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A robust method for microseismic event detection based on automatic phase pickers

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ABSTRACT

We present a robust method for the automatic detection and picking of microseismic events that consists of two steps. The first step provides accurate single-trace picks using three automatic phase pickers adapted from earthquake seismology. In the second step, a multi-channel strategy is implemented to associate (or not) the previous picks with actual microseismic signals by taking into account their expected alignment in all the available channels, thus reducing the false positive rate. As a result, the method provides the number of declared microseismic events, a confidence indicator associated with each of them, and the corresponding traveltime picks. Results using two field noisy data records demonstrate that the automatic detection and picking of microseismic events can be carried out with a relatively high confidence level and accuracy.

1. Introduction

Microseismicity studies have become an essential tool in nowadays oil reservoir geophysics (Kendall et al., 2011) and geological carbon dioxide (CO_2) storage (Oye et al., 2012; Verdon, 2011). In oil secondary recovery, high-pressure fluid injection is used to promote or to enhance the gas/oil production. This generates microfractures in the vicinity of the reservoir whose spatio-temporal distribution needs to be monitored for better controlling both the injection process and the development of the reservoir (Maxwell, 2011; Maxwell and Urbancic, 2001). In some cases, these processes require a real-time mapping of the microseisms' hypocenters, where efficiency and reliability are crucial for taking cost-effective decisions. Usually, both P- and S-waves arrival times and an approximate velocity model are needed to derive accurate hypocenter locations. Therefore, the automatic detection of microseisms and accurate picking of the associated traveltimes are of paramount importance for the monitoring of the induced hydraulic fracturing processes.

Microseismic monitoring is frequently carried out by placing triaxial-geophone arrays within one or more monitoring wells in the nearby of the extraction well. Thus, a few hours long continuous records are obtained in order to detect the occurrence of microfractures. Alternatively, when nearby wells are not available, geophone arrays may be placed along the surface. In the former case, the arrays typically consist of 8 to 12 geophones, and so the records consist of 24 to 36 channels, respectively. On the other hand, when using surface arrays, the number of receivers may be as large as several thousands (Duncan, 2012). Both scenarios give rise to large data volumes with low signal-to-noise ratios, specially when hypocenters are deep and distant from the monitoring array. One key issue that also explains the low signal quality is that microseisms induced by hydraulic injection are characterized by very small magnitudes (Shemeta and Anderson, 2010). Moreover, depending on the polarization pattern arriving to the receivers, the signal may be partially or totally masked by noise in one or two of the three components. Consequently, one of the main challenges when processing microseismic data is not only to automatically detect the actual microseismic signal arrivals precisely, but also to avoid the picking of false events.

Since microseisms caused by hydraulic fracturing are interpreted as "tiny" earthquakes, automatic phase pickers can be used to process microseismic data (Sabbione and Velis, 2012). In global seismology, the most common approach to detect the advent of a given phase is to compute certain attribute or "characteristic function" (CF), which is devised to enhance the signal changes, and calculate its average within two time-windows of different sizes: the short-term average (STA) and the long-term average (LTA). Then, an event is declared when the ratio between these two terms exceeds a given threshold value, giving rise to the so-called STA/LTA methods (Allen, 1982). The preceding approach has already been used to detect microseisms by different authors. Munro (2004) developed an algorithm in which the averaged attribute is the energy. Similarly, Chen and Stewart (2006) used a characteristic function based on the trace absolute values. Recently, Wong et al. (2009) presented the "modified energy ratio" method (MER), which is validated comparing it to a classical STA/LTA algorithm. The window scheme in the MER is similar to the one used by Earle and

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Shearer (1994) to detect earthquake phases, but the chosen attributes and criteria for selecting the window lengths are different. More recently, Vera-Rodriguez et al. (2011) presented a new method in which the time picks are obtained using blocky STA/LTA curves recovered from inversion with a sparsity constraint.

In this work we present a simple and robust technique to detect microseismic events and pick their arrival times automatically that works well even under noisy conditions. Our method consists of two steps and is applied to data collected at a monitor well. First, potential events and their corresponding traveltimes are determined based on three automatic phase pickers that proved to be specially adequate to process global seismology data (Sabbione, 2012). The time picks are obtained using either the Earle and Shearer's method (Earle and Shearer, 1994), or some modifications to the Allen's method (Allen, 1978) or the Baer and Kradolfer's method (Baer and Kradolfer, 1987). Secondly, a multi-trace strategy is proposed to declare a microseism (or not) based on number of the picks obtained in the previous step using a fixed-length (moving) search window. As a result, the number of declared microseisms, an indicator of the confidence associated with each of them, and the arrival times for those traces in which the microseism is detected are obtained automatically. The results using two field datasets show that the proposed method performs very well, providing accurate traveltimes and reliable detections with no false alarms.

In what follows, we first describe the theory and methods we propose to detect microseismic events and pick their arrival times automatically. In this sense, we present the three automatic phase picker algorithms used to scan each trace of the record looking for potential microseism arrivals. Also, the multi-trace approach devised to asses the presence (or not) of a microseism together with a confidence indicator are justified and depicted in order to complete the methodology description. Next, the proposed strategy is illustrated using two field data records with regular and poor signal-to-noise ratios, respectively. Then, we provide a discussion to interpret the results and point out the main contributions of our method. Finally, we enumerate the conclusions of this work.

2. Theory and methods

2.1. Trace-by-trace picking

The first step of the proposed approach is a trace-by-trace process based on one of the three automatic phase pickers: (1) the method presented by Earle and Shearer (1994), (2) the classical method introduced by Allen (1978), and (3) the method proposed by Baer and Kradolfer (1987). These algorithms were borrowed from earthquake seismology and were selected regarding its better performance compared to other autopickers (Sabbione, 2012). The three methods, together with the proposed modifications, are briefly described below.

2.1.1. Earle and Shearer's method (ESM)

In this method, the characteristic function is given by the envelope of the signal ES_i and is computed via

$$ES_i = \sqrt{s_i^2 + \tilde{s}_i^2}, \tag{1}$$

where s_i is the i-th sample of the signal (seismogram) and $\tilde{s}_i$ its Hilbert transform. Then, ES_i is averaged within two consecutive moving windows of lengths T_{STA} and T_{LTA}, respectively, with $T_{LTA} > T_{STA}$. Thus, the STA/LTA ratio is obtained by means of

$$\frac{\mathrm{STA}_i}{\mathrm{LTA}_i} = \frac{\frac{1}{N_{STA}}\sum_{j=i}^{i+N_{STA}-1} ES_j}{\frac{1}{N_{LTA}}\sum_{j=i-N_{LTA}}^{i-1} ES_j}, \tag{2}$$

where N_{STA} and N_{LTA} are the corresponding lengths of the non-overlapping windows.

To avoid rapid fluctuations that may lead to wrong picks, a low-pass Hanning filter is used to smooth the results. Finally, the events are declared when the smoothed STA/LTA ratio exceeds a given threshold *THR*, and the arrival times are picked at the inflection point that immediately precedes the maximum of the STA/LTA ratio. The Earle and Shearer's method is depicted in Fig. 1.

2.1.2. Modified Allen's method (MAM)

This STA/LTA method is based on the classical approach presented by Allen (1978), who proposed to calculate the characteristic function as

$$CF_i = s_i^2 + C_i(s_i - s_{i-1})^2, \tag{3}$$

with

$$C_i = \frac{\sum_{j=1}^{i} |s_j|}{\sum_{j=1}^{i} |s_j - s_{j-1}|}. \tag{4}$$

Note that C_i is a weighting factor that balances the two terms of CF_i: the first one related to the signal energy, and the second one to the signal frequency.

Next, we modify the classical Allen's method: in the MAM, we use the same window scheme as in the ESM (see Fig. 2b). Thus, the STA/LTA ratio is computed by replacing ES_j with CF_j into Eq. (2), and then it is assigned to the first sample of the window ahead in time. After smoothing the STA/LTA ratio using a Hanning filter, an event is declared when this smoothed ratio exceeds a given threshold *THR*. Finally, the arrival times are picked at the corresponding local maxima, as shown in Fig. 2c.

2.1.3. Modified Baer and Kradolfer's method (MBKM)

The method proposed by Baer and Kradolfer (1987) relies on an approximation of the envelope function E_i^2 given by:

$$E_i^2 = s_i^2 + \frac{\sum_{j=1}^{i} s_j^2}{\sum_{j=1}^{i} \left(s_j - s_{j-1}\right)^2}(s_i - s_{i-1})^2. \tag{5}$$

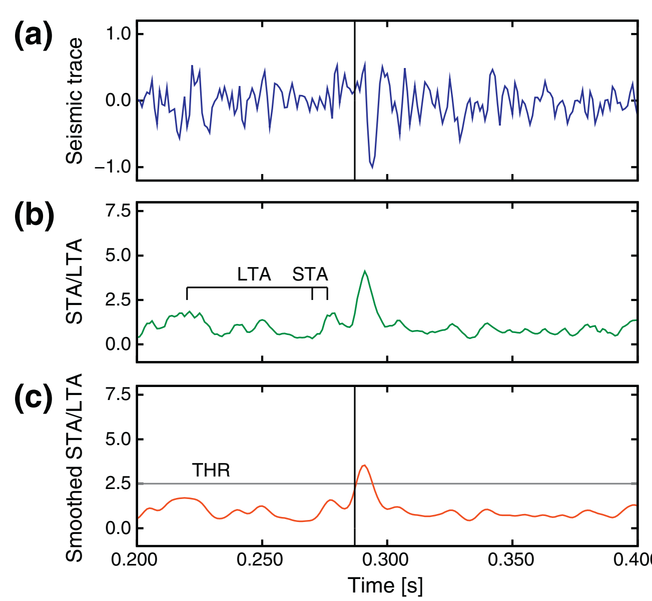

Fig. 1. ESM: (a) Normalized seismic trace and final pick (vertical line). (b) STA/LTA ratio and window scheme. (c) Smoothed STA/LTA ratio and final pick at the inflection point that precedes the maximum above THR.