Double difference method for locating microseismic events from a single well

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Summary

The double difference (DD) inversion method has long been applied for locating a cluster of earthquakes, using data recorded at surface seismic stations. We implement a particular DD method for locating a cluster of microseismic events with data from a single well. We assume a 1-D velocity model and a vertical monitoring well, thus projecting all events to a 2D profile. Event azimuth solutions are determined from separate analysis of initial P wave polarizations. Synthetic tests suggest that a DD method using data from a single well can constrain event depth better than a localization method based on absolute traveltimes. Our input data includes the difference between events of P or S traveltimes (like the traditional DD method). However, the inversion results seem sensitive to initial event locations, and the lateral location resolution is poor. When we also include the S-P traveltime differences for each event into the inversion, the lateral resolution improves. In addition, this reduces the dependence on the initial guess for the event locations and the velocity model.

Introduction

Microseismic monitoring, since the initial idea in the 1970s and its commercialization around 2000, has proven to be a vital tool for understanding underground processes (Warpinski et al., 2009). It plays an important role in hydraulic monitoring, water-flooding, and many other production methods. Microseismic location methods include, for example, grid searches and migration-based imaging methods (Rodi et al., 2006; Reshetnikov et al., 2010). Several factors affect the accuracy of the determined locations; such as uncertainty in the velocity model and uncertainty in traveltime picks.

In earthquake seismology, the double difference (DD) inversion method has been developed to reduce the effect of a poorly known velocity model (Waldhauser and Ellsworth, 2000). It requires arrival time picks from multiple events and infers accurate relative locations for the group. One assumption is that the hypocenter separation between two earthquakes is small, with respect to the distance between the event and the recording station. The hypocenter separation should also be small with respect to the scale length of the velocity heterogeneities. Zhang et al. (2006) propose a DD tomography method using both absolute and relative arrival times for surface data.

Recently, the DD method has been used to determine microseismic locations (Fernando et al., 2013). DD methods have the advantages of a high precision of relative arrival times by using a cross-correlation method. Obtaining the absolute event locations using a grid search method is always the first step. The second step is to compute cross-correlations to obtain the relative arrival times between any pair of two events. Finally, the DD method is used to obtain highly accurate relative event locations. However, the assumptions for DD break if the event cluster distribution is larger than the distance to (Mukhtarov et al., 2012). Li et al. (2012) developed an extended DD tomographic method using an anisotropic tomography. In this study, we explore the issues associated with monitoring microseismic events using an improved microseismic DD method (including the S-P traveltime differences) for data from a single well.

Theory

1. *Traditional double-difference method*

The traditional DD method is an earthquake location method, and it is developed for obtaining the relative location of hypocenters (Waldhauser and Ellsworth, 2000). The relationship between event locations and traveltimes is highly nonlinear. After using a truncated Taylor expansion to linearize this relationship, the residuals are linearly related to the perturbations of parameters. We combine all event pairs for all receivers to form a system of linear equations of the following form：

$$G_{pp}\Delta m = d\ , \tag{1}$$

Where G_{pp} is the sensitivity matrix containing the partial derivatives of P-wave differential arrival times with respect to the model parameters. This matrix has dimensions: $n(n-1)/2*mr*3n$, (where n is the event numbers, mr is the receiver numbers). The dimension of the d vector is $n(n-1)/2*mr$, and Δm is a vector of length $3n$, containing the changes of location parameters (Δx, Δz, $\Delta\tau$).

There are several issues when we apply DD on data recorded in a single well. If we attempt to locate an event recorded by one station, by fitting the relative arrival times of two events. The event locations could be on a series of concentric circles with the radius at the distance between source and receiver (see Figure 1b). If we attempt to locate an event recorded by three stations, by fitting the relative arrival times of two events. There are three sets of such concentric circles (isochronous surfaces). The true events' locations must be at the intersection of the three circles. If the distance between the array and the events' true locations increases, the curvature of the concentric circles intersection will decrease. This results in an increasing uncertainty of the horizontal absolute locations. This problem is eliminated when we use more then one well.

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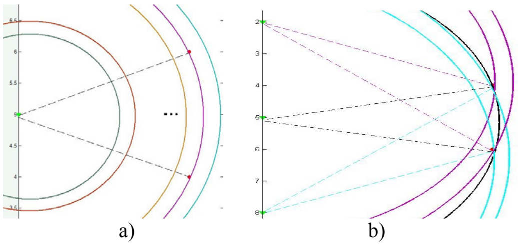

a) b)

Figure 1: Single well monitoring geometry, green triangles indicate the receivers and the red stars indicate the sources. a) Two events recorded by only one receiver, the event locations could be on concentric circles. b) Two events recorded by 3 receivers, the events are located at the intersection of the concentric circles.

2. *Microseismic double-difference method*

The traditional DD method (Waldhauser and Ellsworth, 2000) utilizes the relative P-wave or/and S-wave traveltime information. Zhang and Thurber (2006) proposed the DD tomography method by adding the absolute arrival times.

We propose to include the P- and S-wave differential arrival time between for each event. This has several advantages. Firstly, the P- and S-wave differential arrival time adds information on the absolute event's locations. Secondly, the P- and S-wave differential arrival eliminates the dependency on the unknown event origin times. The differential arrival times can be added into equation (1), we find the following system of linear equations:

$$\begin{bmatrix} G_{pp} \\ G_{ss} \\ G_p - G_s \end{bmatrix} [\Delta m] = [d] \quad . \tag{2}$$

Where G_{ss} is the sensitivity matrix containing the partial derivatives of S-wave differential arrival times with respect to the model parameters (with dimensions: $n(n-1)/2*mr*3n$). And G_p-G_s is the sensitivity matrix containing the partial derivatives of P- and S-wave differential arrival times with respect to the model parameters (with dimensions $n*mr$).

The vertical and horizontal location uncertainty

The location with absolute arrival times has the drawback that the uncertainty of the vertical location is higher than in horizontal location (Zimmer, et al. 2011). We compare the accuracy of a conventional absolute localization method (Geiger, 1910) and the traditional DD method by plotting the traveltime misfits of both methods (see Figure 2). In the DD misfit figure, we let the distance between two events be a constant and each grid point represents the average residual. At the minimum residual we find the optimum location for the two events. Figure 2 shows that the absolute location method has a bad vertical resolution while the traditional DD method has a high vertical resolution.

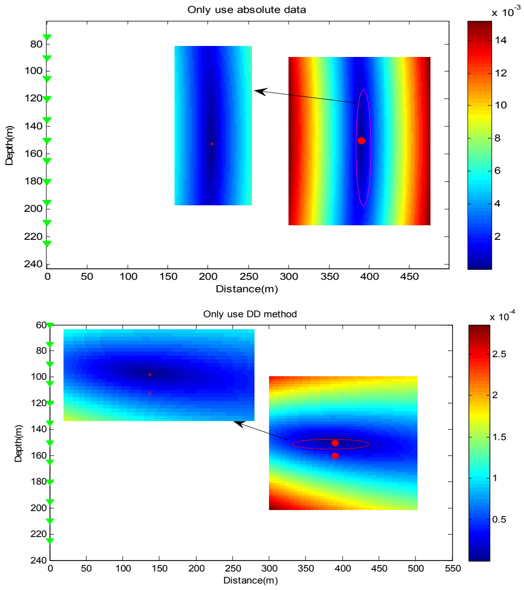


Figure 2: Top panel; the traveltime residuals of the absolute location method; Bottom panel; the residuals of the traditional DD method. Red points indicate the true locations and green triangles indicate the receivers.

Figure 3 shows the geometry of our monitoring system with a single well. We design a four layer horizontal velocity model, where the second layer is a low velocity layer. There are 10 receivers in the borehole with 15 meter receiver spacing, and there are 4 sources. The dataset of traveltimes from each event to each receiver is computed using a ray tracing code.

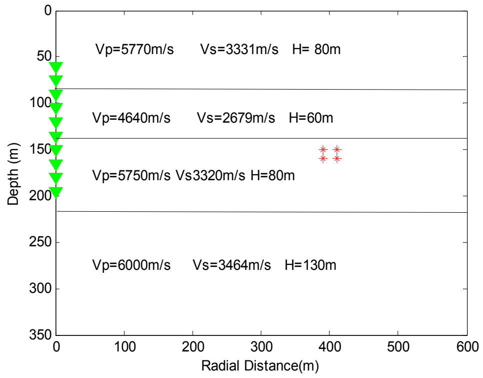
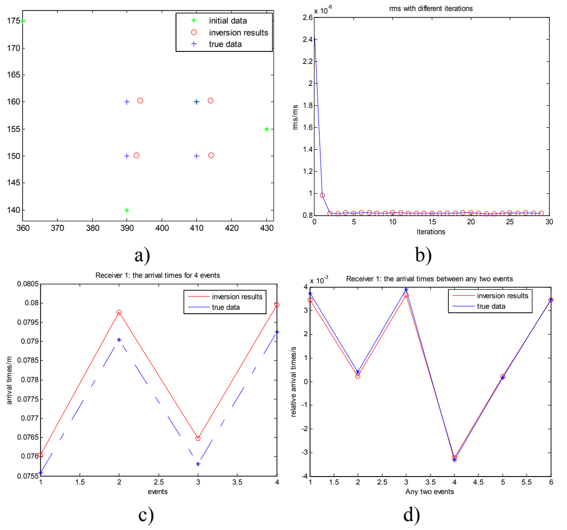


Figure 3: Velocity model and acquisition geometry with 4 test events (red stars) and a shallow geophone array with 10 receivers (green triangles).

We use the traditional DD method to determine the locations. Figure 4a and 4b shows that we retrieve the vertical position well, but do not find the correct horizontal position. In order to understand this result, lets take the first receiver as an example: As shown in Figure 4c and 4d, for each receiver the calculated arrival times using the determined locations are similar to the calculated arrival times using the true locations. We compare the relative arrival times for any pair of two events; they approximate overlap.



a) b) c) d)

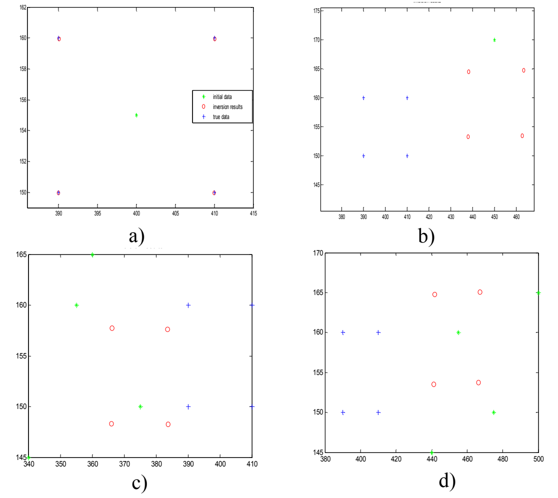
Figure 4: a) the located events with traditional DD method, include the true locations (blue plus), initial event locations (green stars) and the determined locations (red circles). Note that in the vertical direction we have better location accuracy than on the horizontal direction; b) RMS misfit as a function of iteration; c) the arrival times for 4 events at the first receiver, the red line indicates the inversion results and the blue dotted line indicates the true values; d) the relative arrival times for any pair of two events.

The initial location of the center of the event cluster

Figure 5 demonstrates that the center value of the initial event location is very important. We can obtain better location results when the center of the initial event location is close to the correct value. Table 1 shows the center of the event cluster before and after event localization.

	Before location		*After location*	
Model	X/m	Z /m	X /m	Z /m
true data	400.000	155.000	400.000	155.000
(a) model	400.000	155.000	400.029	154.948
(b) model	450.000	170.000	450.604	159.005
(c) model	357.500	155.000	374.924	152.971
(d) model	467.500	155.000	454.186	159.301

Table 1: Location results with different initial events centers.



a) b) c) d)

Figure 5: Location results with different initial event locations: a) the initial event center is same as with the true values; b), c) and d) the initial event center is far away from the true value.

DD method tests in different microseismic monitoring scenarios

We design a few different microseismic monitoring scenarios; including two kinds of geophone arrays and four groups of events (see Figure 6). From the results of determining locations, we can conclude that if the event depth is deeper than the receivers, the location accuracy will deteriorate.

1. *Adding the differential S-P arrival times*

In tests presented in Figure 6, it is obvious that the traditional DD method has the weaknesses that it relies heavily on an initial event location. In an attempt to mitigate this weakness, we use the microseismic DD location method with the addition of the differential S-P arrival times. Figure 7 show that this improved microseismic DD method can obtain better accurate locations than traditional DD method in both horizontal and vertical directions.

2. *The effect of noise and velocity model uncertainty*

Field data always contains noise, such as the arrival time picking errors and receiver interferences. In order to simulate the picking errors, we add a random noise level of about 0.2 ms to the relative arrival times, and add a random noise level of about 2 ms to the absolute arrival times (Figure 8a). In addition, we test the consequence of an inaccurate velocity model (Figure 8b). Results shows that our improved microseismic DD method can perform well in the presence of noise and velocity model inaccuracities.

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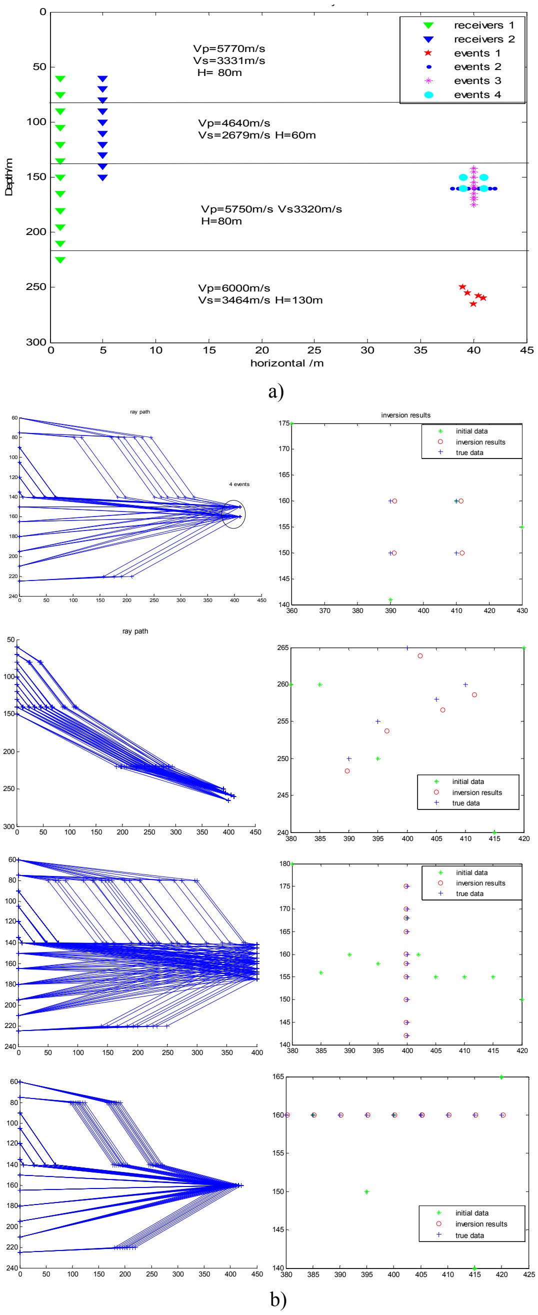
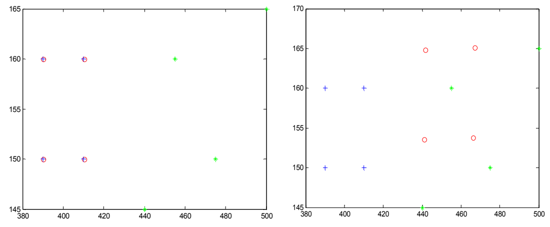


a)

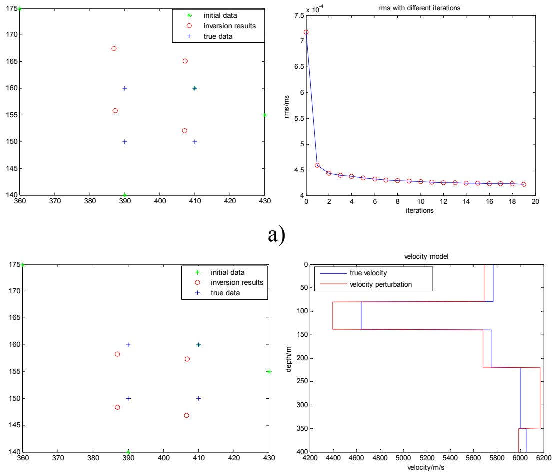
b)

Figure 6: a) Different observation systems; blue triangles indicates 10 receivers with a 10m interval and green triangles indicates 12 receivers with a 15m interval. The receiver 1 is for the event 2,3 and 4, while the receiver 2 is for event 1. b) The ray paths and the results of determining the locations using the traditional DD method, for the four models.



a) b)

Figure 7: The located events before (b) and after (a) adding the differential S-P travel times. Note the results are good even if the initial event center is far away from the true value.



a)

b)

Figure 8: The located events with the microseismic DD method; a) the velocity model is accuracy, and add the random noise to arrival times; b) the located events with the inaccurate velocity model and correct arrival times.

Conclusions

We test the feasibility of using the traditional DD method to locate microseismic events from a single well. It has high resolution in the vertical direction compared to absolute location methods. Nevertheless, the initial event locations have strong influence on the localization results. In order to solve this problem we add the differential S-P arrival times. Numerical experiments show that the microseismic DD method can provide a better location results. In addition, the method is able to handle noise and velocity model inaccuracies.

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EDITED REFERENCES

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