

Landslides (2016) 13:1181–1196
 DOI 10.1007/s10346-015-0640-z
 Received: 23 April 2015
 Accepted: 14 September 2015
 Published online: 10 October 2015
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Automatic detection of debris flows and debris floods based on a combination of infrasound and seismic signals

Abstract Processes like landslides, debris flows, or bed load transport, at the intersection between the natural environment and human activity, constitute an increasing threat to people and property. The ability to detect these processes prematurely is an essential task for mitigating these hazards. Past studies have shown that debris flows and debris floods emit detectable signals in the low-frequency infrasonic spectrum and induce characteristically seismic signals. A number of monitoring devices and detection methods to identify debris flows using these signals have been developed, but up to date, no warning system based on a combination of seismic and infrasound sensors has been considered. Previous studies have already shown that seismic and infrasonic signals of alpine mass movements are correlated and complementary and that the combination of these two sensor types can serve as basis for an error-resistant detection and warning system. So this work aims to develop a detection system for detecting debris flows and debris floods by analyzing the seismic and infrasound waves. The system is build up on a minimum of one seismic and one infrasound sensor which are co-located and a microcontroller which runs a detection algorithm to detect debris flows and debris floods with high accuracy in real time directly on-site. The detection algorithm is based on an analysis of the evolution in time of the frequency content of the mass movement signal and has been tested with debris flows and debris flood signals monitored at different test sites in Austria and Switzerland. This paper describes the current version of the detection system and gives an example of event detection at the Tyrolese test sites Lattenbach, Dristenau, and Farstrinne.

Keywords Debris flows · Debris floods · Early detection system · Infrasound signals · Seismic signals

Introduction

Early warning systems for alpine hazards are essential in order to decrease the potential threat to humans and buildings. Monitoring systems based on seismic or infrasound signals are quite common and have been used to study alpine mass movements like debris flows, debris floods, and avalanches for many years. For monitoring purposes, both seismic waves as well as infrasonic waves have benefits and drawbacks. Seismic waves can be divided into body waves (frequency 0.02–100 Hz, velocity up to 5,000 m/s in granite) and surface waves (frequency 0.003–0.1 Hz) which travel more slowly when they are located directly under the surface. Body waves, travelling through the interior of the earth, can further be divided into primary waves (longitudinal or pressure waves) and secondary waves (transverse waves). They vary according to density and modulus (stiffness) of the ground. The distance between the sensor and the mass movement and the characteristics of the site has a strong influence on the registered seismic signals

(Biescas et al. 2003). The main source of the seismic energy generated by debris flow is the basal friction of the dense body inside the flow in contact with the ground (e.g., Arattano 2003; Biescas et al. 2003).

Infrasound signals (0.01–20 Hz) are longitudinal pressure waves travelling through the air with a velocity of 343 m/s (standard temperature and pressure (STP)), which is approximately that of audible sound. Mass movement-generated infrasound signals have a specific amplitude and occupy a relatively noise-free band in the low-frequency acoustic spectrum. Infrasound can travel thousands of kilometers and remain detectable over such distances. This is due to the frequency dependency of atmospheric attenuation, absorbing high-frequency (audible and ultra-) sound more than low-frequency (infra-) sound (Pilger and Bittner 2009). Infrasound signals of debris flows are expected to be produced by the violent surge front and the collision (or abrasion) between debris flow and the channel loose boundary (Chou et al. 2007, 2010; Kogelnig et al. 2010).

Various previous studies on debris flows (e.g., Wu et al. 1990; Marchi et al. 2002; Arattano 2003; Huang et al. 2003, 2007; Vilajosana et al. 2008; Coviello et al. 2015) and avalanches (e.g., Suriñach et al. 2000; Biescas et al. 2003) have already shown that it is possible to detect and monitor these processes with geophones and that it is possible to distinguish them from other seismic sources. The first attempts of infrasound monitoring of debris flow (Chou et al. 2007, 2010; Kogelnig et al. 2008; Kogelnig et al. 2009; Zhang et al. 2004), landslides (Bedard 1996), and avalanches (Bedard 1989, 1994; Scott 2004, 2006; Scott et al. 2007; Sommerfeld 1977; Sommerfeld and Gubler 1983) have already proven the viability of infrasonic waves in the detection and monitoring of these types of mass movements. However, the potential combination of infrasonic and seismic sensors for monitoring natural hazards has only been evaluated rarely (Hübl et al. 2041; Kogelnig et al. 2010, 2012; Suriñach et al. 2009), and no automatic event detection based on a combination of those signals has been developed to date. This combination can take advantages of both sensor technologies and minimized disadvantages (e.g., seismic: lower disturbances due to wind and weather but strong dependency on the geology of the site and high attenuation with increasing distance between mass movement and sensor; infrasound: little attenuation in the air at local distances but high background noise induced by wind).

This paper presents a new approach to early detection systems and hazard monitoring based on this combination of seismic and infrasound sensors. The benefits of this system include independence from weather conditions with regard to visibility, no structural need for sustainability, same system for snow avalanches (Schimmel et al. 2013a) and debris flows/debris floods, and monitoring from a remote location unaffected by the process.

Detection system

System setup

The main idea for the setup is to build up a very simple system based on the infrasound and seismic sensor (Fig. 1) with data processing in real time directly at the sensor site, which can be easily installed near a torrent and can offer a cost-efficient solution for early warning. The system presented in this paper acts as a detection system for debris flow and debris flood which can be enhanced to an early warning system. Therefore, the system has to be tested in a long-term use regarding its stability and extended to communicate the threat (e.g., radio control, SMS alarm, etc.). The area of application of such a warning system could be, e.g., the protection of roads and railways by controlling a traffic light or to get information of the frequency of alpine mass movements to assist regional or local authorities whose task is to actively reduce the risk of such hazards. The easy installation of such a system will also offer a good solution for protecting workers at construction sites inside torrents as who are clearing the basin after a debris flow event.

Currently, two different types of infrasound sensors and two different geophones are used for this system. The mainly used infrasound sensor is the Chaparral Physics Model 24 which has a resolution of 2 V/Pa and a frequency range of 0.1 to 100 Hz. The seismic signal is measured by a geophone of the type Sercel SG-5 with a resolution of 80 V/m/s and a natural frequency of 5 Hz. Additionally, the infrasound microphone MK-224 with a resolution of 50 mV/Pa and a frequency range of 3 to 200 Hz as well as geophones of the type SENSOR SM-4 with resolution of 28.8 V/m/s and natural frequency of 10 Hz are used. The data processing is done by a Stellaris Luminary Evaluation board LM3S8962 with a 50-MHz ARM Cortex-M3 microprocessor. The input signal is adapted to the microcontroller ADC input range by an operational amplifier circuit. For this input circuit, an inverting amplifier with a gain of 0.2 for the infrasound sensor Chaparral Physics Model 24 and a gain of 8 for the MK-224 is used, which results in a final resolution of 400 mV/Pa for the infrasound signal. The seismic signal is converted with a gain of 100 which led to a resolution of 8 mV/ $\mu\text{m/s}$ for the SG-5 sensors and an overall resolution of 2.88 mV/ $\mu\text{m/s}$ for the SM-4 sensors. The input from the infrasound

sensor is filtered by a high-pass filter based on a RC circuit with a cutoff frequency below 1 Hz to eliminate the constant component. The signals are recorded by the microcontroller at a sample rate of 100 samples/s with a 32 \times hardware oversampling to avoid aliasing effects. The evaluation board offers the possibility to store the data on a micro-SD card with a size up to 16 GB, and it also provides ethernet access for remote control and download of data. The data is written in hour-files and a 16-GB card offers space for 3,560 files, which means a storage time for up to 4 months. A great advantage of this system is that the microcontroller makes it very flexible and adaptable for the special requirements of a detection system and the setup is low cost, highly effective, and applicable in harsh alpine environments. Also, the energy consumption of this system is very low which makes this setup very useful for standalone stations with solar power supply. The setup works with a power supply of 12 V DC and needs an electrical power below 1.5 W.

In the summer season of 2013, five test sites in Austria were equipped with this system, whereby four stations used the Chaparral Physics Model 24 and one station (Dristenau) was equipped with the MK-224 infrasound sensor. Since the SG-5 geophones were purchased in August 2013, the SM-4 geophone was first used for all stations, and two of the stations (Dristenau, Farstrinne) were equipped with SG-5 geophones for the second half of the season. In summer 2014, the infrasound setup has not been modified, but the SG-5 geophones were used for all stations. The Wartschenbach test site was not in operation in this season, and the system at Schüsserbach worked due to power supply problems only for the first half of the summer. A view of the test sites locations is given at the map in Fig. 2, and Table 1 shows the times of operation and an overview of the used equipment.

For a proper functionality of the detection system, the installation sites have to fulfill some requirements: An ideal system setup is close to the torrent protected from wind (e.g., dense forest) and other sources of interference like cars, trains, etc., and the site has a consolidated soil or rock for the installation of the seismic sensor. If there is no other possibility for power supply, a solar power supply is used; the site has to get sufficient hours of solar radiation per day. In an optimal way, there should also be the possibility for remote control via a mobile network.

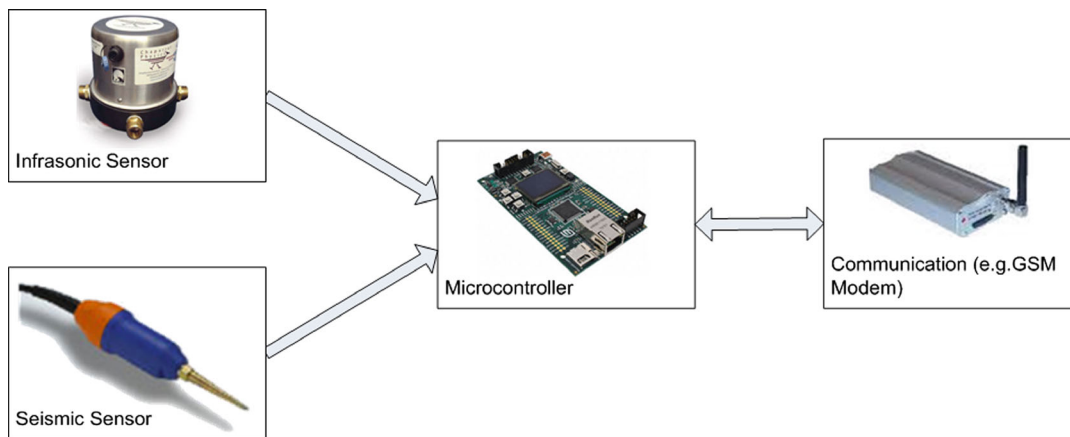


Fig. 1 System overview



Fig. 2 Map of the test sites equipped with the warning system since 2013

Detection algorithm

This section describes the current version of a detection method to automatically detect debris flows and debris floods based on seismic and infrasound data. The requirement on this detection algorithm is to identify events as early as possible without many false alarms in an uncomplex way so that the algorithm can be run in real time directly at the sensor site without high computational effort (e.g., on a microcontroller). This leads to an approach of analyzing the development of the amplitudes of the signals in a time-frequency range. The automatic detection of an event is limited by a minimal event size, weather condition, distance, and background noise. The system has two different levels for the detection output which are based on the amplitudes of the infrasound and seismic signal, to distinguish between small and larger events. The infrasound signal and the seismic signal are processed by fast Fourier transform (FFT) every second and analyzed with respect to time, time-frequency, and amplitude. For the FFT, the Bluestein FFT algorithm (also called the chirp z-transform algorithm; Rabiner et al. 1969) is used with 100 samples. This algorithm computes the discrete Fourier transform (DFT) of non-power-of-two sizes by re-expressing the DFT as a convolution.

Different methods are used for the event identification based on seismic and infrasound signals. For the infrasound signals, the detection algorithm compares the development of the signal over time in four frequency bands. These frequency bands were chosen to represent the whole characteristic spectrum of infrasound signals produced by debris flows and debris floods (e.g., Kogelnig 2012, Hübl et al. 2013) whereby a lower frequency band is used for debris flow and a higher one for debris flood. The infrasound signals of debris flows/debris floods present a typical divergence over time within these frequency bands, so the average amplitudes of these different frequency bands can be used as detection criteria. In the current version of the detection criteria, the average amplitudes of the debris flow/debris flood frequency bands ($avAmp_{DFlow}$ $avAmp_{DFlood}$) have to be beyond the average amplitudes of the band below and above ($avAmp_{low}$ $avAmp_{high}$), and they have to exceed a certain limit. To distinguish between different event sizes, two limits are used for the average amplitudes, a limit of 10 Pa to detect even small events (level 1 (L1): $AmpLimitL1$) and a limit of 30 Pa for events with higher magnitude (level 2 (L2): $AmpLimitL2$). These limits can be changed depending on the application of the detection system and the background noise.

Table 1 Overview of the equipment at the test sites and operation times

Test site	Infrasound sensor	Seismic sensor	Start	End	Operating hours
Lattenbach	Chaparral M24	SM-4	5 June 2013	27 December 2013	4,915
Lattenbach	Chaparral M24	SG-5	30 April 2014	14 January 2015	6,184
Farstrinne	Chaparral M24	SM-4/SG-5	09 July 2013	21 October 2013	2,490
Farstrinne	Chaparral M24	SG-5	30 April 2014	15 October 2014	4,026
Wartschenbach	Chaparral M24	SM-4	04 July 2013	16 September 2013	1,771
Dristenau	MK-224	SM-4/SG-5	06 June 2013	28 September 2013	2,740
Dristenau	MK-224	SG-5	16 May 2014	24 September 2014	3,141
Schüsserbach	Chaparral M24	SM-4	01 August 2013	13 September 2013	1,025
Schüsserbach	Chaparral M24	SG-5	21 May 2014	17 July 2014	1,364

As an additional criterion, the variance of the amplitudes of the seismic and infrasound signals can be used. Since the variance of an artificial noise is high compared to the variance of the broadband debris flow or debris flood signal because in most cases they are produced by narrow-band sources, these criteria can be used to eliminate artificial interfering signals. For a detection, the variance of the amplitudes of the debris flow/flood frequency band ($\text{AmpVar}_{\text{DFlow}}$, $\text{AmpVar}_{\text{DFlood}}$) has to be under a certain limit (VarLimit) to ensure that this is a natural signal.

These detection criteria for the infrasound signals are shown by the following formulae:

Amplitude criteria—level 1:

$$\text{avAmp}_{\text{DFlow}} \geq \text{AmpLimitL1} \text{ or } \text{avAmp}_{\text{DFlood}} \geq \text{AmpLimitL1} \quad (1)$$

Amplitude criteria—level 2:

$$\text{avAmp}_{\text{DFlow}} \geq \text{AmpLimitL2} \text{ or } \text{avAmp}_{\text{DFlood}} \geq \text{AmpLimitL2} \quad (2)$$

Distribution criteria:

$$\text{avAmp}_{\text{DFlow}} > \frac{\text{avAmp}_{\text{high}}}{\text{avAmp}_{\text{low}}} \text{ or } \text{avAmp}_{\text{DFlood}} > \frac{\text{avAmp}_{\text{high}}}{\text{avAmp}_{\text{low}}} \quad (3)$$

Variance criteria:

$$\text{AmpVar}_{\text{DFlow}} \leq \text{VarLimit} \text{ or } \text{AmpVar}_{\text{DFlood}} \leq \text{VarLimit} \quad (4)$$

with:

$\text{AvAmp}_{\text{DFlow}}$:

Arithmetic mean of amplitudes from $\text{FB}_{2_{\text{low}}}$ to $\text{FB}_{2_{\text{high}}}$ (frequency band 2)

$\text{AvAmp}_{\text{DFlood}}$:

Arithmetic mean of amplitudes from $\text{FB}_{3_{\text{low}}}$ to $\text{FB}_{3_{\text{high}}}$ (frequency band 3)

$\text{AvAmp}_{\text{low}}$:

Arithmetic mean of amplitudes from $\text{FB}_{1_{\text{low}}}$ to $\text{FB}_{1_{\text{high}}}$ (frequency band 1)

$\text{AvAmp}_{\text{high}}$:

Arithmetic mean of amplitudes from $\text{FB}_{4_{\text{low}}}$ to $\text{FB}_{4_{\text{high}}}$ (frequency band 4)

$\text{AmpVar}_{\text{DFlow}}$:

Variance of amplitudes from $\text{FB}_{2_{\text{low}}}$ to $\text{FB}_{2_{\text{high}}}$ (frequency band 2)

$\text{AmpVar}_{\text{DFlood}}$:

Variance of amplitudes from $\text{FB}_{3_{\text{low}}}$ to $\text{FB}_{3_{\text{high}}}$ (frequency band 3)

In the former version (Schimmel et al. 2013b), the distribution criteria were also used for the seismic signals, but for the detection of smaller events, this method failed, since the divergences at the frequency bands get extenuated for smaller amplitudes. So for a detection based on seismic signals, the amplitude criterion within one frequency band and the variance criteria have to met.

For the distinction of event sizes also, two different limits are used for the amplitude of the seismic signal. For small events (level 1: AmpLimitL1), the average amplitude of the seismic frequency band ($\text{avAmp}_{\text{DFlow/DFlood}}$) has to be over $0.4 \mu\text{m/s}$, and for level 2 events, the amplitude has to be over $1.2 \mu\text{m/s}$ (AmpLimitL2).

The detection criteria for the seismic signals are shown by the following formulae:

Amplitude criteria—level 1:

$$\text{avAmp}_{\text{DFlow/DFlood}} > \text{AmpLimit1} \quad (5)$$

Amplitude criteria—level 2:

$$\text{avAmp}_{\text{DFlow/DFlood}} > \text{AmpLimit2} \quad (6)$$

Variance criteria:

$$\text{AmpVar}_{\text{DFlow/DFlood}} \leq \text{VarLimit1} \quad (7)$$

with:

$\text{AvAmp}_{\text{DFlow/flood}}$:

Arithmetic mean of amplitudes from $\text{FB}_{2_{\text{low}}}$ to $\text{FB}_{2_{\text{high}}}$ (frequency band 2)

$\text{AmpVar}_{\text{DFlow/flood}}$:

Variance of amplitudes from $\text{FB}_{2_{\text{low}}}$ to $\text{FB}_{2_{\text{high}}}$ (frequency band 2)

All these criteria have to be met independent of the infrasound and the geophone signals, within a specific time span which is set to 12 s to report an event identification and send out a detection signal. This combination of all the detection criteria based on both signal types results in a strong reduction of false alarms. The sequence of this detection algorithm, which is calculated every second, is shown as a flow chart in Fig. 3, and Fig. 4 presents this detection principle depicted in running spectra of a debris flow.

The limits and time span for the detection algorithm have been determined in the analyzing processes of different debris flows/debris floods and interfering signals, and they are currently evaluated at several test sites. Frequent fine tuning of the algorithm and change in the parameters were applied to reduce the number of false alarms and to increase the detection probability within early detection times even for small events. The current settings for the frequency bands, the limits, and the time span for detection are listed in Table 2. The amplitude limits for level 1 and level 2 are chosen in this version aiming to detect events as soon as possible neglecting whether the events are debris flows or debris floods and even ensure the detection of small debris floods events. In a future application as warning system, these limits should be adapted to the local conditions (background noise, required early warning times, minimum event size for warning, etc.) and might be set to higher values.

The applicability of this detection algorithm is shown in Section 3 in the examples of a debris flow at the Lattenbach test site and debris floods at the Dristenau and Farstrinne test sites.

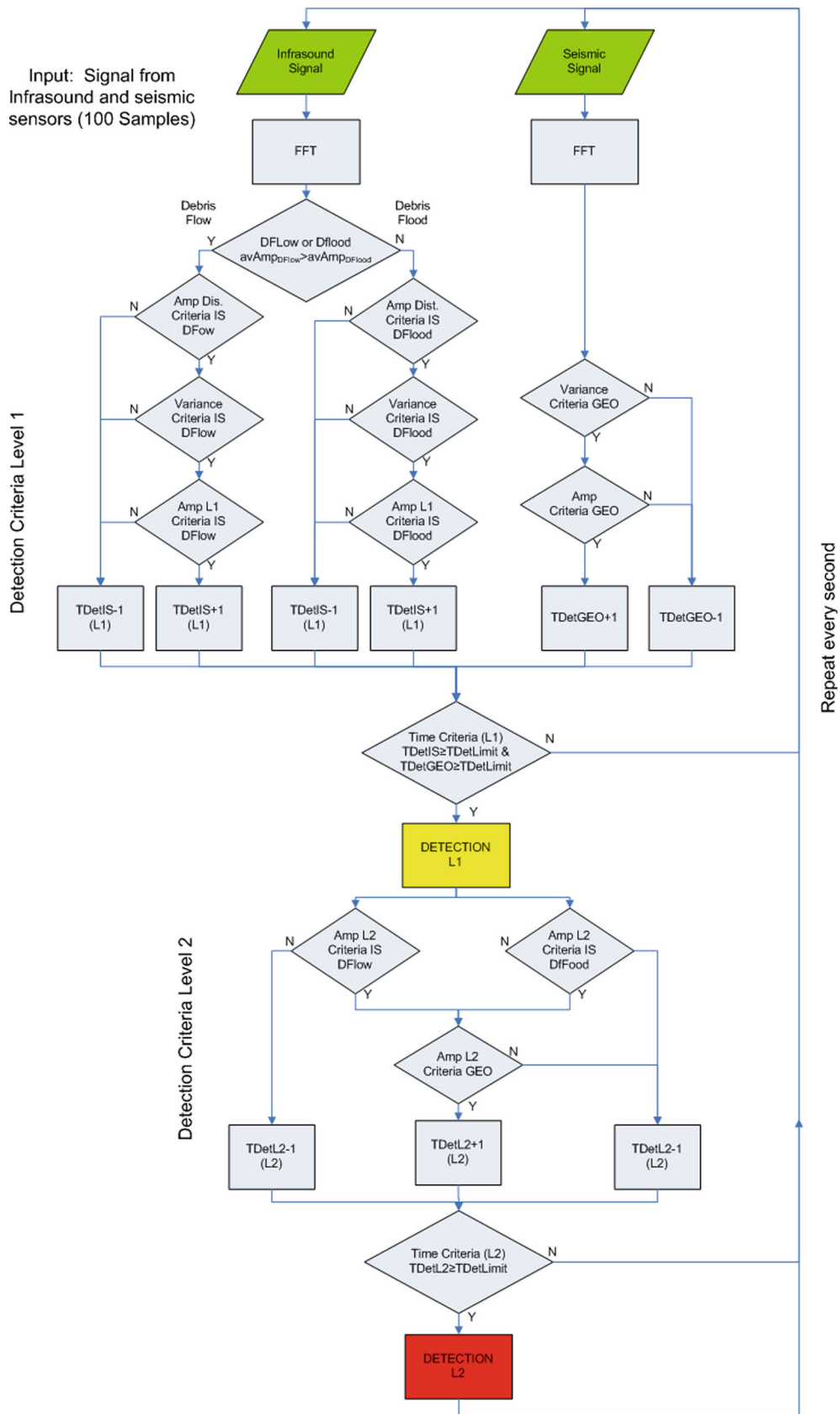


Fig. 3 Flow chart of the detection algorithm

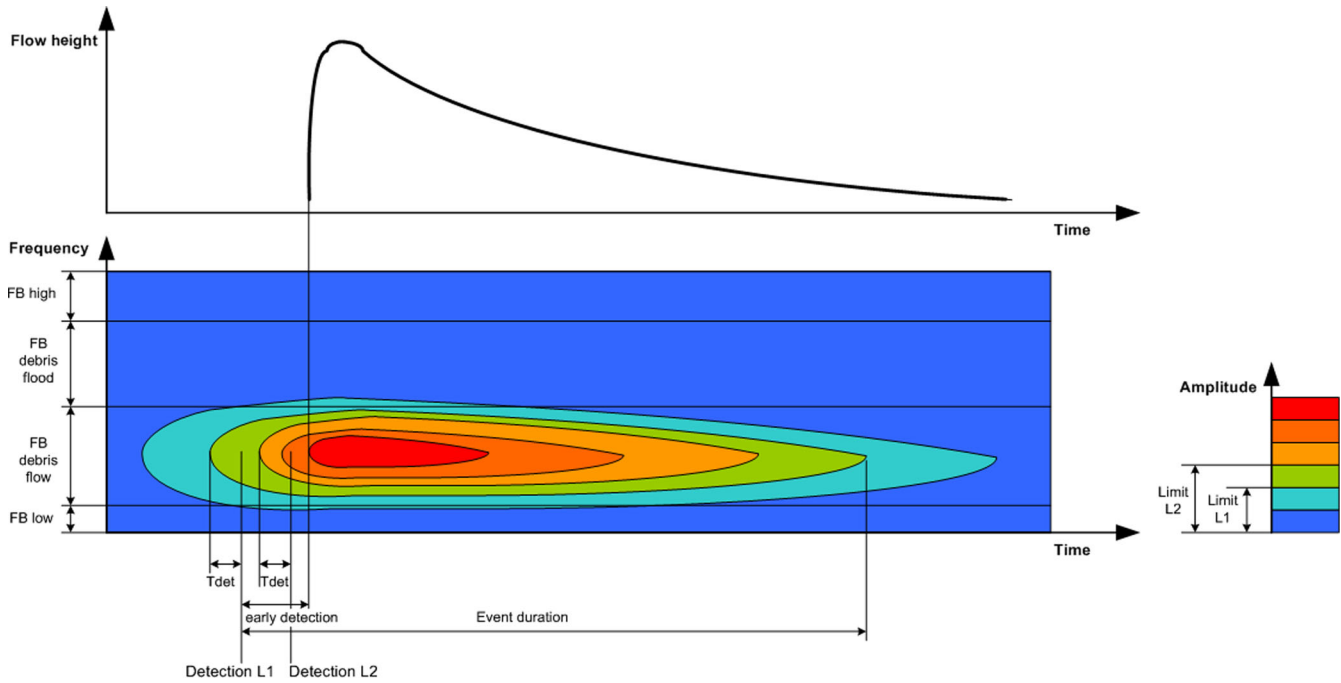


Fig. 4 Detection principle depicted in a running spectrum of a debris flow

Detection examples

Debris flow—test site Lattenbach

For this example, the described approach for the detection algorithm has been applied to the seismic and infrasound signals of a debris flow at Lattenbach. The Lattenbach torrent in Tyrol (catchment 5.3 km²) is an observation site for debris flows, operated by the Institute of Mountain Risk Engineering (BOKU, Vienna) and has been equipped with infrasound and seismic sensors since 2004. Three monitoring stations are installed along the torrent which are equipped with radar gauges, geophones, and video cameras. Since July 2012, the detection system consisting of a Chaparral infrasound sensor and a SM-4 geophone (changed in 2014 to a SG-5 geophone) is installed at the test site near the monitoring station 2. An overview of the test site with the location of the monitoring station and the catchment area is shown in Figs. 5, and a detailed map of the monitoring setup at station 2 is given in

Fig. 6. The registered infrasound and seismic signals are verified by the flow stage level recorded with the radar gauge that is also placed at the monitoring station 2 which starts recording when the flow height reaches 30 cm.

This debris flow event, used as an example for the detection algorithm, was recorded on 1 September 2008 and had a peak discharge of 380 m³/s and a total volume of 14,000 m³. Detailed information of the debris flow and the recorded infrasound and seismic data can be found at Kogelnig et al. (2012). Since this event occurred before the installation of the new detection system, the data was collected with a Campbell Scientific CR1000 data logger, and the detection algorithm was applied to this data afterwards. Figure 7 shows the infrasound and seismic data of this debris flow and the level measured by the radar gauge. In the time series of both sensors, the arrival of the debris flow is characterized by a sudden increase in amplitudes at 650 s (Fig. 7a, b). The two parallel lines over the diagrams indicate the points in time of the first detection for the different detection levels.

Table 2 Current settings for the detection algorithm

		Infrasound signal	Seismic signal
Frequency band 1	FB1 _{low} –FB1 _{high}	3 to 5 Hz	–
Frequency band 2—debris flow	FB2 _{low} –FB2 _{high}	5 to 15 Hz	10 to 30 Hz
Frequency band 3—debris flood	FB3 _{low} –FB3 _{high}	15 to 35 Hz	10 to 30 Hz
Frequency band 4	FB4 _{low} –FB4 _{high}	35 to 50 Hz	–
Limit for amplitudes—level 1	AmpLimitL1	10 mPa	0.4 μm/s
Limit for amplitudes—level 2	AmpLimitL2	30 mPa	1.2 μm/s
Limit for variance	VarLimit	0.6	0.6
Time span for detection	T _{det}	12 s	12 s

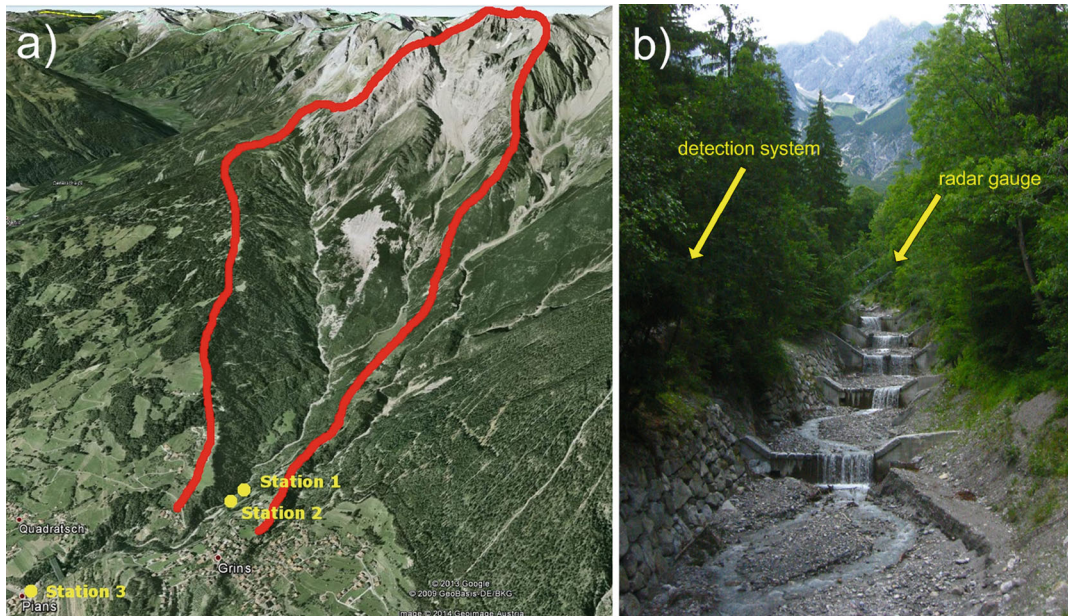


Fig. 5 Overview catchment area and monitoring stations at the Lattenbach torrent (a) (background image source: Google maps) and the place of the detection system (b)

The maximum amplitudes of the infrasound signals produced by the debris flow are up to 5 Pa, and the maximum seismic amplitudes are up to 2×10^{-3} m/s. As demonstrated in Kogelnig et al. (2012), wave packages corresponding to four surges of the debris flow can be identified in the time series between 650 and 800 s (Fig. 7a, b). Both signals present a spindle shape in the time series. The total duration of the debris flow signal in the seismic and the infrasound data is 1,650 s (650 to 2,300 s). The average amplitudes of the four frequency bands (Fig. 7c) show that the infrasound signal of the debris flow has its peak frequencies in the 5- to 15-Hz band. The running spectra of the debris flow (Fig. 7e, f)

show a similar signal pattern in the seismic and infrasonic data. Both have a spindle shape with a rather sudden increase in frequencies, and energy as the debris flow approaches the sensor location. The frequency content slowly decreases again in both sensors when the debris flow moves downstream far from the monitoring station. The event will be registered based on the seismic signal at second 207, while it will be identified by the infrasound data at 539 s for level 1 and at 636 s for level 2. So at this setup, the detection of the debris flow will be determined by the infrasound signal, and the combination of both sensors will detect the debris flow first 111 s before it passes the sensor site (at 650 s) for the level 1 alarm, which is an adequate time for early warning and 14 s before passing for the level 2 alarm.

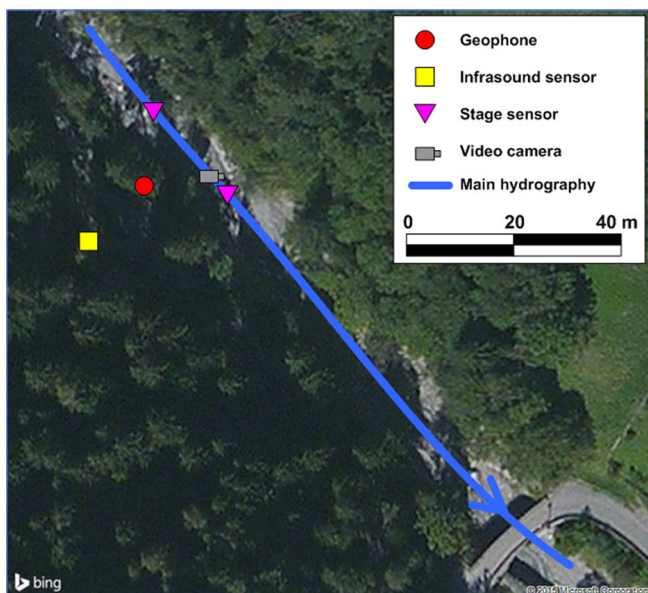


Fig. 6 Map of the monitoring setup at the Lattenbach torrent (background image source: Bing maps)

Debris flood—test site Dristenau

The Dristenau torrent is located in the northern limestone alps near Pertisau in Tyrol. The catchment area is about 9.9 km² with frequent sediment transport and debris floods. Two monitoring stations (Fig. 8) equipped with precipitation gauge, video camera, and radar are installed in the upper part of the torrent. The detection system provided with a MK-224 infrasound sensor and a SM-4 geophone (2013) and a SG-5 geophone (2014), respectively, have been installed in June 2013 closed to monitoring station 1 as shown on the map in Fig. 9.

The debris flood used in this example occurred on 9 July 2013 at 3 pm with a maximum flow height of 57 cm. The infrasound and the seismic signals and the flow depth are presented in Fig. 10. The maximum amplitudes of the infrasound signals are up to 400 mPa, and the maximum seismic amplitudes are up to 400×10^{-7} m/s. The duration of the debris flood identified in the time series of the seismic and infrasound signals is approximately 5,000 s (2,000 to 7,000 s).

In the time series of the infrasound signal, several high amplitude peaks are observed in the interval (0 to 2,000 s) (Fig. 10a). Similar peaks but with smaller amplitude are

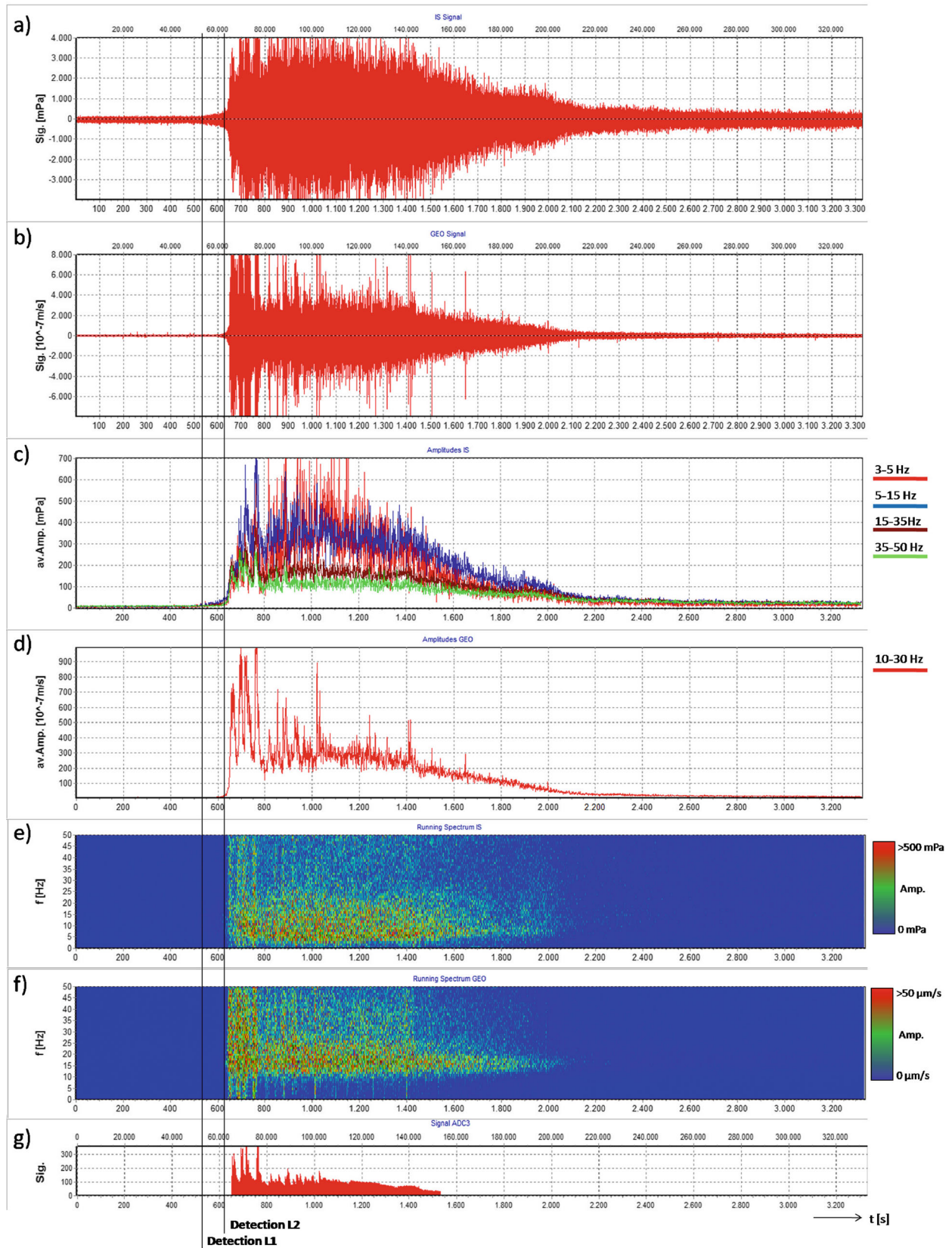


Fig. 7 Infrasound and seismic data of a debris flow monitored at the Lattenbach test site on 1 September 2008. Signals are represented with a common base of time. **a** Infrasound time series. **b** Seismogram. **c** Average amplitude of the four frequency bands of the infrasound signal. **d** Average amplitude of the frequency band of the seismic signal. **e** Running spectrum of the infrasound signal. **f** Running spectrum of the seismic signal. **g** Flow depth. *Lines*: time of first detection based on infrasound and seismic data for level 1 and level 2

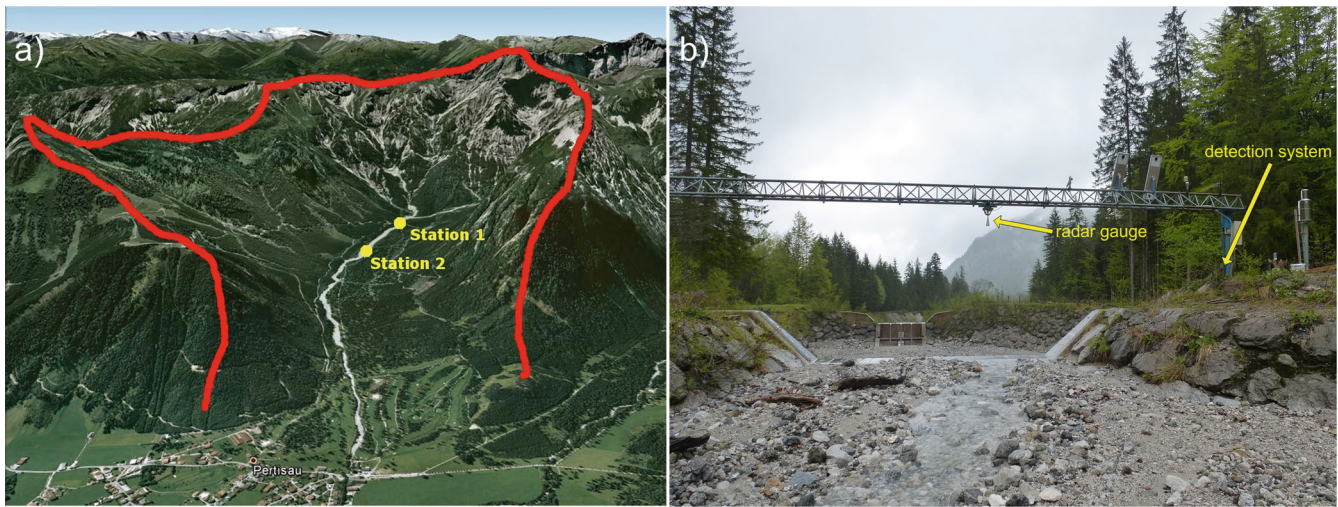


Fig. 8 Overview catchment area and monitoring stations at the Dristenau torrent (a) (Source: Google maps) and the place of the detection system (b)

observed in the seismic data as well in the same interval (Fig. 10b). As explained in Kogelnig et al. (2012), these amplitudes might correspond to the passing of a thunderstorm over the area. In the time series of both sensors, a sharp increase in amplitudes at 2,000 s (Fig. 10a, b) is observed, corresponding to the passing of the main surge of a debris flood which can also be seen at the signal from the level sensor. Unfortunately, the radar gauge was not time synchronized with the detection system, so this may explain the increment of the flow height before the seismic and infrasound signals rise. After the passing of the main surge at 2,200 s, the infrasound signal forms again a spindle shape in the time series. The frequencies distribution in the seismic spectrum (Fig. 10f), have no characteristic distributions like in the debris flow signal at Lattenbach, due to the rather small size of the debris flood. Looking only at the signals

in the time series, no significant difference (except the magnitude) to the debris flow event discussed in Section 3.1 can be identified. However, the frequency distributions of the infrasound signal in the running spectrum (Fig. 10e, f) or the average amplitudes of the four frequency bands (Fig. 10c) reveal the difference.

The infrasound signals have peak frequencies in the 15- to 35-Hz band, whereas for the debris flow event discussed previously, the peak frequencies range from 5 to 15 Hz. These values hint that the characteristics of the processes must be different. This difference in the frequency distribution is clear in the figure of the total spectrum of the debris flow at Lattenbach and the debris flood at Dristenau (Fig. 11). So the frequency of the main amplitude of the infrasound signal can give information about the difference in the processes, and it could be used to distinguish between debris flows and debris floods. The detection algorithm recognized the first level 1 detection based on both infrasound and seismic signals on 389 s after the start of recording, which was the first small surge with a duration of about 20 s. The main event was detected based on both signals at 2,004 s for level 1 and later at 2,083 s for level 2. That means the event could only be detected after the surge passes the sensor site (~2,000 s). One reason for the late detection might be the small event size, another reason is that the monitoring station is located very close to the valley end where debris flows or debris floods are generated, so that there is only a short distance for a detection in advance. This shows that the event magnitude and the geographical conditions have high impact to the detection and early warning times.

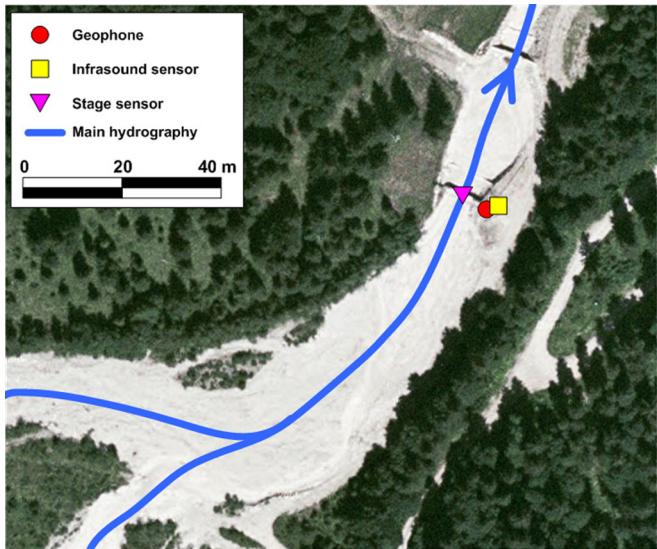


Fig. 9 Map of the monitoring setup at the Dristenau torrent (background image source: Google maps)

Debris flood—test site Farstrinne

The torrent Farstrinne is a new test site of the Institute of Mountain Risk Engineering and is located near Umhausen in the Ötztal in Tyrol. The catchment area of this site is about 5.5 km², and the detection system equipped with a Chaparral infrasound sensor and a SG-5 geophone is now installed there since July 2013. In August 2014, a debris flow radar (Koschuch et al. 2015) and a

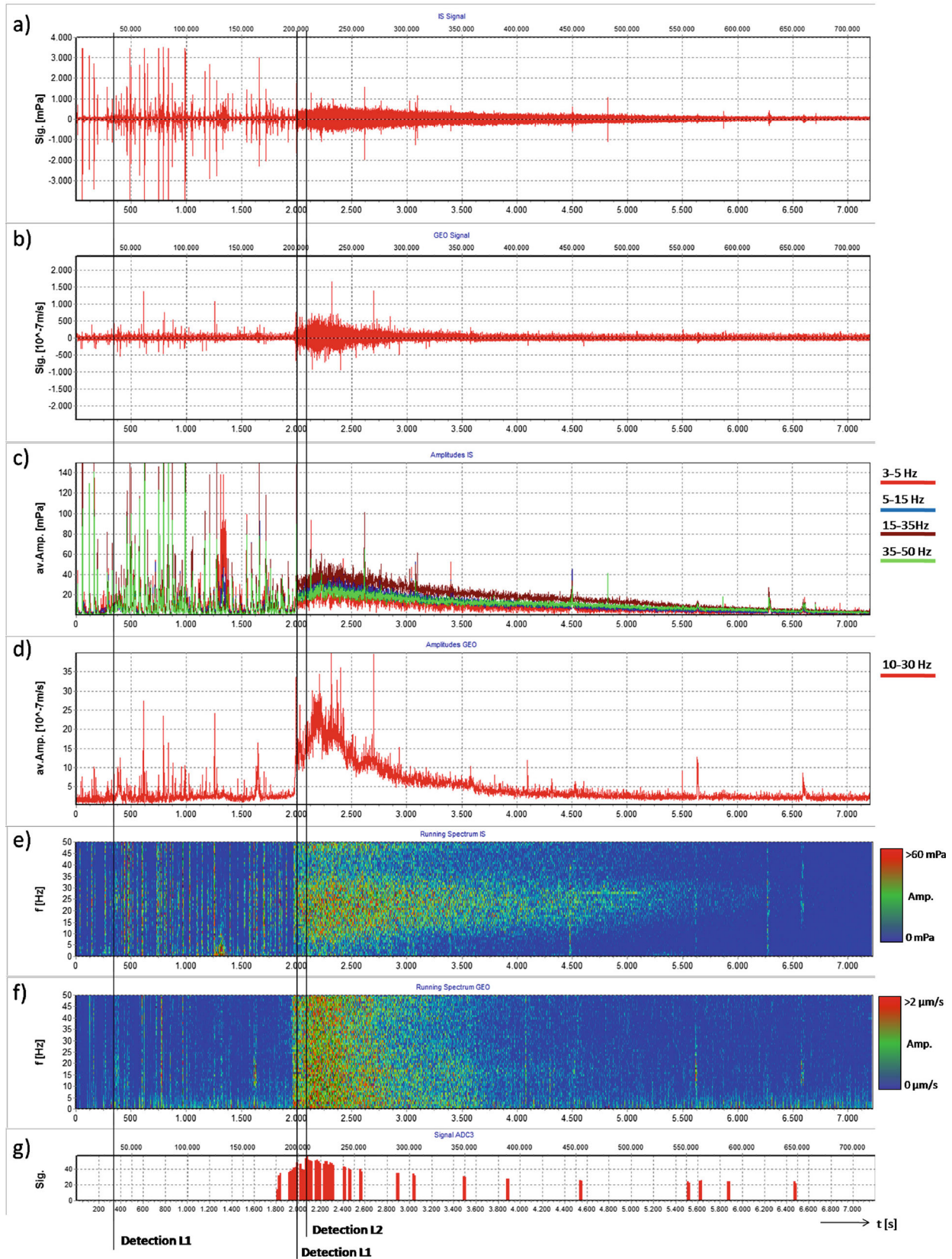


Fig. 10 Infrasound and seismic data of a debris flood monitored at the Dristenau test site on 9 July 2013. Signals are represented with a common base of time. **a** Infrasound time series. **b** Seismogram. **c** Average amplitude of the four frequency bands of the infrasound signal. **d** Average amplitude of the frequency band of the seismic signal. **e** Running spectrum of the infrasound signal. **f** Running spectrum of the seismic signal. **g** Flow depth. **Lines:** time of first detection based on infrasound and seismic data for level 1 and level 2

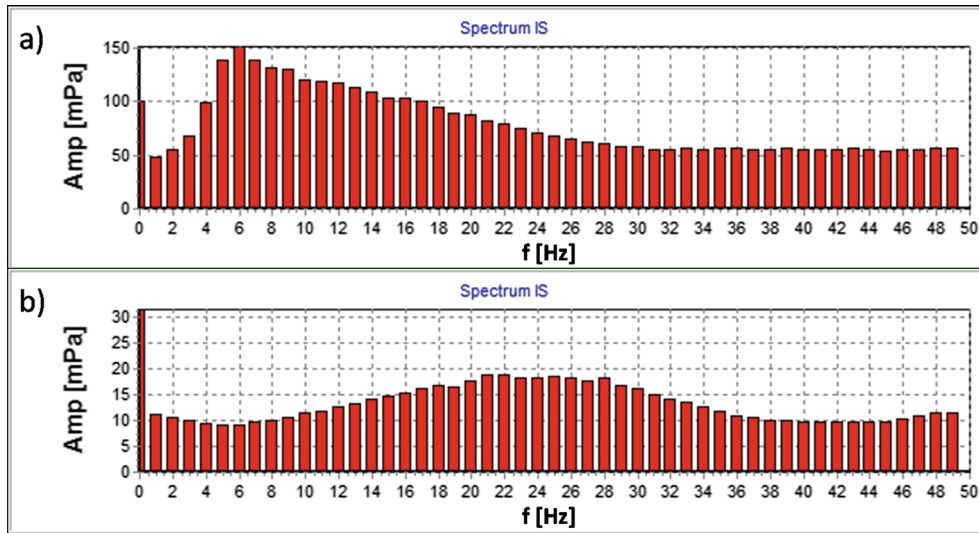


Fig. 11 Total spectrum of the infrasound signal of the debris flow at Lattenbach (a) and of the debris flood at Dristenau (b)

video camera have been also installed there. Figure 12 gives an overview of the test site with the location of the monitoring station and the catchment area, and Fig. 13 presents a detailed map of the setup.

The event took place in the night of 30 July 2014 to 31 July 2014, whereby the first debris flood occurred at 23:08, and afterwards, a second event occurred few hours later at 5:00. The total discharge of these two events was approximately 5,000 m³, and they stopped at the upper end of the basin. Unfortunately, the debris flow radar was not operated at the time of the events, so there was no possibility to verify the exact time when this event occurred. But pictures before and after the night of the events showed a shifting of the torrent from the left (Fig. 14a) to the right side (Fig. 14b) and the deposit at the retention basin verified the event surely occurred.

From the frequency range of the infrasound signal, these events seem more likely to be debris floods, since the main amplitudes are located in 15 to 35 Hz band, which indicates a higher water content, but the difference from the debris flow frequency band is not so significant like in the Dristenau event described in Section 3.2. The maximum amplitudes of the infrasound signals produced by the both debris floods are up to 400 mPa for the first event and 800 mPa for the second and the maximum seismic amplitudes are up to 300 and 500×10^{-7} m/s, respectively. The infrasound and the seismic signals of the first event are presented in Fig. 15 and of the second event in Fig. 16.

The detection of both events was accomplished by the seismic signals only, and for the first event, the level 1 detection took place at 1,759 s and the level 2 detection at 1,787 s. For the second event, they took place at 1,301 s (level 1) and

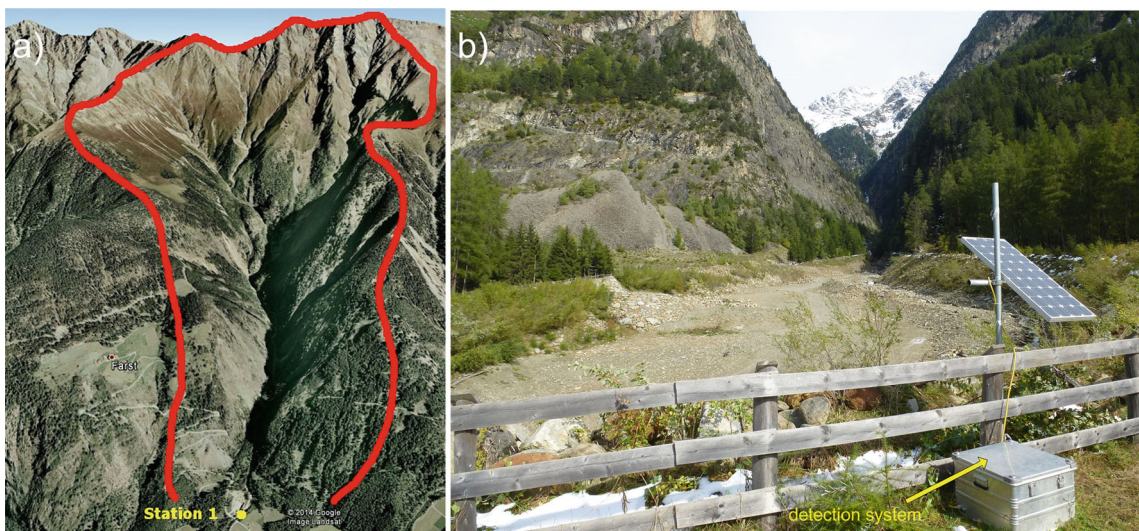


Fig. 12 Overview catchment area and monitoring stations at the Farstrinne torrent (a) (source: Google maps) and the place of the detection system (b)

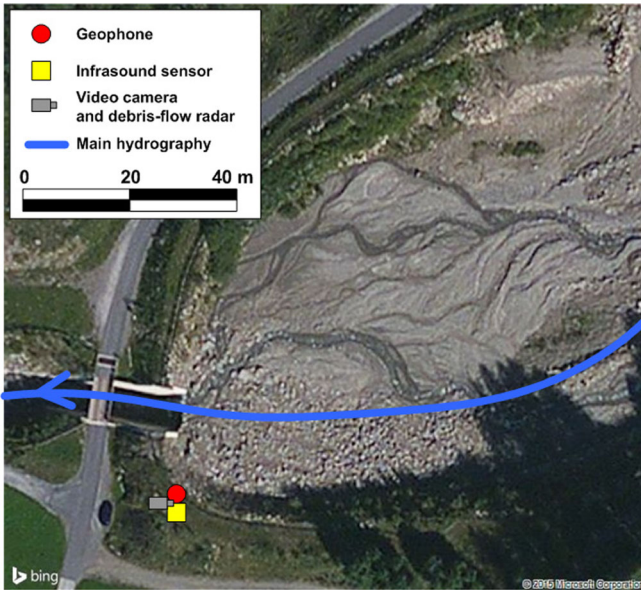


Fig. 13 Map of the monitoring setup at the Farstrinne torrent (background image source: Bing maps)

1,353 s (level 2), respectively. So the events were detected at level 1 at 21 and 99 s, respectively, before the main surge passed through the sensor site (first event 1,780 s, second event 1,400 s). If the detection based only on the infrasond signal were accomplished earlier, warning times of 98 and 170 s, respectively, would be possible, but this would result in more false alarms. The limitation for the early detection time caused by the seismic detection might be a result of the not optimal selected geophone position in the unconsolidated soil at the top of the dam, and so, the detection time could be increased by a better seismic setup (e.g., fixing the geophone in the concrete of the check dam). The comparison of the results of the detection algorithm for the events at Lattenbach, Dristenau, and Farstrinne shows significant differences between the detection times based on seismic or infrasond data depending on the signal sequence, magnitude, and local conditions that could lead to a wide variance of the early warning times.

Discussion

This paper presents a first approach for a debris flow/debris flood detection system based on a combination of seismic and infrasond sensors. The combination of both sensor technologies increases the detection probability and minimizes false alarms. For example at the test site Farstrinne, 176 detections based only on seismic data and six detections based only on infrasond data (analysis per hour) have been registered in the 2014 season; however, the combination of both sensors leads to only two correct event detections and no false alarm. An overview of the number of events at the different test sites and the detections or false alarms for the season 2013 is given in Table 3 and for 2014 in Table 4. In these tables, for the sake to compare the detection efficiency, the events are classified depending on their maximum amplitude of the infrasond signal into very small, small, and medium scale events. At 2013 and 2014, no larger event occurred at the equipped test sites.

All medium-sized events with infrasond amplitudes greater than 400 mPa have been detected successfully in both years, and even the smaller events have been detected with high accuracy. The false alarms registered at the test site Lattenbach in the year 2013 have been caused by a not correctly working geophone. After the change of the geophone at the test site Lattenbach in 2014, no false alarm was registered any more. The false alarms at Dristenau are of unknown reason. At the detection level 2, no false alarm occurred in both years at the test sites Lattenbach and Dristenau. As already discussed, a large variation of detection times at the different test sites has been identified. While for larger events and optimal location of the detection system the time between detection and passing of the main surge can be up to 1 min and more (Lattenbach), this time can go down to zero or less for smaller events and disadvantageous sensor sites (Dristenau). So the setup of the sensors has to be chosen carefully: close to the torrent, protected from wind and other sources of interference and on consolidated soil or rock for the geophone.

Conclusion

The main objective of this work was to design a detection system which is based on a minimum of one seismic and one infrasond sensor that are co-located and a microcontroller which runs a detection algorithm to detect debris flows and debris floods with high accuracy in real time directly on-site. This system can easily be

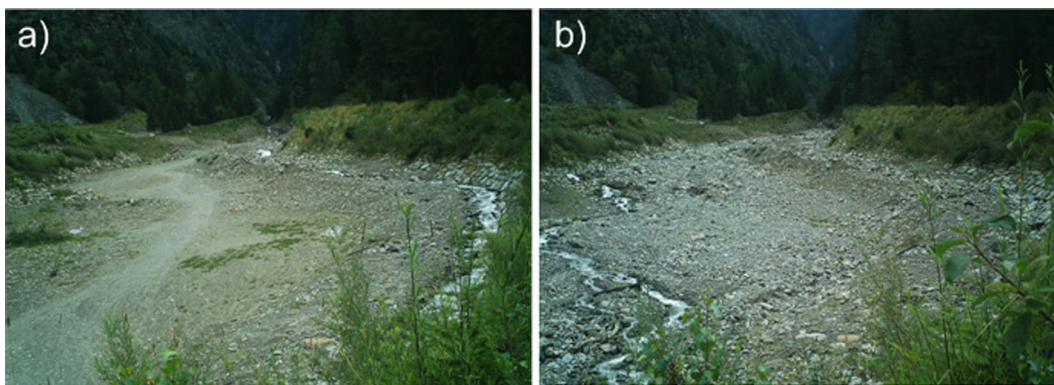


Fig. 14 Change of the Farstrinne torrent caused by the events at the night of 30 to 31 August 2014

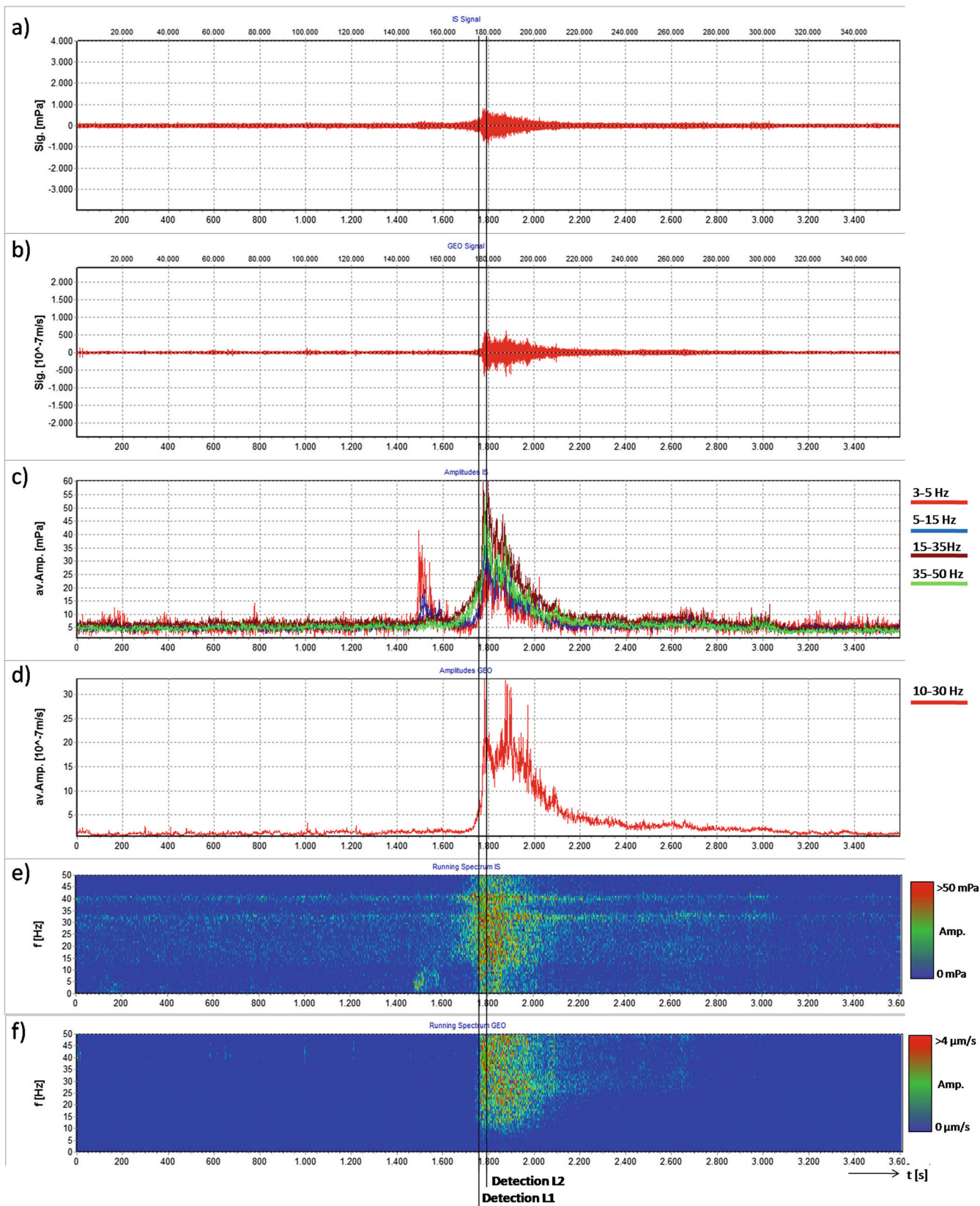


Fig. 15 Infrasound and seismic data of the first debris flood monitored at the Farstrinne test site on 30 July 2014. Signals are represented with a common base of time. **a** Infrasound time series. **b** Seismogram. **c** Average amplitude of the four frequency bands of the infrasound signal. **d** Average amplitude of the frequency band of the seismic signal. **e** Running spectrum of the infrasound signal. **f** Running spectrum of the seismic signal. *Lines*: time of first detection based on infrasound and seismic data for level 1 and level 2

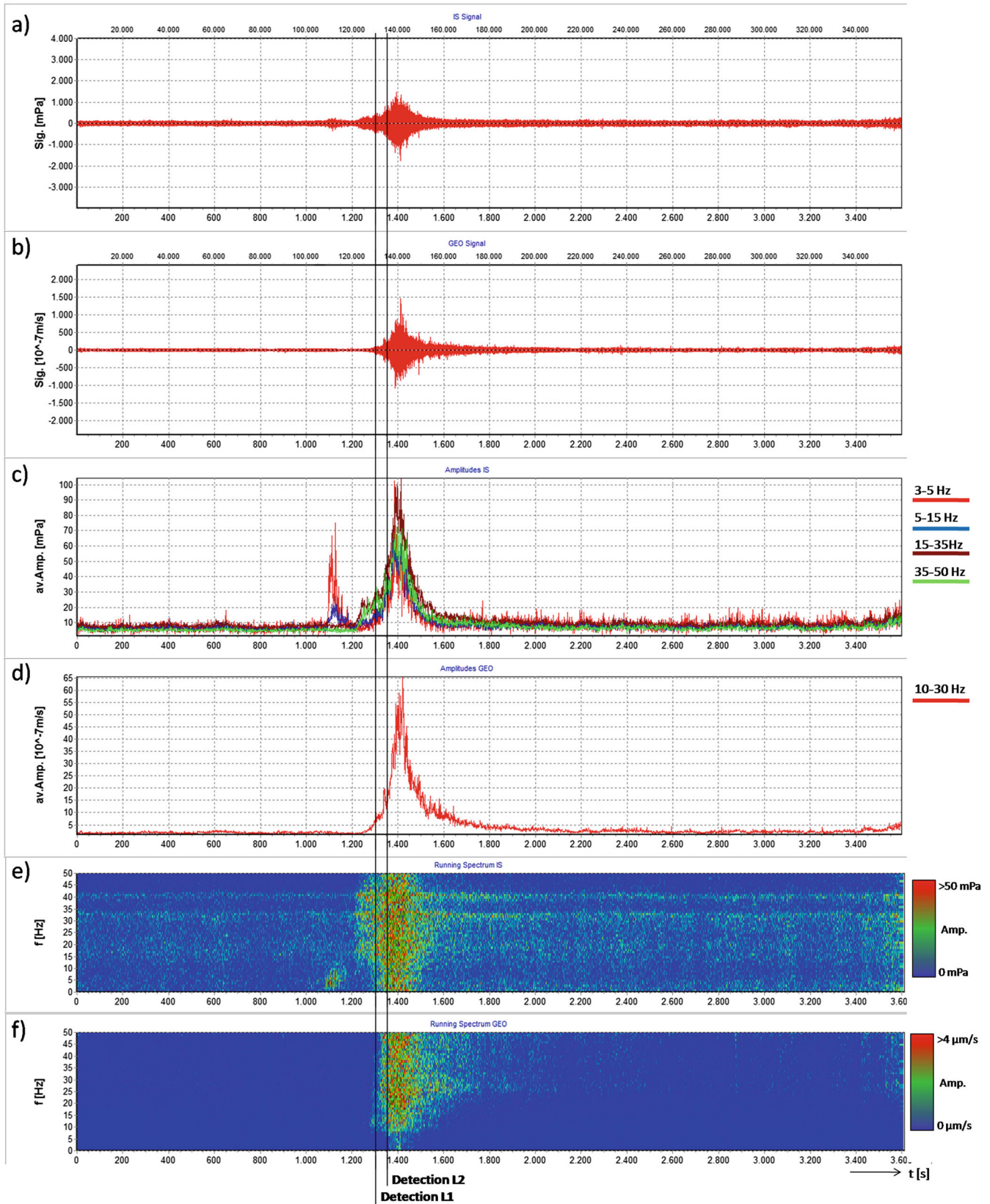


Fig. 16 Infrasound and seismic data of the second debris flood monitored at the Farstrinne test site on 31 July 2014. Signals are represented with a common base of time. **a** Infrasound time series. **b** Seismogram. **c** Average amplitude of the four frequency bands of the infrasound signal. **d** Average amplitude of the frequency band of the seismic signal. **e** Running spectrum of the infrasound signal. **f** Running spectrum of the seismic signal. *Lines*: time of first detection based on infrasound and seismic data for level 1 and level 2

Table 3 Overview of events and detections in 2013

Test site	Number of events			Detections			False alarms
	Size of event: Very small <100 mPa	Small >100 mPa <400 mPa	Medium >400 mPa	Very small <100 mPa	Small >100 mPa <400 mPa	Medium >400 mPa	
Lattenbach	0	0	0	0	0	0	4
Wartschenbach	8	3	1	2	2	1	0
Farstrinne	0	0	0	0	0	0	0
Dristenau	18	4	4	12	3	4	2
Schüsserbach	2	3	1	0	2	1	0
				50 %	70 %	100 %	6

Table 4 Overview of events and detections in 2014

Test site	Number of events			Detections			False alarms
	Size of event: Very small <100 mPa	Small >100 mPa <400 mPa	Medium >400 mPa	Very small <100 mPa	Small >100 mPa <400 mPa	Medium >400 mPa	
Lattenbach	3	0	0	2	0	0	0
Farstrinne	0	0	2	0	0	2	0
Dristenau	10	1	1	4	1	1	1
Schüsserbach	0	0	0	0	0	0	0
				45 %	100 %	100 %	1

enhanced to be a quick and simple to install low-cost warning system. First tests of the detection system in 2013/2014 at five test sites in Austria showed already promising results. Although no larger debris flows occurred in that period within these test sites, the system has detected all medium-sized events (nine events) with infrasound amplitudes greater than 400 mPa and also over 70 % of smaller events, while only seven false alarms were registered. However, the application of seismic and infrasound sensors for monitoring and detection of alpine mass movements is not a straightforward task. Understanding the propagation and the attenuation mechanism of seismic and infrasonic waves and the background noise characteristics under the studied conditions are crucial for the interpretation of the recorded seismic and infrasonic signals and for the development of the detection algorithm. The equipment and the placement of the sensors have to be chosen carefully. Also, the settings of the detection algorithm (amplitude limits) have to be adjusted appropriate to the application of the system and the local conditions of the site. So, if the site is exposed to wind, the detection probability will be reduced and a site with too much artificial noise (cars, trains, power plants, etc.) might need higher amplitude limits for the detection algorithm, which will also reduce the detection probability and early warning times, or too much false alarms can be registered. In summary, the analyses confirmed that debris flows and debris floods produce seismic and infrasonic signals with the characteristics that are reproducible at very different experimental sites and environmental conditions. Therefore, for the monitoring of alpine mass movements, the combination of

infrasound and seismic sensors and using these signals for an automatic detection should lead to the promising result.

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