Passive (Micro-)Seismic Event Detection

Introduction

Among engineers there is considerable interest in the real-time identification of "events"within time series data with a low signal to noise ratio (S/N). This is especially true for acoustic emission analysis, which is utilized for the monitoring and inspection of the integrity and safety of many structures (such as metal and concrete bridges, gas and oil pipe lines, large storage tanks, and aerospace vehicles) and is also applied in the field of passive seismic monitoring (PSM). Here an array of seismic receivers are used to acquire acoustic signals to monitor locations where seismic activity is expected: underground excavations, deep open pits and quarries, reservoirs into which fluids are injected or from which fluids are produced, permeable subsurface formations, or sites of large underground explosions.

Some specific examples of the use of PSM are:

> *Mining*
> Prevention and detection of rock failures in the vicinity of (underground) excavations. These rock failures are generally caused by the sudden release of strain energy resulting from the redistribution of stresses around openings.
>
> *Oil and Gas*
> Detection of stress changes as a result of enhanced oil recovery (e.g., steam stimulation in oil sands). These stress changes can result in failures of the overlying strata and the migration of hydrocarbons to aquifers or to the ground surface. PSM can be used to satisfy environmental concerns, meet regulatory requirements and assess the development of induced fracturing within the reservoir.
>
> *Dam Safety*
> Monitoring the stress changes during filling of hydroelectric or large irrigation reservoirs. The changes in regional loading and pore pressures cause significant stress variations within the surrounding rock mass. In turn these can induce a wide range of micro and macroseismic events, some of which are capable of causing damage to adjacent structures or to the dam itself.

PSM consists of four elements:

- system specification (e.g., type of sensors, orientation and location)
- event detection
- source location estimation
- source parameter estimation (e.g., attenuation, seismic moment, source radius, static stress drop, peak particle velocity, seismic energy and failure mechanism).

The most important of these elements is obviously event detection: the monitoring of seismic acoustic emissions is a continuous, real-time process which typically runs 24 hours a day, seven days a week, and therefore a PSM system with poor event detection can easily acquire terabytes of useless data as it does not identify crucial acoustic events.

PSM event detection consists generally of two steps:

1. Apply a digital filter to the acquired seismic data to increase the S/N.
2. Calculate the short term average / long term average ratio (STA/LTA): if this ratio exceeds a user specified threshold then an event is assumed to have occurred and the seismic data is stored.

BCE's SEED™ Algorithm

In the area of PSM BCE's main focus is the first of these two steps: the design of sophisticated digital filters to increase the S/N. As part of this BCE implements a novel and robust model of the source wave: the Amplitude Modulated Sinusoid (AMS), which has shown to be a highly robust and accurate approximation for many analytical representations of seismic source waves (such as the exponentially decaying cyclic waveform, the mixed-phase Berlage wave, the zero-phase Ricker wave, and the zero-phase Klauder wave). In addition, the AMS wave has proven very accurate in modeling seismic data acquired during passive seismic monitoring and vertical seismic profiling.

The algorithm we developed for this application, the so-called ***SEED™*** (Signal Enhancement and Event Detection) algorithm, uses real time Bayesian Recursive Estimation (BRE) digital filtering techniques to analyze the raw data. As a first step the algorithm applies a bank of finite sinusoids ($i = 1$ *to* N) with dominant frequencies varying from low to high (e.g., 30 Hz to 430 Hz). The seismic event is approximated as an AMS, whereby the sinusoid is modulated by an amplitude modulating term (AMT).

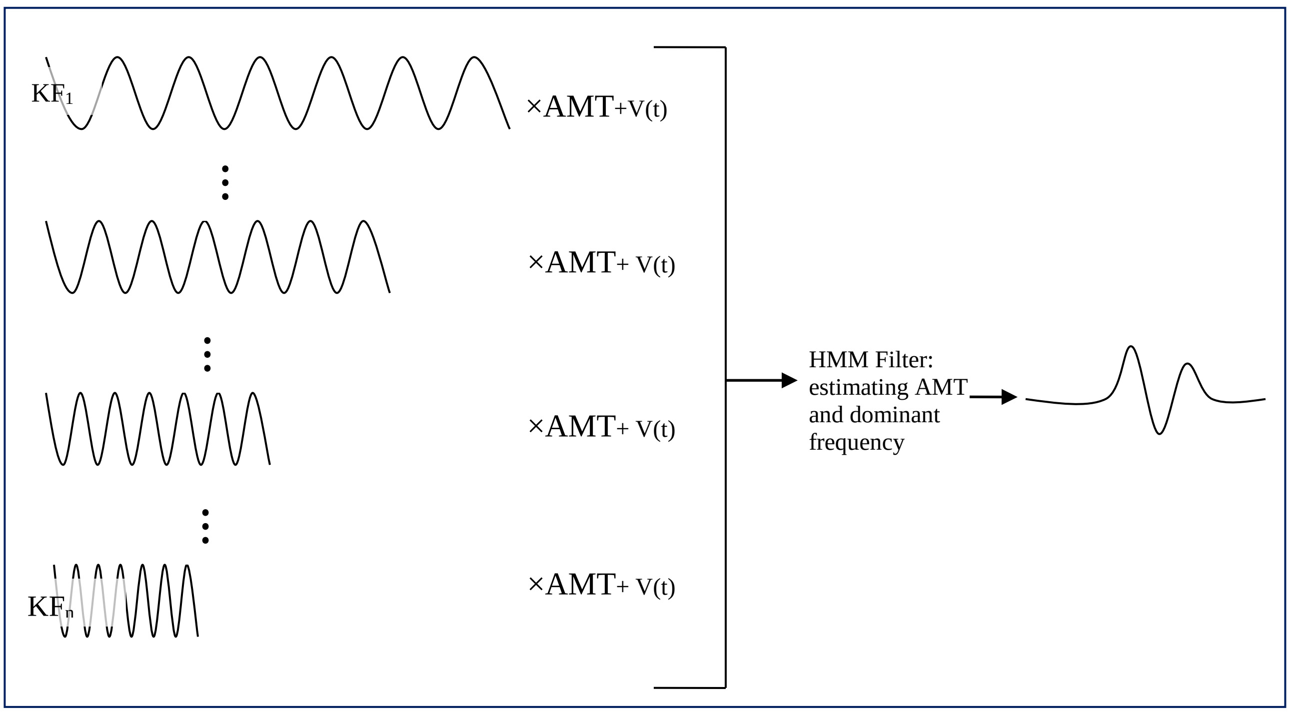


Figure 1. BCE's BRE event detection filter configuration.

As illustrated in Figure 1, a fixed set of possible sinusoids with corresponding dominant frequencies is specified at the outset. A bank of Kalman Filters (KFs) is then utilized, whereby the possible seismic event is approximated as a sinusoid multiplied by an AMT. The KF system equations include the AMT components which are modeled as a two state first order Taylor series with the velocity component represented by a Gauss-Markov process. The KF measurement equations incorporate the sinusoidal components $sin(\omega_i t)$ where $\omega_i = 2\pi f_i$ and f_i is the dominant frequency. The frequency components are incorporated as states within a Hidden Markov Model (HMM) filter formulation. The background noise is also included within the KF system equations through the Gauss-Markov process. The Gauss-Markov process is a very robust noise model, and yet it has a relatively simple mathematical description. As in the case of all stationary Gaussian processes, specification of the process autocorrelation completely defines the process: the variance, σ^2, and time constant, T_c. These parameters can be derived from the seismic time series in real-time by windowing on the noise portion of the trace and calculating the autocorrelation of the background noise.

As part of the PSM effort, the monitoring system acquires a user specified ring buffer of seismic data at a pre-specified rate. The ***SEED***™ algorithm automatically determines the statistically background noise parameters, and calculates the AMT component and the dominant frequency of the AMS source. A second (STA/LTA) algorithm is then applied to the derived AMT to determine if an event occurred, and if the user specified threshold was exceeded and the estimated frequency resided within a user specified bandwidth (e.g., P-wave and S-wave bandwidth) then an event is assumed to have occurred and the seismic data is stored to file.

Performance Results

Figure 2 illustrates a Berlage source wave with a dominant frequency of 100 Hz, arrival time of 40 ms and maximum absolute amplitude of 7.2.

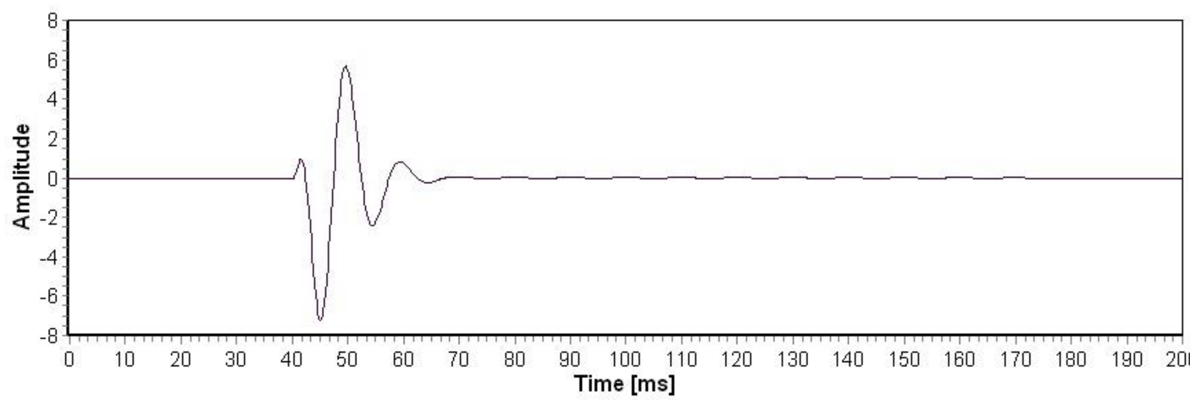


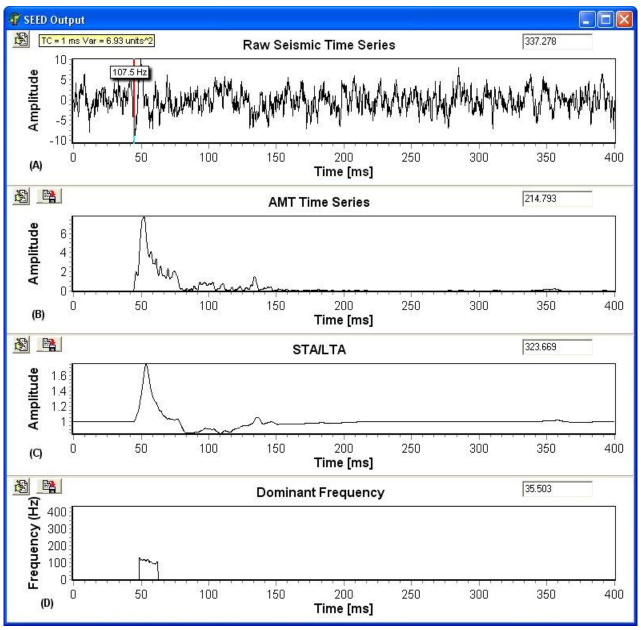
Figure 2. Berlage source wave with dominant frequency of 100 Hz.

Example 1:

The source wave shown in Figure 2 is embedded within ambient noise with variance $\sigma^2$of 6 units^2 and time constant T_C of 1 ms as illustrated in Figure 3(A). BCE's ***SEED***™ algorithm is then applied on this noisy seismogram with a HMM frequency bandwith and resolution of 30 - 430 Hz and 2 Hz, respectively. A STA/LTA threshold of 1.2 was specified.

The resulting AMT and STA/LTA is illustrated in Figures 3(B) and 3(C), respectively. The ***SEED***™ algorithm also provides the dominant frequencies when the STA/LTA ratio exceeds the threshold of 1.2 as shown in Figure 3(D).

The results using the using the ***SEED*™** algorithm can be compared with the outcome when using a standard frequency filtering algorithm (applying an eight order digital bandpass (30 Hz to 150 HZ) filter) as illustrated in Figure 4. It is clear that ***SEED*™** algorithm provides a considerable S/N improvement compared to the standard frequency filtering.



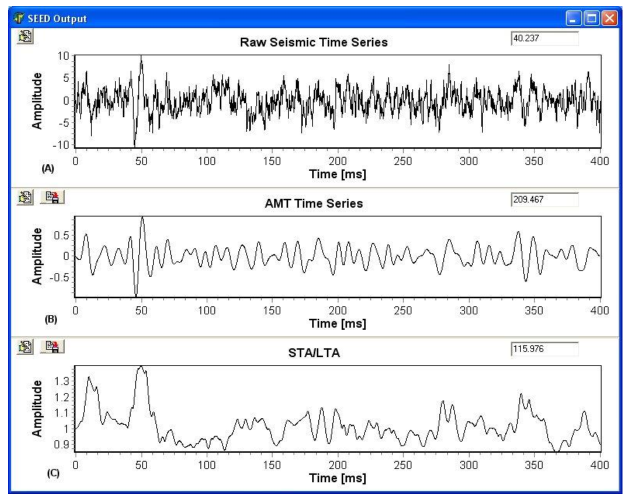


Figure 3.(A) Seismogram with source wave of Figure 2 embedded in ambient noise; (B) Derived AMTusing the SEED™ algorithm; (C) Derived STA/LTA using the SEED™ algorithm; (D) Estimated frequencies when STA/LTA threshold of 1.2 exceeded using the SEED™ algorithm.

Figure 4. (A) Seismogram with source wave of Figure 2 embedded in ambient noise;(B) Derived AMT after applying an eight-order zero phase bandpass (30 Hz to 150 Hz); (C). DerivedSTA/LTAof filtered trace.

Example 2:
The source wave shown in Figure 2 is embedded within ambient noise with variance $\sigma^2$of 9 units^2 and time constant T_C of 3 ms as illustrated in Figure 5(A). BCE's ***SEED***™ algorithm is then applied on this noisy seismogram with a HMM frequency bandwith and resolution of 30 - 430 Hz and 2 Hz, respectively. A STA/LTA threshold of 1.2 was specified.
The resulting AMT and STA/LTA is illustrated in Figures 5(B) and 5(C), respectively. The ***SEED***™ algorithm also provides the dominant frequencies when the STA/LTA ratio exceeds the threshold of 1.2 as shown in Figure 5(D).

The results using the using the ***SEED*™** algorithm can be compared with the outcome when using a standard frequency filtering algorithm (applying an eight order digital bandpass (30 Hz to 150 HZ) filter) as illustrated in Figure 6. It is clear that ***SEED*™** algorithm provides a considerable S/N improvement compared to the standard frequency filtering.
The other aspect to be considered in this case is the number of times the STA/LTA exceeds the specified threshold: the analysis with the ***SEED*™** algorithm indicates that there is only 1 event, whereas standard frequency filtering implies that there were possibly 8 events.

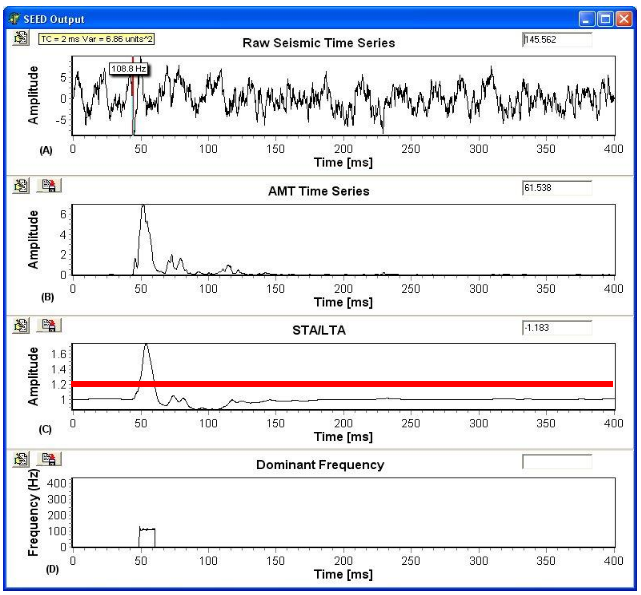


Figure 5.(A) Seismogram with source wave of Figure 2 embedded in ambient noise; (B) Derived AMTusing the SEED™ algorithm; (C) Derived STA/LTA using the SEED™ algorithm; (D) Estimated frequencies when STA/LTA threshold of 1.2 exceeded using the SEED™ algorithm.

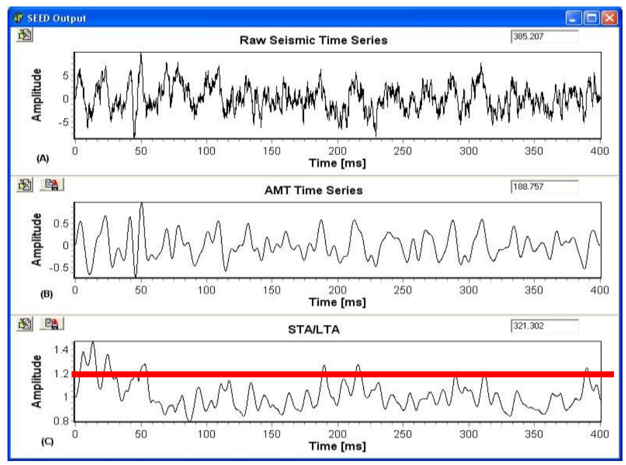


Figure 6. (A) Seismogram with source wave of Figure 2 embedded in ambient noise; (B) Derived AMT after applying an eight-order zero phase bandpass (30 Hz to 150 Hz); (C). Derived STA/LTA of filtered trace.

From the discussion and examples provided in this technical note, it is obvious that BCE's ***SEED***™ algorithm provides considerable event detection advantages when processing passive (micro-)seismic data, such as:

- Ability to identify events embedded in high variance and correlated noise environments
- Significant S/N improvement
- Ability to derive noise statistics
- Dominant frequency estimation

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*BCE's Seismic Data Analysis software packages SEED™ and µSEIS-DAC™ provide the user the option of applying the **SEED**™ algorithm for sophisticated event detection. For more information about these packages (incl . a copy of the user manual please visit our website (www.bcengineers.com)) or contact our offices:*

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