Automatic time-picking of first arrivals on noisy microseismic data

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ABSTRACT

Arrival time-picking is a critical step in the analysis of microseismic data, since hypocenter location requires the arrival times of direct P and/or S events. A passive-seismic monitoring system may record tens of thousands of microseismic traces while monitoring a hydraulic fracturing process, so a time-picking method that is fast, accurate, and automatic is highly desirable. We developed a time-picking scheme for individual traces based on a modified energy ratio (MER) attribute. Using both synthetic and field data, we compared its performance against the STA/LTA method commonly used in the microseismic analysis community. We found that both methods give essentially the same time picks on noise-free seismograms, but the MER yields more consistent first-arrival times on noisy microseismic traces. If there is sufficient moveout on the first arrivals recorded on a downhole or surface array of sensors (geophones or hydrophones), and if the velocity structure is known, hypocenter location can be done using the differences between the arrival times (the differences are independent of the unknown event time). We have developed a minimum variance technique for finding such time differences on sets of noisy seismograms.

STA/LTA RATIO

Let x_i be the times series representing a seismogram. Let the number of points in a short-term window be ns, and the number of points in a long-term window be nl, with nl > ns. Then the average energies in the short and long term windows preceding the time index i are

$$STA = \frac{1}{ns} \sum_{j=i-ns}^{i} \chi_{j}^{2}$$
, (short-term average) (1)

$$LTA = \frac{1}{nl} \sum_{j=i-nl}^{i} \chi_{j}^{2} \quad , \qquad (\text{long-term average}) \tag{2}$$

If $j \le 0$, set $x_j = (x_1 + x_2)/2$.

Then define:

$$r_i = \frac{STA}{LTA}$$
 . (STA/LTA ratio) (3a)

The STA/LTA ratio has been widely used for arrival time-picking. Form the numerical derivative of the ratio:

$$d_i = r_{i+1} - r_i, \quad i=1, 2, \dots, (N-1); \quad d_N = 0.$$
 (3b)

For noise-free seismograms, the maximum value of the numerical derivative of the STA/LTA ratio is close to the first-break time of the first arrival, as is shown on the left side of Figure 1.

MODIFIED ENERGY RATIO

Let x_i be the times series representing a seismogram with the time index i = 1, 2 ... N. Let the number of points in an energy window be *ne*. Then the ratio of energies in windows following and preceding the time index *i* is given by:

$$er = \sum_{j=i}^{i+ne} \chi_j^2 / \sum_{j=i-ne}^{i} \chi_j^2 \quad , \qquad \text{(energy ratio)}. \tag{4}$$

If $j \le 0$, set $x_j = (x_{1+} x_2)/2$. If j > N, set $x_j = (x_{N-1+} x_N)/2$.

$$er3_i = (abs (x_i)^* er)^3$$
, (modified energy ratio). (5)

The peak of the modified energy ratio (MER) $er3_i$ is very close to the first break on noise-free seismograms, as is shown on the left side of Figure 1.

For the results shown on Figures 1 to 4, we have set the STA and LTA energy window lengths at 10ms and 100ms, respectively, and the MER energy window length at 10ms. Since the sample rate on the seismograms is 0.25ms, we have ns=40, nl=400, and ne=40.



FIG. 1. First-arrival time picks using the STA/LTA ratio and the MER attribute on noise-free (left diagram) and noisy (right diagram) seismic traces. The STA/LTA picks are displayed as black vertical lines; the MER picks are displayed as red vertical lines. The noisy seismogram was created from the noise-free seismogram by adding random noise with maximum amplitude set to one-third times the maximum amplitude on the noise-free seismogram.

THE EFFECT OF NOISE

The right side of Figure shows how a high level of random noise affects the accuracy of the timepicking. For both the STA/LTA and MER methods, noise moves the time picks away from the first break towards later times where the coda has larger amplitudes.

On Figure 2, we show seismograms generated by a casing perforation shot and recorded with an array of twelve downhole 3C geophones spaced 11.75m apart. 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 using the MER algorithm. Very little noise exists preceding the first-arrivals, so the automatic picks are very close to the first breaks (a few of the vertical component traces have such weak first arrivals that a later part of the coda is picked).



FIG. 2. First-arrival time-picking using the modified energy ratio (MER) method on clean field seismograms. The time picks are the red triangles.

Figure 3 shows the same seismograms, but with synthetic random noise added. The maximum noise amplitude was set to one-third times the maximum amplitude on each noise-free trace. The MER first-arrival time picks, shown at the top, are later than for noise free-data, but are still very close to the first breaks. The STA/LTA time picks for noisy seismograms are shown at the bottom. For noisy data, the STA/LTA first-arrival time picks are less coherent spatially and somewhat later than the MER first-arrival picks.



FIG. 3. First-arrival time-picking on noisy field seismograms. Top: using the modified energy ratio (MER) method. Bottom: using the STA/LTA method. The signal-to-noise ratio (SNR) is about 3.

NOISE REDUCTION USING A MINIMUM VARAIANCE METHOD

If the waveforms of adjacent seismograms are similar, it is valid to use averaging to reduce noise and mitigate its adverse effect on automatic time-picking. Noise reduction by averaging adjacent seismograms leads to a significant improvement on picking accuracy. We use a minimumvariance principle to do trace averaging on normalized seismograms.



FIG. 4. Minimum variance averaging of three noisy traces (Rx1, Rx2, and Rx3) to create an average sum trace (shown in red) with increased SNR. For first-arrival time-picking with the MER or STA/LTA method, the sum trace can be used to replace any of the input traces and reversing the time shifts.

Consider for example the inline horizontal traces at three adjacent depths. Normalize them and apply a suitable window to isolate the first arrivals. The length and position of the window can be 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 Equations 6 and 7 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 $var(\Delta t_1, \Delta t_2)$:

$$m(t) = [Rx1(t + \Delta t_1) + Rx2(t + \Delta t_2) + Rx3(t)]/3 , \qquad (6)$$

$$var(\Delta t_1, \Delta t_2) = \sum_{t=0}^{tmax} \left\{ [m(t) - RxI(t + \Delta t_1)]^2 + [m(t) - Rx2(t + \Delta t_2)]^2 + [m(t) - Rx3(t)]^2 \right\}.$$
(7)

The variance is least when the windowed waveforms from the three receivers are in phase. The optimal average trace m(t) corresponding to the minimum variance is less noisy (has larger signal-to noise ratio) than the input traces, and can be used to replace the reference trace for

time-picking. This method of reducing noise is called minimum-variance averaging, or MVA. Figure 4 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., 2009). 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. Windowed traces immediately above and below and centered about a reference depth can be time-shifted and added to get an average trace (the trace at the reference depth is not shifted, and time shifts for the traces above and below can differ in both sign and magnitude). If one common trace is used as the reference, the time shifts relative to this single trace can be used for hypocenter location without knowing the microseismic event time.

CONCLUSION

We have developed a first-arrival time-picking algorithm based on a modified energy ratio (MER) attribute. It is simpler and faster than the widely-used STA/LTA method and the multiwindow algorithm described by Chen and Stewart (2005) and by Munro (2005). All three methods are effective at picking first-break times on low-noise seismograms. As random noise increases on a seismogram, the automatic first-arrival picks from all three methods move to later times to settle near the first large peak or trough following the first break.

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