Master event relocation of microseismic event using the subspace detector

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Summary

Microseismic events can be induced in hydrocarbon reservoirs due to human activities. Automated detection and location of these events is desirable in monitoring reservoir changes and revealing extent of fracture growth in real time. Most detection algorithms produce initial estimates of arrival times which sometimes contain large errors, degrading the accuracy of earthquake location procedures. The uncertainty associated with the estimated hypocenter locations can sometimes be larger than the source dimensions as a result, restricting the resolution of the seismicity image. We have developed an efficient method for reprocessing arrival time measurements using the subspace detector. Previously detected events are used to construct a signal subspace which represents similar but significantly variable microseismic signals. The basis waveforms comprising the subspace representation have improved signal-to-noise ratios permitting a more accurate definition of the absolute arrival time. These are then used to correct arrival time inconsistencies via cross correlation. A workflow for implementing this procedure from event detection to location is shown and tested on real data. We find the performance of the repicking method is comparable with manually picked arrival times and dependent on the signal-to-noise ratio of the basis waveforms.

Introduction

Activities such as fluid injection and wastewater disposal can cause an increase in pore pressure in the subsurface, which allow faults to slide under pre-existing shear stress (van der Elst et al., 2013). The resulting stress perturbations reactivates faults and opens or closes new fracture sets, resulting in the generation of microseismic events (De Meersman et al., 2009). Automated detection and location of these microseismic events is a valuable tool in monitoring reservoir changes. Finding the exact location of a seismic source is one of the most important tasks as it can reveal fracture geometry and progress of fluid fronts during production (Oye & Roth, 2003). Most microseismic events have low magnitudes and are usually contaminated by high amplitude noise. This tends to reduce the signal-to-noise ratio (SNR), reducing the accuracy of P and S waves arrival time picks (Song et al., 2014). Standard location techniques utilize arrival times and back azimuths across stations to determine event hypocenters and origin times. This is achieved by minimizing the sum of the difference between the predicted and observed parameters (arrival times and back azimuths). However, the effects of unmodeled velocity structure as well as the effects of limited source-receiver configuration and arrival time picking errors tend to decrease the accuracy of the event locations (Schaff et al., 2004; Pavlis, 1992). In this article we introduce an efficient means of repicking arrival times using the subspace detector. The subspace detector (Harris, 2006; Scharf & Friedlander, 1994) projects a sliding window of continuous data onto a vector subspace spanning a collection of signals expected from a particular source(s). The signals to be detected are modeled as a linear combination of orthogonal basis waveforms. One advantage of the subspace detector is the improvement in the SNR in the basis waveforms. Improvements in arrival time picks can then be obtained by cross correlation in a search region around our events with the basis waveforms. A workflow showing a practical implementation from event detection to repicking will be outlined, and the performance will be evaluated real life examples.

Theory

The standard method for obtaining phase arrival time picks involves visual inspection of the traces to determine onset times. Due to large data volumes and the subjectivity involved this method is usually inefficient, especially in real time monitoring. Numerous algorithms exist to this effect such as the short time average over long time average detector (Allen, 1978; Trnkoczy, 1999), autoregressive modeling (Sleeman and Van Eck, 1999) and correlation techniques (Molyneux and Schmitt, 1999; De Meersman et al., 2009). However, they are heavily influenced by the SNR conditions present. In this study correlation techniques are used as they can provide very high precision arrival time measurements. This is especially useful for correcting time picking inconsistencies between microseismic multiplets. A multiplet is defined as groups of more than 2 similar events which have separation distances of less than a quarter of the dominant wavelength (Geller & Mueller, 1980). If two microseismic events are highly similar, their time picks must be at the same position. The time lag corresponding to the maximum peak of the cross correlation function between both events can be used to correct inconsistencies in arrival time picks. De Meersman et al., 2009 use an iterative stacking procedure to improve arrival time picks across a receiver array. If there is little variation in signal between the stations, the stack is used to improve arrival time picks. This is due to the improvement in the signal to noise ratio allowing a more accurate definition of the absolute arrival time. In most cases, there is significant variation across the receiver array, making this technique non-feasible. An efficient means of repicking arrival times involves the subspace detector.

The subspace detector projects a sliding window of data onto a vector subspace spanning a collection of events expected from a particular source(s) (Harris, 2006). The projected data is a least-squares estimate of the signal in the detection window, and gives a measure of the linear dependence between the windowed data and the signals comprising the signal subspace. Construction of the signal subspace begins with detection of high signal-to-noise ratio events assumed to characterize the source(s) signals of interest. The waveforms are then clustered based on correlations between them, and the cluster of interest selected. The waveforms are then aligned and a singular value decomposition (SVD) is applied to the aligned set to obtain an orthonormal representation of the waveforms. A truncation of the orthonormal representation may be done such that signal energy is best represented while noise energy is minimized. The SVD tries to capture the essential features present in the data i.e. it contains information common to the template waveforms. The basis vectors obtained from the SVD represent the direction of the maximum variance possible. This usually results in a modest amount of noise reduction on the basis vectors and a subsequent improvement in their signal-to-noise ratio. Barrett & Beroza (2014) found the first basis vector closely approximates the stack, with the other singular vectors contributing the remaining information common to the templates within the design set in decreasing amounts. Thus it is possible to obtain more accurate estimate of the arrival times on these basis vectors. These can then be used to correct initial arrival time picks from detection by searching in a time window within the vicinity of the picks. The basis vector which corresponds to the highest peak correlation value with the windowed data is subsequently selected to correct the inconsistency in arrival time picks for a certain event.

Examples

Workflow

We analyze microseismic data that occur over a 2 day period during a hydraulic fracture treatment of 2 wells near Rimbey, in Alberta (Eaton et al., 2014). A total of 68 events were selected for analysis from an hour of data and used to test and demonstrate the performance of the repicking method. These events were located using 3 different subspace detectors. The first singular vector for the P-waves and the first two singular vectors for the S-waves are used in the repicking procedure. Figure 1 and 2 shows the workflow for implementing the repicking procedure using the singular vectors from singular value decomposition and an example of repicked arrival times for an event respectively.

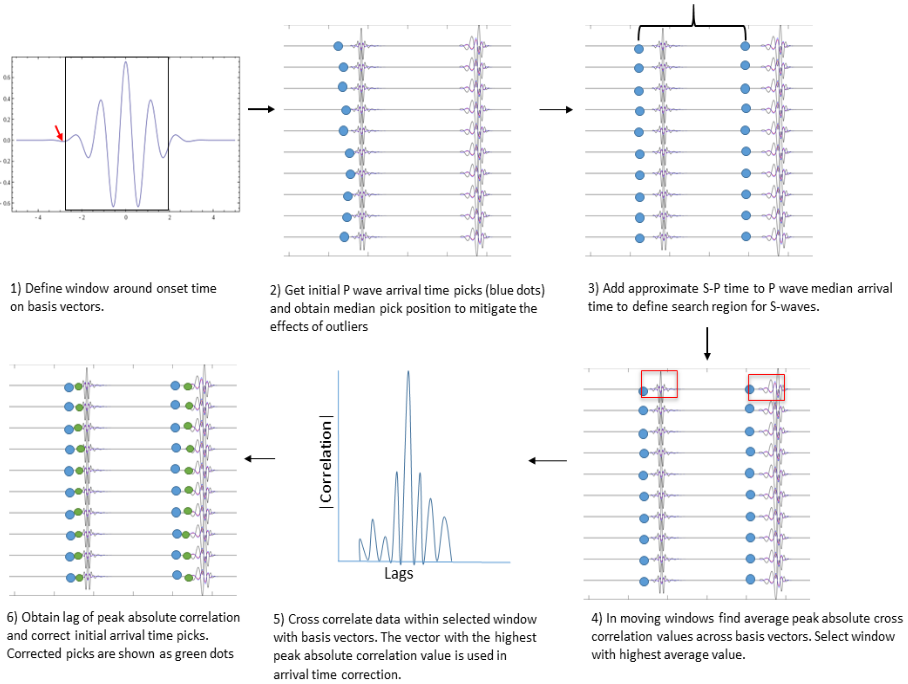

Figure 1: Workflow highlighting how initial arrival time picks are corrected using the basis vectors of the subspace detector. P and S wave vectors are utilized in this procedure.

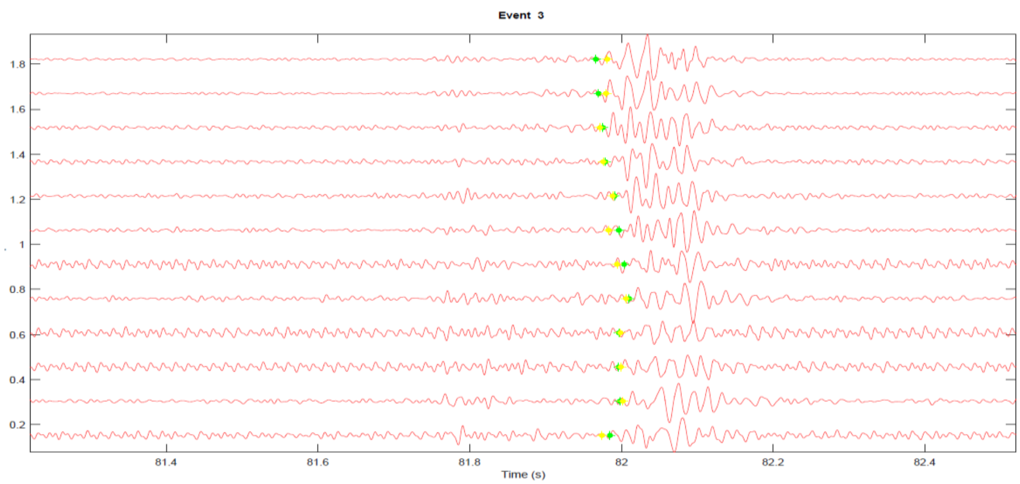

Figure 2: Vertical component of an event file highlighting the S-wave arrival. Manual arrival time picks (green dots) as well as subspace repicked arrival times (yellow dots) are shown.

<u>Absolute locations</u>

For events in a multiplet, it is assumed that the hypocentral separation between the 2 earthquakes is small compared to the event-station distance (Geller & Mueller, 1980; Waldhauser & Ellsworth, 2000). Therefore we can perform some quality control by comparing the average event distances obtained from both manually picked and repicked arrival times. We focus our analysis on the 2 largest groups containing 13 and 10 events respectively. We removed events which could not be located within our model space and the events with locations using both manual and repicked arrival times are shown in figure 3. The quality of the templates influences the accuracy to which the arrival time picks can be corrected. The SVD operation at the heart of the subspace detector captures variability present within the design set of waveforms to be described, and as such the basis vectors produced display high similarity with the source waveforms. The use of only one basis vector does not always guarantee a high correlation with the signals to be detected, therefore a search over the representative singular basis waveforms is more robust. Increased noise levels degrade the quality of the templates making it difficult to use higher number of basis or pick accurate starting positions on the basis waveforms. Our application of the repicking procedure revealed some key points. Comparing the locations obtained using repicked and manually picked times for the larger cluster, the locations obtained using the manually picked arrival times are more tightly clustered than those obtained from repicking. Most of the events in this cluster displayed higher correlations with the noisier basis vectors. The onset times for these vectors were harder to determine accurately and could have introduced bias in our estimates of arrival times. Correlation with noise could also have influenced the picking accuracy. However the locations are still reasonably close together. In contrast, the locations of events from the smaller cluster using the repicked time are more tightly clustered than those manually picked. All the events in this cluster had high correlation with basis vectors with high SNR which had more accurate onset picks. The closeness of the locations acts as quality control since we expect these events to be spatially close to each other.

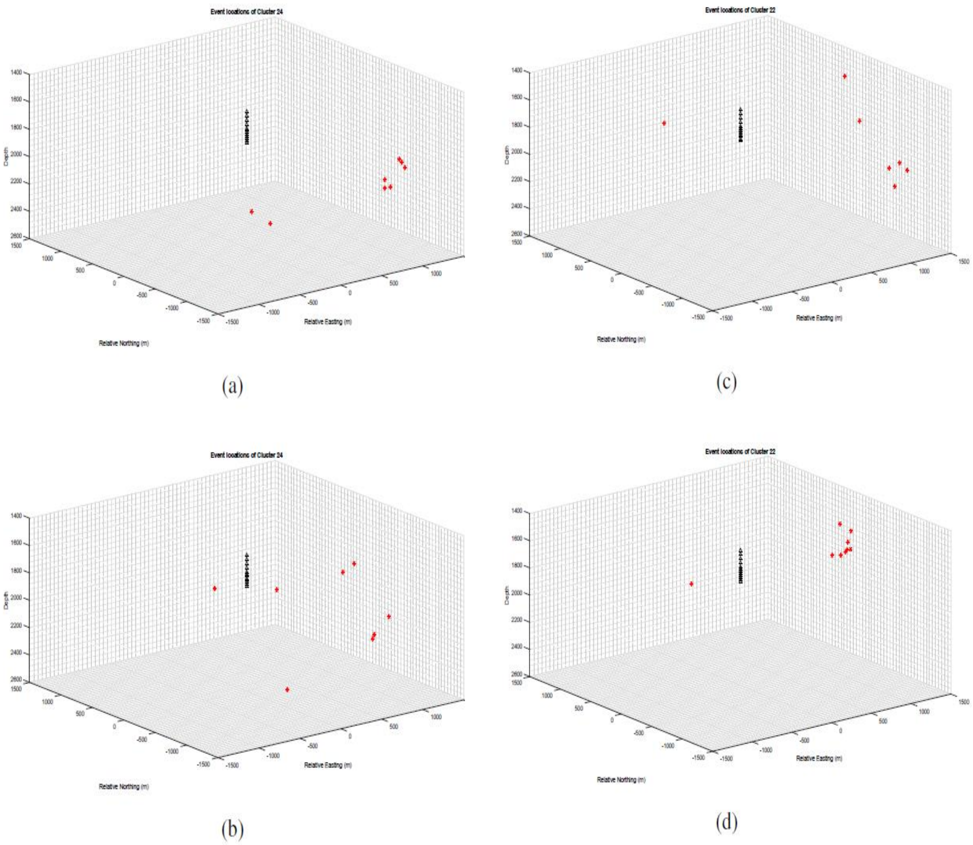

Figure 3: Hypocenter locations of events from 2 multi event clusters. Receivers shown as black triangles, and locations displayed as red stars (a) Manual picking locations for largest group (b) Repicked locations for largest group (c) Manual picking locations for second largest group (d) Repicked locations for second largest group

Conclusions

This study shows that is possible to accurately repick arrival times using the subspace detector, and this procedure can be implemented in an automated detection and location workflow. However, the accuracy of the picks are dependent on the noise levels of the signals used in detection and the ability to select the right starting window on our template waveforms. The use of a 1-D velocity model in our analysis of the real data set introduced some biases into our locations, and the poor station coverage increased uncertainty in azimuthal information. Nevertheless, the repicking procedure was still shown to perform quite well, revealing tight clusters of events for multiplet groups where accurate picking was possible, and performing reasonably well compared to manual picking.

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