Topic	Understanding and parameter setting of STA/LTA trigger algorithm
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1 Introduction

By introducing digital seismic data acquisition, long-term continuous recording and archiving of seismic signals has become a demanding technical problem. A seismic network or even a single seismic station operating continuously at high sampling frequency produces an enormous amount of data, which is often difficult to store (and analyze) locally or even at the recording center of a network. This situation has forced seismologists to invent triggered seismic data acquisition. In a triggered mode, a seismic station or a seismic network still process all incoming seismic signals in real time (or in near-real-time) but incoming data is not stored continuously and permanently. Processing software - a trigger algorithm - serves for the detection of typical seismic signals (earthquakes, controlled source seismic signals, underground nuclear explosion signals, etc.) in the constantly present seismic noise signal. Once an assumed seismic event is detected, recording and storing of all incoming signals starts. It stops after trigger algorithm 'declares' the end of the seismic signal.

Automatic trigger algorithms are relatively ineffective when compared to a seismologist's pattern recognition ability during reading of seismograms, which is based on years of experience and on the enormous capability of the human brain. There are few exceptions, where the most complex detectors, mostly dedicated to a given type of seismic signals, approach to human ability. In all practical cases, automatic trigger loose some data on one side and generate falsely triggered records, which are not seismic signals, on the other. Small amplitude seismic signals are often not resolved from seismic noise and are therefore lost for ever, and, if the trigger algorithm is set sensitively, false triggers are recorded due to irregularities and occasionally excessive amplitude of seismic noise. False triggers burden off-line data analysis later and unnecessarily occupy data memory of a seismic recording system. As a result, any triggered mode data acquisition impairs the completeness of the recorded seismic data and produces some additional work to delete false records.

Several trigger algorithms are presently known and used - from a very simple amplitude threshold type to the sophisticated pattern recognition, adaptive methods and neural network based approaches. They are based on the amplitude, the envelope, or the power of the signal(s) in time domain, or on the frequency or sequency domain content of seismic signal. Among the more sophisticated ones, Allan's (1978; 1982) and Murdock and Hutt´s (1983) trigger algorithms are probably the most commonly known. Many of these algorithms function in association with the seismic phase time picking task. Seismic array detection algorithms fall into a special field of research, which will not be discussed here. For more advanced algorithms see, e.g., Joswig (1990; 1993; 1995). However, in practice, only relatively simple trigger algorithms have been really broadly accepted. and can be found in seismic data recorders in the market and in most network's real time processing packages.

The simplest trigger algorithm is the amplitude threshold trigger. It simply detects any amplitude of seismic signal exceeding a pre-set threshold. The recording starts whenever this threshold is reached. This algorithm is rarely used in weak-motion seismology but it is a standard in strong motion seismic instruments, that is in systems where high sensitivity is mostly not an issue, and where consequently man-made and natural seismic noise amplitudes are much smaller than the signals which are supposed to trigger the instrument.

The root-mean-square (RMS) threshold trigger is similar to the amplitude threshold algorithm, except that the RMS values of the amplitude in a short time window are used instead of 'instant' signal amplitude. It is less sensitive to spike-like man-made seismic noise, however it is rarely used in practice.

Today, the ‘short-time-average through long-time-average trigger' (STA/LTA) is the most broadly used algorithm in weak-motion seismology. It continuously calculates the average values of the absolute amplitude of a seismic signal in two consecutive moving-time windows. The short time window (STA) is sensitive to seismic events while the long time window (LTA) provides information about the temporal amplitude of seismic noise at the site. When the ratio of both exceeds a pre-set value, an event is 'declared' and data starts being recorded in a file.

Several more sophisticated trigger algorithms are known from literature (e.g., Joswig 1990; 1993; 1995) but they are rarely used in the seismic data loggers currently in the market . Only some of them are employed in the network's real time software packages available. When in the hands of an expert, they can improve the events/false-triggers ratio significantly, particularly for a given type of seismic events. However, the sophisticated adjustments of operational parameters to actual signals and seismic noise conditions at each seismic site that these triggers require, has proven unwieldy and subject to error in practice. This is probably the main reason why the STA/LTA trigger algorithm still remains the most popular.

Successful capturing of seismic events depends on proper settings of the trigger parameters. To help with this task, this Information Sheet explains the STA/LTA trigger functioning and gives general instructions on selecting its parameters. Technical instructions on setting the trigger parameters depend on particular hardware and software and are not given here. Refer to the corresponding manuals for details.

2 Purpose

The short-time-average/long-time-average STA/LTA trigger is usually used in weak-motion applications that try to record as many seismic events as possible. These are the applications where the STA/LTA algorithm is most useful. It is nearly a standard trigger algorithm in portable seismic recorders, as well as in many real time processing software packages of the weak-motion seismic networks. However, it may also be useful in many strong motion applications, except when interest is limited to the strongest earthquakes.

The (STA/LTA) trigger significantly improves the recording of weak earthquakes in comparison with amplitude threshold trigger algorithms. At the same time it decreases the number of false records triggered by natural and man-made seismic noise. To some extent it also allows discrimination among different types of earthquakes.

The STA/LTA trigger parameter settings are always a tradeoff among several seismological and instrumental considerations. The goal of searching for optimal parameter settings is the highest possible seismic station sensitivity for a given type of seismic signal (which may also includes the target 'all earthquakes') at a still tolerable number of false triggers.

The STA/LTA trigger is most beneficial at seismically quiet sites where natural seismic noise (marine noise) is the dominant type of seismic noise. It is also effective in case of changes of 'continuous' man-made seismic noise. Such changes, for example, occur due to day/night variation of human activity nearby or in urban areas. The STA/LTA algorithm is less effective in the presence of irregular, high amplitude man-made seismic noise which is often of burst and/or spike type.

3 How it works - basics

The STA/LTA algorithm continuously keeps track of the always-present changes in the seismic noise amplitude at the station site and automatically adjusts the seismic station's sensitivity to the actual seismic noise level. As a result, a significantly higher sensitivity of the system during seismically quiet periods is achieved and an excessive number of falsely triggered records is prevented, or at least mitigated, during seismically noisy periods. Calculations are repeatedly performed in real time. This process is usually taking place independently in all seismic channels of a seismic recorder or of a seismic network.

The STA/LTA algorithm processes filter seismic signals (see section 5.1 'Selection of trigger filters' in this Information Sheet) in two moving time windows – a short-time average window (STA) and a long-time average window (LTA). The STA measures the 'instant' amplitude of the seismic signal and watches for earthquakes. The LTA takes care of the current average seismic noise amplitude.

First, the absolute amplitude of each data sample of an incoming signal is calculated. Next, the average of absolute amplitudes in both windows is calculated. In a further step, a ratio of both values — STA/LTA ratio—is calculated. This ratio is continuously compared to a user selected threshold value - STA/LTA trigger threshold level. If the ratio exceeds this threshold, a channel trigger is declared. A channel trigger does not necessarily mean that a multi-channel data logger or a network actually starts to record seismic signals. All seismic networks and most seismic recorders have a 'trigger voting' mechanism built in that defines how many and which channels have to be in a triggered state before the instrument or the network actually starts to record data (see section 5.4 below - 'Selection of voting scheme parameters'). To simplify the explanation, we shall observe only one signal channel. We will assume that a channel trigger is equivalent to a network or a recorder trigger.

After the seismic signal gradually terminates, the channel detriggers. This happens when the current STA/LTA ratio falls below another user-selected parameter - STA/LTA detrigger threshold level. Obviously, the STA/LTA detrigger threshold level should be lower (or rarely equal) than the STA/LTA trigger threshold level.

In addition to the data acquired during the 'trigger active' time, seismic networks and seismic recorders add a certain amount of seismic data to the event file before triggering – pre-event-time (PEM) data. After the trigger active state terminates, they also add post-event-time (PET) data.

For better understanding, Figure 1 shows a typical local event and the trigger variables (simplified) during STA/LTA triggering. Graph a) shows an incoming continuous seismic signal (filtered); graph b) shows an averaged absolute signal in the STA and LTA windows, respectively, as they move in time toward the right side of the graph; and graph c) shows the ratio of both. In addition, the trigger active state (solid line rectangle), the post-event time (PET), and the pre-event time (PEM) (dotted line rectangles) are shown. In this example, the trigger threshold level parameter was set to 10 and the detrigger threshold level to 2 (two short horizontal dotted lines). One can see that the trigger became active when the STA/LTA ratio value exceeded 10. It was deactivated when the STA/LTA ratio value fell below 2. On graph d) the actually recorded data file is shown. It includes all event phases of significance and a portion of the seismic noise at the beginning.

In reality, the STA/LTA triggers are usually slightly more complicated, however, the details are not essential for the understanding and proper setting of trigger parameters.

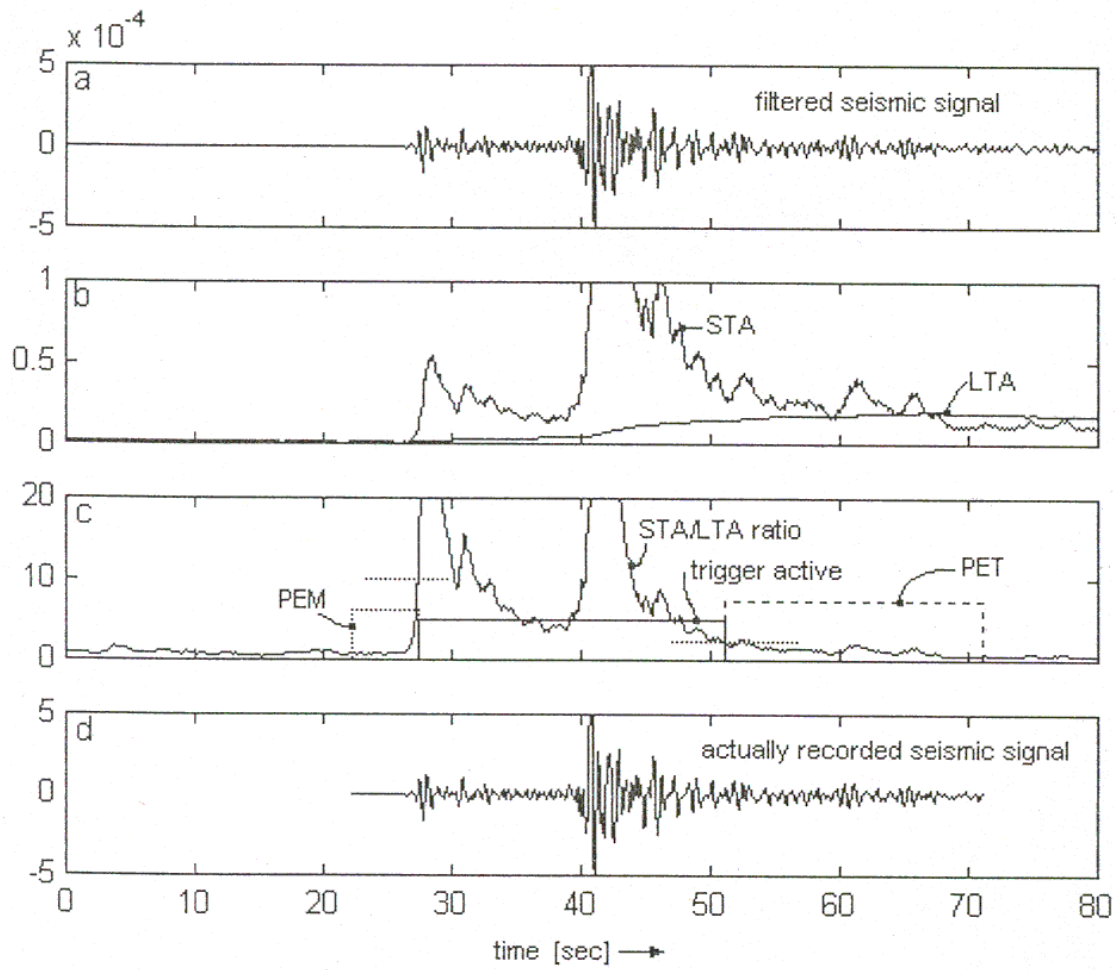

Figure 1 Function and variables of STA/LTA trigger calculations (see text for explanations).

4 How to adjust STA/LTA trigger parameters

To set the basic STA/LTA trigger algorithm parameters one has to select the following:

- STA window duration
- LTA window duration
- STA/LTA trigger threshold level
- STA/LTA detrigger threshold level.

However, optimal triggering of a seismic recorder or a seismic network does not depend only on these parameters. There are usually four additional associated parameters which, only if well tuned with the trigger parameters, guarantee optimal data recording. These parameters are:

- trigger filters
- pre-event time (PEM)
- post-event time (PET)
- trigger voting scheme.

Although not directly related to the STA/LTA trigger algorithm, these additional parameters are also be discussed below in order to provide a complete information.

The STA/LTA trigger parameter and associated parameters' settings depend on the goal of the application, on the seismic noise condition at the site, on the properties of seismic signals at a given location, and on the type of sensor used. All these issues vary broadly among applications and among seismic sites. Obviously, there is no general, single rule on setting them. Each application and every seismic site requires some study, since only practical experience enables the determination of really optimal trigger settings.

Note that seismic recorders and network software packages come with a set of default (factory set) trigger and trigger associated parameter values. They are rarely optimal and must therefore be adjusted to become efficient in a particular application. For best results, changing these parameters and gradually finding the best settings is a process which requires a certain amount of effort and time.

4.1 Selection of short-time average window (STA) duration

Short-time average window measures the 'instant' value of a seismic signal or its envelope. Generally, STA duration must be longer than a few periods of a typically expected seismic signal. If the STA is too short, the averaging of the seismic signal will not function properly. The STA is no longer a measure of the average signal (signal envelope) but becomes influenced by individual periods of the seismic signal. On the other hand, STA duration must be shorter than the shortest events we expect to capture.

To some extent the STA functions as a signal filter. The shorter the duration selected, the higher the trigger's sensitivity to short lasting local earthquakes compared to long lasting and lower frequency distant earthquakes. The longer the STA duration selected, the less sensitive it is for short local earthquakes. Therefore, by changing the STA duration one can, to some extent, prioritize capturing of distant or local events.

The STA duration is also important with respect to false triggers. By decreasing the duration of the STA window, triggering gets more sensitive to spike-type man-made seismic noise, and vice versa. Although such noise is usually of instrumental nature, it can also be seismic. At the sites highly polluted with spike-type noise, one will be frequently forced to make the STA duration significantly longer than these spikes, if false triggers are too numerous. Unfortunately, this will also decrease the sensitivity of the recording to very local events of short duration. Figure 2 explains the effect of STA duration on local events and spike-type noise.

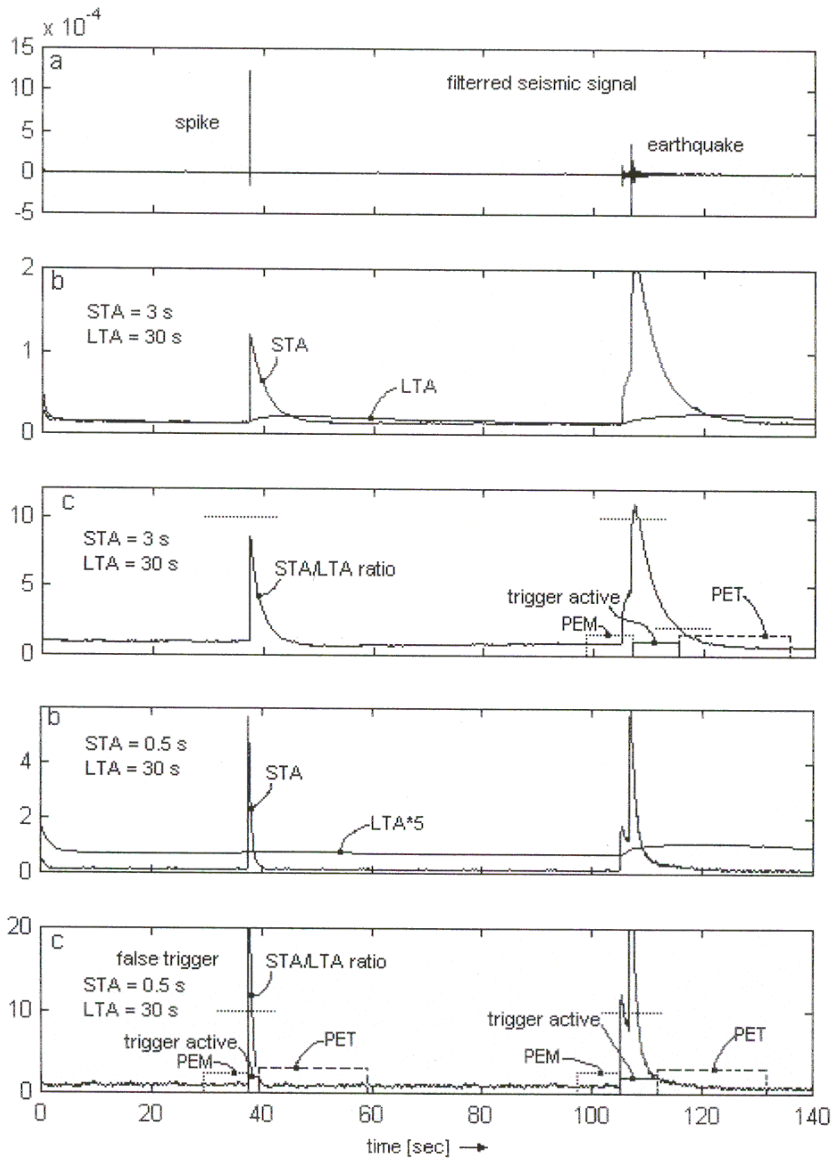

Figure 2 Influence of STA duration on trigger sensitivity to short local events and 'spiky' noise in seismic signals.

On graph a) a signal with an instrumental spike on the left and with a short, very local earthquake on the right side is shown. Graphs b) and c) show STA, LTA, STA/LTA ratio, and trigger active states along with PEM and PET. The STA/LTA trigger threshold was set to 10 and detrigger threshold to 2. One can see that when using a relatively long STA of 3 sec, the earthquake did trigger the system, but only barely. However, a much bigger amplitude (but shorter) instrumental spike did not trigger it. The STA/LTA ratio did not exceed the STA/LTA threshold and there was no falsely triggered record due to the spike. The lower two graphs show the same variables but for a shorter STA of 0.5 sec. The spike clearly triggered the system and caused a false record. Of course, the earthquake triggered the system as well.

For regional events, a typical value of STA duration is between 1 and 2 sec. For local earthquakes shorter values around 0.5 to 0.3 s are commonly used in practice.

4.2 Selection of long-time average window (LTA) duration

The LTA window measures average amplitude seismic noise. It should last longer than a few 'periods' of typically irregular seismic noise fluctuations. By changing the LTA window duration, one can make the recording more or less sensitive to regional events in the 'Pn'-wave range from about 200 to 1500 km epicentral distance. These events typically have the low-amplitude emergent Pn- waves as the first onset. A short LTA duration allows the LTA value more or less to adjust to the slowly increasing amplitude of emergent seismic waves. Thus the STA/LTA ratio remains low in spite of increasing STA (nominator and denominator of the ratio increase). This effectively diminishes trigger sensitivity to such events. In the opposite case, using a long LTA window duration, trigger sensitivity to the emergent earthquakes is increased because the LTA value is not so rapidly influenced by the emergent seismic signal, allowing Sg/Lg waves to trigger the recording.

Figure 3 explains the described situation. In graph a) an event with emergent P waves is shown. Graphs b) and c) show the time course of trigger parameters for a relatively long LTA of 60 sec. The LTA does not change fast, allowing the STA/LTA ratio to exceed the STA/LTA trigger threshold (short horizontal dotted line) and a normal record results. Graphs d) and e) show the same situation with a shorter LTA of 30 s. The LTA value increases much faster during the initial phase of the event, thus decreasing the STA/LTA ratio value which does not exceed the STA/LTA trigger threshold. No triggering occurs and the event is missed.

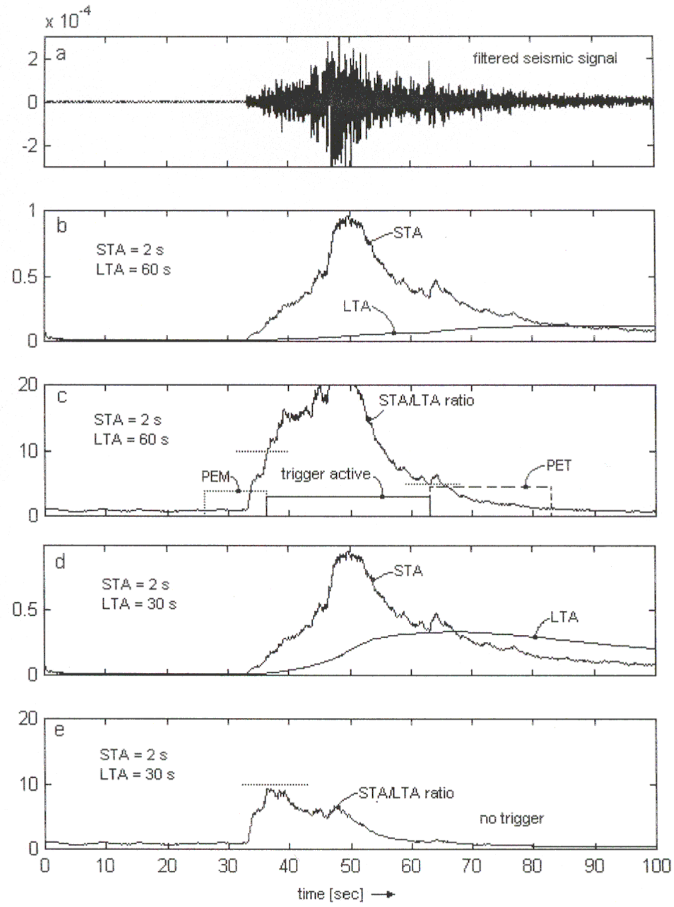

Figure 3 Influence of LTA duration on trigger algorithm sensitivity to earthquakes with emergent seismic signals.

Similarly, efficient triggering of recording of events with weak P waves compared to S waves requires a longer LTA for two reasons. First, if P waves do not trigger, they 'contaminate' true information about seismic noise prior to the event measured by LTA, since their amplitude exceeds the amplitude of seismic noise before the event. This results in diminished trigger sensitivity at the moment when S waves arrive. This 'contamination' is decreased if a longer LTA duration is selected. Second, longer LTA makes the trigger more sensitive to P waves as well, if they are not strictly of impact type.

Figure 4 represents such a case. Graph a) shows a typical event with significantly bigger later phase waves than P waves. Graphs b) and c) show trigger parameters for a long LTA of 100 s. P wave packet as well as S wave packet trigger the recorder. Appropriate PEM and PET assure that the event is recorded as a whole in a single file with all its phases and a portion of seismic noise before them. Graphs d) and e) show the same situation but for a shorter LTA of 45 sec. One can see that the P waves did not trigger at all, while the S waves barely triggered. The STA/LTA ratio hardly exceeds the STA/LTA trigger threshold. As the result, the recorded data file is much too short. P waves and information about seismic noise before them are missing in this record. A slightly smaller event would not trigger at all.

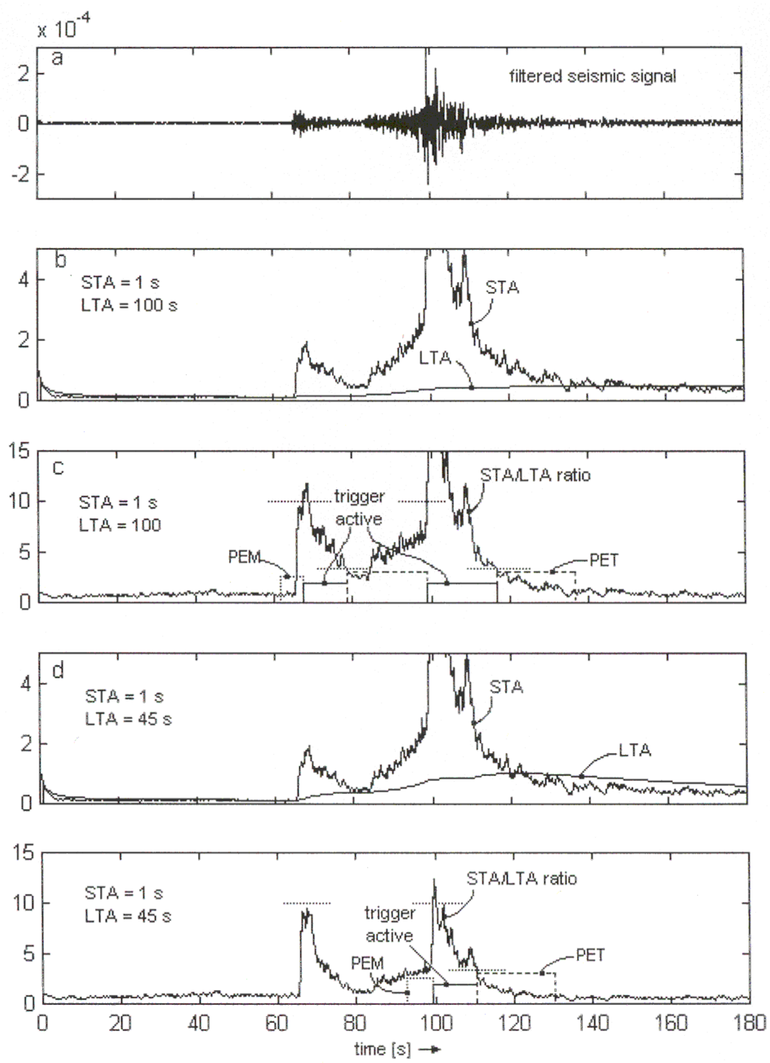

Figure 4 Influence of LTA duration on trigger algorithm sensitivity to earthquakes containing weak P waves.

On the other hand, a short LTA will successfully accommodate recorder sensitivity to gradual changes of 'continuous' man-made seismic noise. Such 'transition' of man-made seismic noise from low to high is typical for night-to-day transition of human activity in urban areas. Sometimes, using a short LTA can mitigate false triggers due to traffic. Examples of such cases could be a single heavy vehicle approaching and passing close to the seismic station on a local road, or trains on a nearby railway. A short LTA can 'accommodate' itself fast enough to such emerging disturbances and prevent false triggers.

Figure 5 shows an example of the LTA response to increased seismic noise. Graph a) shows seismic noise, which gradually increased in the middle of the record. Note that the change of its amplitude is not sudden but lasts about 20 to 30 sec. Graphs b) and c) show the situation at a short LTA of 30 sec. One can see that the LTA value more or less keeps track of the increased noise amplitude. The STA/LTA ratio remains well below the STA/LTA trigger threshold and there is no false trigger in spite of significantly increased seismic noise at the site. Graphs d) and e) show the situation with a longer LTA of 60 s. In this case, the LTA does not change so rapidly, allowing a higher STA/LTA ratio during noise increase. As the result, a false trigger occurs and a false record is generated which unnecessarily occupies data memory.

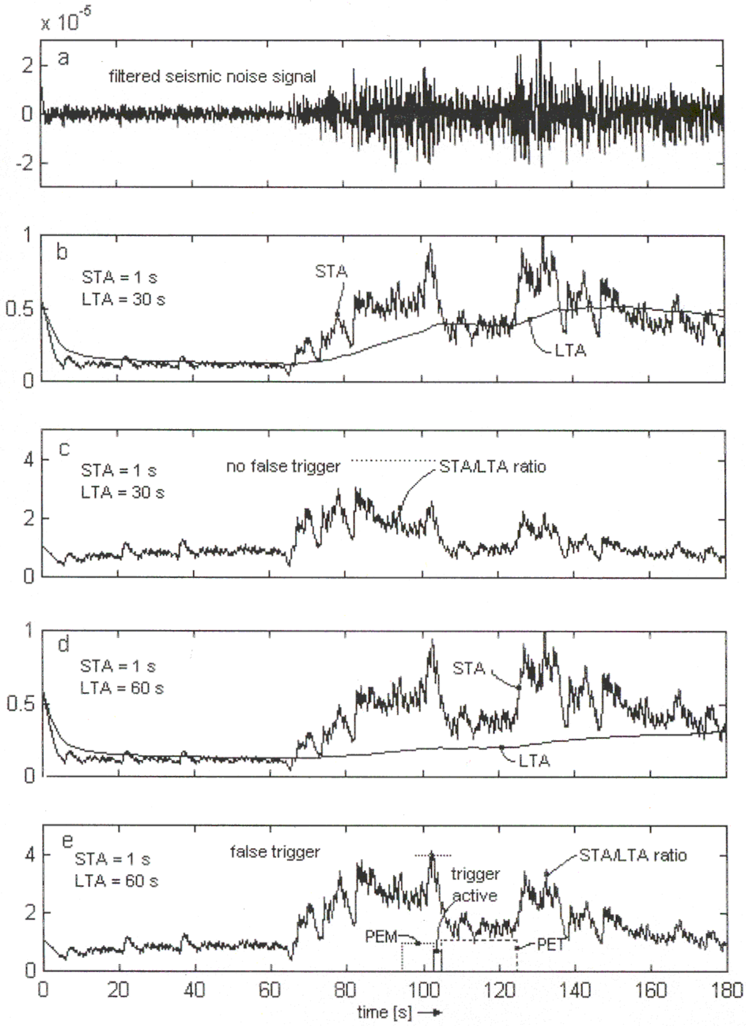

Figure 5 Influence of LTA duration on false triggering when seismic noise conditions change.

Natural seismic noise (marine noise) can change its amplitude by a factor exceeding the value of twenty. However, these changes are slow. Significant changes can occur only during a few hours period, or at worst, in several tens of minutes. Therefore even the longest LTA duration is short enough to allow LTA to accommodate completely to marine noise amplitude variations.

The LTA duration of 60 seconds is a common initial value. A shorter LTA duration is needed to exclude emergent regional events from triggering, if desired, or if quickly changing man-made noise is typical for the site. A longer LTA can be used for distant regional events with very long S-P times and potentially emergent P waves.

4.3 Frozen versus continuously updated LTA during events

Calculations of the LTA value during an event, that is after a channel trigger is declared, can be performed in the first approximation in two different ways.

Either the LTA value is continuously updated and calculated during the event as usual, or the LTA value is kept frozen at the moment when channel trigger is declared. In this case the LTA is not allowed to change (increase) during an event at all. Most of seismic recorders available in the market have both frozen or continuously updated LTA user-selectable options. However, each approach has its good and bad points.

The 'frozen' LTA window (the word 'clamped' is also used in literature) can force the unit into a permanently triggered state in case of a sudden increase of man-made seismic noise at the site. The situation is illustrated in Figure 6.

Graph a) shows an earthquake during which seismic noise increases and remains high even after the termination of the event. Such a situation can happen if, for example, a machinery is switched on in the vicinity of the recorder. In such a case, a completely frozen LTA (graph b) would never again allow the STA/LTA ratio to fall below the STA/LTA detrigger threshold level (graph c) and a continuous record would result. The result is that the seismic recorder's memory soon gets full and blocks further data recording.

A continuously updated LTA (the word 'unclamped' is also used in literature), on the other hand, frequently terminates records too early. Graphs d) and e) of Figure 6 explain this situation. Very often records with truncated coda waves result because the LTA increases rapidly if the beginning portion of a large earthquake signal is included in its calculation. Thus the STA/LTA ratio decreases too rapidly and terminates recording prematurely. Coda waves of the event are then lost, as shown in the Figure 6. This undesired result could be even much more distracting for records of regional events with longer duration.

Some seismic recorders work with a special calculation of LTA. The LTA value is, to the first approximation, 'frozen' after a trigger. However, this 'freezing' is not made complete. Some ‘bleeding’ of event signal into the LTA calculation is allowed. Such an algorithm tries to solve both problems: it does not cause endlessly triggered records in the case of a rapid permanent increase of seismic noise and, at the same time, it does not cut coda waves too early.

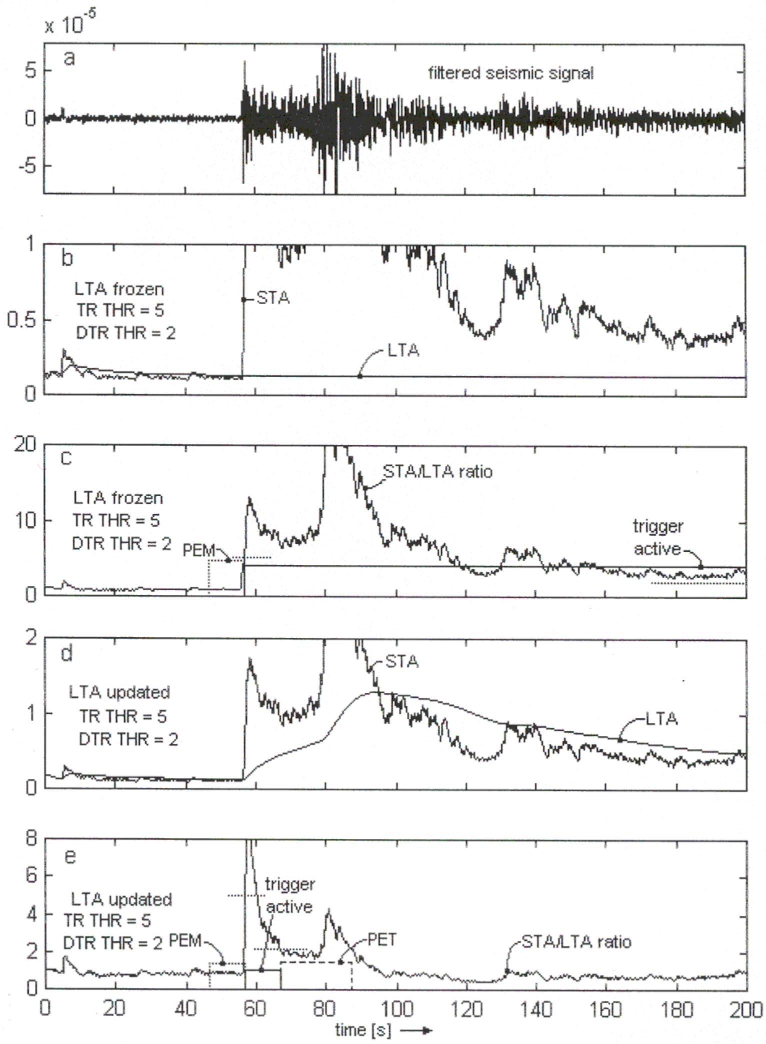

Figure 6 Potential problems with two conventional ways of calculating the LTA: an endless record with a completely frozen LTA and cut coda waves with updated LTA calculations.

4.4 Selection of STA/LTA trigger threshold level

The STA/LTA trigger threshold level to the greatest extent determines which events will be recorded and which will not. The higher value one sets, the more earthquakes will not be recorded, but the fewer false-triggers will result. The lower the STA/LTA trigger threshold level is selected, the more sensitive the seismic station will be and the more events will be recorded. However, more frequent false triggers also will occupy data memory and burden the analyst. An optimal STA/LTA trigger threshold level depends on seismic noise conditions at the site and on one's tolerance to falsely triggered records. Not only the amplitude but also the type of seismic noise influence the setting of the optimal STA/LTA trigger threshold level. A statistically stationary seismic noise (with less irregular fluctuations) allows a lower STA/LTA trigger threshold level; completely irregular behavior of seismic noise demands higher values.

Note that some false triggers and some missed earthquakes are an inevitable reality whenever recording seismic signals in an event-triggered mode. Only a continuous seismic recording, if affordable, completely solves the problem of false triggers and incompleteness of seismic data.

It is a dangerous trap to select a very high STA/LTA trigger threshold level and a high channel gain simultaneously. Many recorders in the market allow this setting without any warning messages. This situation is particularly dangerous in extremely noisy environments, where, due to too many false triggers, the instruments are usually set to record only the strongest events.

Suppose one has set the STA/LTA trigger threshold level to 20. Suppose also that one has set the gain of the channel in such a way that it has about 150 mV of average seismic noise signal at the input of the recorder and the input full scale voltage of the channel is ± 2.5 V. Obviously, this setting would require a 0.15 V×20 = 3 V signal amplitude to trigger the channel. Since its maximum input amplitude is limited to 2.5 V, it can never trigger, no matter how strong an earthquake occurs. Note that this error is not so obvious, especially in low seismicity regions with rare events. One can operate an instrument for a very long time without records and forever wait for a first recorded earthquake.

With certain products in the market, this potential danger of an erroneous setting is solved in the following way: whenever one uses the STA/LTA algorithm, an additional threshold trigger algorithm remains active in the 'background'. Because of it, the channel triggers whenever its input amplitude exceeds 50% of channel input voltage range, for example, in no relation to the STA/LTA trigger setting. In this way, the strongest and therefore the most important events are still recorded, no matter how carelessly the STA/LTA trigger algorithm parameters are set.

An initial setting for the STA/LTA trigger threshold level of 4 is common for an average quiet seismic site. Much lower values can be used only at the very best station sites with no man-made seismic noise. Higher values about 8 and above are required at less favorable sites with significant man-made seismic noise. In strong-motion applications, higher values are more common due to the usually noisier seismic environment and generally smaller interest in weak events.

4.5 Selection of STA/LTA detrigger threshold level

The STA/LTA detrigger threshold level determines the termination of data recording (along with the PET parameter – for more information see 5.3 below on “Selection of post-event time (PET) parameter”).

The STA/LTA detrigger threshold level determines how well the coda waves of recorded earthquakes will be captured in data records. To include as much of the coda waves as possible, a low value is required. If one uses coda duration for magnitude determinations, such setting is obvious. However, a too low STA/LTA detrigger threshold level is occasionally dangerous. It may cause very long or even endless records, for example, if a sudden increase in seismic noise does not allow the STA/LTA ratio to fall below the STA/LTA detrigger threshold level. On the other hand, if one is not interested in coda waves, a higher value of STA/LTA detrigger threshold level enables significant savings in data memory and/or data transmission time. Note that coda waves of distant earthquakes can be very long.

In general, the noisier the seismic site, the higher the value of the STA/LTA detrigger threshold level should be used to prevent too long or continuous records. This danger is high only at sites heavily polluted by man-made seismic noise.

A typical initial value of the STA/LTA detrigger threshold level is 2 to 3 for seismically quiet sites and weak motion applications. For noisier sites higher vales must be set. For strong-motion applications, where coda waves are not of the highest importance, higher values are frequently used.

5 How to adjust associated parameters for proper triggering and data recording

5.1 Selection of trigger filters

Nearly all seismic recorders and networks have adjustable band-pass trigger filters. They continuously filter the incoming seismic signals prior to the trigger algorithm calculations. Selection of these filters is important for a proper functioning of the STA/LTA trigger algorithm (as well as for amplitude threshold trigger algorithm). The purpose of these filters is three-fold:

- they remove DC component from incoming seismic signals, namely, all active seismic sensors have some DC offset voltage at the output which, if too high, deteriorates the STA/LTA ratio calculation. The calculation of the absolute value of the signal becomes meaningless if the DC component is higher than the seismic noise amplitude. This results in malfunction of the STA/LTA trigger algorithm and drastic reduction of trigger sensitivity for weak seismic events;
- their frequency band-pass can prioritize frequencies corresponding to the dominant frequencies of seismic events one wants to record; and
- their stop-band can attenuate dominant frequencies of the most distracting seismic noise at a given site.

The trigger filter pass-band should generally accommodate the frequencies of the maximum energy of expected seismic events. At the same time it should have a band-pass that does not coincide with peak frequency components of typical seismic noise at the site. If this is possible, a significant improvement of the event-trigger/false-trigger ratio results. Obviously, one can understand that if the peak amplitudes of seismic noise and the dominant frequencies of the events of most interest coincide, the trigger filter becomes inefficient.

One should not forget that the frequency response function of the seismic sensor used with a recorder or in a network channel also modifies the frequency content of events and noise signals at the input of trigger algorithm. Therefore the sensor used is an important factor in the choice of a trigger filter. The type of sensor output - proportional to either ground displacement, velocity or the acceleration - has a similar effect. Sensors with ground acceleration proportional output - accelerometers - emphasize high frequencies. They usually require a filter protection against excessive high-frequency man-made seismic noise. Ordinary seismometers have typically an output proportional to ground velocity, sometimes also to ground displacement and they are less influenced by high-frequency man-made seismic noise.

The adjustment flexibility of high- and low-corners of these filters varies among different products. The same is true for the steepness of the filter flanks. Generally, one does not need very steep (high order) filters and a lot of flexibility, because events, similar to the seismic noise, are highly variable. It is generally impossible to determine very precisely where exactly to set the frequency limits of these filters.

5.2 Selection of pre-event time (PEM) parameter

Ideally, the triggered earthquake records should include all seismic phases of an event and, in addition, a portion of the seismic noise signal prior to it. Selection of an appropriate pre-event time (PEM) assures that the earthquake records are complete. For the majority of weak events, the trigger algorithm usually does not trigger at the beginning of the event but sometimes during the event, when the waves with the maximum amplitude of ground velocity reach the station. This happens very often with the earthquakes that have emergent onset waves, and with most of the weak local and regional events where the S phase amplitudes can be much bigger than the P phase. In practice, triggering on the S waves of the weak local and the regional earthquakes is actually more frequent than triggering on the P waves. But for seismological reasons, the P onset waves, plus some seismic noise prior to them, should be included in the record. A proper PEM should take care of this.

Technically this is solved in the following way. In seismic recorders and in a network's central recording computer, a portion of seismic signal prior to the instrument trigger time is temporarily stored in a pre-event ring buffer (abbreviation PEM denotes 'pre-event-memory') and added to the data recorded.

PEM must surmount the following periods of time:

- the desired record duration of seismic noise prior to the event;
- the maximal expected S-P time of earthquake records; and
- time needed to calculate the STA/LTA ratio, which, in the worst case, equals one STA window duration.

Add these three time periods and the result is the appropriate PEM value.

The effect of a too short PEM is shown in Figure 7. Graph a) shows an event approximately 400 km away from the station with weak P waves partly buried in the seismic noise. On graph b) the STA and the LTA values are shown. Graph c) shows the STA/LTA ratio and the trigger and detrigger thresholds (short horizontal dotted lines). The trigger threshold is set to 6.

One can see that the channel triggers on the S waves. However, a PEM of 10 seconds is much too short to catch the P waves. Graph d) shows the actually 'recorded' event. It starts much too late and contains no seismic noise record. Graphs e) and f) show the same event but with a properly set PEM parameter. Seismic noise as well as the P waves are properly recorded.

The maximum expected S-P time depends on the maximal distance of relevant earthquakes from the station and on seismic wave velocity in the region. For practice and for local and regional events, accurate enough results can be gained by dividing the maximum station-to-epicenter distance of interest by 5 (distance in miles) or by 8 (distance in km) to get the required maximum S-P time in seconds.

The application dictates the choice of the desired pre-event noise record duration. At least a few seconds are usually required. Note that if one wants to study spectral properties of weak events, seismic noise spectra are usually required to calculate signal-to-noise ratio as a function of frequency. This, however, requires a significant length of noise records depending on the lowest frequency of interest. The PEM must be set accordingly.

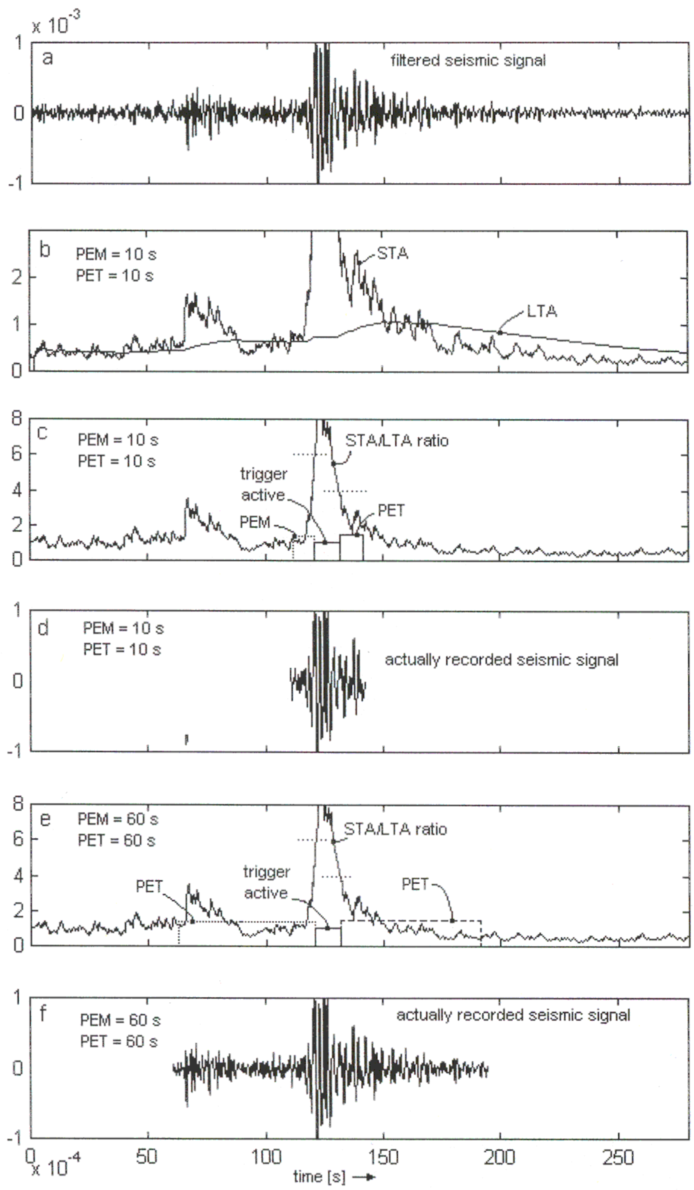

Figure 7 Proper and improper setting of the pre-event time (PEM) and the post-event time (PET)

As an example, let us calculate a required PEM parameter value for a temporary local seismic network with 50 km aperture, where 0.5 sec is set for the STA duration. Suppose that no coincidence trigger exists and all stations run independent trigger algorithms. The operator of the network is interested in the seismicity 200 km around the center of the network. He would also like to have a 10 sec long record of seismic noise before the P waves. We need 0.5 sec for STA calculation, 10 sec for seismic noise, and ≈ (200 km + 50/2km)/8 ≈ 28 sec to cover the maximum expected S-P time. Note that the most distant station from the epicenter in the network still has to record P waves — that is why we added one half of the network aperture to the maximum epicentral distance of interest. The PEM should therefore be set to 0.5 + 10 + 28 ~ 40 sec. Obviously, smaller networks and shorter ranges of interest require shorter PEM and vice versa.

5.3 Selection of post-event time (PET) parameter

The post-event time parameter assures complete recording of seismic events after a detrigger. The main purpose of PET is catching the remaining earthquake coda waves that are smaller in amplitude than the STA/LTA detrigger threshold level. Functionally PET is simply a fixed recording time added to the event file after an instrument or a network (not individual channels!) detriggers. It has a similar effect on coda waves as the STA/LTA detrigger threshold level parameter. However, its effect is event-size independent. This makes it a less effective coda wave 'catcher' than a low STA/LTA detrigger threshold level. It is most suitable for local events. Practical values of PET are usually too short to be of any help for large distant earthquakes with very long coda waves. Contrary to a very low STA/LTA detrigger threshold level that may cause re-triggering problems, a long PET is safe in this respect (see 4.5 above on “Selection of STA/LTA detrigger threshold level”).

Optimal PET duration depends mostly on the application. If coda waves are important, a long PET should be selected. If coda waves have no significance, use a short PET. Obviously, the short local events require only a short PET, regional and teleseismic events, on the other hand, would require much longer PET.

A reasonable value for local seismology would be 30 sec, and 60 to 90 sec for regional seismology, assuming one wants the coda waves well recorded. To find optimal value, observe coda waves of your records and adjust the PET accordingly.

There are usually no practical instrumental limitations on selection of the longest PET. However, note that very long PETs use up the recorder's data memory easily. So, do not exaggerate, particularly in seismically very active areas or if a high rate of false triggers is accepted.

5.4 Selection of voting-scheme parameters

The coincidence trigger algorithm, available either in seismic networks or within a multi-channel stand-alone seismic recorder, or in a group of interconnected seismic recorders, uses voting scheme for triggering. The voting-scheme parameters are actually not directly related to the STA/LTA trigger algorithm. However, inappropriate setting of voting scheme prohibits efficient functioning of overall triggering of a network or a recorder. For that reason we also deal with the voting scheme parameters in this section.

In section 4 'How to adjust STA/LTA trigger parameters', we described how each individual channel would trigger if it were the only one in an instrument or in a network. In the following section we describe how the individual channel triggers are combined to cause the system to trigger in a multi-channel recorder or in a seismic network. We call this 'voting', as a number of votes or weights can be assigned to each seismic channel so that they may cause the system to trigger. Only if the total number of votes exceeds a given pre-set value, does the system actually trigger, a new data file opens, and data acquisition begins.

How this voting system is set up depends on the nature of the signals that one is trying to record and on the seismic noise conditions at sensor sites. The noisy channels, which would frequently falsely trigger, will obviously have less 'votes' or assigned weights than the quiet, ‘reliable’ channels. One will need some first-hand experience of the conditions at the sites before optimizing this voting scheme. The voting mechanism and the terminology differ to some extent among products. However, there are usually four basic terms associated with the voting scheme parameters, namely:

- Channel weights (votes)

A channel weight defines the number of votes the channel contributes to the total when it is triggered. If the channel has a good signal/noise ratio, assign it a positive number of votes. The more 'reliable' the channel in terms of the event trigger/false trigger ratio is, the higher the number should be selected. If a channel is noisy and frequently falsely triggers, give it lesser or even zero weight. In case you want a channel to inhibit triggering (a rare case indeed), give it negative weights.

- Trigger weight

This is the total number of weights required to get the seismic recorder or the network to trigger.

- Detrigger weight

The Detrigger weight is a value below which the total trigger weights (sum of all individual weights) must fall in order to cause a recorder or a network to detrigger. The Detrigger weight of 1 usually means that all voting channels must be detriggered before the recorder will detrigger. However, other definitions are also possible.

- External channel trigger weight

This value represents the number of weights one assigns to the 'external trigger channel' source. This parameter is most useful in networks of interconnected stand-alone seismic recorders. In this configuration every triggered recorder 'informs' all other units in the network that it triggered. If one wants to ensure that all recorders in the network trigger when one unit triggers, the external trigger channel should have the same weight as the Trigger weight. If one wants to use a combination of an external trigger with other internal criteria, one should set the weights accordingly.

Understanding of the voting scheme parameters is best gained through examples. The following section gives a few examples of various voting schemes.

- A classic strong-motion seismic recorder set at a free-field site has no interconnected units and normally has a three-component internal FBA accelerometer. One would set all three Channel weights to 1 and also set the Trigger weight to 1. Consequently any channel could trigger the system. At noisier sites a Trigger weight set to 2 would be more appropriate. In the latter case, two channels must be in a triggered mode simultaneously (or within a time period usually named aperture propagation window (APW) time, which is an additional parameter available with seismic networks) for the beginning of data recording.

- A small weak motion seismic network around a mine is designed for monitoring local micro-earthquakes. It consists of 5 surface seismic stations with vertical component short-period seismometers and one three-component down-hole accelerometer. An 8-channel data logger is used at the network's center. One of the surface stations is extremely noisy due to nearby construction works. All others have approximately the same seismic noise amplitudes. One can temporally set a Channel weight 0 to the noisy station to exclude its contribution to triggering and channel weights of 1 to all other surface stations. The down-hole accelerometer is very quiet but less sensitive than surface stations (accelerometers). Select Channel weight 2 for each of its components. For this network a trigger weight of 3 would be an adequate initial selection. The system triggers either if at least three surface stations trigger, or two components of the accelerometer trigger, or one surface station and one component of the accelerometer trigger. Suppose also that there are frequent blasts in the mine. If one wishes, one can use an External trigger channel weight set to -8 and manually (with a switch) prevent seismic network recording of these blasts (down-hole: 3x2 channel votes + surface stations: 4x1 channel vote - 8 External votes < 3 Trigger votes).

- Let us suppose that an interconnected strong motion network of two seismic recorders with the internal three-component FBA accelerometers is installed in a building, one in the basement and one on the roof. Initially one can set the Channel weights to 1 for each signal channel, as well as for the External trigger channel. Suppose the Trigger weight is set to 1 as well. As a result each channel of the system can trigger both units in the system.

After a while one discovers that the seismic recorder on the roof triggers the system much too frequently, due to the swaying of the building in the wind. Changing the voting scheme of the roof unit so that Trigger weight is 3, its channels have 1 weight, while the External trigger channel has 3 weights, can compensate for this action. Now, the recorder installed on the roof triggers only if all its three channels trigger simultaneously or if the ‘quiet’ recorder in the basement triggers. The number of falsely triggered records will be drastically reduced.

- A small regional radio-frequency (RF) FM modulated telemetry seismic network, with a coincidence trigger algorithm at the central recording site, has 7 short period three-component seismic stations. The three stations, #1 west of the center and #2 and #3 east, not far from the center, have a low seismic noise and are connected to the center via three independent reliable RF links. The two stations north to the center, #4 and #5, are linked with the center via a joined RF repeater. The link between this repeater and the center is, unfortunately, frequently influenced by RF interference, resulting in frequent and simultaneous spikes and glitches in all six transmitted seismic signals. Due to unfavorable geology these two stations have a relatively high seismic noise. The two stations south of the center, #6 and #7, are also connected to the center via another common RF repeater. The station #6 is very quiet and the station #7 is influenced by traffic on a nearby new busy freeway. The RF link from this repeater to the center is less RF interference prone.

In such a situation (apart from trying to technically solve the RF link problem with the northern stations and repositioning of the station #7) an appropriate initial voting scheme would be as follows. A Trigger weight set to 7 (to disable otherwise much too frequent false triggering of the system due to RF interference on all 6 channels of the two northern seismic stations) and a Channel weight 1 to all channels of the northern stations (their total Channel weight should not exceed the Trigger weight), a channel weight 3 to all three channels of the station #1 (to allow independent triggering of the system if all three channels of this good station are triggered), a channel weight 2 to all channels of the stations #2 and #3 (to allow triggering of the whole system if at least four channels of these two closely situated stations are activated), a channel weight 2 to all channels of the station #6 (to accentuate its low seismic noise characteristics but to prevent independent triggering of the system due to occasional RF interference), and a weight 0 to all channels of the station #7 (to exclude its partition in triggering due to excessive man-made seismic noise).

These examples should give enough insight into the flexibility of the coincidence triggering options and about some of the ways in which this flexibility can be used for a particular application. Note also that any initial voting scheme can be significantly improved after more experience is gained with seismic noise conditions at the sites.

6 Practical recommendations for finding optimal triggering parameters

A systematic approach is required for successful adjustment of the optimal triggering and the associated parameters. First, the goals of the seismic installation must be carefully considered and *a priori* knowledge about seismic noise (if any) at the site(s) must be taken into account. Based on this information, the initial parameters are set. Information about them must be saved for documentation purpose. Start with rather low trigger threshold level settings than with a too high setting. Otherwise one can waste too much time in getting a sufficient number of records for a meaningful analysis required for further adjustment steps.

Then the instrument or the network is left to operate for a given period of time. The required length of operation without changing recording parameters depends strongly on the seismic activity in the region. At least several earthquakes and/or falsely triggered records must be recorded before the first readjustment of parameters is feasible. Judgments based on a single or a few records rarely lead to improvements. Such work simply doesn't arrive at any meaningful adjustment.

Afterwards, all records, including those falsely triggered, must be inspected. The completeness of the event records is checked (seismic noise, the P arrivals, the coda waves), and the causes of the false triggers are analyzed. The ratio of event-records/false-records is calculated and compared to the target level. If the number of false triggers does not reach the accepted level, increase the trigger sensitivity by lowering the STA/LTA trigger threshold level(s). Basically, one will acquire more seismic information for nearly the same price and effort. If the number of false triggers is too high, find the reasons why and try to mitigate them by changing STA/LTA and/or voting scheme parameters. Only if this doesn’t help, must one decrease trigger sensitivities.

After the analysis is finished, the parameters are changed according to its findings and the new settings archived for documentation purposes. Again the instrument or the network is left active for a certain period of time, the new records are analyzed, and other changes made if needed. By repeating this process one will gradually find the best parameter setting.

References (see References under Miscellaneous in Volume 2)