Schweizer and van Herwijnen, 2013). Most recently, we also developed and deployed a low-cost monitoring systems with the long-term goal of

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deploying many such systems over a large area to monitor regional avalanche activity. While the automatic detection of avalanches is still a work in progress, in this paper we present results highlighting the potential of using accurate avalanche activity data to improve our understanding of avalanche formation processes. Furthermore, we show preliminary results from our low-cost monitoring system, which we tested during the winter of 2013-2014 below a fixed avalanche control tower.

2. METHODS

2.1 Sites and instrumentation

Currently, we monitor avalanches at three sites above Davos (Figure 1). At all our field sites, we continuously record data from the seismic sensors and transfer the data to the SLF either through long distance wifi links or through a direct wired internet connection.

Since 2008, at the Wannengrat field site we have an array of 7 vertical component geophones deployed in an avalanche start zone at an elevation of about 2500 meters. The commercial data acquisition system consists of low-noise, high-precision 24-bit analog to digital converters (ADC) and data are sampled at a rate of 500 Hz. The Wannegrat field site is located approximately 4.5 km from the SLF and is instrumented with several automatic meteorological stations (AMS). Data are transferred through a wifi link.

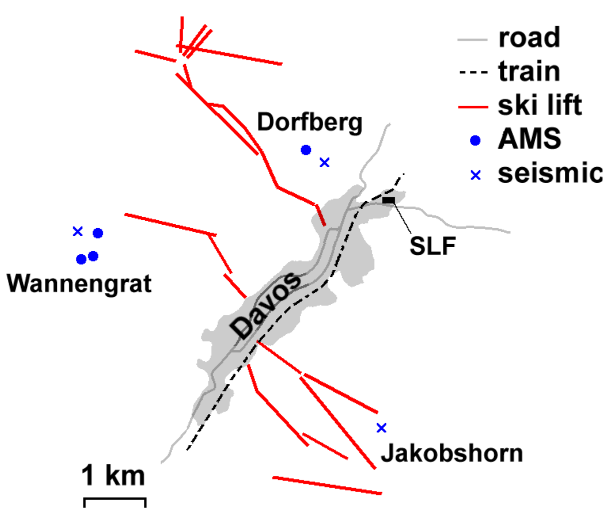

Figure 1: Overview of our three field sites instrumented with seismic monitoring systems around Davos, Switzerland. Also shown are the main roads, railway line, mountain cable ways and the locating of automatic meteorological stations (AMS).

Since 2009, at the Dorfberg field site, we have one vertical component geophone deployed on a grassy slope at an elevation of about 1900 meters, where glide-snow and wet-snow avalanches release almost every season. The data acquisition system consists of a low-noise, high-precision 24-bit ADC and data are sampled at a rate of 500 Hz. The Dorfberg site is located approximately 1.5 km from the SLF and is also instrumented with an AMS and continuously monitored with automatic cameras from offices at the SLF (e.g. van Herwijnen et al., 2013a). Data are transferred through a wifi link.

Since 2013, at the Jakobshorn field site we have three vertical component geophones deployed below a fixed avalanche control installation, securing steep slopes above an access ski run at an elevation of about 2500 meters. The low-cost system (about $1000) consists of off-the-shelve 16-bit ADCs connected to a low power single board computer (Raspberry Pi), and data are sampled at a rate of 860 Hz. At the site, located approximately 3.5 km from the SLF, we have access to power and a wired internet connection for data transfer.

2.2 Signal processing and avalanche detection

To identify seismic signals generated by avalanches, we initially relied on images from automatic cameras for validation. Since there is considerable environmental noise in seismic data, for instance due to airplanes, traffic or ski lifts, it is extremely important to distinguish seismic signals generated by avalanches from environmental noise (e.g. van Herwijnen and Schweizer, 2011a). Using avalanches identified on the images from automatic cameras allowed us to learn what typical characteristics are associated with signals generated by avalanches. Unfortunately, this learning step must be done for each site separately, since local topography and geology strongly affect signal transmission. For instance, due to its proximity to the town of Davos, the Dorfberg field site is seismically very noisy. On the other hand, even though our instrumented slope at the Jakobshorn was in the middle of a ski area, there was very little noise in the data, mainly due to the relatively low density loose soil at the site.

Nevertheless, despite these site specific differences, seismic signals generated by avalanches still consistently had distinct temporal and spectral characteristics (e.g. Surinach et al., 2000; van Herwijnen et al., 2013b). To identify avalanches in the seismic data we therefore performed a visual inspection of the waveform and the spectrogram, i.e. the evolution of the frequency content of the signal with time (Figure 2). For the Wannengrat field site, we inspected two winters of data from one sensor, namely the winters of 2009-2010 and 2010-2011, referred to as 2010 and 2011, respectively. For the Dorfberg field site, we focused on a period of high wet-snow avalanche activity during the spring of 2013. Finally, we inspected all the data from the winter of 2013-2014 for the Jakobshorn field site.

2.3 Detrended cross-correlation analysis

To investigate typical time scales involved in avalanche formation processes requires cross-correlating avalanche activity data with meteorological parameters. However, due to the presence of strong non-stationary fluctuations in meteorological data, it is not possible to perform a 'standard' cross-correlation. For instance, over the course of a season, air temperature will exhibit two clear trends: diurnal fluctuations (it is generally warmer in the afternoon than at night) and a large upward trend (it is generally warmer in April than in January). The cross-correlation between avalanche activity and air temperature will therefore exhibit the same trends, not because a correlation exists, but because the cross-correlation function is being used for a non-stationary time series.

Detrending the data is therefore essential to properly analyze the time-series. Thus, we performed a so-called detrended cross-correlation analysis (DCCA). The DCCA is designed to investigate cross-correlations between different simultaneously recorded time-series in the presence of non-stationarities (for more details see Zebende, 2011). The dimensionless cross-correlation coefficient with lag time ranges between -1 (perfect anti-correlation) and 1 (perfect correlation), similar to the more well known Pearson linear correlation coefficient.

3. RESUTLS AND DISCUSSION

3.1 Relating avalanche activity to meteorological drivers

Using avalanche activity data from the Dorfberg field site from the spring of 2013, we see that for lag times of up to about 72 hours (3 days), the correlation between avalanche activity and air temperature, snow surface temperature and total net radiation was positive (top in Figure 3). The highest correlations were obtained for lag times of 24 hours. These results are in line with a recent study on wet-snow avalanches which showed the predictive power of 24 hour mean snow surface temperature and 3 day total energy balance (Mitterer and Schweizer, 2013). The correlation between avalanche activity and wind speed as well as snow height, on the other hand, was negative (orange and red lines in Figure 3). This means that there were more avalanches with decreasing snow height and low wind speeds, as one would expect for wet-snow avalanches (Baggi and Schweizer, 2009).

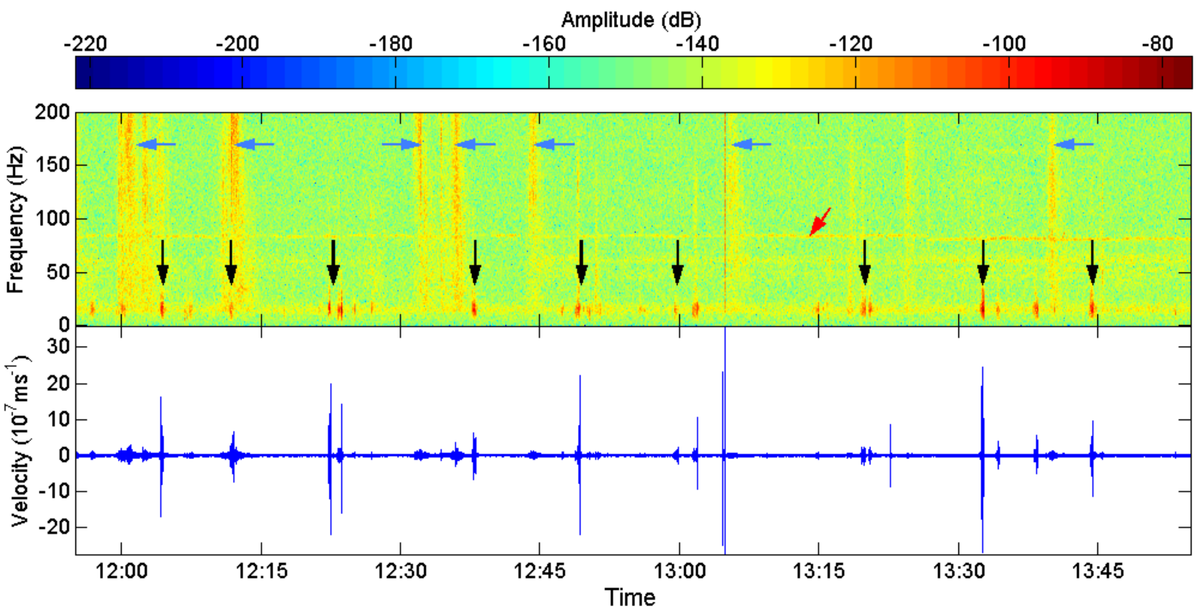

Figure 2:Seismic signals generated by avalanches and environmental noise for two hours on 23 March 2010. Top: spectrogram showing the frequency content of the signal with time. The black arrows show confirmed avalanches, based on images from automatic cameras. The blue arrows show airplane signals. The red arrow shows the noise band from ski lifts. Bottom: corresponding waveform.

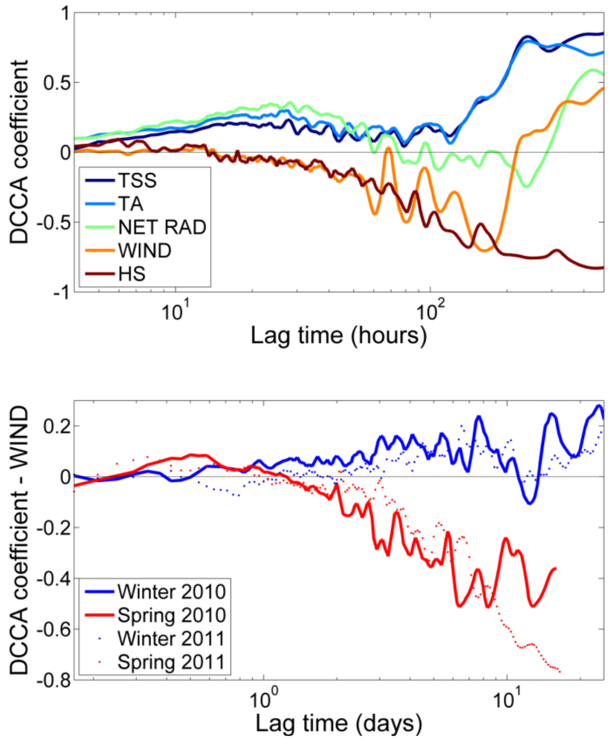

Figure 3: Top: detrended cross correlation coefficient (DCCA) with lag time between avalanche activity and snow surface temperature (TSS), air temperature (TA), net total radiation (NET RAD), wind speed (WIND) and snow height (HS). Avalanche activity data from the Dorfberg field site between 1 and 11 March 2013. Bottom: DCCA coefficient with lag time between avalanche activity and wind speed for winter and spring data from the Wannengrat from 2010 and 2011.

Using the avalanche activity data from the Wannengrat field site from 2010 and 2011, we can investigate longer time scales. During the winter period, roughly up to the middle of March, the correlation between avalanche activity and wind speed steadily increased up to a lag time of 6 to 7 days for both winters (blue lines in bottom Figure 3). In spring time, however, there was a negative correlation between wind speed and avalanche activity for lag times longer than a day (red lines in bottom Figure 3), similar to the Dorfberg field site (compare orange line in top Figure 3). Interestingly, despite the substantially different avalanche activity patterns in 2010 and 2011, the trends in the cross-correlation curves were remarkably similar, suggesting some universality in the underlying processes. Although more data are needed to confirm our results, they highlight the potential to improve our knowledge on the complex interaction between meteorological drivers and avalanche formation processes.

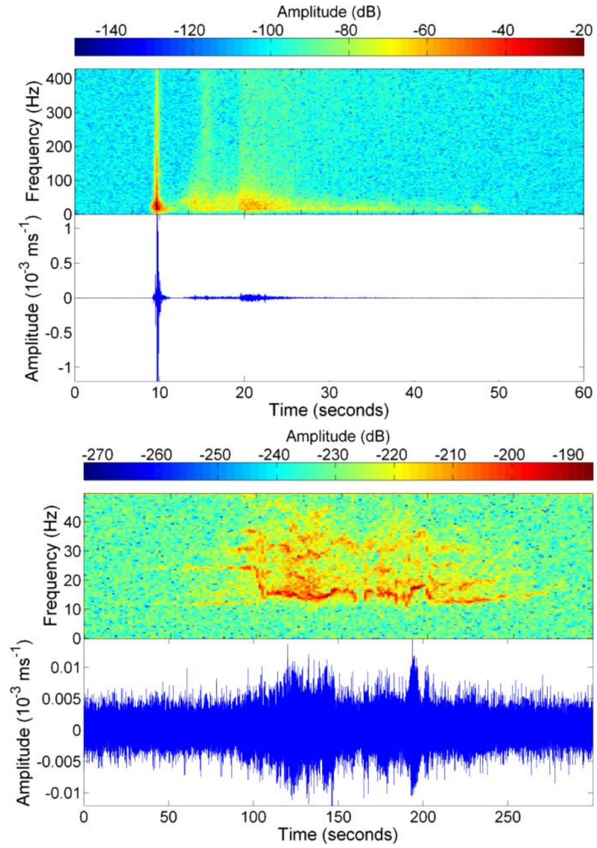

Figure 4: Seismic signals (trace and spectrogram) generated by a detonation and the subsequent avalanche (top) and by snow grooming equipment (bottom).

3.2 Monitoring artificial avalanche release

The results described above related to natural avalanche release. The question therefore remains whether seismic monitoring can also be used to confirm artificial avalanche release by explosives, widely used to reduce avalanche hazard, especially in ski areas. Specifically, we investigated if a low-cost seismic monitoring system can be used to remotely detect artificially triggered avalanches below a fixed installation (GAZEX) at the Jakobshorn ski area above Davos. The use of fixed, remotely controlled avalanche control installation has dramatically increased over the past decades. Such installations, which can safely be operated at any time by the push of a button, are now widely used, in particular in the European Alps. Nevertheless, despite the increase in safety and ease of use, on-site confirmation is still required to verify if an avalanche was released.

Based on visual inspection of the data, we found that the three main sources of seismic signals at our field site were (Figure 4): 1) detonations, characterized by short, high amplitude broadband signals; 2) Avalanches, which generate longer, low frequency, low amplitude signals; 3) Snow cats, which generate long, low amplitude signals with clear resonant frequencies. Based on the frequency content and amplitude of the signals, it was relatively straightforward to distinguish the different events.

Over the entire winter, we identified 157 detonations in the seismic data: 18 detonations from the fixed installation at our site, 36 detonations from two nearby installations and 103 detonation from hand charges in the ski area. Based on our observations, we can conclude that our system can detect detonations within a radius of approximately 500 m.

We identified 26 avalanches: 18 triggered by the installation on our slope, 6 triggered by nearby installations or hand charges, and 2 natural avalanches which released after the ski resort had closed. Our results show that each detonation at our site resulted in the release of a (small) avalanche, suggesting excellent yield. While we detected each avalanche on the instrumented slope, even very small slides, due to the poor coupling between the sensors and the ground, we only detected large avalanches released further away from our slope. Due to bad visibility we could not determine the size of each avalanche. Nevertheless, the limited data we have suggests that signal duration correlates with avalanche size (not shown), as previously reported by van Herwijnen et al. (2013b).

Finally, it comes as no surprise that the main source of background noise at a ski resort originates from snow grooming. While the frequency content of the seismic signals is similar to that of an avalanche, due to the long signal duration and the presence of resonant frequencies, these signals can easily be distinguished from avalanches by visual inspection of the spectrogram. It was, however, somewhat surprising that we did not observe any other environmental noise. We attribute this to the poor coupling between the sensors and the loose low-density soil at the site.

4. CONCLUSIONS AND OUTLOOK

In this study, we highlighted the usefulness of accurate avalanche activity data obtained through seismic monitoring for improving our understanding of avalanche release processes. Our results show that highly resolved avalanche activity data can provide valuable and novel insight into time scales involved in the complex interaction between meteorological drivers and avalanche formation processes.

Using visual inspection of the waveform and the spectrogram, i.e. the evolution of the frequency content of the seismic signal with time, we obtained accurate avalanche activity data for two entire winters and one period of 10 days with intense wet-snow avalanche activity in the spring of 2013. Wet-snow avalanche activity correlated with air temperature, snow surface temperature and total net radiation, up to a lag time of three days. On the other hand, snow height and wind speed were negatively correlated for lag times larger than one day. For dry-snow avalanches, on the other hand, avalanche activity correlated with air temperature up to a lag time of six to seven days. These results suggest that there are inherently different time scales involved in dry and wet-snow avalanching.

Our analysis was based on visual inspection of the seismic data, which is a time consuming endeavor. Without automatic avalanche detection, seismic monitoring can therefore not be used for operational avalanche forecasting, especially when focusing on natural avalanche activity. The situation is somewhat different when monitoring artificial avalanche release below fixed avalanche control towers. Indeed, our results showed that detonations and subsequent avalanches were very well detected with a low-cost seismic monitoring system placed directly below the control installation. Since signals from detonations are very large, for operational use, it is therefore possible to use a simple amplitude threshold to activate the system and graphically display the subsequent data. This would enable the avalanche safety personal to rapidly assess if an avalanche released without requiring visual on-site confirmation.

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