Time picking and random noise reduction on microseismic data

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ABSTRACT

Methods based on the STA/LTA ratio and the modified energy ratio (MER) are studied for their efficacy in automatic first-arrival time picking on high-noise microseismograms. Testing of the two methods on both field and synthetic data indicate that they can pick arrival times for signal-to-noise (SNR) levels as low as 1.7, but that MER time picking yields more consistent results. Moreover, MER time picking is significantly faster than STA/LTA time picking.

For many seismic processing procedures, reducing the random noise on the input seismograms will lead to much improved results. Trace averaging (i.e., stacking) over a group of seismograms aligned in phase is a standard method for reducing random noise. Time shifts for trace alignment can be found using one of two methods: finding the average trace that gives minimum variance to the shifted input traces, and using the time picks from the MER method. A noise-signal separation (NSS) technique, developed as an extension to simple trace averaging, separates a noisy seismogram into a noise-reduced signal component and a random noise component while preserving the relative signal amplitudes on the input seismograms.

INTRODUCTION

Arrival-time picking is a fundamental and ubiquitous process in the seismic industry. For example, with seismic surface surveys, we need first-arrival picks to derive the velocity information on near-surface low-velocity zones for making static corrections. With full waveform sonic (FWS) logs, we need first-arrival picks to derive the velocity information on formation intervals encountered by the logging tool as it moves up or down the well (Han et al., 2008). In the analysis of microseismic data, arrival-time picking on microseismograms must be done before hypocenter location can be done (Han et al., 2009; Wong et al., 2009b).

Many seismic processing and imaging methodologies are limited by random noise in the raw field seismograms. In the microseismic case, the hodogram/back-azimuth method for hypocenter location using low input seismograms with signal-to-noise ratios (SNR) leads to unacceptably large uncertainties in the microseismic source coordinates. To improve the end product of these processing procedures, random noise on field seismograms must be attenuated. We have developed a random noise suppression methodology that involves trace averaging and a subsequent noise-signal separation (NSS) step.

TIME PICKING ON MICROSEISMIC DATA

Arrival time-picking for direct P and/or S events is a critical step for achieving the primary goal of microseismic monitoring and analysis, namely, estimating hypocenter locations to track fracture growth during reservoir stimulation by hydraulic fracturing. In other applications (Maxwell and Urbancic, 2001), microseismic data from a passive seismic monitoring system may be recorded every 15 seconds for a period of days, months, or even years. Therefore, a microseismic dataset may consist of tens or hundreds of thousands of seismic traces, even if the vast majority is discarded after being classified as containing no useful information.

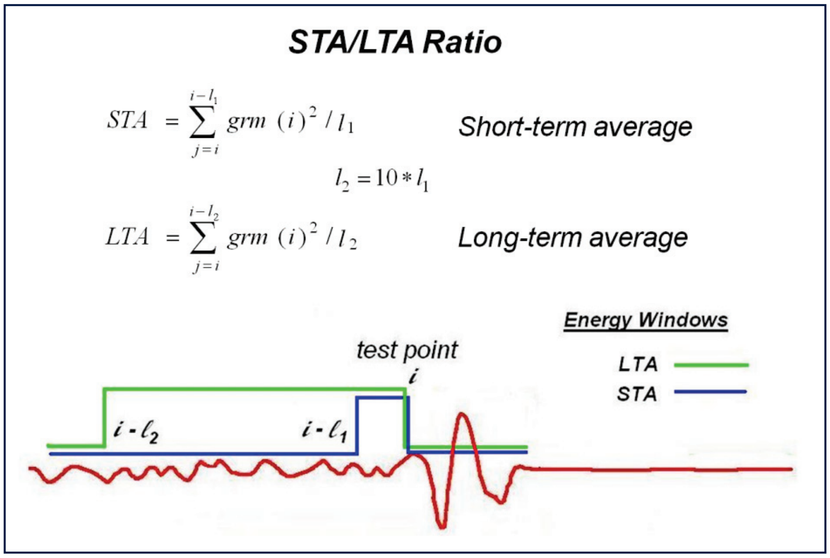


FIG. 1: Definition of the STA/LTA method. The length of the LTA energy collection window is five to ten times the length of the STA energy collection window, which needs to be on the order or two to three times the dominant period of the seismic arrival.

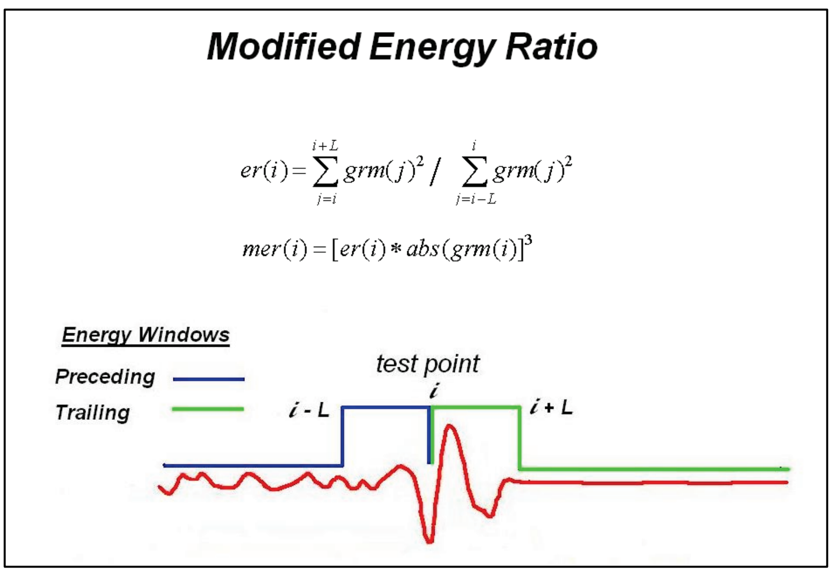


FIG. 2: Definition of the MER method. Preceding and following energy collection windows with equal lengths are located at a test point. The window lengths are two to three times the dominant periods of the seismic arrival.

For handling such large numbers of traces, the time-picking method must be fast, accurate, and automatic. We have developed the modified energy ratio (MER) method as a faster alternative to the STA/LTA method widely used for microseismic and earthquake analysis.

Figure 1 shows the definition for the STA/LTA ratio (Chen and Stewart, 2005; Munro, 2004). Figure 2 shows the definition of the MER method. Both methods rely on energy ratio calculations, differing only on the lengths and positions of energy-collecting windows and the details of ratio evaluation at each test point. For the STA/LTA method, the time pick occurs at the maximum of the rising slope of the ratio (or, equivalently, for digitized plots, at the maximum of the numerical derivative). For the MER method, the time picks occurs at the peak of the MER attribute.

Comparison of different modified energy ratios

Equation 1 defines the basic energy ratio attribute:

$$er(i) = \sum_{j=i}^{i+L} grm(j)^2 \,/\, \sum_{j=i}^{i-L} grm(j)^2 \ , \tag{1}$$

where i is the test point index, L is the length of the energy collection windows preceding and following the test point, and $grm\ (j)$ is the seismogram value at index j.

The basic energy ratio can be modified by combining with the absolute values on the seismogram in different ways:

$$er1(i) = er(i) \cdot abs(grm(i)) \ , \tag{1a}$$

$$er2(i) = er(i) \cdot [abs(grm(i))]^3 \ , \tag{1b}$$

$$er3(i) = [er(i) \cdot abs(grm(i))]^3 \ . \tag{1c}$$

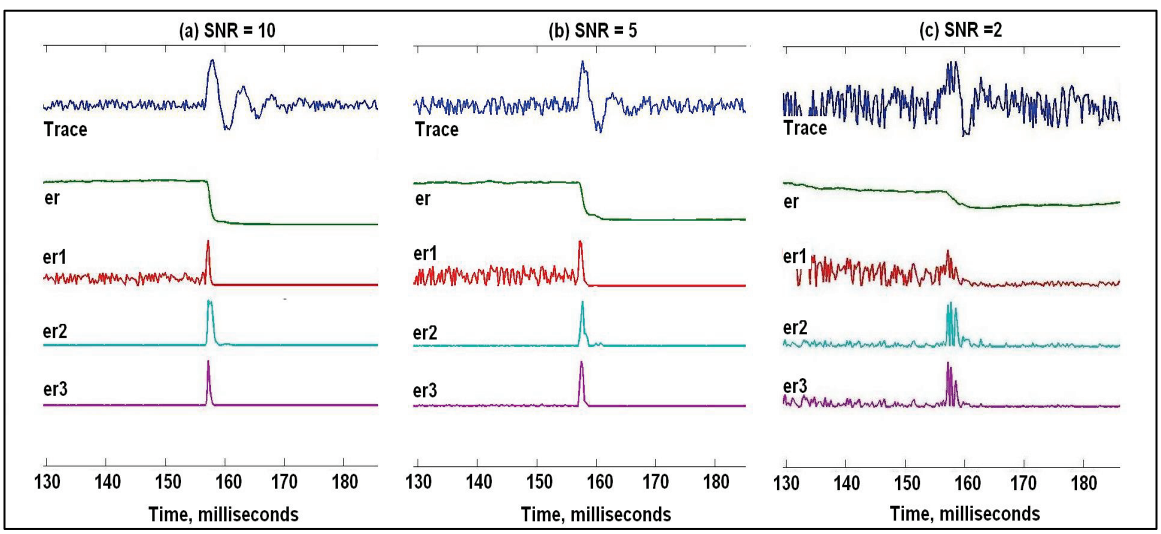


FIG. 3: Comparison of different modifications of the basic energy ratio for various noise levels.

The modifications improve the ability for the attribute to detect the onset of a seismic arrival in the presence of random noise. On Figure 3, we have plotted the different modified energy ratios for three levels of noise. On the basis of these plots, we decided to use *er3(i)* version for general time-picking. In the rest of this report, the MER acronym refers to *er3(i)*.

Comparison of the STA/LTA and MER time picking methods

On Figure 4, we have plotted the STA/LTA ratio and MER for low-noise and high-noise signals. For high SNR arrivals, both techniques yield arrival times very close to the first-break time. For signals with low SNR, the picks for both methods occur somewhat later and closer to a peak absolute amplitude.

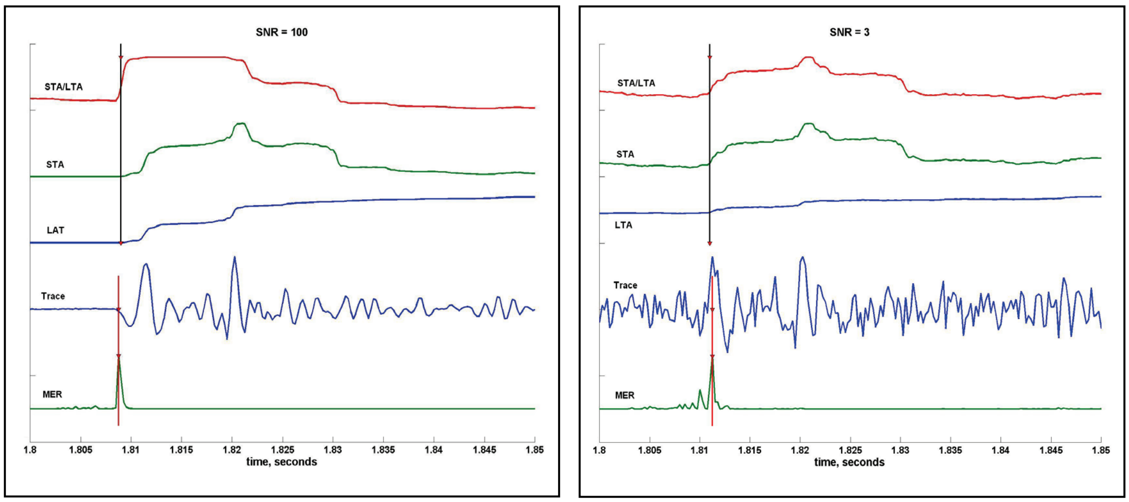


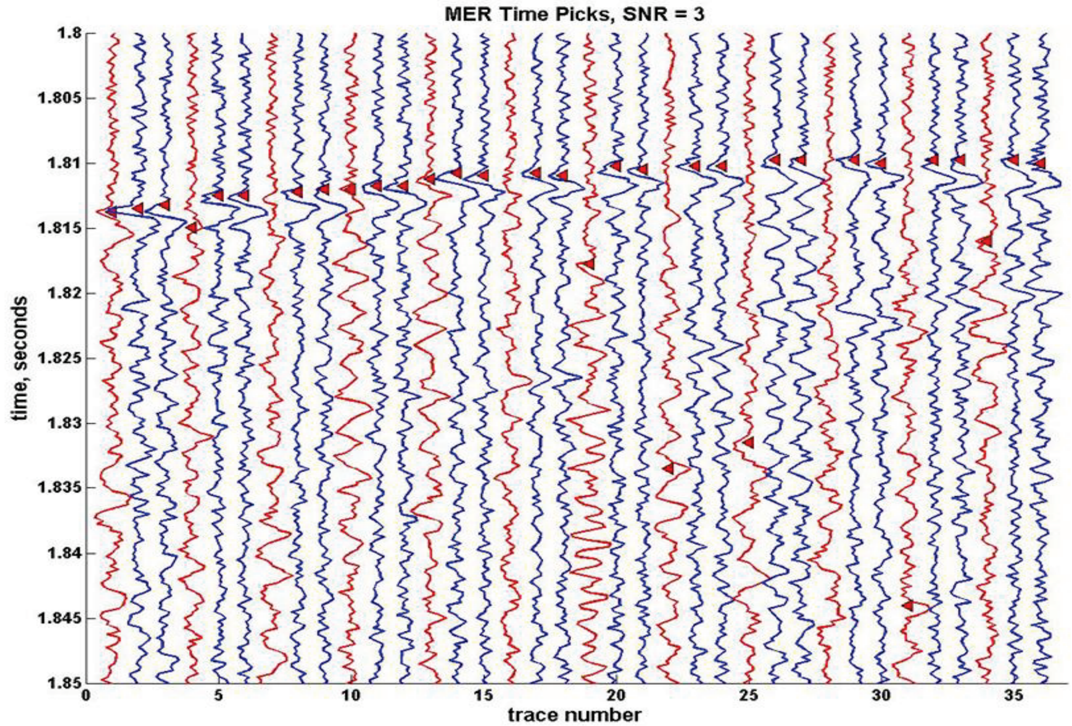
FIG. 4: STA/LTA and MER time-picking on a clean trace and on a noisy trace. The noisy trace (SNR=3) was created by adding synthetic random noise to the clean trace (SNR=100). For the clean trace, the MER and STA/LTA methods both give an arrival time at the first break. For the noisy trace, both the STA/LTA and MER picks occur at a later time.

Testing on field seismograms

Figure 5 shows time picks from field seismograms recorded with an array of twelve 3C geophones spaced 11.75m apart in an observation well located about 575m from a treatment well. The seismograms were generated by a casing perforation shot at a depth of 2150m in the treatment well. Synthetic random noise was added to the raw seismograms to yield the plotted traces (SNR approximately 3). We see that the picks using the MER method appear to be more consistent and accurate than the STA/LTA picks. In addition, the MER method was almost five times faster than the STA/LTA method (this is due to the fact that LTA energy window is much longer than the MER energy windows).

Testing on synthetic seismograms

Gathers of synthetic microseismograms were created to represent recordings by a microseismic monitoring system. The system consisted of an array of twelve 3C geophones spaced vertically at 25m in an observation well. The distance between the microseismic source and the geophone array is assumed to be 500m.



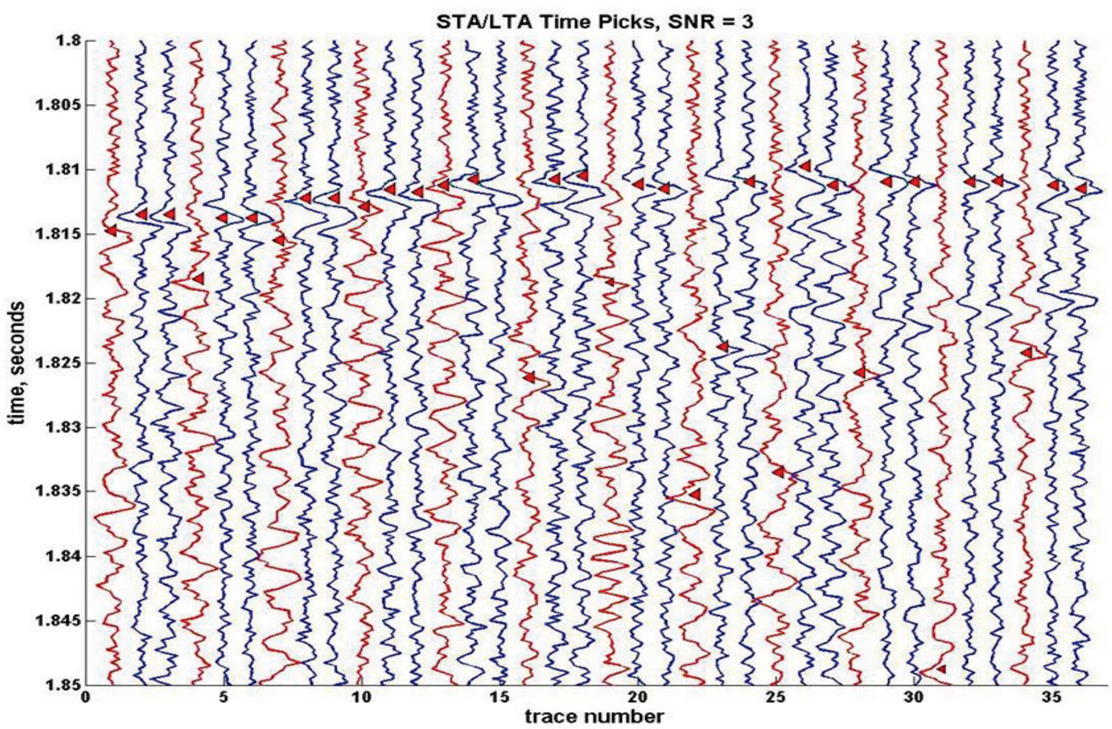


FIG. 5: MER and STA/LTA time picks for noisy field microseismograms. The vertical component traces for the geophones are shown in red, while the horizontal component traces are shown in blue. The red triangles are the first arrival time picks. The time picks from the MER method (top) are more consistent and accurate than those from the STA/LTA method (bottom).

The source signal is simulated by a minimum-phase wavelet of the form

$$w(t) = \sin(2\pi f t) \cdot \exp(-kt) \ ,$$

where t is in seconds, f is 80Hz or 200Hz, and k is 50 nepers/s. The earth model used to calculate arrival times through ray-tracing is homogeneous and isotropic in P-wave or S-wave velocities. A particular geophone signal is synthesized by convolving the source wavelet with a delta function located at the calculated arrival time. Various levels of Gaussian random noise are then added in order to study the limitations on the time picking methods caused by noise.

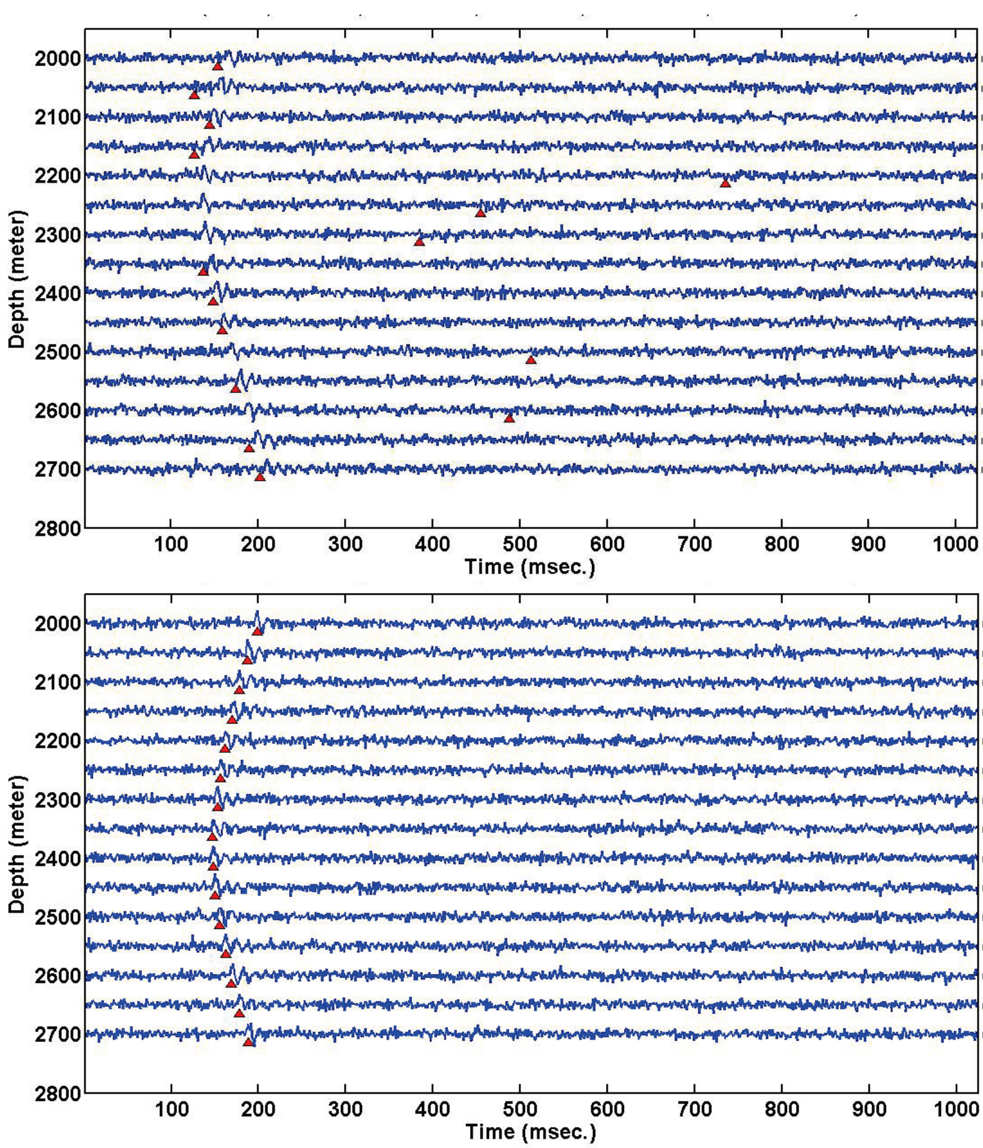


FIG. 6: Time picking using the ER (top) and the MER (bottom) attributes on synthetic seismograms with Gaussian noise (SNR=2.5). The ER attribute picks incorrect arrival times for many traces. The MER attribute picks correctly for all traces.

Figure 6 shows why the MER attribute should be used instead of the basic energy ratio ER for time picking when SNRs are low. The ER picks are incorrect for a good number of the traces in the synthetic gather. On the other hand, the MER picks are all correctly placed near the first break times of the arrivals.

Trace windowing for traces with extremely low SNRs

When traces are extremely noisy, the MER time picks often have outliers. This is the case for the picks on Figure 7, where five of the MER picks (plotted in green) are outliers. Applying a 5-point median filter changes the picks to the green crosses and eliminates the worst outliers. However, the filtered picks are incorrect for many of the traces. We must re-do the picking, but only after windowing the traces.

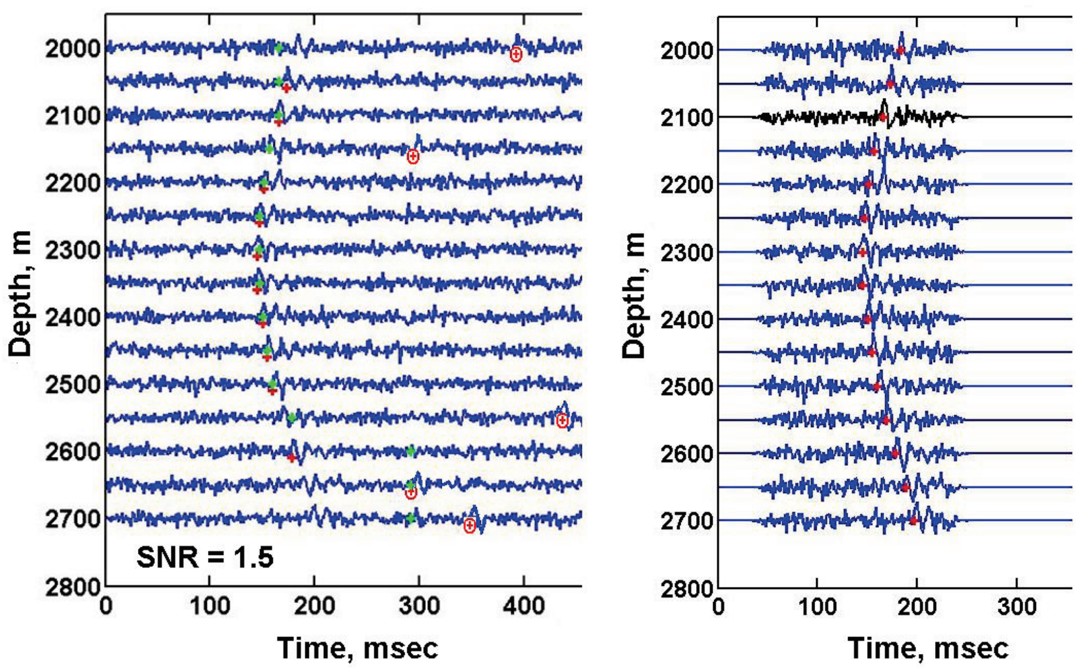


FIG. 7: Left: the red crosses are initial MER time picks, showing five outliers (circled in red); the green crosses are the picks after 5-point median filtering. Right: MER picks after applying a window (defined following the steps in the text) to eliminate the outliers.

Define the window in the following way. Let t_{min} and t_{max} be the minimum and maximum values of the median-filtered time picks. Estimate the dominant period T of the seismic arrival. Let t_1 be a value in the range $2T$ to $4T$. Set the leading edge of the window at (t_{min} - t_1) and the trailing edge at (t_{max} - t_1). The right side of Figure 7 shows the results of re-picking after windowing. The picks are correctly placed on all the arrivals, even though the noise levels are very high (SNR=1.5). Windowing in this way reduces the likelihood of outlier picks.

Time picking of multiple arrivals on seismograms

The ability of time picking software to correctly determine multiple arrivals on a seismic trace is important, because a microseismogram will often contain both P and S arrivals. A modified version of the MER technique allows us to include picking of multiple arrivals. Figure 10 indicates how the modification handles multiple events for different noise levels. For SNRs greater than about 3.5, the arrival times for well-separated coherent events are picked accurately. For SNRs less than 3.5, outliers begin to appear. For future work on this problem, we need to develop coherence filters to handle the outliers so all the picks are spatially coherent. We also must investigate how closely spaced the events can be before the technique fails to pick them separately.

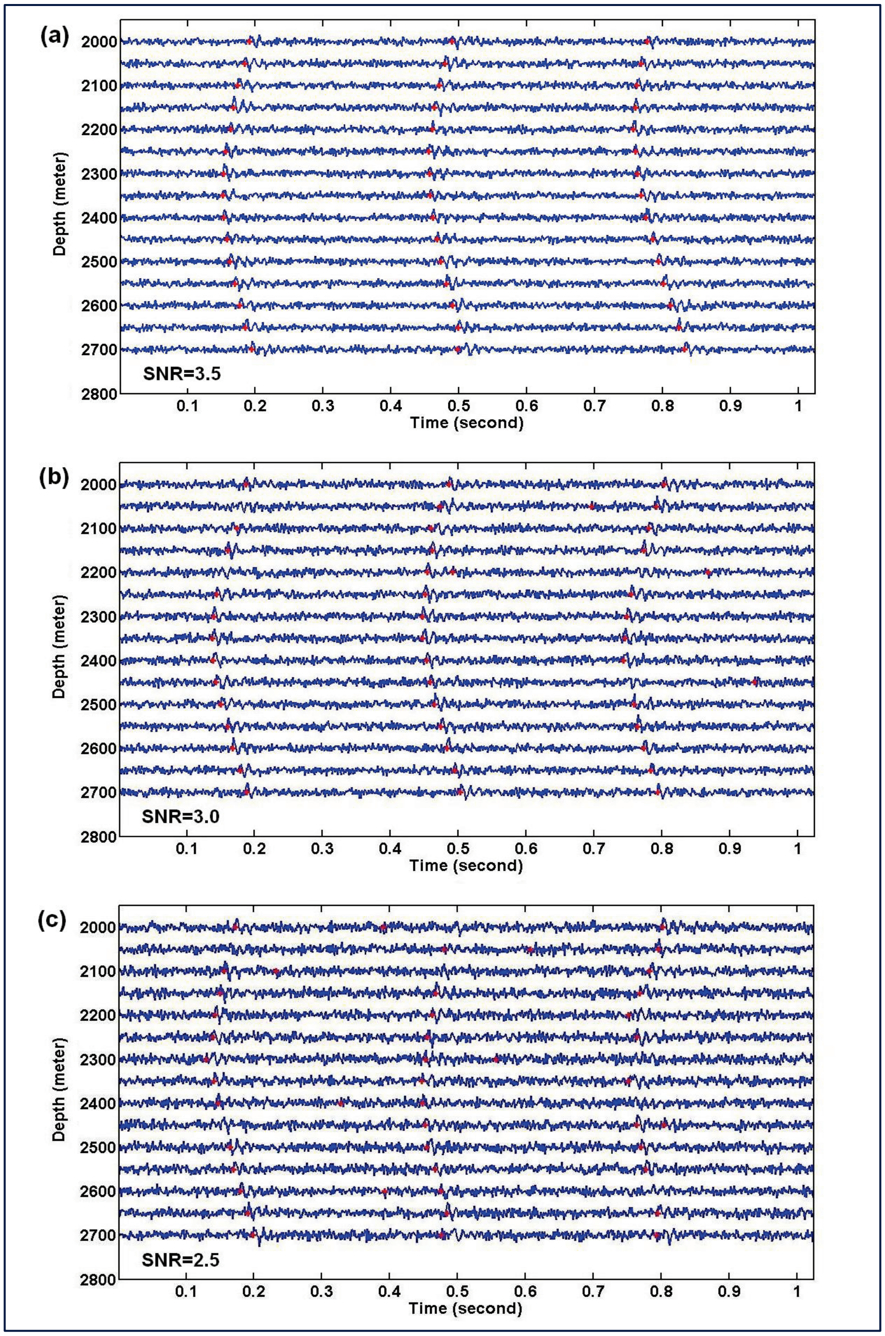


FIG 8: Time picking of multiple noisy arrivals. (a) SNR=3.5; (b) SNR=3.0; (C) SNR=2.5. Outliers begin to appear for SNR less than 3.5.

RANDOM NOISE REDUCTION BY TRACE AVERAGING

Random noise limits the quality of outputs from many seismic processing procedures. Therefore, noise suppression on raw seismograms with low SNR prior to any other procedure is highly desirable. If waveforms on a group of adjacent seismograms are similar and exhibit coherence, trace averaging is an effective way to reduce noise and mitigate its adverse effect. Trace averaging begins with applying time shifts to a group of traces so that arrival waveforms are all aligned in phase. The required time shifts can be found by using a minimum variance principle. Alternatively, for seismograms with exceptionally low SNRs, the time shifts can be obtained by combining the MER time picking method with a correction step involving cross-correlation.

Trace alignment and noise reduction using a minimum variance principle

Consider for example three noisy seismograms with similar waveforms but displaced in time. Normalize them and apply a suitable window to roughly isolate the first arrivals. The length and position of the window are based on the envelopes and dominant frequencies of the raw noisy seismograms. Label the windowed seismograms as *Rx1*, *Rx2*, and *Rx3*. Keeping *Rx3* unshifted as the reference trace, systematically shift the *Rx2* and *Rx1* traces by times of Δt_1 and Δt_2 (these shifts may have different amplitudes and signs). Add the three traces to form the average sum trace $m(t)$. Then find the difference or error between the average trace and each input trace at each time index. The sum of the squared errors over all the time indices is the variance $var(\Delta t_1,\Delta t_2)$. We use the following equations to calculate $m(t)$ and $var(\Delta t_1,\Delta t_2)$ for many values of $(\Delta t_1,\Delta t_2)$ until we find a minimum for $var(\Delta t_1,\Delta t_2)$:

$$m(t) = [Rx1(t+\Delta t_1) + Rx2(t+\Delta t_2) + Rx3(t)]/3\ ,$$

$$var(\Delta t_1,\Delta t_2) = \sum_{t=0}^{t\max} \{ [m(t) - Rx1(t+\Delta t_1)]^2 + [m(t) - Rx2(t+\Delta t_2)]^2 + [m(t) - Rx3(t)]^2 \}\ .$$

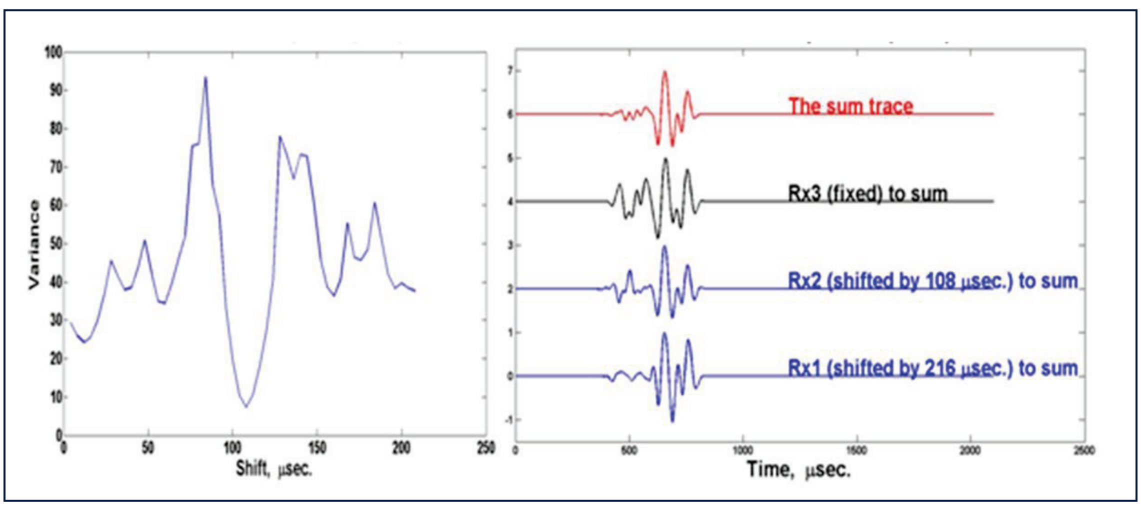


FIG. 9: Minimum variance averaging of three noisy traces (*Rx1*, *Rx2*, and *Rx3*) to create an average sum trace (shown in red) with increased SNR. Before further processing, the average sum trace can be used to replace any of the input traces and reversing the time shifts.

The variance is least when the windowed waveforms are in phase. The optimal average trace *m(t)* corresponding to the minimum variance is less noisy than the input traces, and can be used to replace the reference trace. This method of reducing noise is called minimum-variance averaging, or MVA.

Figure 9 illustrates the technique using three high-frequency seismograms from a full-waveform sonic log, where $\Delta t_1 = \Delta t_2 = \Delta t$ (Wong et al., 2009a). The method is not restricted to three input traces. The average trace can be calculated using 3, 4, 5, or more adjacent traces as inputs. Once it is found, the optimal sum trace can be used to replace each of the noisy input seismograms after reversing the optimal time shifts.

Figure 10 shows an example where twelve noisy synthetic microseismograms have been aligned and averaged for noise reduction using MVA. The technique is noise-limited. The SNR level of 3.5 appears to be the lowest SNR level for which the technique is successful. As is shown on Figures 11(d) to 11(f), higher noise levels leads to unstable time shifts that do not correctly align all traces.

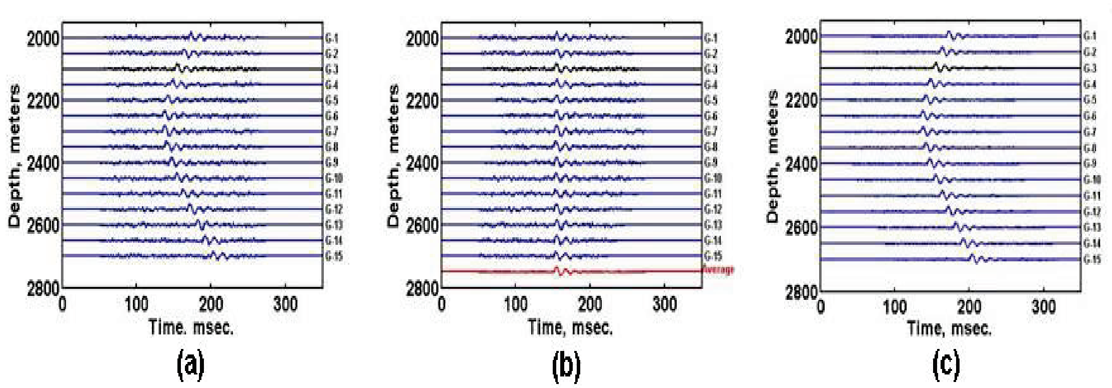


FIG.10: Alignment and noise reduction using MVA: (a) original seismograms with Gaussian random noise (SNR=3.5); (b) aligned noisy seismograms with the average trace shown in red; (c) noisy seismograms replaced by the average trace.

The minimum variance method for finding optimal time shifts and noise reduction is similar to the semblance technique described by Sheriff (2006) or the match filtering (cross-correlation) method described by Eisner et al. (2008).

Trace alignment and noise reduction using MER time picks

The robustness of the MER technique for time picking in the presence of random noise has been demonstrated by examples in above sections. We can take advantage of the reliability of the MER picks for trace alignment when SNR levels are very low. Figures 11(a) to 11(b) demonstrate that accurate time shifts for phase alignment can be obtained by the MER method for seismograms with SNRs as low as 2.5, whereas shifts from MVA do not correctly align traces at such low SNR levels.

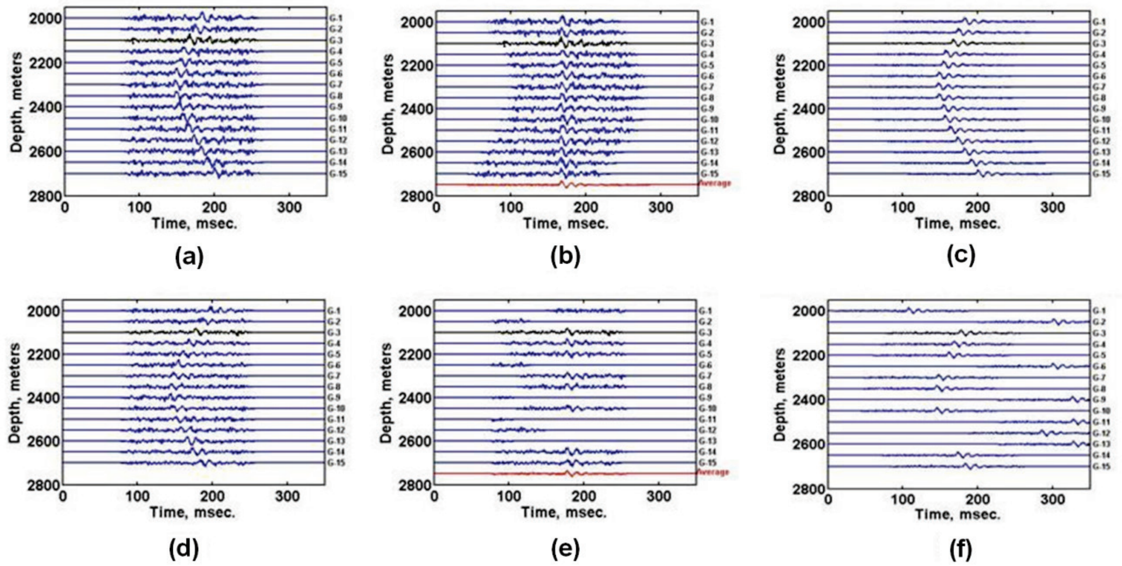


FIG.11: Trace alignment and noise reduction using MER time picks. (a) original seismograms with Gaussian noise (SNR=2.5); (b) noisy seismograms aligned using MER time picks with the average trace shown in red; (c) noisy seismograms replaced by the average trace with time shifts reversed. Shifting with MVA fails at this noise level, as shown in the bottom figures: (d) original seismograms (SNR=2.5), (e) trace shifting with minimum variances with the average trace shown in red; (f) traces replaced by the average trace with time shifts reversed.

A NOISE-SIGNAL SEPARATION (NSS) PROCEDURE

The standard convolution representation of a seismogram is given by:

$$s(t) = w(t) * r(t) + n(t) , \tag{2}$$

where $s(t)$ is the seismic trace, $w(t)$ is a source wavelet, $r(t)$ is the reflectivity, and $n(t)$ is random noise. For our situation, where we have a group of aligned noisy traces with their noise-reduced average, Equation 2 can be simplified to

$$s_i(t) = a_i \times s_{av}(t) + n_i(t) , \tag{3}$$

where $s_i(t)$ is an individual noisy trace from the group, the reflectivity $r(t)$ is replaced by a scalar factor a_i, the source wavelet $w(t)$ is replaced by the normalized (relatively noise-free) average trace $s_{av}(t)$, and $n_i(t)$ is the random noise component of the noisy trace.

Taking the dot product of both sides of the above formula with $s_{av}(t)$, and assuming that $n_i(t) \cdot s_{av}(t)$ is zero, we can rearrange to find an expression for a_i:

$$a_i = s_i(t) \cdot s_{av}(t) / s_{av}(t) \cdot s_{av}(t) \quad . \tag{4}$$

In this way, we can separate each noisy trace into a noise component and a signal component $a_i \times s_{av}(t)$ that is noise-free to the extent that the dot product $n_i(t) \cdot s_{av}(t)$ is zero. This method of deriving the noise-free component of a seismogram preserves the relative signal amplitudes within the group of noisy seismograms.

Figure 12 displays results from application of NSS on synthetic microseismograms with a high level of Gaussian noise (SNR≈ 1.5). For such noisy seismograms, we resorted to an iterative technique for trace alignment. First, we aligned the traces using the MER time picks, and obtained a provisional average trace. Then we cross-correlated the provisional average trace with the shifted noisy traces to find corrections to the MER time shifts. The trace alignment was adjusted by applying these corrections, and a second average trace was obtained. The normalized second average trace is the $s_{av}(t)$ used in Equations 3 and 4.

There appears to be little or no coherence between the average trace and the noise components, indicating that the dot product $n_i(t)\cdot s_{av}(t)$ is much less than the dot product sb$(t)\cdot s_{av}(t)$.

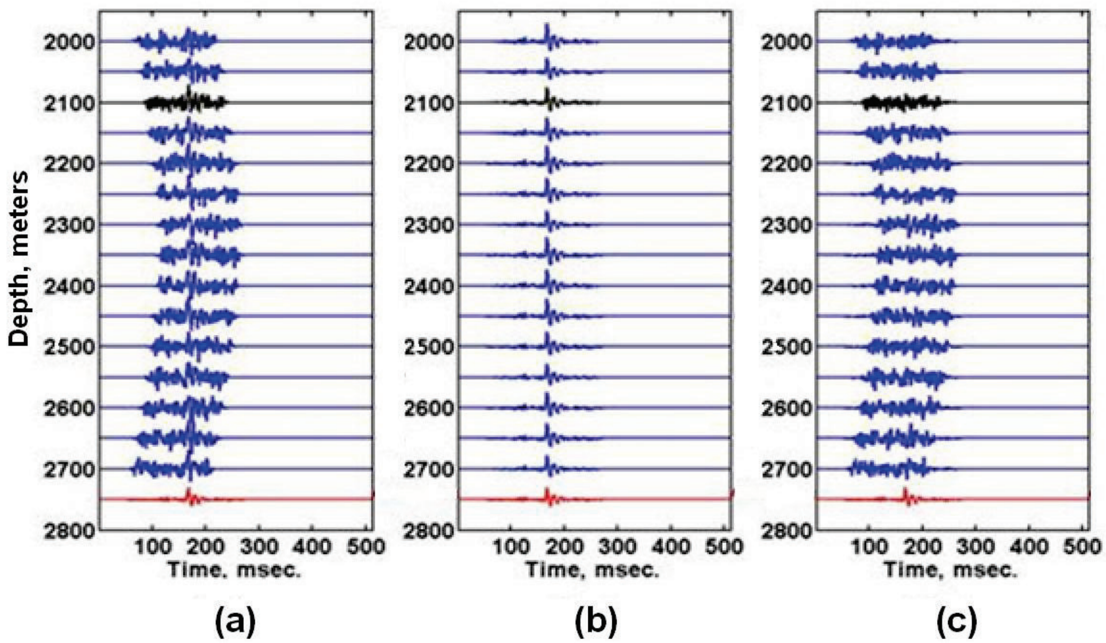


Fig.12: Noise-signal separation (NSS) for SNR≈1.5. (a) Original aligned seismograms; (b) noise-free signal components, and (c) Gaussian noise components.

SUMMARY AND CONCLUSIONS

Comparisons of the STA/LTA and MER time picking methods indicate that both techniques work well for microseismograms with good signal-to-noise ratios. However, when SNRs are 3.5 and lower, the MER method is more accurate and gives more consistent arrival times. For groups of very noisy seismograms with SNR as low as 1.5, windowing the traces in time is critical for picking reliable arrival times. The position and length of a suitable window are obtained by analyzing the arrival times from an initial application of MER picking. After windowing the raw traces, a second application of MER picking gives arrival times that are free of outliers caused by noise.

With reliable arrival times to use for aligning noisy microseismograms, trace averaging can be done to obtain a noise-reduced average trace from the group of windowed noisy traces. We tested two time-shift detection schema for trace alignment:

one using a minimum variance principle and one using the MER technique. Compared to the minimum variance technique (which breaks down at SNR levels below 3.5), the MER technique is more robust at low SNR values for determining arrival-time shifts.

Having obtained a noise-reduced average trace, we used it as the reference trace to perform noise-signal separation (NSS) on the raw seismograms in the group. This procedure separates each noisy seismogram into a (relatively) noise-free component and a random noise component. The procedure largely preserves the relative signal amplitudes of traces in the group to the extent that there is near-zero semblance of the average trace to the random noise components. Preservation of relative amplitudes is important for subsequent hypocenter location via hodogram analysis (Han et al., 2009, this volume).

ACKNOWLEDGEMENT

We express our gratitude to NSERC and the industrial sponsors of CREWES for supporting this research. The perforation shot field seismograms were provided by Talisman Energy Inc.

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