

Optimization of Low-Cost Monitoring Systems for On-Site Earthquake Early-Warning of Critical Infrastructures

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Abstract. In the last years, monitoring systems based on low-cost and miniaturized sensors (MEMS) revealed as a very successful compromise between the availability of data and their quality. Also applications in the field of seismic and structural monitoring have been constantly increasing in term of number and variety of functions. Among these applications, the implementation of systems for earthquake early warning is a cutting-edge topic, mainly for its relevance for the society as millions of peoples in various regions of the world are exposed to high seismic hazard. This paper introduces the optimization of an already established seismic (and structural) monitoring system, that would make it suitable for the implementation of the earthquake early warning. In particular, the sampling code has been improved and a new triggering algorithm able to automatically detect the ground shaking due to the propagation of the seismic waves has been developed. The preliminary results indicate that the system is very flexible and easy to implement, and encourage to perform further developing steps.

Keywords: Seismic monitoring · Structural monitoring · MEMS · Earthquake early warning · Trigger algorithm

1 Introduction

In the last decade, the technological development resulted in the increasing interest in the monitoring of the urban centers and their built heritage exposed to seismic risk. As an example, the recent seismic history of Italy proves that the effects of large earthquakes are often destructive in the high vulnerable urban

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areas. Specifically designed monitoring networks are essential to cope with the seismic risk in the urban areas, to assess the damage scenarios which are useful for the preservation of the strategic functions and services, and to improve the community resilience to earthquakes [12].

The possibility to establish local-scale networks has been favored by the technological development of the sensors, data transmission, computational power, and data storage capability. Local-scale networks can be established in relatively short times and with limited costs, usually resorting to micro electro-mechanical systems (MEMS) sensors which enable high-density of nodes, easy installation and low-costs (Fig. 1). A large number of institutions (either scientific and for civil protection) around the world have gained interest in this promising technology over the past decade by designing and implementing urban or regional seismic networks based on the MEMS technology (see [18] and [31] for a complete review).

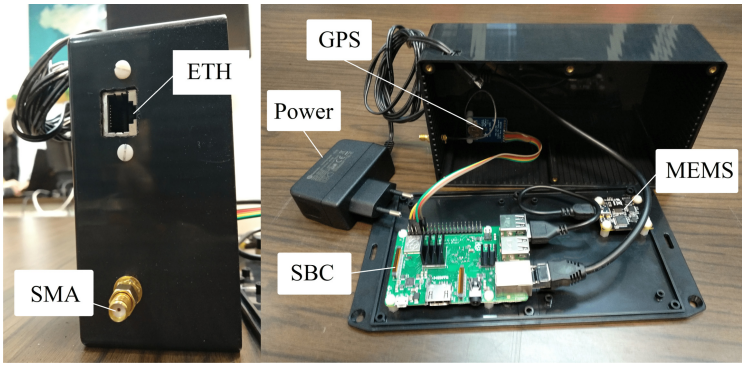

Fig. 1. Example of an operational MEMS station in an urban seismic network; from [14]

The application and reliability of these devices have been evaluated [16,17] and they are able to record strong regional earthquakes or even moderate local earthquakes (M∼3) [7,13,15,24,26,38]. The main tasks of an urban seismic network can be summarized with a continuous chain of actions, before, during, and after that the strong ground motion reach the nodes of the network. These tasks include the rapid evaluation of earthquake damage through the automatic production of shakemaps, the procedures for search and rescue, the seismic microzonation. However, the most crucial action would be a system for a rapid alert. The seismic monitoring station at each site detects the P-wave arrivals using an automatic earthquake recognition procedure and estimates the intensity of the impending strong shakings in a few fractions of second. The warning can be issued before S-wave arrivals, taking advantage of the difference between the P and S waves velocities (Fig. 2).

Earthquake early warning systems can be implemented in existing urban scale network, especially when they are already operating into strategic buildings, which should be the priority structures for warning systems. Strategic buildings are identified owing to their function in case of emergency or their value in term

of exposed peoples. The most vulnerable buildings are hospitals, schools, and all the facilities devoted to public security.

This paper presents the optimization of the computation performance of a monitoring device already operating in urban seismic networks located in Italy. Moreover, an automatic procedure for earthquake recognition is proposed. The algorithm is flexible to provide reliable results both for local, moderate earthquakes and for large, regional earthquakes. The developed codes can be easily implemented in the monitoring devices and, upon further tests, would allow to upgrade the monitoring system into an early warning system.

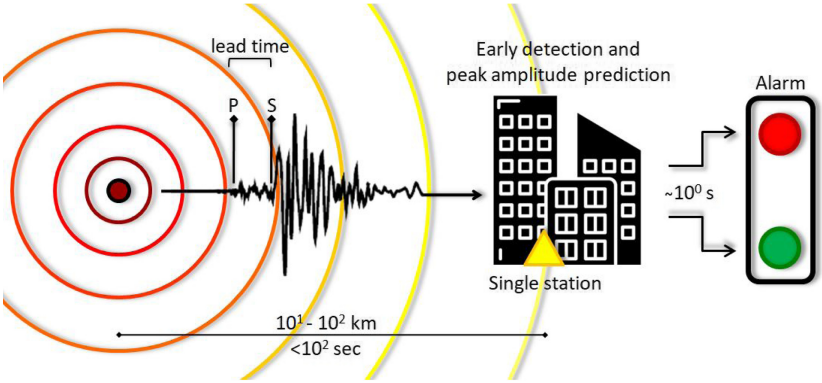

Fig. 2. Scheme of the on-site earthquake early warning system.

2 Earthquake Early Warning Systems

Systems for rapid warning in case of potential damaging earthquakes are rapid developing in many regions of the world. From experimental systems, they are becoming more and more reliable so that, in some case, they have been adopted as institutional systems. The objective of such systems is to provide an alarm with sufficiently in advance to take some pre-arranged actions.

The first example of a country-scale earthquake early warning (EEW) is the "ShakeAlert" which is mainly based in California and operates also in others countries in the western United States. It has been developed, improved, and tested and in about 10 years [10,20,21,25] and in October, 2019 it became fully operating [34]. ShakeAlerts gives a real-time alert for moderate to large earthquakes directly to the smartphones of the users within tens of seconds before the arrival of the ground shaking. Two different approaches are usually adopted for EEW, which mainly depend on the distance from the potentially damaging seismic sources, but also on the specific aims of the warning system [2,3,30,33]. The regional (or network based) approach includes a monitoring network in the vicinity of a known earthquake source. The signals are elaborated as soon as

they are received in the various nodes and when the size of the event exceed a given threshold, a warning is sent to the target area (usually tens to one hundred km away).

The on-site approach (Fig. 2) include a single station in the target site which is usually in the proximity of a known earthquake source. The signal is elaborated in order to estimate the peak ground motion at the site. A real-time alarm, which valid only for the site of the station, is sent for a given expected amplitude.

Both the approaches have pros and cons. The warning time of an EEW system is constrained by the arrivals of the seismic waves taking into account that P-waves are the faster but with a lower energy content, while S-waves are slower but more energetic. For the regional system, the warning time is the temporal difference between the P-wave arrival at the network and S-wave arrival at the site; for the on-site system the warning time is the difference between the P- and S-waves arrivals at the site. Within a certain distance (∼35 km) the on-site systems is the one that provide the most rapid alarm, but at longer distance the regional one ensure an increasing warning time. The regional approach provide a more robust evaluation of the earthquake parameters and of the expected peak ground shaking, while the on-site systems have a rougher estimation on the earthquake parameters.

The prediction of the peak ground shaking from the first onset of the signal is the most critical issue in the on-site EEW [27]. Several algorithms have been proposed to accomplish this task. The algorithms are based on empirical relationships between early P-wave arrivals and peak ground motion associated to the S-waves calibrated on catalogues of past earthquakes in the target region. In the last 15 years have been proposed many of these algorithms for several regions in the world [4–6,8,9,11,19,22,23,32,36,37,39].

It is at short distance from the epicenter of severe earthquakes, that the EEW system are potentially more useful, even though the warning time is extremely reduced. The warning time depends on the time required for the earthquake to evolve and the time for the seismic waves to arrive at the target location; additional time is due to the time required for elaboration of the signal and the alarm sending [28]. For this reason, the data processing system of the EEW should be realized in order to reduce the computation time and the latency as much is possible.

3 MEMS-Based Monitoring Station

The cheap MEMS technology allows the creation of low-cost monitoring stations and entire networks for seismic observation and structural health monitoring. Multiple MEMS stations can be purchased with the same resources as a single traditional system. For some purposes, these devices can be as efficient as the one used in the traditional seismic networks. The monitoring stations considered in this work is the one developed by [14] (Fig. 1) and it is here briefly described in its hardware and software components.

3.1 Hardware

The monitoring stations are based on the MEMS Phidgets 1043_0 sensor, triaxial accelerometer with digital output, suitable, in term of bandwidth and selfnoise, for the detection of strong seismic events and for structural monitoring [16]. In particular, the Phidget 1043_0 accelerometer integrates a three-axis capacitive accelerometer. The analog-to-digital converter (ADC) is internal to the device, for which the outputs are already in digital format. By setting the full scale in the range of ±2 g, the resolution stands at 76.3 μg and the white noise at 280 μg. By integrating 24-bit ADCs and 4.5 Hz bandwidth velocimeters, it will be possible to merge the information of both systems and reconstruct the complete shape of all the components of the agitation and explore a wider frequency band [35].

The brain of the seismic station is a single board computer (SBC; Raspberry Pi3), equipped with a 1.2 GHz 64-bit quad-core ARM processor and which runs a dedicated code. The ADC samples the signals when the analog sensor is incorporated. The ADC provides digital output that can be managed and processed by the SBC. The scheme of operation of the station is shown in Fig. 3.

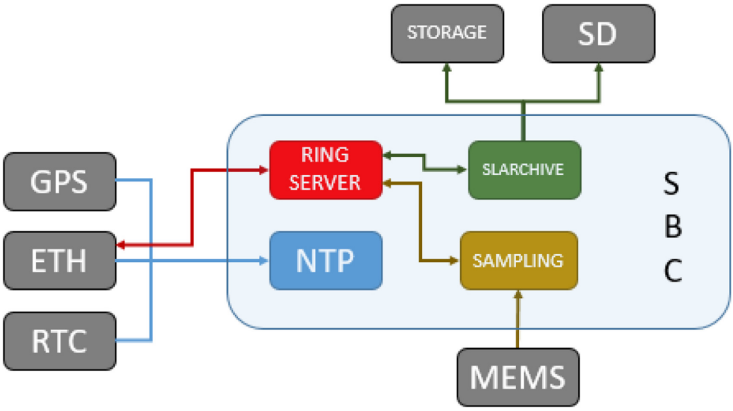

Fig. 3. Scheme for an earthquake monitoring station based on MEMS.

3.2 Software

The code is automatically executed when SBC starts. After checking if the various hardware components are connected correctly and functioning, the software runs the sampling thread from the digital sensor (or from the ADC). The sampling frequency is by 100 Hz (can be varied from 1 500 Hz); synchronization with UTC time is ensured by the NTP (Network Time Protocol) service which retrieves the time from the GPS integrated in the system if there is a fix of at least 4 satellites, otherwise it relies on the servers used by the network. The synchronization of the signals between the various stations is fundamental for

determining the relative position of the earthquake epicentre. In fact, the location of earthquakes is essentially based on the readings of the travel time of the seismic phases. In the absence of connectivity, the system initially synchronizes via an RTC (Real Time Clock) waiting for the GPS fix.

The waveform file contains all the components sampled by the station, it is written in miniSEED format in the form of BigStreang (multi-track format). The miniSEED (or mSEED) is a short version of the SEED (Standard for the Exchange of Earthquake Data) format, primarily intended for the storage and exchange of seismological time series data [1]. Reading the input data from the sensor and writing mSEED data files require appropriate libraries (both in C and Python). The local transmission and storage of data takes advantage of the ring-server and slarchive, conceived by the Incorporated Research Institutions for Seismology (IRIS) for the transmission and storage of mSEED data; they are widely tested and used in the scientific community. The role of the *ring-server* is to connect the sample loop with the software that manages the seismic recording tracks. The role of the *slarchive* is to query the ring-server and store the data into a local archive 3.

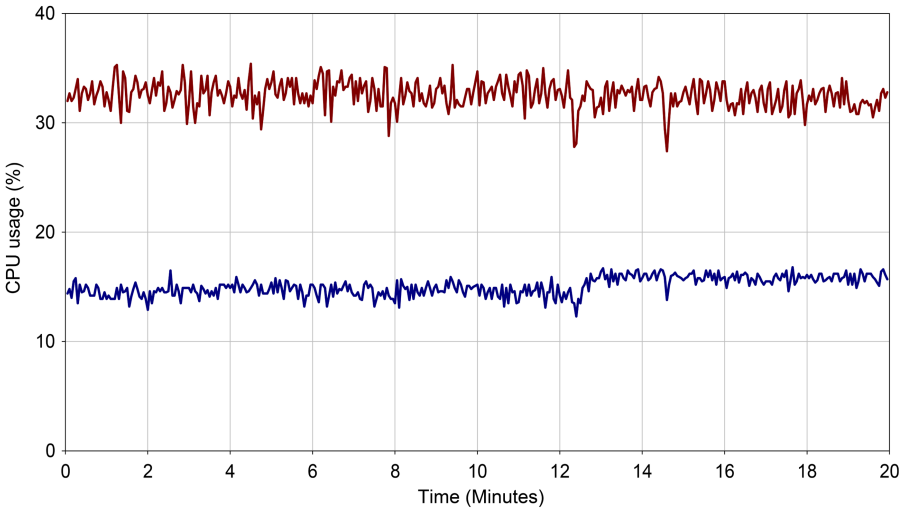

Fig. 4. Percentage of CPU usage for the C (blue line) and the Python (red line) processes. (Color figure online)

4 Code Optimization and Implementation

The optimization of the performance of the code of the monitoring system includes both the part devoted reading and writing tasks (sampling code), and

the part devoted to the continuous inspection of the signal with the task to discriminate the onset of the ground shaking from the background noise (trigger algorithm).

4.1 Sampling Code

The earlier version on the sampling code was implemented with Python [13,14]. As upgrade step, a new sampling software has been developed in C. The choice of C language is motivated by the large availability of compilers and high efficiency of the developed code.

Data from the MEMS sensor can be easily acquired by the C implementation through the use of the *phidget22* library [29]. In particular, the accelerometer class *PhidgetAccelerometer* is used to get samples from the MEMS. Through the *functionPhidgetAccelerometer_create(ch)* an instance of a Phidget channel *ch* is created, and a *PhidgetReturnCode* is returned. All the features of the accelerometer are accessed through the channel *ch*. The function *Phidget_openWaitForAttachment* is used to open the channel and to set also a timeout value in milliseconds (in this case is set it to 5,000). This function blocks the access to the device until the channel is opened or a timeout occurs. The function *PhidgetAccelerometer_setDataInterval* is be used to set the rate in seconds at which the device channel will deliver data to channel *ch*; in our case this value is set to 1.

To measure in real-time the change in *accelerationPhidgetAccelerometer_setOnAccelerationChangeHandler()* event is used. This event is caught continuously in run time and it uses a callback function to constantly detect the changes in acceleration values. In this callback function the code reads the samples from MEMS using the function *PhidgetAccelerometer_getAcceleration* and the time component from the system, writing them in pipe system call. The *pipe* system call manages simultaneously the sampling and the packaging. Instead, in an infinite loop the samples are read, and the time component from the pipe and save them to file using microsecond info. To avoid signal loss, the microsecond is the time unit associated to the samples. In summary, the samples and the associated time component are read at a sampling rate 100 Hz; files are then saved in files in ASCII format. ASCII format is then converted into mSEED standard format using the ascii2mseed library [https://github.com/iris-edu/ascii2mseed].

C is faster than Python because is compiled vs interpreted programming language. The performance of the C and Python processes have been tested simultaneously on the same seismic station. It emerged that, for 20 min of parallel execution, the percentage use of the RAM is fixed at 0.4% for the C process and 7.2% for the Python process; therefore, C uses around 70% less RAM than Python. The percentage use of CPU is 15.06 ± 0.84 and 32.58 ± 1.24 for C and Python processes respectively (Fig. 4); therefore, C uses around 50% less CPU than Python. These CPU load times show that the C implementation is preferable. The efficiency of the sampling process reflects on the rapidity of the earthquake detection, and consequently the promptness of the alert message. The sampling code is the base for the triggering algorithm described in the following paragraph.

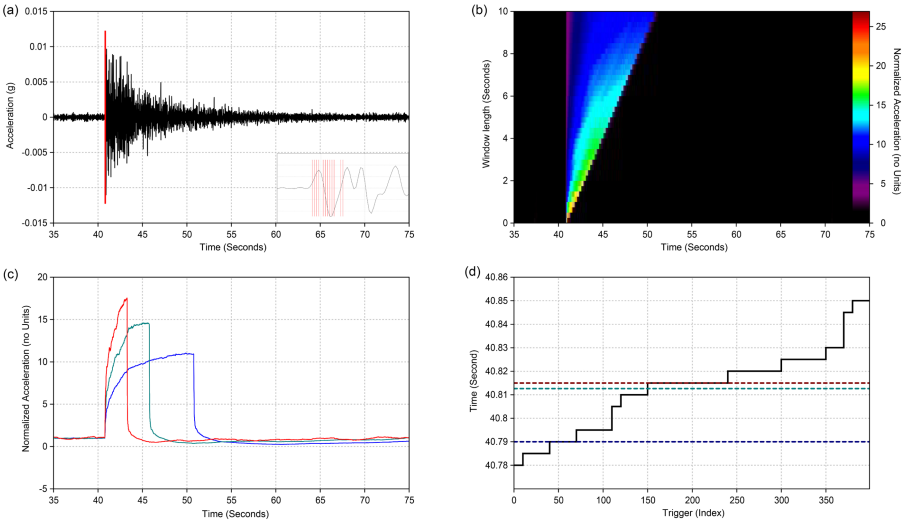

Fig. 5. Synthetic seismogram for M = 3 earthquake, with hypocentral depth of 2 km and observed at epicentral distance of 5 km; (a) the original seismogram with the triggers highlighted in red; (b) the SD value (normalized acceleration) determined for the sliding windows of different width; (c) the SD value for windows of 2.5 s (red), 5 s (green), and 10 s (blue); (d) trigger time (continuous black line) obtained for different sliding windows and different trigger threshold (dashed blue line = theoretical value; dashed green line = mean value; dashed red line = median value); the trigger times are also shown in the inset of (a). (Color figure online)

4.2 Trigger Algorithm

In literature there are many algorithms for the real-time triggering of seismic events. Most of these are based on complex algorithms, necessary for correct application in standard velocimeters or accelerometers. A monitoring network based on homogeneous MEMS sensors, such as those described in this paper, certainly has some advantages. Although MEMS accelerometers have a low sensitivity, which makes them unusable for recording small earthquakes, they have a high temporal stability of self-noise which makes the implementation of trigger algorithms quite simple. For this reason, a simple algorithm that determines the Standard Deviation (SD) of the signal in variable-width moving windows has been implemented. For zero average signals, such as in the case of seismograms, the standard deviation is equal to the Root Mean Square (RMS) of the signal. SD is therefore a quantity linked to the variations in signal energy and so the SD determined in variable-width moving windows, can measure the energy variations present in the signal and which is related to the arrival of a new seismic phases. At each time unit, the quantity SD is calculated for a time window w with the following formula:

$$SD_{w_t} = \sqrt{\frac{\sum_{i=1}^{N}(a_i)^2}{N}} \quad (1)$$

where a is the measured acceleration and $N = W * f$, for each window w of duration W sampled at frequency f.

The ability to detect changes in energy is linked to the correct choice of the window width (W). Narrow windows will be able to measure sudden changes in energy, like the ones linked to high frequency seismic events; wide windows will better measure slow changes in energy, like the ones related to low frequency events. Since it is not possible to know in advance the frequency content of an earthquake, an effective triggering algorithm will implement multiple sliding windows of variable width W. Small magnitude events recorded at small epicentral distances are generally rich in high frequencies (up to 100 Hz), while moderate to strong magnitude events recorded at greater distances are typically rich in low frequencies (1 Hz). For this reason, after several optimization tests, the triggering algorithm is based on 40 simultaneous moving windows, with a temporal width of 0.25 to 10 s, geometrically spaced (geometric factor of 2). Each value of SD relative to a window (calculated with Eq. 1) is normalized for the SD value of the previous window. This allows to measure relative energy variations in the signal, rather than absolute variations. Multiple value strategy has been used also in the choice of the trigger threshold because a threshold too low can generate false alarms, but a threshold too high may fail to trigger some events, or trigger them with considerable delay. After several optimization test, 10 trigger levels have been used, from 3 to 30, geometrically spaced (geometric factor of 2).

Figures 5 and 6 show the application of triggering algorithm on two synthetic seismograms: the first one refers to a M = 3 earthquake, with hypocentral depth of 2 km and observed at epicentral distance of 5 km, while the second one refers to a M = 5 earthquake, with hypocentral depth of 10 km and observed at epicentral distance of 50 km. The two synthetic cases aims at simulate two representative situations: a shallow little earthquake recorded in epicentral area and rich in high frequencies, and a moderate earthquake recorded at regional distance and rich in lower frequencies. In both Figs. 5 and 6 four panels are shown: (a) the original seismogram with the triggers highlighted as vertical red line; please note that the temporal scale is not the same because of the different duration of the events; (b) the SD value (normalized acceleration) determined for the sliding windows of different width; (c) the SD value for three specific windows (red line = 2.5 s, green line = 5 s, blue line = 10 s); (d) trigger time (continuous black line) obtained for different sliding windows and different trigger threshold (dashed blue line = theoretical value; dashed green line = mean value; dashed red line = median value).

In both the cases the implemented algorithm is able to early detect the arrival of the seismic shaking just from the first instants of the P-wave. Regardless of the window and the threshold used, the first P-wave arrival, i.e. the beginning

of the earthquake, is detected in a few tenths of a second. The simultaneous use of windows of different widths and different detection thresholds guarantee the possibility for the specific case of setting robust validation algorithms able to avoid false alarms.

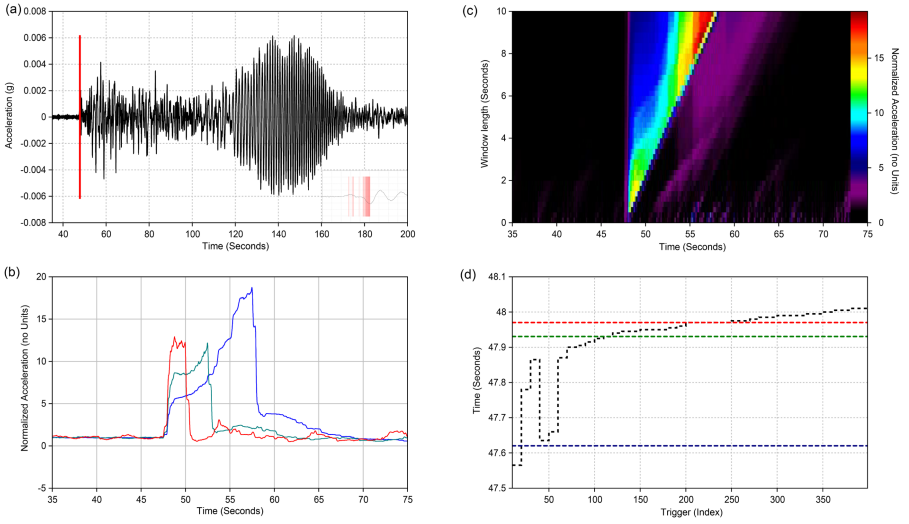

Fig. 6. Synthetic seismogram for M = 5 earthquake, with hypocentral depth of 10 km and observed at epicentral distance of 50 km; (a) the original seismogram with the triggers highlighted in red; (b) the SD value (normalized acceleration) determined for the sliding windows of different width; (c) the SD value for windows of 2.5 s (red), 5 s (green), and 10 s (blue); (d) trigger time (dashed black line) obtained for different sliding windows and different trigger threshold (dashed blue line = theoretical value; dashed green line = mean value; dashed red line = median value); the trigger times are also shown in the inset of (a). (Color figure online)

5 Discussion and Conclusion

For an effective EEW system, each step of the system must be optimized to be performed in the shortest time possible and to be the most reliable possible. The ability to promptly and properly target the arrival of an earthquake are the first and fundamental steps for the implementation of a protection system for critical infrastructure. However, as results clearly from the two cases shown in this paper, the quick detection of a seismic event is not enough for the implementation of an onsite early alarm. A further indispensable condition is necessary, namely that the site to be protected is sufficiently far from the seismic source in order to have enough time to send the alarm (Fig. 2). In the first case (Fig. 5) the lead time is extremely short and after the detection of the event, there would be only

a few seconds to implement any form of protection; in the second case (Fig. 6), the lead time is more than one minute, therefore sufficiently in advance before the arrival of the most energetic part of the seismic waves which is carried by the surface waves.

The approach proposed in this paper is flexible and easy to implement, also in already established seismic (or structural) monitoring systems. The next steps in the pursuit of the optimization of the proposed system will be:

i) bypass the conversion from ASCII to mSEED in C process to further reduce the latency and increase the effective time to give an alarm;
ii) define standard and robust tests to assess the performance of the trigger algorithm and define appropriate confidence thresholds in the evaluation of false alarms and missed detections;
iii) validate the system through dedicated simulations and detailed statistical analyses;
iv) tune the whole system for some representative applications within the wide range of potential real-cases (distance from source, expected magnitude, type of building, etc.).

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