4D seismic travel time tomography for detecting temporal velocity changes

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It has been a challenge to image temporal velocity changes by seismic travel time tomography. Standard time-lapse velocity tomograms are generally obtained by subtracting velocity models resulting from separate seismic tomography for different time periods. However, this could introduce some artifacts in temporal velocity changes because of different data distribution and data quality at different time periods. If more seismic events are included in the tomographic system, the inverted velocity models do not have the necessary time resolution to resolve velocity changes. But if fewer events are used for separate time periods, the system is less stable, and the inverted model may contain some artifacts and thus resolved velocity changes may not be real. To mitigate against these issues, we developed three different schemes to conduct 4D (or time-dependent) seismic travel time tomography.

The first scheme is based on the concept of double-difference (DD) seismic tomography (Zhang and Thurber, 2003). We redefined the DD tomographic equations by considering two events from two different time periods in order to evaluate the temporal velocity changes. The new method inverts data from two adjacent epochs simultaneously for the temporal velocity model changes to minimize differential arrival time residuals. We applied the new method to a surface microseismic monitoring dataset for underground longwall coal mining. It clearly shows that velocity increases in the front of the mining face where the stress increases and velocity decreases in the gob area where material is loose, which is expected from numerical modeling of stress distribution and is more consistent than the standard time-lapse seismic tomography.

The 2nd scheme combines the multiscale property of wavelet representation and the fast converging property of the simultaneous algebraic reconstruction technique (SART) to solve the velocity model at multiple scales and in near real time. By using the multiscale property of the wavelet representation, this wavelet-based method is able to solve the model at different scales. Therefore, this method is suitable for the time-dependent tomography because data may be limited at the beginning, and only large scale features can be resolved. With more data coming in, the fine scale features could be resolved. We have validated the usefulness of this method with both synthetic data and real data using the real event and station distribution for the Etna volcano in Italy.

The 3rd scheme is based on the Kalman filter formulation of travel time tomography and has the ability to recursively update the model covariance along with the model. The key point of this method is that we update the model at each recursive step so that we can obtain more accurate ray paths through performing ray tracing with the new model, whereas the conventional inversion schemes do the ray tracing for all ray paths using the same model. We have tested the method to a downhole microseismic dataset to detect temporal seismic velocity variations induced by fracturing and fluid migration as well as to the Etna volcano seismic data.