Post-processing technique to Relocate Microseismic Events using the Double-Difference Method

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Summary

In this work we describe a post-processing technique to relocate microseismic events based on the double-difference method. First, we use a crosscorrelation technique to assess waveform similarity between events and identify multiplet groups. Then, we correct relative arrival time inconsistencies between doublets. Next we apply the double-difference (DD) algorithm, which is a relative location method that tries to minimize the residuals between observed and calculated travel-time differences for pairs of microseismic events at each station, done by iteratively adjusting the differences between all pairs of events in each multiplet group. This technique is applied to a microseismic data set from the mining industry. Results of DD are shown for one major multiplet group of microseismic events, where it collapses the diffuse locations into a sharper image of seismicity that is most likely related to shaft activities. We also show plots that reveal time picks and location uncertainties for quality control purposes.

Introduction

Microseismic events can be induced by human activity (e.g. oil and mining extraction) due to changes in stress distribution. Although microseismic events can potentially occur anywhere, in most cases, they tend to re-rupture in the same zone. These repeating events, called multiplets, have similar waveforms since they come from the same region. Moreover, finding the event locations, one of the main objectives of basic microseismic monitoring, is mainly affected by several factors: a limited source-receiver configuration, errors in time picks and in the velocity model used, which is usually 1-D and cannot exactly represent the true velocities of the Earth (Pavlis, 1992). To reduce the effect of these errors, we apply a post-processing workflow that seeks to reduce the effects of both time picking errors and unanticipated velocity models to a data set of microseismic events from the mining industry by (i) identifying repeating events or multiplets, (ii) Repicking of doublets through crosscorrelation, and (iii) applying a relocation procedure based on the double-difference method (DD).

Theory and/or Method

Event similarity

In this work we use a technique to identify microseismic doublets (Arrowsmith and Eisner, 2006). The main assumption is that events originated in the same source region will be highly correlated since they exhibit very similar waveforms. For that reason, we crosscorrelate all events with each other, and define a doublet as two microseismic events that are highly correlated, and a multiplet as more than two highly correlated microseismic events (see Figure 1). Filtering must be applied beforehand to attenuate noise that might affect crosscorrelation values.

After calculating crosscorrelation coefficients for all event pairs, we generate an *NxN* crosscorrelation coefficient upper triangular matrix, where *N* is the number of events (Figure 2). Then, we choose a minimum crosscorrelation level as unique criteria to define if two events are considered doublet. We allow the events to be grouped in a chain-like fashion, so they can belong to the same multiplet group even if there is limited mutual similarity among all event pairs. The double definition is highly subjective, for that reason, we should a common value of 0.8 as threshold for doublet detection.

P-wave Repicking

Errors in time picks add uncertainty in the event locations; therefore, we take advantage of the similarity between doublets to improve relative arrival time readings through crosscorrelation. If two microseismic events are highly similar, their corresponding time picks should be at the same position. This P-wave pick refinement consists of extracting two time windows that encompass both P-wave phases and perform crosscorrelation. Then, the time lag corresponding to the maximum peak of the crosscorrelation function represents the lag that needs to be corrected to remove any inconsistency in the picks. This is done in all three components and weighted by each crosscorrelation value (Figure 3).

Double-Difference Method

Once the multiplet groups are detected, we apply the double-difference method (DD), which is a relative relocation method that seeks to reduce the effects of errors due to unanticipated velocity heterogeneities in the structure (Waldhauser and Ellsworth, 2000). The main assumption in the DD method is that ray paths between two events will be very similar if their hypocentral separation is small compared to the source-receiver distances; therefore, relative travel-time difference at a common station will be proportional to the spatial offset between both events. In other words, the effects of most velocity heterogeneities will cancel out, such that only knowledge of the velocities in the source region is required.

For two events *i* and *j*, recorded at a station *k*:

$$(t_k^i - t_k^j)^{obs} - \left(t_k^i - t_k^j\right)^{cal} = \frac{\partial t_k^i}{\partial x}\Delta x^i + \frac{\partial t_k^i}{\partial y}\Delta y^i + \frac{\partial t_k^i}{\partial z}\Delta z^i + \Delta t^i - \frac{\partial t_k^j}{\partial x}\Delta x^j - \frac{\partial t_k^j}{\partial y}\Delta y^j - \frac{\partial t_k^j}{\partial z}\Delta z^j - \Delta t^j . \qquad (1)$$

Where $(t_k^i - t_k^j)^{obs} - \left(t_k^i - t_k^j\right)^{cal}$ is double-difference residual, $\left(\frac{\partial t_k^i}{\partial x}, \frac{\partial t_k^i}{\partial y}, \frac{\partial t_k^i}{\partial z}, 1\right)$ and $\left(\frac{\partial t_k^j}{\partial x}, \frac{\partial t_k^j}{\partial y}, \frac{\partial t_k^j}{\partial z}, 1\right)$ the respective partial derivatives with respect to the model parameters and $(\Delta x^i, \Delta y^i, \Delta z^i, \Delta t^i, \Delta x^j, \Delta y^j, \Delta z^j, \Delta t^j)$ are the eight unknown changes in the hypocentral parameters or perturbations we need to determine to better fit the data. For all event pairs and all stations, a system of linear equations is set. Due to different orders of magnitude between source location parameters and origin time, the system becomes unstable. Hence, we scale the partial derivative matrix by normalizing the L2-norm of each column so numerical stability is assured. In the double-difference algorithm, the weighting scheme plays an important role since it gives more importance to observations involving similar events and less importance to uncorrelated or distant events. Here, for events closed together, e.g., within a multiplet group, the square of the crosscorrelation coefficient is used to weight each event pair, so that more importance is given to highly correlated events. Whereas for farther apart events, we can use a biexponential function dependent on source separations (Waldhauser and Ellsworth, 2000). Figure 5 show the results after DD is applied in one multiplet group, where we observe a collapse of events whose locations are related to activities in the main shaft of the mine.

In Figure 6 we observe event pairs having a correlation level higher than 0.8 and large separation distances. Note that after relocation, most doublets separated by larger distances have been collapsed to shorter distances. There are still some event pairs which have larger distances after relocation, which might be due to poor event linking; hence, their correlation level is below 0.8. Thus, this plot can be used for quality control purposes.

Examples

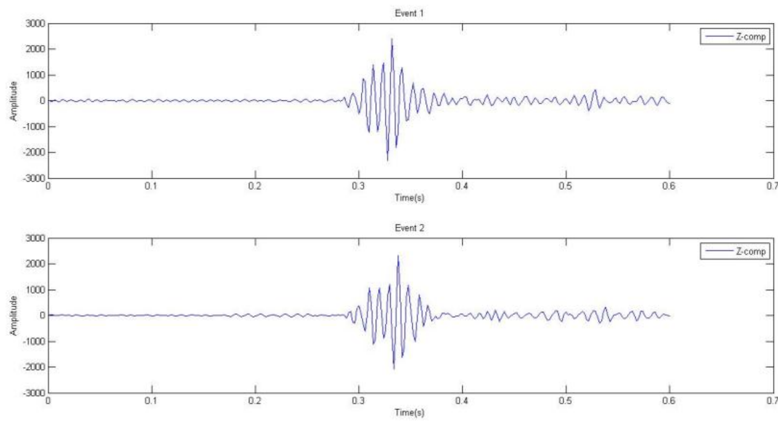


Figure 1: Vertical component of two highly similar microseismic events. This pair is 90% similar.

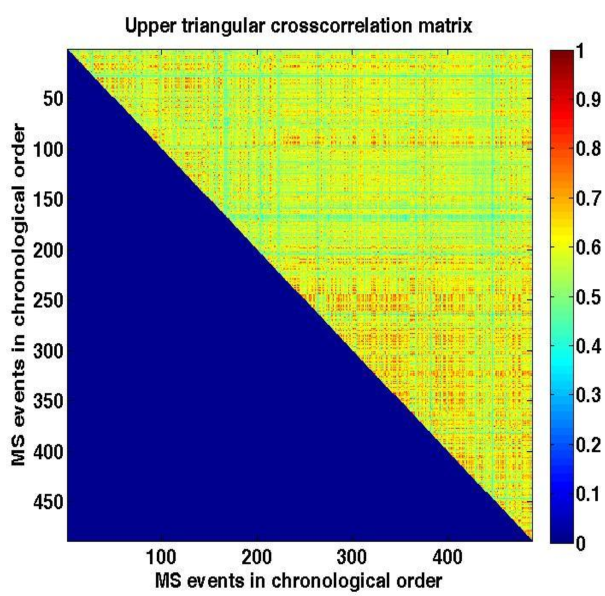


Figure 2. Upper triangular crosscorrelation matrix. Each cell gives the crosscorrelation coefficient between any pair of events. A cell is blue for crosscorrelation coefficient of zero and red for crosscorrelation coefficient of one.

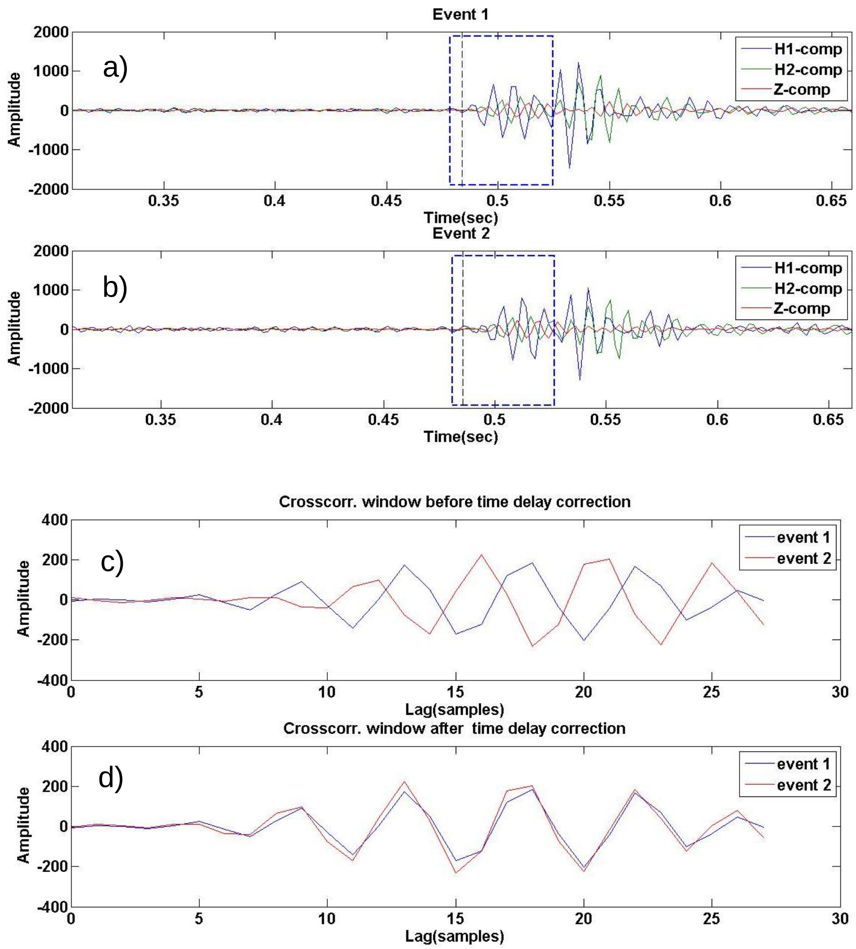


Figure 3: P-wave repicking method. a) and b)Two highly similar events recorded at one station. The crosscorrelation window is defined by the dashed blue line. c) Inconsistency in pick between similar events. d) Waveform alignment after P-wave picking correction.

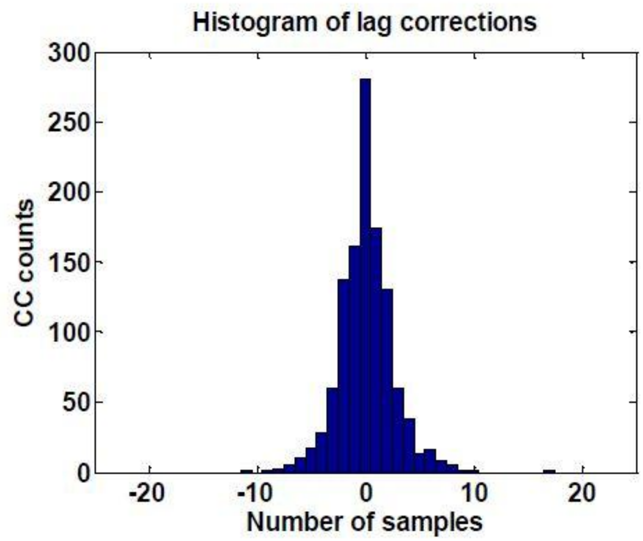
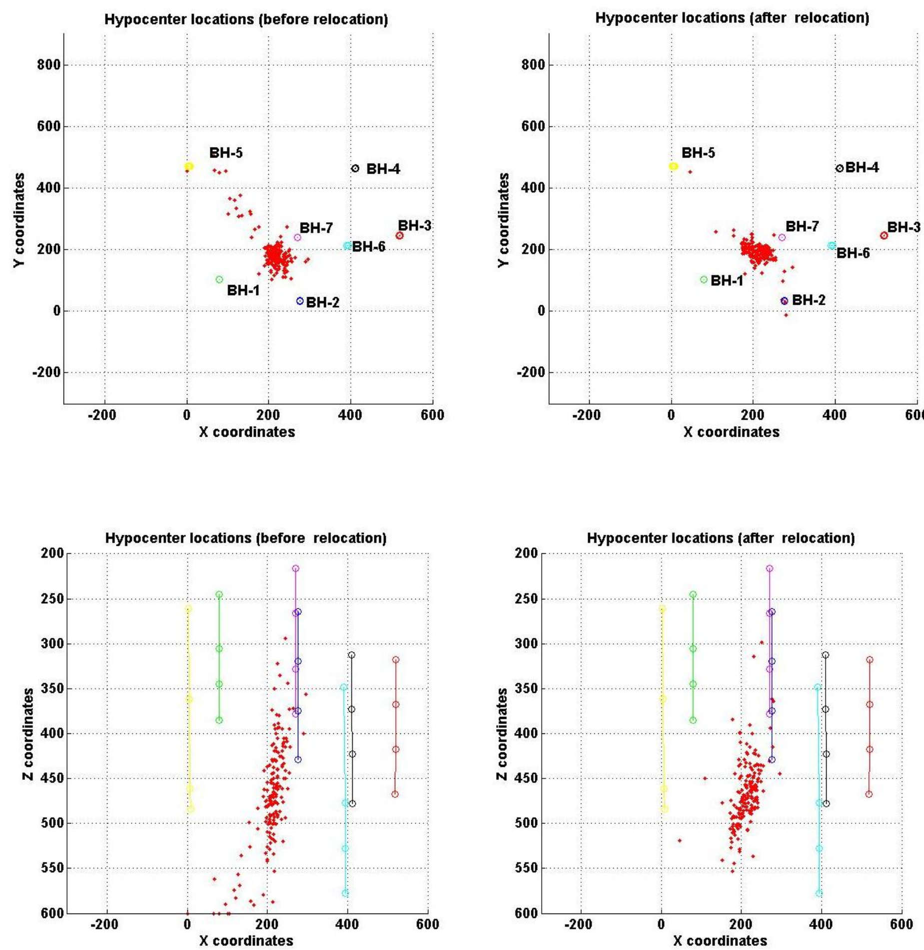


Figure 4: Histogram of time delays corrected after improving relative arrival time readings between doublets. With information on time delay corrections and velocity structure, location uncertainties caused by picking errors can be inferred.



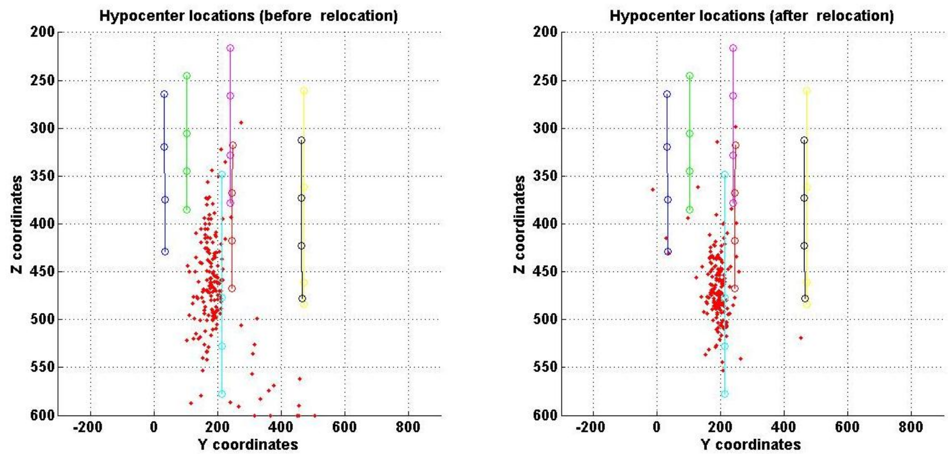


Figure 5: Microseismic event locations before and after relocation. After relocation, this main event cloud has been confined to depths between 420 and 530 m, closer to one of the main shafts. Some events are farther apart from the cluster, which might be caused by poor event linking.

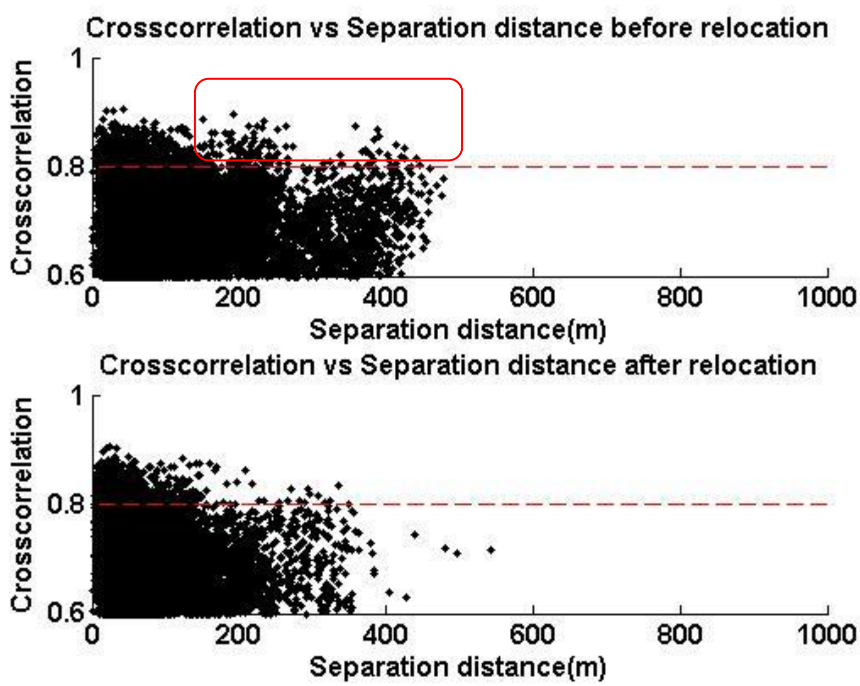


Figure 6: Crosscorrelation coefficient as a function of separation distance before (top) and after (bottom) relocation. Note that after relocation, most doublets separated by larger distances (red rectangle) have been collapsed to shorter distances. This plot can be used as quality controls since doublets with large separation distances suggest location errors due to mispicks.

Conclusions

We have proposed a post-processing technique that takes advantage of event similarity assumptions to relocate microseismic events using the double-difference method. This technique has been applied to a data set recorded near a mine where a collapse of event clouds is observed after relocation. This seismicity is most likely related to mining activities closed to the main shaft. Additionally, we have refined relative P-wave arrival time readings between doublets through crosscorrelation, which shows that mispicks are a significant source of location errors. The double difference is able to improve relative locations, not necessarily the absolute ones, for that reason, we keep the barycenter fixed before and after relocation. We also learned that a simple plot of correlation values as a function of separation distances can be used to assess location errors between similar events, which can be converted to location errors. The main advantage of this relocation technique is that we only need to know the velocity structure in the source region, which is crucial especially when we do not have enough velocity information along source-receiver raypaths. This is of paramount importance when monitoring mine activities, since an accurate location of events can help alleviate concerns when unexpected seismic activity occurs, or any extraction and excavation process. This technique can also be applied to any other microseismic monitoring scenario (hydraulic fracturing, heavy oil reservoir monitoring) and is ideal for QC of location errors and uncertainty assessment.

Acknowledgements

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References

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