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Evaluation of Seismic Events Detection Algorithms

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Abstract: Identification of seismic events from continuously recorded seismic data in real-time through a Digital Seismic Data Recording system is a difficult task. Despite the vast amount of research in this field, the signal processing and event parameters discrimination algorithms have not yet fully come of age. Presently, we have a wide spectrum of trigger algorithms, ranging from a very simple amplitude threshold type to the sophisticated ones based on pattern recognition approaches. Some of the other approaches use adaptive technique and neural network methods. Researchers are continuously making efforts for the development of algorithms using various techniques, which produce minimum false trigger. Some approaches have been reported which are accurate for detecting first phase of events and take minimum possible computational time. In this paper several approaches for detecting event signals in background noise are presented and their precision evaluation is discussed.

Keywords: Seismic events, Detection, Algorithms.

INTRODUCTION

Seismograph is an instrument that makes a record of seismic waves caused by an earthquake, explosion or other Earth-shaking phenomenon. Seismic sensor is a part of seismograph that translates ground motion into electrical signal, which are processed and recorded by the instrument based on analog or digital circuits. Analog Seismographs record the seismic signal continuously on smoked paper or thermal/ink paper. This type of recorder requires replacement of paper every now and then. Identification of actual seismic event from continuous signal is a highly complicated and experience based job. With the development of new measurement and digital techniques, seismograph has progressed in technology from simple analog recording to digital recording based on microprocessor, micro-controller, DSP and other advanced PC processors making the signal processing and analysis easy and seismic event calculations reliable. In digital seismic analysis systems, recording seismic signal continuously requires a lot of memory space and also identification of the actual event from continuous digital data is highly time consuming process. This situation forced seismologists/scientists to invent triggered seismic data acquisition. In a triggered mode, a seismic station or a seismic network still processes all incoming seismic signal in real time, but incoming data is not stored continuously and permanently. Once an assumed seismic event is detected, recording and storing of all incoming signal starts. Recording stops automatically after trigger algorithm 'declares' the end of the seismic signal as per program of a predetermined time step of the recording system. In digital seismic data recorders, the events are recorded with pre-event and post-event data, so that back ground noise and after event signal behaviour can be studied by seismologists.

VARIOUS EVENT DETECTION APPROACHES

Many investigators have already developed event detection algorithms for seismic data from earthquakes and explosions. These algorithms are implements with various seismic instruments through hardware and software. Implementation of any algorithm through hardware requires significant discrete hardware circuitry. However, most of the seismic instruments, which are now available, use microprocessors, microcontrollers or personal computers. Implementation of event detection algorithms through software results in a significant saving of hardware. Moreover, seismic instruments are field operated; hence these may be made more portable, compact and low power by using software to replace hardware. Therefore, a number of approaches were tried for seismic event detection by many researchers and computation was made through software. From time to time many groups of investigators

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have attempted seismic signal processing and developed signal detection algorithms for various users by applying different techniques and technologies.

Freiberger (1963) developed the theory of the maximum likelihood detector assuming Gaussian signal superimposed on Gaussian noise. But real seismic data are not so statistically predictable. The off-line signal processing scheme, for long-period data obtained from the large aperture seismic array located in eastern Montana, (USA) was described by Capon et al. (1969). They have made a report which discusses the effort for future requirement of hardware and software for the study of seismic signal processing and event discrimination. The scheme is not suitable for real time on-line applications. Allen (1978) developed a detector based on an envelope that is equal to the square of the data plus the weighted square of the first derivative. This creates a time series that includes components of both the unfiltered and high-pass filtered data. The processed data stream is then subjected to a set of logical and mathematical tests for phase identification and timing. The scheme works well for short period data (frequencies > 1Hz). It missed events from tele-seismic and volcanic events. Amplitude threshold and short duration average to long duration average event-detection algorithms were implemented together in hardware for Digital Cassette Seismograph by Terra Technology, USA (1980). The amplitude threshold trigger simply searches for any amplitude exceeding a preset threshold. Recording starts whenever this threshold is reached. This algorithm is normally used in strong motion seismic instrument, where high sensitivity is not an issue, and where consequently man-made and natural seismic noise is not critical. Implementation of short duration to long duration average event detection needs lot of hardware which increases the power of recording system, making it unsuitable for field operation.

Clark and Rodgers (1981) described an adaptive prediction scheme suitable for small event detection. They used a low-pass filter to remove high-frequency noise and the adaptive prediction was used as a noise canceller with the reference noise equal to a delayed version of the input. When an event occurs, it represents data that is not correlated with the background noise. However, drawback of the algorithm is that the signal becomes distorted during processing and event and noise components in the same frequency range are not separated well. Similar scheme was also described by Stearns and Vortman (1981). Using this scheme also it is not possible to separate an event and noise components in the same frequency range. Goforth and Herrin (1981) and Fretcher et al. (1983), described an approach to seismic event detection based on the Walsh transform theory. This approach involves complicated computation and takes more time, making it unsuitable for on-line real time seismic applications. Houliston et al. (1984) have described a short-term to long-term average ratio algorithm for a multichannel seismic network system. The algorithm based on Short Term Average to Long Term Average (STA/LTA) principle is found more suitable for earthquakes and Strong Motion detection. It depends on the amplitude fluctuations of seismic signal rather than signal polarization and frequencies. For a uniform amplitude signal, the moving average is constant. But if the input signal changes rapidly (for example, a step change) then the average will change. This concept has been used for seismic signal discrimination. If the current average is greater than previous sample average, the increment change can be assessed. For seismic signals, the current average over a short period and the previous average over a long period will be different whenever an event occurs. To use an event discrimination algorithm based on this technique, three parameters will be required the short term average, the long term average and a threshold value (α). For true event the following condition must be satisfied.

$$\alpha \geq STA / LTA$$

The short period average represents the average of the shortest period over which an event of interest could occur. The long period average represents the average of the longest period to assess the background noise. α is the threshold value of the ratio of the short period average to the long period average that will cause event discrimination. Whenever the short period average to long period average ratio becomes equal or greater than the preset threshold value, the event discrimination criteria is met. But it also records some of the false events and misses some actual seismic events. However, an algorithm based on this principle is suitable for detecting local, micro and distant earthquake as per parameters selection. The averaging process is simple to compute and takes less time, making it suitable for on-line seismic applications. But at sites with high, irregular man-made seismic noise, the STA/LTA trigger usually does not function well.

Frederking and Magotra (1988) developed a real-time seismic event detection and source location (RSEDSL) algorithm for underground nuclear explosions. Magotra et al. (1989) also described a seismic event detection and source location (SEDSL) algorithm for off-line processing of nuclear explosion and strong motion earthquake signals. They used the polarized nature of seismic signals to develop the algorithms. They also explained that these algorithms are effective in detecting teleseismic waves or strong motion earthquake. These algorithms have not been found suitable for local or micro earthquakes detection. Roberts et al. (1989) described real-time event detection algorithm on vector theory, and it was assumed that north, east and vertical components of noise are uncorrelated. But sometimes noise (e.g. local cultural noise) is correlated with the horizontal component of the signal; it may lead to false detections. Simple averaging algorithm was also developed and implemented though hardware using discrete digital components by Shamshi et al. (1990). Under this scheme the incoming signal was converted in to frequency using voltage to frequency converter and pulses were counted for short duration (SD) and long duration (LS). The SD counts and LD counts were divided by the SD and LD values for computing the averages. The SD quotient value was divided by LD quotient value and compared with the pre-set threshold value. If the result is greater than the pre-set value, the event is declared true otherwise the process is repeated again after SD period for next count values till the occurrence of event is declared. But in this technique lot of hardware is required, which consumes appreciable power and increases the bulk size of recorder, making it unsuitable for field application. Secondly, there is problem of under- or over-flow of data. After the availability of suitable processors and other peripheral devices, computation has become easy through software making the algorithm more accurate and reliable.

Young et al. (1996) developed the waveform correlation event detection algorithm in time domain using statistical processing. They computed recursive STA/LTA rather than standard STA/LTA and also described the Z-detector for seismic events. The recursive STA/LTA is similar to the standard STA/LTA except that for each successive time step, a fraction of the average data value, rather than a specific data point value is removed.

$$\text{Standard } STA_{i+1} = STA_i + \{x(i) - \mathrm{x}(i\text{-}N_{STA})\}/\mathrm{N}_{\mathrm{STA}}$$
$$\text{Recursive } STA_{i+1} = STA_i + \{x(i) - STA_i)\}/\mathrm{N}_{\mathrm{STA}}$$

Where $\mathrm{N}_{\mathrm{STA}}$ is the number of STA points, i is the set points data values in STA. Similarly the standard and recursive values for LTA have been computed. If the STA/LTA is equal or greater than the preset value for event true condition, then the event is declared true and seismic data is recorded. They explained that the recursive STA/LTA is smoother than the standard STA/LTA algorithm. They also explained the Z-detector algorithm defining:

$$Z = (Xn - mean) / \text{Standard deviation}$$

where *Xn* is the sum of current n values of data set and mean has been taken of the background noise.

The advantage of this algorithm is its adaptive adjustment to background noise level. However, it does not enhance the facility for post P-phases detection for setting the de-triggering in the seismic recording system. Mitchell et al. (1998) explained a comparison of selected trigger algorithms for automated global seismic phase and event detection. They explained STA/LTA, Z-statistic, frequency transient, and polarization etc algorithms. They concluded that no algorithm was clearly optimal under all source, receiver, path and noise conditions. STA/LTA algorithm is better for computation point of view and provides better result in comparison to other algorithms. Patrizia Tosi et al. (1999), developed an algorithm based on measuring the fractal dimension of the seismic signal to detect the presence of seismic phases in single-station continuous recordings. This algorithm was found more suitable for small signal detection. This scheme allows only for fractal detector, more research work is required for the complete analysis of the entire frequency range. Mitchell et al. (1999) developed an automated local and regional seismic event location system based on waveform correlation. They explained that to avoid complex models that require detailed waveform matching, the data are processed using an adaptive STA/LTA energy ratio algorithm and correlation with a corresponding theoretical time series. Lot of data sets are required for testing the algorithm. After event detection, computation of epicenter by this algorithm, an error of less than 3 km for local and 10 to 20 km for regional events were observed. The simplest trigger algorithm detects amplitude of seismic signal exceeding a pre-set threshold described by Jens Havskov (2001). The recording starts whenever this threshold is reached. This algorithm is normally used in strong motion recording seismic instrument where high sensitivity is not an issue. One mail problem with amplitude threshold algorithm is that it records most of the false events due to man-made and natural seismic noise that create a spike having amplitude higher than the threshold value. However, this algorithm is suitable for intruder detection and other homeland security applications. Chung et al. (2001) have described the estimation of seismic wave parameters and signal detection using maximum-likelihood method. The statistical characteristics of finite Fourier- transform data motivate the use of approximate maximum-likelihood (ML) method which allows simultaneous detection and wave parameters estimation. The detection strategy developed based on the likelihood ratio indicates the presence of a seismic event and resolved different phases of seismic events arriving within a time interval of interest. The method overcomes the resolution limitation of parameters and SNR threshold problem of other methods. The price paid for this statistically advantageous algorithm is the high computational burden in optimizing likelihood functions.

Botella et al. (2003) have developed a real-time STA/LTA based earthquake detector with prefiltering by wavelets, which increased the detection rate and reduced the false alarm rate in contrast to other detectors. The algorithm proceeds as follows:

(1) The signal is filtered by a first difference filter:
$dx(n) = [x(n) - x(n-1)]$ (1)
Where $x(n)$ represent the input signal.

(2) The quotients STA and LTA are computed recursively by
$STA\ (n) = \mathrm{STA}(n-1)+(dx(n) - \mathrm{STA}(n-1))/Tsta$ (2)
$LTA\ (n) = \mathrm{LTA}(n-1)+(STA(n) - STA(n-1))/Tlta$ (3)
Where Tsta and Tlta are window sizes used to compute STA and LTA averages, respectively. Minimum threshold for LTA is always set to LTA_{min} bound.

(3) α (n) the threshold value for true event is given by:
$\alpha\ (n) = dx(n) / LTA(n)$

When $\alpha\ (n)$ the threshold critical value exceeds already programmed, a trigger in this channel is declared and prediction enters into state 2. LTA value of this sample as a *prelta* has been saved for computation of triggering in state 2. The *prelta* value is the latest LTA computed value. In state 2, if threshold value is greater than or equal to STA (n)/*prelta*, then the event is declared true for recording seismic data, otherwise return is made to state 1. The result of this algorithm was found better than the simple STA/LTA algorithm. However this algorithm missed some small events where the signal amplitude got reduced after applying wavelet prefiltering.

Vincent et al. (2004) developed an algorithm using evolutionary computation for seismic signal detection for homeland application. The time-frequency response (TFR) signal was generated by an array of seismic sensors which was also used to monitor signals generated by individual people, groups of people, and vehicles of different types. Under this algorithm, attention was given to evolutionary algorithms applied to alternative data structures that are used to map sensed inputs to desired outputs. Such structures include crisp and fuzzy rules, decision trees, finite state machines, neural networks and other mathematical constructs. In this type of algorithm, the experimental design required one experiment of training on one set and testing on the other, followed by training on the previous test set and testing on the previous training set. The overall correct result performance was found to be 76 per cent. Steven et al. (2006) explained the detection of low magnitude seismic events using array-based waveform correlation technique. They explained that small event signal is most effectively detected by cross-correlating the incoming data stream with a waveform template. But many spurious triggers occurred in this study whereby short section of signal exhibited coincidental similarity with unrelated incoming wave fronts. Sharma et al. (2006) developed and implemented STA/LTA algorithm for 16-bit seismic data recording system using 80C85 microprocessor and its peripheral devices. For very large LTA value, there was a problem for overflow. De-triggering was included in STA/LTA by Kumar et al. (2009), during the development of PC architecture based 24-bit Seismic Data Acquisition System. Computation of STA and LTA are performed in real time mode. In this trigger algorithm, filtered seismic signal processes in two moving windows (STA and LTA). First absolute amplitudes of each data sample of incoming signal are computed. Next, average of absolute amplitude in both windows is computed and then added to compute LTA value. After calculation of LTA value, fresh STA value is computed. Computed average of current STA/LTA is compared with programmed trigger value (á) for detection of seismic event. If computed value does not meet triggering criteria then LTA will be updated as:

LTA= LTA - first STA value + current STA value

STA value will be shifted to left to store new STA value in defined memory location. New STA value is always computed and compared with trigger ratio. If event is not true, LTA value is updated. In case, the event is declared true, LTA value is freezed for rest of the computations. The ratio of freezed LTA and current STA values is compared with de-trigger value (programmed by user) for declaring end of seismic event. The de-trigger value is generally set higher to the background noise. Under this scheme users need not require the setting of event duration. All events are automatically recorded fully irrespective of the length of events.

CONCLUSION

Several trigger algorithms are presently known and used, from a very simple amplitude threshold type to the sophisticated pattern reorganization, adaptive methods and neural network based approaches. These algorithms are based on the amplitude, the envelope, or the power of the signals in time or frequency domain. None of the seismic event detectors are optimum under all situations. Among the discussed algorithms the STA/LTA trigger algorithm in different forms are probably most commonly known. Many of seismic event detection algorithms, which fall into a special extensive field of research, are not discussed here. Several more sophisticated trigger algorithms are known from literature but they are rarely used. The investigative studies pertaining to various seismic event detection techniques have been made for most of the available algorithms. The precision evolution of seismic events detection algorithms has also been done. In order to reduce false event identification and incorrect time picking, a better approach for earthquake identification is the concern for researches. An effective scheme for real-time seismic data recording systems is still the challenging task, because all the processes must be completed within one sample period otherwise the incoming data information might be lost. Time is most critical especially at high sample rates, when the event is declared true and system is recording incoming processed data. Therefore, continuous research efforts are required for highly efficient real time seismic event detector for real time seismic data recording system. Authors are making efforts to improve the sensitivity of events and making it more suitable especially for small events detection.

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