Improving microseismic imaging: role of acquisition, velocity model, and imaging condition

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ABSTRACT
Surface microseismic data is being increasingly used in monitoring hydraulic-fracturing. Here, we suggest changes in the acquisition as well as processing stages to improve microseismic imaging and source characterization. Improved microseismic hypocenter imaging and reliable source mechanism estimation can be achieved by illuminating the hypocenter evenly from all directions. We introduce methodologies for designing optimized surface arrays for 2D and 3D acquisitions. Accurate microseismic imaging also requires the exact Green’s function between the image point and the receivers. An inaccurate Green’s function leads to poor focusing and numerous spurious microseismic hypocenters. We also introduce imaging conditions that can yield accurate source signatures even if they are extended in space and time. Such source signatures can yield the time history of fracture propagation in space and might be used to infer the time-varying slip along pre-existing fractures. These imaging conditions also reduce spurious events in the image. All conclusions are supported with numerical examples.

1 INTRODUCTION
Microseismic monitoring using surface arrays is becoming increasingly popular because of its reduced cost and increased aperture compared to borehole monitoring. Surface microseismic data is commonly acquired using a star-shaped array or on a regular grid. These receivers can be placed on the surface or can be buried in the ground to improve the signal-to-noise ratio. Little attention is paid towards designing the array to optimize imaging using a fixed number of receivers. Therefore, optimizing a survey design can not only lead to better microseismic characterization but also result in cost savings. In fact, it is nowadays routine to perform illumination studies in order to design the best acquisition surveys in conventional reflection seismology. Here, we discuss how surface microseismic arrays can be designed to yield better hypocenter imaging.

Other important aspects of microseismic imaging involve the choice of imaging condition and the knowledge of the exact Green’s functions between the image point and the receivers. The recorded data are imaged through a Kirchhoff-summation based algorithm or a reverse-time approach with the primary aim being the location of microseismic hypocenters. Reverse-time imaging and Kirchhoff-summation based algorithms commonly use a smooth velocity model for imaging and therefore might not yield an accurate Green’s function. We discuss the importance of an accurate subsurface model and its impact on imaging microseismic data.

Recent developments by Ulrich et al. (2013), Douma et al. (2013) and Bazargani & Snieder (2013) show that better temporal and spatial focusing can be achieved by designing optimal inverse-filters from the recorded data which are then back-propagated through a velocity model. Here, instead of optimizing the focusing of the microseismic data, we compute the source signature of the microseismic events. Imaging of microseismic data commonly refers to the reconstruction of the hypocenters of the microseismic sources. Therefore, microseismic images are usually displayed only as a function of the spatial axes. Microseismic sources, however, are functions of time as well. For example, it is most likely that the opening of a fracture is not instantaneous; instead different portions of the fracture likely open at different times resulting in a microseismic source extended both in space and time. Another example of such sources would be microseismic tremors that occur...
due to the slow slippage along a fault or fracture plane. Hence, by *microseismic imaging* we refer to the process of finding the microseismic source signature as a function of both space and time. By computing the source signatures as a function of time and space, we can infer the time history of fracture propagation in space and the time-dependent slip along natural fractures. Therefore, we introduce and analyze different imaging conditions that look for coherence in time as well as space between the computed Green’s functions and the recorded data and test their effectiveness in imaging microseismic data. Our approach is particularly useful for microseismic sources that are extended in time and space.

2 SURFACE ACQUISITION

In order to obtain the best possible focus through imaging and also decipher the source radiation pattern accurately, one needs to sample the hypocenter evenly from all angles. In other words, the hypocenter must be evenly illuminated from all directions. If the microseismic source is imaged using plane waves evenly spaced in angle (Figure 2a), one can obtain an evenly illuminated image. However, neither a star-shaped surface array nor a regular-grid array would illuminate the hypocenter evenly from all directions. Instead, such receiver arrays will lead to the preferential illumination of certain angles (Figure 2a) thereby resulting in X-shaped hypocenter images. More importantly, such uneven angular sampling of the hypocenter might lead to an incorrect estimation of the source radiation pattern.

Figure 1. Plan-view of star-shaped surface microseismic array. The blue lines represent the receiver arrays. Source: Duncan & Eisner (2010).

![Figure 1](Image)

Figure 2. Hypocenter reconstruction using plane waves (a) evenly incident from all directions and (b) incident from receivers evenly spread along a line on the surface.

(a) ![Image](Image)
(b) ![Image](Image)

Figure 3. 2D surface array for optimized design (a) and conventional design (b). The optimized array is designed for a hypocentral depth of 1800 m, maximum offset of 6000 m and a constant velocity gradient of \( \approx 1.3 \text{ s}^{-1} \).

2.1 Optimal design

Here, we suggest using a modified surface array designed with the aim of illuminating the microseismic hypocenters evenly from all directions. To design such an array one needs an approximate smooth velocity model of the subsurface, approximate center of the zone of microseismicity, maximum receiver offset, and the number of receivers. A practical solution would be to use a constant vertical velocity-gradient of the subsurface being monitored. Since most unconventional reservoirs undergoing hydraulic fracturing are fairly laterally-homogeneous, a well-log could be used to find the best-fit vertical velocity gradient. The mid-point of the hydraulically-fractured zone can be used for the center of the microseismicity-zone. By knowing the maximum offset and the number of receivers, one can shoot rays from the microseismicity-zone-center at equally-spaced (in angle) takeoff angles. The intersection of these rays with the surface determine the optimal locations of the surface receivers. For such simple velocity models, one can use analytic ray-path formulations for determining the location of the surface receivers; for more complicated models, one can use ray-tracing. Such a modified design was also proposed by Foulger & Julian (2011); Miller *et al.* (1998) with the above aim in mind (sampling the hypocenter evenly in angle). Miller *et al.* (1998) used ray-tracing to op-
The computation of these evenly-spaced (in takeoff angle) rays is straightforward in 2D where the polar angle at the hypocenter has to be divided into $n-1$ angular sectors with $n$ being the number of surface receivers. An example of an optimal 2D surface receiver array is shown in Figure 3a; a conventional array (equally spaced on the surface) is also shown in Figure 3b for comparison. For 3D acquisition design, however, the computation of the equi-spaced takeoff angles is more involved because the whole sphere around the hypocenter needs to be evenly sampled (instead of the circular aperture in 2D).

Figure 4. (a) Geodesic grid used in sampling the imaginary sphere surrounding the hypocenter. (b) Icosahedron that is divided to construct a geodesic grid. Source: Geodesic polyhedra, René K. Müller

Figure 5. Plan view of the optimized surface acquisition in 3D. The optimized array is designed for a hypocentral depth of 1800 m, maximum offset of 6000 m and a constant velocity gradient of $\approx 1.3 \text{ s}^{-1}$.

Miller et al. (1998) and Foulger & Julian (2011) use the intersection points of the latitudes with the longitudes of a sphere to determine the azimuth and take-off angle of each ray. Their approach, however, will not sample the sphere evenly; it will lead to finer sampling of points near the poles and sparse-sampling of points close to the equator. Here, we use a geodesic grid (Figure 4a) to determine the azimuth and takeoff angles of the rays because the sphere surrounding the hypocenter is sampled evenly on a geodesic grid. Depending on the number of receivers, an icosahedron (Figure 4b) is divided evenly to yield a geodesic grid. The vertices of the geodesic grid yield the azimuth and takeoff angles of the rays. As described above, intersection of these rays (shot from the hypocenter at the computed azimuth and takeoff angles) with the surface determines the optimal locations of the receivers. An example of such an optimal 3D microseismic survey is shown in Figure 5. Note the marked difference in the optimal receiver pattern from that of a star-shaped array and a regular-grid array.

The instrumentation of borehole receiver strings prevents me from suggesting the above optimized receiver spacing for borehole acquisition. However, if multiple strings are used in monitoring microseismicity, one could still use the above optimization scheme to design a borehole acquisition geometry that illuminates the zone of microseismicity evenly from all directions.
2.2 Imaging

An acquisition design optimized to illuminate the hypocenter evenly from all directions should yield better images of the microseismic source. Images in Figures 6a and 6b are obtained using reverse-time imaging of the microseismic data acquired on an optimized array (Figure 3a) and a conventional array (Figure 3b), respectively. Note that the event focusing is better in Figure 6a than in Figure 6b. The individual plane waves forming the focus at the hypocenter are also visible. As expected, the plane waves in Figure 6a are evenly spaced in angle while in Figure 6b they are unevenly spaced and concentrated at specific angles. Increasing the number of receivers increases the image quality (Figures 6c and 6d) for both acquisitions; however, the uneven illumination of the conventional acquisition still leads to an X-shaped image in Figure 6d. Note the similarity of Figures 6c and 6d to the plane-wave schematic in Figure 2a and 2b, respectively.

3 IMPORTANCE OF THE SUBSURFACE MODEL

Reverse-time imaging (McMechan, 1982; McMechan et al., 1983; Lu, 2002) of microseismic data involves time-reversal of the data and their re-injection into a smooth velocity model. Following back-propagation, an imaging condition is applied which is usually some snapshot of the back-propagated wavefield at some time that is thought to be the initiation time of the microseismic source. Reverse-time imaging can, therefore, be written as

\[
I(\omega; x_0) = \left[ \sum_{x_r} d^*(\omega; x_r) G_s(\omega; x_s, x_r) \right]^* = \left[ \sum_{x_r} S^*(\omega; x_0) G^*(\omega; x_r, x_0) G_s(\omega; x_s, x_0) \right]^* = S(\omega; x_0) \left[ \sum_{x_r} G^*(\omega; x_r, x_0) G_s(\omega; x_s, x_r) \right]^* \]  

(1)
where $I(\omega; x_s)$ is the image at image point $x_s$, $x_r$ represent the receiver coordinates, $\omega$ is the frequency, $^*$ represents complex conjugation, $d$ is the microseismic data, $G$ is the true Green’s function, $G_s$ is the Green’s function computed during back-propagation in a smooth background velocity, and $S$ is the source signature at image point $x_s$.

Ideally we would like equation 1 to yield the true source signature at location $x_s$, i.e., $I(\omega; x_s) = S(\omega; x_s)$. This means that in order to get the best possible image, $G_s$ should be equal to $G$. This can be achieved by using the exact velocity (and density) model for back-propagation of the recorded data. For example, the well-log derived velocity (and density) could be used for back-propagation in laterally-homogeneous media. If a smooth model is used instead, the image (Figure 8a) could be substantially different from the true image (Figure 8b). In the absence of a detailed and accurate velocity model, an alternate approach suggested by Behura & Snieder (2013) could be used. It is noteworthy that even if the true Green’s function is used in equation 1, reverse-time imaging will yield a source signature that is scaled by $\sum_{x_r} |G|^2$; therefore, the image obtained using reverse-time imaging will not be accurate unless the subsurface velocity and density are actually slowly varying such that $|G|^2 = \delta$, where $\delta$ is the Kronecker delta.

4 IMAGING CONDITIONS

In order to obtain accurate source signatures of microseismic sources, we need to modify the imaging condition used in reverse-time imaging (equation 1). The microseismic data recorded at receiver $x_r$ due to a source at some location $x_s$ is given by

$$d(\omega; x_r, x_s) = S(\omega; x_s) G(\omega; x_r, x_s),$$

where $\omega$ is the frequency, $d(\omega; x_r, x_s)$ is the data at receiver $x_r$, $S(\omega; x_s)$ is the source signature at $x_s$, and $G$ is the Green’s function between the source location $x_s$ and the receiver location $x_r$. Note that equation 2 is de-
spectrum of the source signature; therefore, although imaging condition 6 might yield the correct phase of the microseismic source, its amplitude will be inaccurate unless $|G|^2 = \delta$. If a smooth velocity model is used for back-propagation, equation 6 becomes the cross-correlation imaging condition 1 used in reverse-time imaging. Figure 9b shows the image resulting from the cross-correlation imaging condition 6.

In the presence of multiple microseismic sources extended in space, imaging conditions 4 and 5 will result in cross-talk between the various sources and might yield degraded images. Also, in the above two imaging conditions (equation 4 and 5), the source signatures are computed for each receiver independently and then stacked. In other words, imaging conditions 4 and 5 use only the temporal coherence between the data recorded at a receiver with the computed Green’s function. It might be possible to reduce cross-talk and improve imaging by exploiting spatial coherence in addition to temporal coherence. Hence, we modify equations 4 and 5 by performing a Fourier transform on the spatial receiver axis to obtain

$$ S(\omega; \mathbf{x}_s) = \sum_{k_r} \frac{d(\omega; k_r, \mathbf{x}_s) G^*(\omega; k_r, \mathbf{x}_s)}{|G(\omega; k_r, \mathbf{x}_s)|^2}, $$

and

$$ S(\omega; \mathbf{x}_s) = \sum_{k_r} d(\omega; k_r, \mathbf{x}_s) G^* (\omega; k_r, \mathbf{x}_s), $$

respectively; $k_r$ is the wavenumber computed over the receiver coordinates. Images resulting from imaging conditions 6 and 7 are shown in Figures 9c and 9d respectively.
Equation 2 can also be written as a linear system of algebraic equations
\[ d = GS. \]

The least-squares solution \(^ \text{Aster et al., 2012} \) for \( S \) from the equation \(^ 8 \) is given by
\[ S_{i,j} = (G^T G)^{-1} G^T d, \]
where \( G^T \) represents the conjugate transpose of \( G \). Equation 9 is solved for each frequency independently to obtain \( S(\omega) \) at every image point of interest. [Note that the above inversion approach in equation 9 is different from that of \(^ \text{Bazargani & Snieder, 2013} \) who design injection sources (to be injected at the receiver locations) that optimally focus the microseismic event at a predefined time and space.] The image obtained from imaging condition 9 is shown in Figure 10c.

Note that the above imaging conditions result in images that are extended in time; images extended in space can be obtained by varying the image point \( x_s \). This is different from conventional imaging conditions where a zero-time imaging condition is applied to the back-propagated wavefield. Such an imaging condition assumes that we know the initiation time of the microseismic source and that the source is compact in time. However, as discussed above, microseismic sources can be extended both in space and time (for example, microseismic tremors); therefore, the imaging conditions introduced above should lead to a better characterization of microseismicity.

We also demonstrate the above imaging conditions on the Sigsbee model (Figure 11a). The microseismic survey comprises of 367 receivers spread on the surface at an equal spacing of 75 ft. Two microseismic sources (Figure 10a) are used for generating the data; the initiation times of the left- and the right-source are 0.096 s and 3.36 s, respectively. Also, the left source has a higher amplitude than the right source. For imaging, we use the smoothed velocity model shown in Figure 10b. The exact Green’s functions necessary for imaging are generated using the algorithm of \(^ \text{Behura & Snieder, 2013} \). The resulting images obtained from the above five imaging conditions are shown in Figure 11b. The images correspond to a depth of 5700 ft. All five imaging conditions reconstruct the source accurately at their correct times and spatial location. However, imaging condition 7 contains the least artifacts (Figure 11d). Overall, Figures 9 and 11 show that imaging conditions 9, 7, and 0 yield the best images while minimizing false positives.

5 DISCUSSION AND CONCLUSIONS

Microseismic imaging can be improved by evenly illuminating the hypocenters from all directions. The modified surface acquisition suggested here results in uniform sampling of microseismic hypocenters and better images as corroborated by synthetic examples.

The optimized surface acquisition design introduced has to be designed with a specific imaging zone in mind. Subsequently, microseismic hypocenters located far away from this imaging zone might not be optimally illuminated using the modified design. Still, most of the microseismicity is confined to the vicinity of the hydraulically-fractured zone which makes the optimized design useful.

The time-space imaging conditions discussed here yield good images and minimize spurious events on the image at the same time. These time-space imaging conditions exploit the similarity of the acquired data with the computed Green’s function in both time and space. An accurate and detailed velocity model is also extremely important in imaging and reducing false positives in microseismic analysis.

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References

Figure 9. Images of the microseismic source in Figure 7a obtained using imaging condition (a), (b), (c), (d), and (e).


Figure 10. (a) The Sigsbee velocity model used in generating the microseismic data and the reflection seismic data. The two pentagrams represent the microseismic hypocenters and the red triangles represent the receivers. The initiation time of the two sources is There are a total of 367 receivers spread on the surface at an equal spacing of 75 ft. (b) The smooth model used in imaging.


Figure 11. Images of the microseismic source in Figure 10a obtained using imaging condition 4 (a), 5 (b), 6 (c), 7 (d), and 9 (e). The images correspond to a depth of 5700 ft. (f) Depiction of the image slices displayed in (a)-(e).