EVALUATING THE PERFORMANCE OF AN OPERATIONAL INFRASOUND AVALANCHE DETECTION SYSTEM AT THREE LOCATIONS IN THE SWISS ALPS DURING TWO WINTER SEASONS

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ABSTRACT: Avalanche occurrences are unambiguous indicators of unstable snow conditions. Information on past and current avalanche activity is therefore crucial for avalanche forecasting. To continuously assess avalanche activity, automatic detection systems are required. In recent years, technological and signal processing advances have led to the development of operational infrasound avalanche detection systems. We evaluated the detection performance of four operationally running infrasound detection systems installed at three different sites throughout the Swiss Alps during two entire winter seasons. To this end, we collected a comprehensive data set of avalanche activity using a network of automatic cameras and supplementary field observations by local observers. The events automatically identified by the systems were then compared to the data set of visually observed avalanches. Only 3% of the observed avalanches were associated with automatic detections and 22% of the automatic detections were confirmed by field observations. However, the majority of observed avalanches were small and most automatic detections occurred during periods of poor visibility. Furthermore, the probability of detection (POD) increased with avalanche size and decreased with distance. Large avalanches (on the order of 100 m wide and 1000 m long) within a distance of 3-4 km from the array were typically well detected (POD ~ 80%). The false alarm ratio was estimated to 10-30%.

KEYWORDS: Snow avalanches, infrasound, array processing, monitoring of avalanche activity

1. INTRODUCTION

Avalanche forecasting and risk management strongly depend on the availability of information on the snowpack and its stability. Since the occurrence of avalanches provides an unambiguous indicator for unstable snow conditions, avalanches can be considered as a good predictor for further avalanches (Schweizer et al., 2012; van Herwijnen et al., 2016). Exact knowledge about the time and location of avalanche events is therefore crucial for regional as well as local forecasting. An increase in avalanche activity might indicate the time to close a road. Also, the decision to re-open the road is facilitated if the frequency of avalanches decreases. Consequently, timely information on the temporal evolution of avalanche activity can reduce risk and closing times.

Monitoring avalanche activity simply by visual observation is not possible though. The visibility of relevant avalanche paths is particularly limited during periods of heavy snowfall, when timely data on avalanche occurrences are particularly wanted. There is thus a need for remote detection systems, which enable real-time monitoring of avalanche activity in a specific area independent of visibility.

Currently, three different technologies exist for the automatic detection of avalanches: infrasonic sensors (e.g. Marchetti et al., 2015; Schimmel et al., 2017; Scott et al., 2007; Thüring et al., 2015) ground based and satellite radar sensors (e.g. Eckerstorfer et al., 2016; Gauer et al., 2007; Schimmel et al., 2017) as well as seismic sensors (Heck et al., 2018). Infrasound detection systems can detect avalanches several kilometers away from the sensor system (Thüring et al., 2015; Ulivieri et al., 2011). However, to the best of our knowledge, no study exists yet that investigates how the detection performance depends on avalanche size and distance to the sensors.

Our objective was therefore to assess the performance of infrasound avalanche detection systems with a special focus on avalanche type and size. We compared automatically detected events to avalanche activity data obtained by visual observations at three different sites throughout the Swiss Alps (Goms, Frutigen and Prato) during the entire winter seasons 2015-2016 and 2016-2017. For the visual survey of avalanche activity, a network of automatic cameras was used and supplemented with detailed field observations by local observers.

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2. METHODS

2.1 Setup and signal processing

The commercially available infrasound monitoring systems known as IDA (Infrasound Detection of Avalanches) consisted of four or five-sensor infrasound arrays with a triangular geometry and an aperture, i.e. the maximum distance between two elements, of approximately 150 m. The array elements were equipped with differential pressure transducers, with a sensitivity of 25 mV Pa^{-1} in the frequency band 0.01-100 Hz and low self-noise (-62 dB $Pa^2 Hz^{-1}$, relative to 1 Pa). Pressure data were recorded at a sampling rate of 50 Hz with a 16-bit digitizer and GPS time synchronization. Digital data from the peripheral sensors were transmitted through fibre-optic cables to the central element of the array where data were synchronized, stored and transmitted via modem to a server where the data were processed in near-real time. For the signal-to-noise discrimination, a multi-channel correlation method was applied to each array record (Marchetti et al., 2015; Ulivieri et al., 2011). Array processing techniques were then applied to compute the infrasonic wave parameters such as the apparent velocity as well as the azimuth angle of the signal source, i.e. the angle between the direction of incidence of the wave emanating from the signal source and the north direction.

To automatically discriminate signals generated by avalanches from other natural (e.g. earthquakes, meteors or thunder) and anthropogenic (e.g. traffic, explosions or cableway) infrasonic events, threshold criteria based on wave parameters were defined by considering avalanches as a moving source of infrasound (Marchetti et al., 2015). The underlying threshold parameters were calibrated for each site. If an event met the threshold criteria partially or completely, it was classified as an avalanche with “medium” or “high” reliability index, respectively. An alarm was automatically sent via text message (SMS) to local avalanche safety personnel when an event with “high” reliability was detected. In the following, we will use the term detections for events that were automatically identified as potential avalanches with either high or medium reliability index.

2.2 Sites

A total of four infrasound arrays were installed at three different sites in the Swiss Alps (Figure 1). One infrasound system was deployed at 1340 m a.s.l. in the Engstligen valley close to Frutigen (Bernese Oberland). Relevant release areas are located on both sides of the valley at elevations of up to 2600 m a.s.l.. A further array was installed in the Valle Leventina (Ticino) at 1340 m a.s.l. close to Prato. Here, potential starting zones extend up to 2700 m a.s.l. and especially the NNE-facing avalanche paths opposite of the system endanger highway and settlements below. The third site was located in the valley of Goms (Valais), where two systems were installed at a distance of about 4.5 km in order to monitor the mountain ranges on both sides of the valley rising up to more than 3000 m a.s.l.

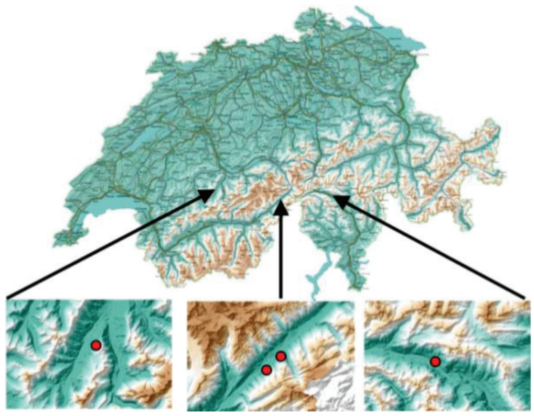

Figure 1: Overview of the three sites Frutigen, Goms and Prato (from left to right). The red dots indicate the position of the IDA systems. In Goms, one system was deployed near Blitzingen and another one 4.5 km further northeast, close to Reckingen.

2.3 Visual survey of avalanche activity

For visual monitoring of avalanches, at each site we installed at least two automatic camera systems to record images in various directions every 10 minutes. The images from the automatic cameras were available online in near real-time and covered most of the relevant avalanche paths. In addition, local observers regularly performed field surveys to record more detailed observations. Observed avalanches were then mapped in a GIS tool. Finally, this data set was supplemented by avalanche events extracted from the database ProTools, an operational information system (Pertschy et al., 2016). We chose to include all natural avalanches within a radius of 10 km around the respective infrasound system to determine whether detections originated from distant avalanches.

For each avalanche observed on the images of the cameras, we determined a plausible release time as the time interval between the last image with sufficient visibility without the avalanche and the first image on which the avalanche was seen. The resulting possible time interval thus amounts to at least 10 minutes and sometimes extended to several days in case of poor visibility. For events not seen on the images of the automatic cameras but recorded by local observers, we also took into account an uncertainty in time of release depending on visibility.

We further classified all avalanches with mapped areas larger than 10,000 m^2 into the three categories wet, dry and mixed (i.e. dry snow in the starting zone but wet snow in the runout) to investigate the influence of the avalanche type on the probability of detection.

2.4 Verification analysis

The data set of detections contains the exact time, signal duration, starting, final and average values of the azimuth angle as well as the associated reliability information for each detected event. In our analysis, we used the latest reprocessed data, using the optimal thresholds for the detection algorithm for each site. Consequently, the detections we analyzed do not necessarily coincide with the real-time detections during operational conditions.

For each detection, we first examined whether the corresponding time was within one of the time intervals assigned to the mapped avalanches. When a match was found, we then checked whether the location of the mapped avalanche also corresponded to the azimuth angle indicated by the system. This assignment was not always straightforward due to uncertainties in the data. For example, if the exact date of the avalanche was unclear, or if several avalanches occurred from a similar azimuthal range during a major snow storm, assigning such events to a specific detection was difficult.

If no avalanche matched a detection, we examined whether it was a false alarm. Each unconfirmed detection was therefore allocated to one of the following categories:

a) *Unrealistic signal:* Signal characteristics did not fit to any avalanche path, e.g. the change in the azimuthal angle or the duration of the signal were unrealistically high.

b) *Good visibility:* Visibility on the day of or after the detection was good, but no avalanche was observed at the potential location indicated by the azimuth angle.

c) *Bad visibility/low danger:* Visibility on the day of and after the detection was poor, but an avalanche was very unlikely due to rather stable snow conditions (avalanche danger level “1-Low” or “2-Moderate”).

d) *Bad visibility/high danger:* Visibility of relevant avalanche paths on the day of and after the detection was limited and a natural avalanche was likely given the rather unstable snow conditions at the time (avalanche danger level “3-Considerable” or higher).

3. RESULTS

3.1 Observed avalanches

During both winter seasons, a total of 673 avalanches of all sizes were visually observed in an area of 10 km around each of the four infrasound systems. These include slab, loose and glide snow avalanches. As any avalanche at the Goms site could potentially have been detected by both infrasound systems at this site (Blitzingen and Reckingen; Figure 1), some avalanches were counted twice. Therefore, the total number of relevant avalanche events was 840.

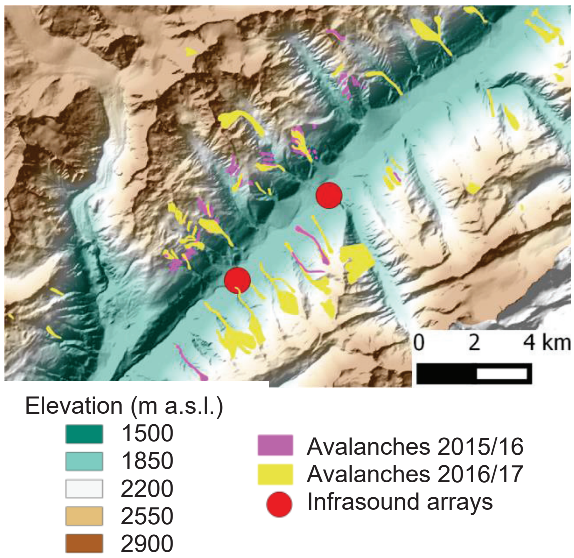

Figure 2: Mapped avalanches of both winter seasons (pink and yellow polygons) and infrasound arrays (red dots) at the Goms site.

Overall, the majority of observed avalanches were small. In fact, 67% of the mapped avalanches had an area <10,000 m^2. The largest avalanches with areas of about 1 km^2 were registered at the Goms site at the beginning of March 2017. These avalanches were mostly classified as “mixed” since they released as dry-snow slab avalanches, whereas the deposit consisted of wet snow. In general, a large portion of the observed avalanches were either wet-snow or mixed-type avalanches due to above-average air temperatures. Among the avalanches with areas >10,000 m^2, about 43% were dry-snow avalanches, while the percentage of wet-snow or mixed avalanches was each about 28%.

3.2 Probability of detection

For all four infrasound systems, the proportion of detected avalanches mapped in the area was small. In total, about 3% of the 840 observations were associated with automatic detections. To assess the influence of avalanche size and source-receiver distance, we grouped all avalanche events into four size classes and three distance classes (Figure 3). For each area-distance class, the respective probability of detection (POD) was calculated as proportion of detected avalanches among all observed avalanches in that particular class. Figure 3 clearly shows that the POD increased with avalanche size and decreased with distance. Small avalanches (on the left) were not detected and only a small fraction (POD=12%) of the medium-sized avalanches (on the order of 100 m wide and 100 m long) within a radius of 3 km were detected. On the other hand, large avalanches (on the order of 100 m wide and 1000 m long) within a distance of 3 to 4 km from the array were well detected (POD=78%). In this size range, the most distant avalanche still detected released almost 6 km away from the infrasound array. However, more data points are needed to assess the detection performance for large avalanches at distances of more than 4 km from the system. The overall low POD (<4%) for medium-sized avalanches at distances >3 km suggests that large avalanches might likewise not be reliably detected at this distance range where attenuation, distortion as well as shading effects produced by near-source topography on the acoustic wave field (Lacanna and Ripepe, 2013) produce ambiguous infrasonic wave parameters strongly reducing the capability of automatic detection.

Among the medium-sized and large avalanches, different types of avalanches were detected, namely dry-snow, wet-snow and mixed avalanches as well as glide-snow avalanches. A calculation of separate detection rates for each of these avalanche types was not feasible, as in the uppermost size range data were limited to only a few avalanches per type. However, in the range of medium-sized avalanches and distances <3 km, where sufficient data points were available, a differentiation between avalanche types results in a POD of 22% for dry-snow and a POD of only 4% for wet-snow or mixed events. This result supports the assumption that the detection of wet-snow avalanches is less reliable than the detection of dry-snow avalanches due to lower acceleration rates and thus smaller pressure differences and infrasound amplitudes.

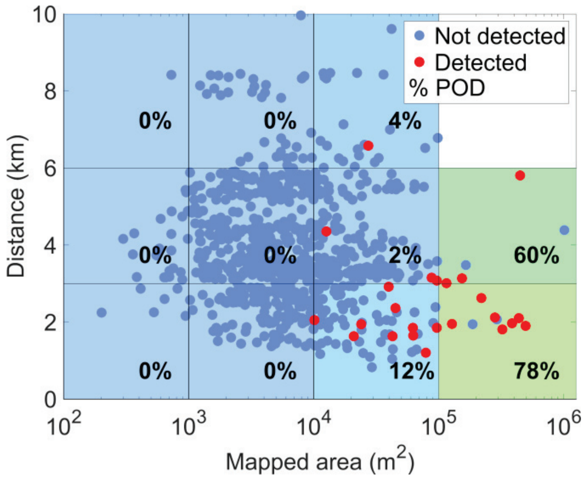

Figure 3: Avalanche detections for all observed events as function of projected area and distance to the nearest infrasound system (blue dots for undetected and red dots for detected events). Numbers (in %) indicate the POD for a particular area-distance class (rectangles); the POD is also visualized by the colors of the rectangles (green: high POD, blue: low POD; N=840).

3.3 False alarm ratio

Overall, the infrasound systems produced 110 detections. Only about every fifth detection was attributed to an observed avalanche. In Figure 4, the classification of unconfirmed detections into one of the four categories defined above is shown. Considering categories (a), (b) and (c) (unrealistic signal characteristics; good visibility and bad visibility/low danger) yielded a false alarm ratio of 28%. Still, some of the detections in category (d) (bad visibility/high danger), which make up 50% of all detections, could be false alarms as well. Hence, the false alarm ratio could as well be higher than 28%. On the other hand, anomalies in the signal characteristics may occur from topographic barriers between the avalanche and the array (category (a)). A lower bound can thus be estimated as 10% by only considering the detections in categories (b) and (c).

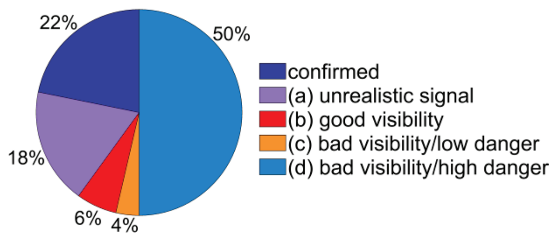

Figure 4: Characteristics of detections. For the unconfirmed detections the four categories as defined above are given (N=110).

4. DISCUSSION AND CONCLUSIONS

We evaluated the detection performance of four operational infrasound detection systems (IDA) over two entire winter seasons. By comparing 110 automatic detections to visually observed avalanche data including 840 avalanches, we found that the probability of detection increased with avalanche size and decreased with source-receiver distance. Large avalanches (on the order of 100 m wide and 1000 m long) within a distance of 3 to 4 km from the array were typically well detected (POD about 80%). On the other hand, the detection probability of medium-sized avalanches (on the order of 100 m wide and 100 m long) was rather low (POD=22% for dry-snow and POD=4% for wet-snow avalanches at distances smaller than 3 km). Small avalanches, which made up the majority (67%) of our verification data set, were not detected at all. Evaluating the false alarm ratio was not straightforward as due to poor visibility more than half of the automatic detections could not be verified. We therefore estimated the false alarm ratio between 10% and 30%.

Our results support the findings of previous studies, which also stated that the detection of small avalanches is not possible, whereas large avalanches are well detected (Schimmel et al., 2017; Steinkogler et al., 2016; Thüring et al., 2015). However, a direct comparison of the POD values calculated in our study with the results of previous studies is not possible, since either no quantitative analysis was undertaken or an overall detection rate was calculated without differentiating between different avalanche sizes.

Overall, our results show that in the absence of major topographic barriers, infrasound avalanche detection systems are well suited to reliably monitor large avalanches up to a distance of about 4 kilometers. Infrasound detection systems can thus provide important additional information for local avalanche safety services during major avalanche cycles.

In future studies, the effect of topographic barriers on the detection performance should be investigated, for instance by deploying several infrasound systems at one site. Moreover, more data should be gathered to distinguish between dry-snow and wet-snow avalanches when calculating detection rates for large avalanches.

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