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High-resolution automatic microseismic source detections

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Summary

Kirchhoff summation is one of the robust techniques to automatically scan for microseismic source locations. It does not require manual picking of P- and S-wave phase arrivals, but assumes the source location to have the largest stacked energy from all receivers. The energy focusing can be ambiguous if data have low signal-to-noise ratio or contaminations from undesirable phase arrivals such as scattered or converted waves. We propose a new high-resolution Kirchhoff summation to sharpen the focusing of the stacked energy objective function. This new approach divides the receiver array into a number of receiver groups. Each receiver group performs a conventional Kirchhoff summation (partial summation image) to improve the signal-to-noise ratio. The final stacked image is a multiplication of all partial summation images. Multiplication of partial images is the key to sharpen and to focus the stacked energy. We have successfully applied this new method on synthetic and microseismic field data and it outperforms conventional Kirchhoff summation by improving focusing and better differentiating overlapping or multiple events.

Introduction

Horizontal drilling and hydraulic fracturing are two key technologies to advance the economic successes of oil and gas recovery in unconventional reservoirs such as tight sandstones and shale. The process of hydraulic fracturing injects high-pressure fluids into a reservoir formation to create new fractures and to activate natural fracture sets. This process is accompanied by shear slippages of the rock equivalent to small earthquakes called microseismic events. The localization of microseismic events provides an indirect measurement of the changes in the stress field, the movements of the fluids, and the distribution of fractures. Microseismic monitoring has become a standard approach to image hydraulic fractures and to estimate the geometry of hydraulic fracture growth. Its success relies on the accurate detection and localization of microseismic events. Conventional source-location methods generally use explicit identifications of P- and S-wave arrivals on microseismic-event records. These measured arrival times are then compared to the theoretical arrival times from a volume of potential-grid locations. The grid point where the measured and theoretical arrival times best match is considered to be the best possible source location (Zimmer and Jin, 2011). However, the picking of accurate arrival times is very labor intensive, time consuming and can be difficult if the data have a low signal-to-noise ratio.

The shortcoming of the traditional approaches leads to an alternative class of event localization algorithms that do not require an *a priori* picking of the phase arrivals, but use the energy stacked along the theoretical arrival times to automatically scan for source locations in space and time (Baker, Granat and Clayton, 2005; Rentsch, Buske, and Shapiro, 2007; and Gharti, Oye, Roth, and Kühn, 2010). This

Kirchhoff summation is widely used to exploit the stacking power of waveforms to automatically search for event locations. The maximum stacked energy is considered the most probable event location. But this method can give ambiguous results when the data contains noise and undesirable interfering waveforms, and often fails to identify weaker events.

We propose a new high-resolution Kirchhoff summation to sharpen the focus of stacked energy. This approach divides the receivers into a number of groups. Each receiver group performs a conventional Kirchhoff summation to give a partial summation image. The final stacked image is the multiplication of all partial images. We apply this technique on synthetic and microseismic field data to demonstrate how it works to increase the resolution of detecting event locations.

Method

Kirchhoff summation is one of the robust techniques to automatically search for event locations. The basic concept is to sum a window of data along a given traveltime curve over all receivers to yield a stacked image:

$$I(x, y, z) = \sum_{j=1}^{N} \sum_{i=t1}^{t2} D_j(x, y, z, t(i)),$$

where I is a stacked image at a potential source grid with coordinates (x, y, z), t1 and t2 define a window of data in time with a Gaussian taper, and N is number of receivers. The source-radiation pattern can cause the amplitude cancellation during the stacking process. We use a Hilbert transform to convert the windowed data into energy envelopes to avoid the amplitude cancellation during stacking. This procedure is repeated for all grid points to generate a 3D stacked volume. The maximum stacked energy represents a most probable source location. Instead of selecting a maximum value, we allow to select a number of largest values for the consideration of other possible event locations in order to account for correlated noise or the arrival of other phases, e.g. reflected phases.

To better focus the stacked energy, we reformulate the conventional Kirchhoff summation into a new high-resolution Kirchhoff summation technique. The high-resolution Kirchhoff summation is:

$$I'(x, y, z) = \prod_{k=1}^{M} \sum_{j=1}^{NS} \sum_{i=t1}^{t2} D_j(x, y, z, t(i)),$$

where I' is a high-resolution stacked image at a potential source grid with coordinates (x, y, z), NS is number of receivers in each group, and M is number of receiver groups. The keys of this approach are: partial summation improves signal-to-noise ratio and the multiplication of all partial images increases the focusing of stacked energy. This method relies on the signal being visible in each receiver group. If a signal is not visible in any one of the receiver group the multiplication result will be small. The fewer receivers the individual groups contain, the better the focusing power of the stacked function. But each group has to be large enough to give a reasonable partial image.

Synthetic examples

The synthetic model consists of five vertical observational wells with two sources close to each other. The spatial separation between the two sources is 100 ft. A finite-difference modeling using a 1D velocity model was used to generate the synthetic data. We considered three cases to evaluate the effectiveness of the high-resolution versus conventional Kirchhoff summation: 1) data set from first source; 2) data set from second source; 3) a combination of previous two data sets in which the data set from second source had a 0.15 s delay from the first data set.

The P-wave direct arrivals on microseismic events from first source were well defined and had good and clear signals (Figure 1). The strong amplitudes of the converted waves interfered with S-wave arrivals. These interfering waves can degrade the S-wave stacking energy. The conventional Kirchhoff summation produces an approximate source location with considerable spatial smearing (Figure 2), but the high-resolution Kirchhoff summation yielded a well-focused correct source location without any visible spatial smearing. We repeated the same analysis on the data from the second source, and obtained a similar conclusion as the previous example. Case 3 contains both data sets (Figure 3). The objective of these combined data sets is to examine how well both summation methods can distinguish between two sources that are only 100 feet apart. The conventional summation appeared to have two distinctive source locations, but one source location deviated considerably from the true source location (Figure 4). On the other hand, the high-resolution summation produced two distinct source locations that correspond closely to the true locations. The synthetic examples demonstrate that high-resolution summation outperforms conventional summation, and produces more accurate and stable solution.

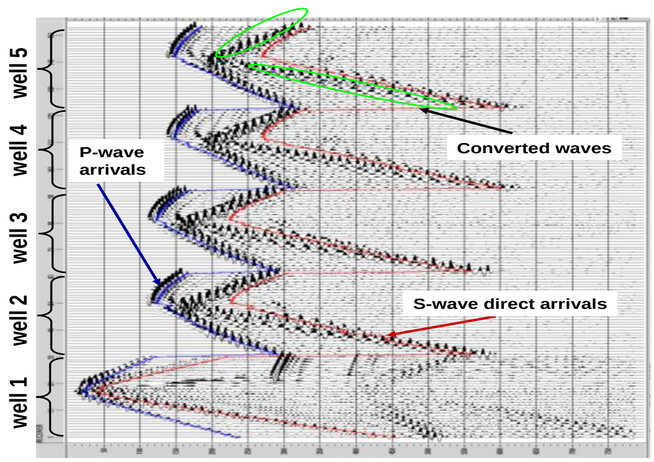

Figure 1 Synthetic data from the first source, showing P- and S-wave direct arrivals as well as converted waves.

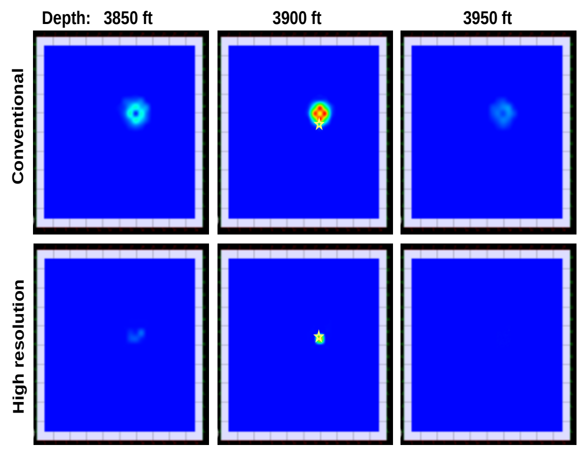

Figure 2. Comparison of stacked images from the first source between convention and high-resolution Kirchhoff summation methods. Star symbol is the theoretical source location.

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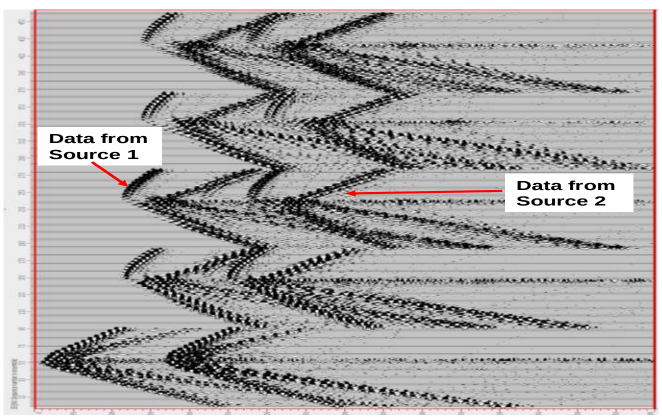

Figure 3. Combination of data sets from the first and second sources in which the data set from the second source had a 0.15 s delay from the first data set.

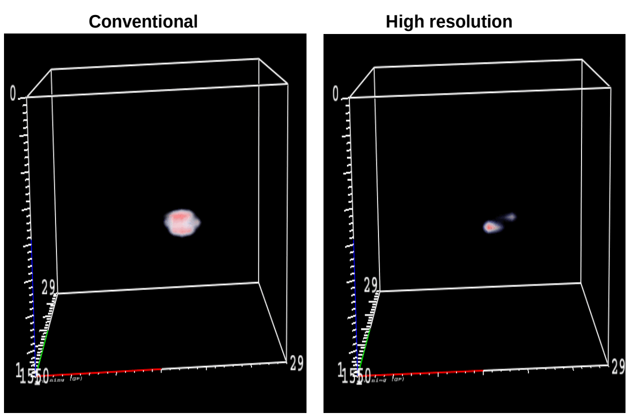

Figure 4. Comparison of 3D stacked volumes from the combined data sets between convention and high-resolution Kirchhoff summation methods.

Field example

The microseismic survey consisted of two vertical observation wells and one horizontal treatment well. Each observation well had 40-receiver levels. We analyzed two field event records with a 10 s data length. Although the two observation wells had similar distances from the treatment location, the event records showed different signal contents. The P- and S-wave arrivals recorded from well 1 had much weaker amplitudes than data from well 2 (Figure 5). The conventional summation tends to produce a cloud of maxima in the objective function that makes it challenging to identify the correct location (Figure 6), but the high-resolution summation yields a well-focused stacked image to give more confidence in the identification of the source location. For the second field example, the data recorded from well 1 were extremely noisy (Figure 7). The analyses only used the data from well 2. There were two distinct events visible in the field records. The first event has much weaker amplitudes than the second event. The stacked image from the conventional summation only indicated a possible source location corresponding to the strongest-amplitude event, but missed the weaker event (Figure 8). In contrast, the high-resolution summation captured both source locations. The field examples further confirms that high-resolution summation is a more preferable method to be used for automatically source locations.

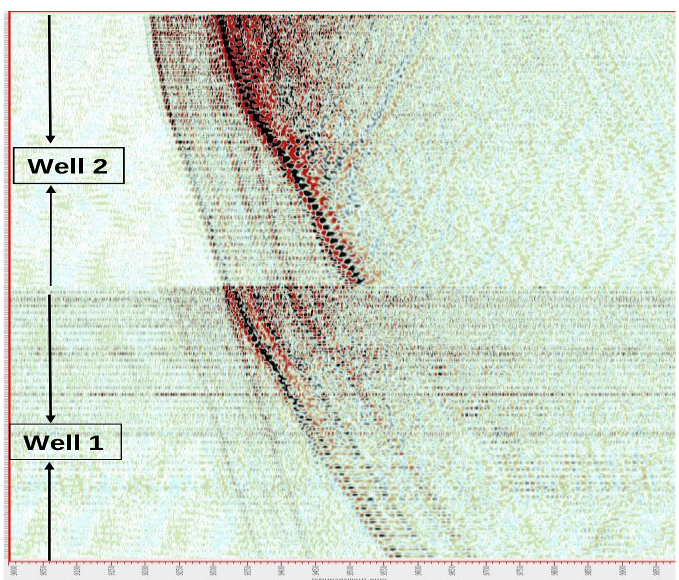

Figure 5. First example of mircoseismic field data recorded by receivers in two observational wells. The event records have a 10 s data length.

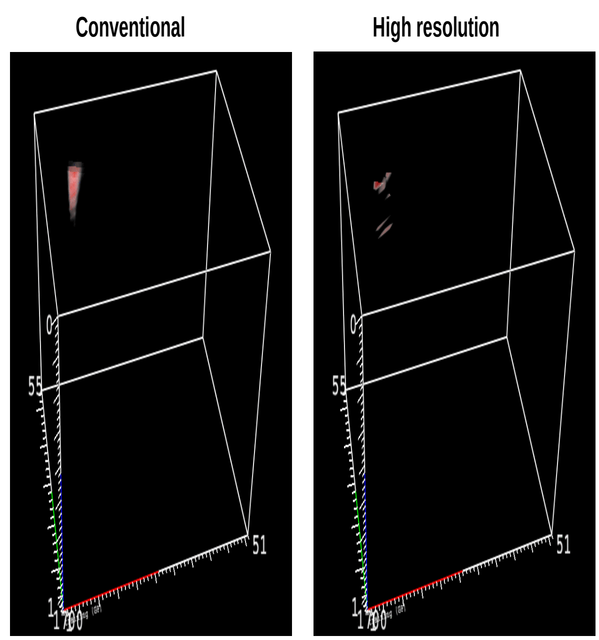

Figure 6. Comparison of 3D stacked volumes from the first field example between convention and high-resolution Kirchhoff summation methods.

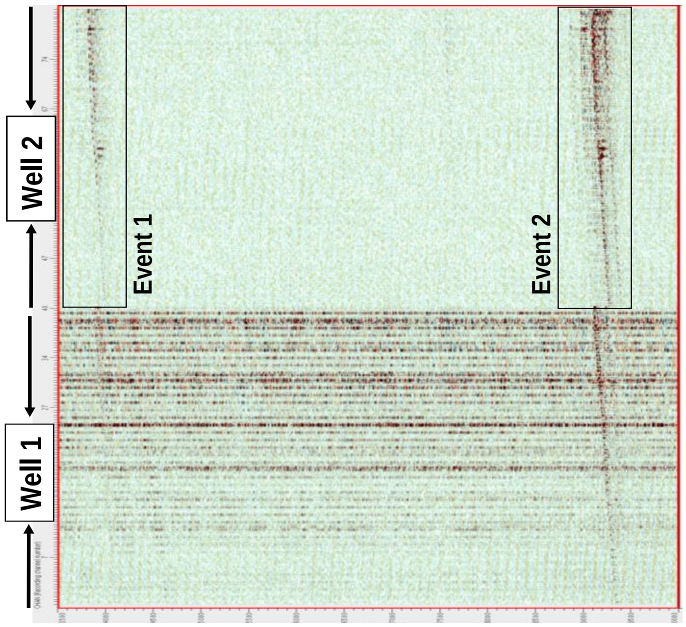

Figure 7. Second example of mircoseismic field data recorded by receivers in two observational wells. The event records have a 10 s data length. Two distinct events are visible on the records.

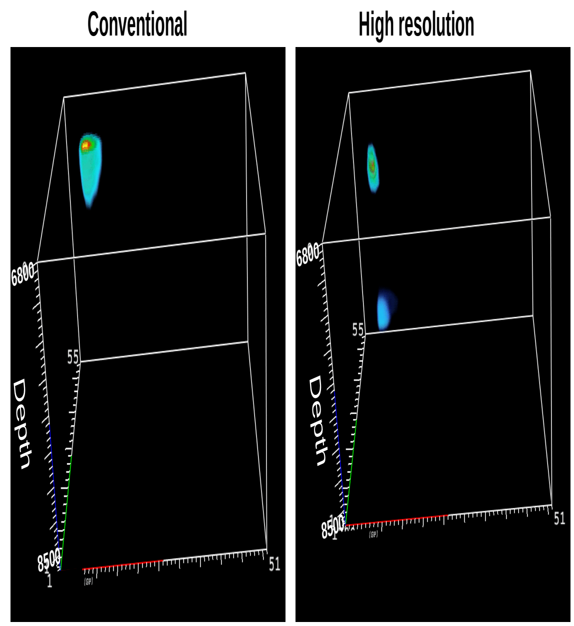

Figure 8. Comparison of 3D stacked volumes from the second field example between convention and high-resolution Kirchhoff summation methods.

Conclusions

The applications of the high-resolution Kirchhoff summation on synthetic and field data clearly demonstrate its effectiveness to give more accurate source locations with minimum spatial smearing when compared with convention summation. In addition, high-resolution summation can handle both strong and weak event records while convention summation misses the weak event. This new approach should provide a more accurate tool to perform automatically source localizations.

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