

Virtual Seismometers for Induced Seismicity Monitoring and Full Moment Tensor Inversion

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ABSTRACT

Induced seismicity is associated with subsurface fluid injection, and puts at risk efforts to develop geologic carbon sequestration and enhanced geothermal systems. We are developing methods to monitor the microseismically active zone so that we can ultimately identify faults at risk of slipping. The virtual seismometer method (VSM) is an interferometric technique that is very sensitive to the source parameters (location, mechanism and magnitude) and to the Earth structure in the source region. VSM works by virtually placing seismometers inside a micro events cloud, where we can focus on properties directly between induced micro events, and effectively replacing each earthquake with a virtual seismometer recording all the others. Here, we show that the cross-correlated signals from seismic wavefields triggered by two events and recorded at the surface are a combination of the strain field between these two sources times a moment tensor. Based on this relationship, we demonstrate how we can use these measured cross-correlated signals to invert for full moment tensor. The advantage of VSM is to allow to considerably reduce the modeled numerical domain to the region directly around the micro events cloud, which lowers computational cost, permits to reach higher frequency resolution, and suppresses the impact of the Earth structural model uncertainties outside the micro events cloud.

1. INTRODUCTION

Typically, methods used to monitor and characterized the micro seismicity at enhanced geothermal system (EGS) are based on classical source inversion methods directly using recorded wavefields at surface and/or borehole seismometers, generating Green's function in a numerical domain extending from the micro events cloud to the surface. Earth property model uncertainties from the micro events to the surface and/or borehole seismometers are thus carried into the inversion.

Work by Curtis et al. (2009) shows that by cross-correlating recorded wavefields from two earthquakes, one can recover a signal that would have been emitted by one earthquake and recorded by the other one, this latter playing the role of virtual seismometer. This is a complementary approach to ambient noise correlation techniques (e.g., Lobkis and Weaver, 2001), which convert one surface seismometer into a virtual source recorded by the other seismometers (see Figure 1). Looking at earthquakes in California and Nevada, recorded by 15 seismometers from the USArray and Berkeley seismic network and using the virtual seismometer approach, Curtis et al. (2009) demonstrate that an earthquake source acts like a double couple, so by reciprocity, the virtual seismometer acts like a strain recorder, contrary to classical seismometers which record ground displacement (or time derivatives).

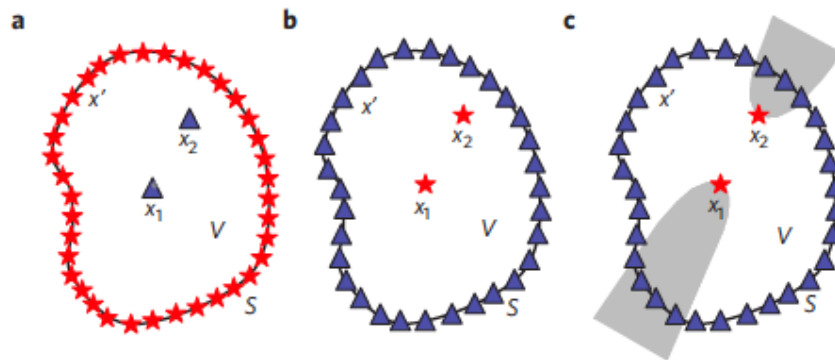


Figure 1: Sketch after Curtis et al. (2009) of source-seismometer geometries used for seismic interferometric methods: (a) Cross-correlation of the wavefields recorded at the seismometers (blue triangles) located at x_1 and x_2 , emitted from the sources x' (red stars) located on a surface S surrounding the volume V, gives the Green's function between the two seismometers – one of the seismometer is transformed into a virtual source. (b) Using reciprocity, the Green's function can be approximated between two sources located at x_1 and x_2 by cross-correlating wavefields recorded on a surface S. (c) It can be shown that most of the reconstruction of the Green's function can be achieved using recorded wavefields along the x_1-x_2 line (grey area).

Here, we further expand the work by Curtis et al. (2009) by showing that the virtual seismometer method (VSM) can be used in enhanced geothermal system setting to directly invert for full moment tensor and focal mechanism within a cloud of micro seismic events.

The advantage of VSM on classical source inversion approaches is that it allows to considerably reduce the modeled numerical domain to the region directly around the cloud of micro events, which (1) lowers computational cost, (2) permits to reach higher frequency resolution, and (3) suppresses the impact of the Earth property model uncertainties outside the cloud of micro events.

2. MICROSEISMICITY AT THE NEWBERRY EGS SITE AND INSIGHTS FROM VSM

AltaRock Energy Inc. injected water into Well NWG 55-29 at the Newberry Volcano, Oregon, October 17 - December 7, 2012 (Figure 2-a). The objective of the project was to create by hydraulic injection a fracture network in the rock penetrated by the well. Then a second (production) well would be drilled to intersect the fracture network created. During this period, a swarm of 180 micro events was detected (see Figure 2-b).

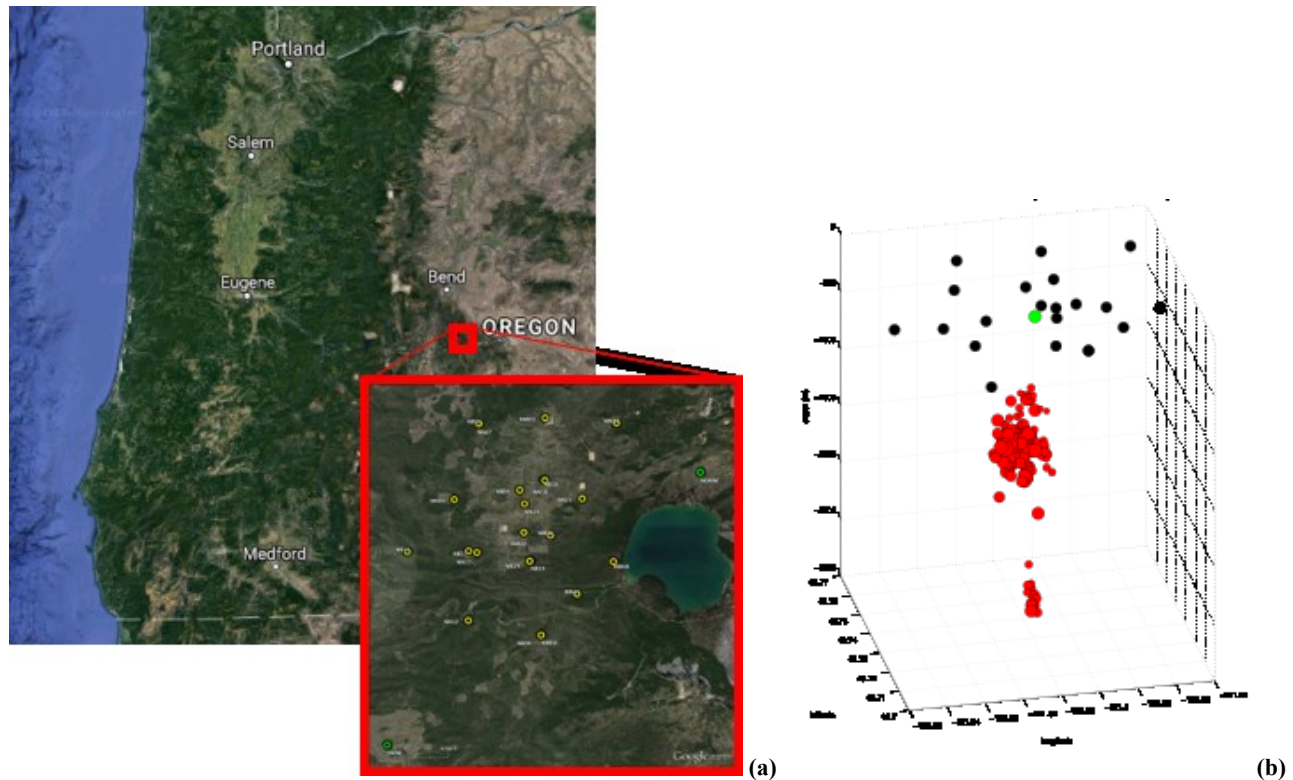


Figure 2: (a) Location of the Newberry EGS site in Oregon and of the seismometer network (yellow circles). The network consists of 9 borehole seismometers and 6 surface seismometers. (b) Relocation of 180 microseismic events (red spheres) from October-December 2012 under Newberry using Bayesloc, a Bayesian locator developed at LLNL (Templeton et al. 2014). The green and black spheres refer to the seismometer network.

Using a subset of the microseismicity beneath the Newberry network, aligned roughly with the station NN24 (see Figure 3-a), we show that the deepest micro event can be turned into a virtual seismometer recording the events above it. Figure 3-b displayed the cross-correlated signals obtained by cross-correlating each wavefields recorded at the station NN24 emitted by each of the micro event, taking the deepest event as the master, thereby defining it as the virtual seismometer (VS). One can measure the moveout of the signals with respect to the distance of the micro event to the VS. The green line marks a velocity of 2,500 m/s, which is in agreement with the compressional wavespeed value in this area. Note that it does not matter in which order these events occurred, as we are only interested in cross-correlating their recorded wavefields.

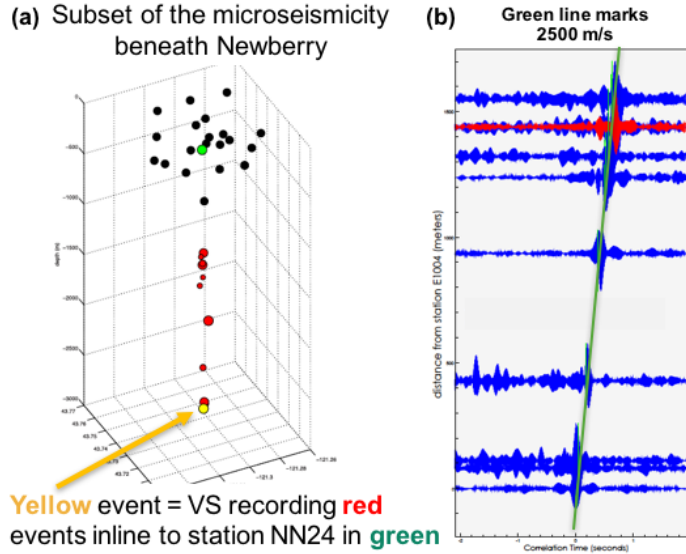


Figure 3: (a) Location of a subset of micro events (red spheres) under the Newberry EGS site seismometer network (black spheres). The green sphere refers to the station NN24, which is roughly aligned with the subset of events. The yellow sphere refers to the deepest event, which plays the role of virtual seismometer (VS) recording all the other events. (b) Resulting signals from the cross-correlation of the recorded wavefields at the surface emitted from each event, using the lowest event as master, i.e., as the VS. The moveout shown by the green line of 2,500 m/s is in agreement with the compressional wavespeed value in the area.

3. VSM FOR FULL FOCAL MECHANISM INVERSION

In the following, we present a synthetic example of VSM for full focal mechanism inversion. For this synthetic case, we use the Newberry EGS geometry (see Figure 4-a). We mimic the appearance of a microseismicity below the site and choose one event to fully characterize, knowing the location and focal mechanism of the others. These events play the role of virtual seismometers (see Figure 4-b). We use the software SPEC-FEM3D Cartesian (Komatitsch & Tromp 1999) to model full waveform propagation and a 3D velocity model including topography.

Based on Curtis et al. (2009), we can write the VSM in the frequency domain as:

$$M_{ip}^2 M_{mq}^1 \partial_p \partial_q \dot{G}_{im}^h(x_2, x_1, \omega) \sim -K \int [\dot{u}_n(x_2, x, \omega) \cdot \dot{u}_n^*(x_1, x, \omega)] d^2x \quad (1)$$

where the right hand term corresponds to the cross correlation of recorded wavefields at seismometers located at x from two earthquakes located at x_1 and x_2 , and the left hand term shows the strain rate recorded by the earthquake located at x_2 , from a signal emitted by the earthquake located at x_1 (M^1 and M^2 refer to the moment tensors of earthquake at x_1 and x_2 , respectively).

Note again that while in classical source inversion approaches, one would need to model the full domain as depicted on Figure 4-a to generate the Green's functions used for source inversion, with VSM, one only needs to model the subdomain displayed on Figure 4-b, to calculate the left hand term of equation (1).

Table 1 shows the results of the source inversion performed to recover M^1 based on VSM using a linear least square method to solve equation (1). In addition to the focal mechanism and the strike, dip and rake parameters of the principal plane, we also present the isotropic, double-couple (DC) and compensated linear vector dipole (CLVD) components of the solution (Jost and Hermann 1989). Discrepancies exist due to (1) the fact that equation (1) is an approximation, and (2) the alignment of the surface seismometers and the events is not always realized (see Figure 4) – note that we do apply an azimuthal angle correction to decrease the effect of resulting spurious signals. Despite these discrepancies, these results show the promising potential of VSM.

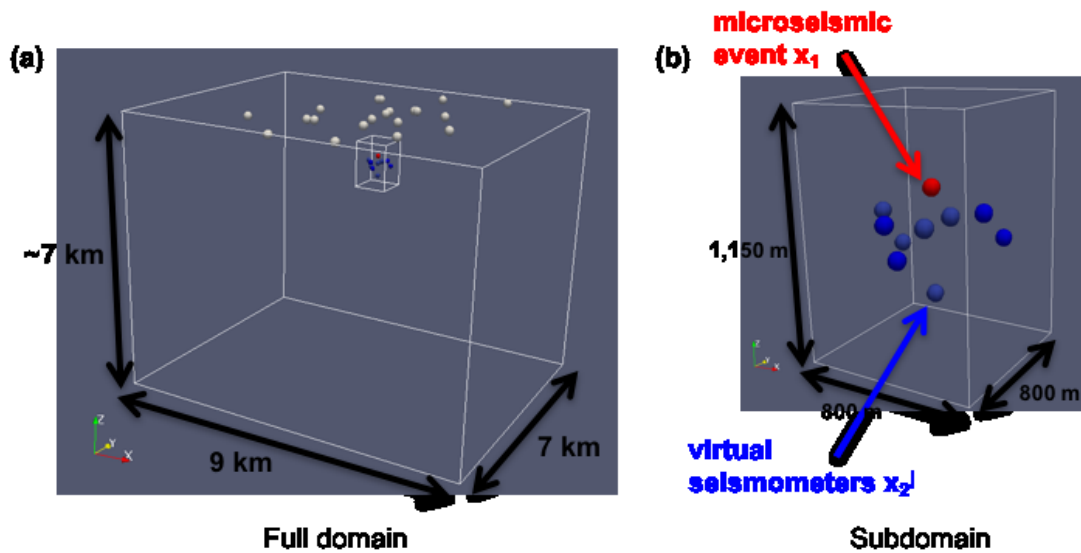


Figure 4: (a) Full numerical domain showing the Newberry seismometer network (grey spheres) location and synthetic microseismicity (red and blue spheres). (b) Zoom in into the micro events cloud. Subdomain used for VSM calculations.

| | Solution | 9 VS | Solution | 9 VS |
|-----------------|----------|------|----------|------|
| Focal mechanism | | | | |
| Isotropic (%) | 0 | 7 | 0 | 17 |
| DC (%) | 100 | 87 | 100 | 81 |
| CLVD (%) | 0 | 6 | 0 | 2 |
| strike (deg) | 270 | 271 | 303 | 298 |
| dip (deg) | 90 | 84 | 90 | 67 |
| rake (deg) | 90 | 128 | 90 | 111 |

Table 1: Results of focal mechanism inversion based on VSM using 9 virtual seismometers (VS) to recover two different solutions. The isotropic, DC and CLVD decomposition is shown, and the strike, dip and rake solution of the principal plane solution is given.

4. CONCLUSIONS

We have shown that VSM allows to virtually place seismometers inside a micro events cloud. Using the dataset from the Newberry EGS site in Oregon, we show that one micro event can be turned into a virtual seismometer which records other events. This example shows that VSM can be used to evaluate local area wavespeeds.

Contrary to classical seismometers, which measure displacement (or time derivatives), virtual seismometers record combinations of strain measurements. A synthetic example shows how VSM can be used to solve for source inversion. Here, we only need to numerically model a small subset of domain around the micro events cloud – enabling better resolution & lower computational cost, contrary to classical approaches, which rely on Green’s function being calculated from the cloud up to the surface seismometers, integrating uncertainties on Earth structural model.

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