Increasing the accuracy of microseismic monitoring using surface patch arrays and a novel processing approach

P.-F. Roux1*, J. Kostadinovic1, T. Bardainne1, E. Rebel1, M. Chmiel1, M. Van Parys1, R. Macault1 and L. Pignot1 present an acquisition and processing technique to further decrease the noise recorded at the surface of the Earth when monitoring hydraulic stimulation.

It is well known that fluid injection into reservoirs, be it in the context of enhanced geothermal systems or for the stimulation of hydrocarbon reservoirs, generates so-called ‘induced’ seismic activity (Evans, 1966). Early on, the link between the stimulation and this activity has been established, and it has become increasingly obvious that measuring the microseismicity generated by the injection would provide a wealth of information on the mechanical processes at work during the stimulation. Historically, downhole geophone tools have been used to monitor microseismic activity during stimulation programmes. Such tools usually offer a very high sensitivity to the microseismic sources, provided that the observation well is close enough to the treated well (Rutledge and Phillips, 2003). However, this becomes limited when more information on the source mechanism (usually termed focal mechanism and represented by the infamous moment tensor) is required. This is because of the three-dimensional nature of the focal mechanism, which means it cannot be retrieved properly using a single observation point. In addition, a poorly situated observation well may indeed lead to a reduced detection capability.

In this paper, we present a novel acquisition technique to further decrease the noise recorded at the surface of the Earth when monitoring hydraulic stimulation. We argue that the wellhead is not the only source of noise in such cases; it is in fact one of the less important ones. Based on this observation, and building upon recent advances in seismic acquisition, we have developed a practical and highly efficient acquisition design, namely a patch array approach. It offers a wide variety of noise cancellation methods while remaining easy to deploy in the field. In addition, we have developed a suite of processing schemes (Macault and Bardainne, 2014; Chmiel and Bardainne, 2014) that take full advantage of the patch array design. We will present them herein, and demonstrate the benefits of such processing techniques within a case study.

Recording microseismic activity using a surface network

One of the most prominent challenges in surface-based microseismic monitoring is its susceptibility to noise. Yet, as pointed out by Scales and Snieder (1998), there is no simple and single definition of what noise is. A simple and convenient way to define noise is the ‘unwanted part of a seismic recording’. As a matter of fact, several noise sources exist that may or not impede the quality of microseismic recordings (Meunier, 2011):

- Digitization-induced noise, caused by rounding error when the input measure is digitized into an n-bit digital word.
- Thermal or Johnson noise, caused by the thermal agitation of the charge carriers. It is often referred to as recorder noise, because most of it is generated in the pre-amplifiers used in seismic recorders.
- Ambient or seismic noise, which corresponds to waves propagating from undesired sources located at the surface of the Earth, and often caused by human-related activities (traffic, cities, factories, etc.).

While the first two items depend only on the set of instruments used to record the data, the last category comprises

---

1 Magnitude (a Baker Hughes – CGG joint venture).

* Corresponding author, E-mail: pierre-francois.roux@cgg.com
Later on at the processing stage (so-called digital array forming, see e.g., Seeni et al., 2014). But, more importantly, trying not to record such ambient noise seems to be the most natural way to increase S/N (Ackerley and Spriggs, 2012).

The patch array (Pandolfi et al., 2013; Auger et al., 2013) is an acquisition strategy that combines both unaliased noise sampling and deployment flexibility to avoid noisy areas. A patch array is a set of small (typically 150 m x 150 m) yet dense networks of typically 48 traces, each recording a 12-geo-phone U-shaped array (insets of Figure 2). Each patch can be seen as an adaptive array acting as a single sensor once stacked, similar to those found in optical astronomy (e.g., Angel et al., 1990). These adaptive sensors focus altogether and simultaneously at both patch and network scales on to the hypocentral region (see the section on Processing patch-array data below).

In an ideal, noiseless situation, patches are located at the surface to achieve the adequate sampling of the focal sphere ‘external’ noise sources and how these interact with the surface and near-surface conditions of the Earth. In particular, ambient noise related to human activity is the largest magnitude and the highest in frequency, typically ranging from 1 Hz up to 30 Hz (Figure 1). It should be noted that the sources of these noise wavefields are distributed over a wide area and not necessarily located at a single position, as often assumed during hydraulic stimulation operations. Although the pumps do generate a large amount of surface waves, they do not impact more than a small portion (typically approx. 1%) of the monitoring network – see Drew et al., (2012) as an example. Roads crossing the lines of the monitoring network, nearby facilities or cities, and other pads or wells being pumped, all contribute to increasing the noise at a given site.

The microseismic signal is obviously uncontrollable, but we do have leverage on the noise – although limited and finite. The relation between the former and the latter is quantified through Signal-to-Noise Ratio (S/N), a concept defined by (Sheriff, 2011) as follows: ‘The energy (or sometimes amplitude) of the signal divided by all remaining energy (noise) at the time. Sometimes the denominator is the total energy, that is, S/(S + N). Signal-to-noise ratio is difficult to determine in practice because of the difficulty in separating out the signal (the desired portion).’

It appears that increasing S/N is paramount to achieving a complete description of the microseismic activity generated by stimulation, and boils down to decreasing the amount of noise that will impede the records. There are two main pathways to attenuate the noise: processing and acquisition. A wide range of noise removal methods are available at the processing stage (f-k, Radon, adaptive/matched filtering being the main ones, (Forghani-Arani et al., 2013; Wang et al., 2009)). Most of these methods assume that noise is correctly sampled. Similarly, Anstey, (1986) demonstrated early on that surface wave-based noise could effectively be reduced at the acquisition stage through spatial-filtering – provided that the areal layout of geophones has an adequate spacing. Should each geophone be recorded independently, such geophone-arrays can be formed later on at the processing stage (so-called digital array forming, see e.g., Seeni et al., 2014). But, more importantly, trying not to record such ambient noise seems to be the most natural way to increase S/N (Ackerley and Spriggs, 2012).

The patch array (Pandolfi et al., 2013; Auger et al., 2013) is an acquisition strategy that combines both unaliased noise sampling and deployment flexibility to avoid noisy areas. A patch array is a set of small (typically 150 m x 150 m) yet dense networks of typically 48 traces, each recording a 12-geo-phone U-shaped array (insets of Figure 2). Each patch can be seen as an adaptive array acting as a single sensor once stacked, similar to those found in optical astronomy (e.g., Angel et al., 1990). These adaptive sensors focus altogether and simultaneously at both patch and network scales on to the hypocentral region (see the section on Processing patch-array data below).

In an ideal, noiseless situation, patches are located at the surface to achieve the adequate sampling of the focal sphere
using a spherical helix as pictured in Figure 3, or any other sampling function of a sphere (e.g., a geodesic dome). Each point on the focal sphere is then propagated up to the surface through ray-tracing (Belayouni et al., 2013). Figure 2 shows an example of a patch array layout generated with this methodology. Furthermore, phase variations caused by the radiation pattern of the microseismic event are of sufficiently large wavelength to allow each patch to be moved away from potential noise sources located nearby.

The geometry of each patch can be refined based on prior knowledge of the ambient noise field and of local, surface-wave propagation characteristics. This is typically done by satellite map inspection and noise surveying at each planned location, as well as by analysing raw shot points from previous surface seismic surveys of the area under scrutiny.

**Processing patch-array data**

In parallel to the development of an acquisition strategy to increase the S/N and, consequently, the sensitivity of a surface network to small events, we have developed a processing methodology that takes full advantage of the patch array design and allows continuously-recorded data to be processed efficiently in real time. It should be noted that because the wavefields are densely sampled at the scale of a single patch, it is possible to pre-process each patch with denoising procedures such as \( f-k \) or \( \tau - p \) based methods. In addition, more advanced procedures (such as surface-wave adaptive denoising, Le Meur et al., 2010) can be applied to further decrease the noise locally, and therefore increase the overall sensitivity of the patch array to small-magnitude microseismic events.

**Multi-array, relative slant-stacking**

The basis of our processing scheme is a delay-and-sum (sometimes termed beam-forming) relative to a template event (Figure 4a), associated with a grid-search in the region of interest (Figure 4b). Figure 4a shows how the time shifts corresponding to each test location are applied to the patch array through its correlation with a template event of known coordinates. For example, work in the wellbore prior to any stimulation (e.g., perforation shots, string shots) can be known with sufficient accuracy to disregard uncertainties on origin time and
position. It is therefore possible to generate a template by using the observed arrival times corresponding to these events, or even to use the corresponding seismogram directly as a template. Such a template acts as an empirical Green’s function, and because events situated nearby share almost identical moveouts (e.g., Spudich and Bostwick, 1987), the correlation of the raw data with the template aligns the data sufficiently to yield a coherent stack (Figure 4a). It is interesting to note that such an operation can be regarded as a time-reversal type of methodology as a correlation is equivalent to convolving the data with a time-reversed version of the empirical Green’s function.

Practically speaking, it is possible to transform the parameter space (discretized hypocentral region) into a two- or three-dimensional grid of slowness – resulting in a so-called slant stack (Figure 5) by assuming planar propagation:

\[ s_u(t) = \frac{1}{M} \sum_{i=1}^{M} d_i(t - t_{ui}) \]

with \( s_u \) the resulting slant-stack for slowness \( u \), \( d_i(t) \) representing the seismogram at receiver \( i \), \( t_{ui} \) representing the travel time to receiver \( i \) for (horizontal) slowness \( u \), and \( M \) is the number of receivers to be stacked (stack-order). Thus, each grid point of coordinates \( \{x_u, y_u, z_u\} \) can be mapped on a surface array as a 2D vector of coordinates \( \{u', u''\} \), or 3D using three-dimensional arrays. Interestingly, and owing to some careful approximations, grid-points/patch couples share many common slowness vectors, thus dramatically decreasing the actual dimensions of the parameter space to be explored. This, in turn, allows a dramatic speed-up of the calculation of so-called focalization maps.

The selection of the event, or events, that are used as templates and the way they are compared to the actual data will define the spatial resolution and sensitivity to smaller microseismic events. In particular, the phase variations at the surface need to be accounted for to ensure constructive stacking and sufficient denoising to lead to detection. Traditionally, the focal mechanism’s radiation pattern is not properly accounted for but rather ignored by signal processing operations using, for instance, characteristic functions such as semblance (Neidell and Taner, 1971), energy, Hilbert envelope, or a more elaborate summation as in Rebel et al., 2011, leading to an inefficient denoising during beam-forming. Furthermore, using a single event template throughout the processing of an entire frac job may lead to increasing location bias with increasing distance from the template.

**Multiple local signed templates**

Using multiple, carefully selected events, including known sources such as perforation shots, to guarantee location accuracy, and keeping the information on both travel times and spatial phase variation caused by focal mechanism radiation diagrams (so-called signed template) can dramatically increase both the sensitivity to small-magnitude events, while ensuring high location accuracy thanks to the relaxed velocity model constraints. Such a methodology has been successfully used in earthquake seismology to detect early aftershocks often masked by the high energy coda of the mainshock (e.g., Lengliné et al., 2012), as well as to determine the relative location of clustered events (see, for instance, Deichmann and Garcia-Fernandez, 1992; Got et al., 1994; De Meersman et al., 2009). This assumes that most events will share identical or near-identical focal mechanisms. However, observations from both surface and downhole arrays show that induced microseismic events tend to group into clusters sharing similar focal mechanisms throughout a stimulation (e.g., Moos et al., 2011; Staněk and Eisner, 2013). This is likely to be due to pre-existing fracture plane orientation with respect to the local stress conditions. This, in turn, ensures that using a sufficiently large panel of template events will enable the detection and location of a representative if not exhaustive part of the induced seismicity.

**Case study: monitoring a Cana-Woodford stimulation programme**

We have applied the aforementioned acquisition and processing approaches to a multi-well stimulation programme carried out in the Cana-Woodford shale. The data set was acquired in 2012 by an array of 35 patches of 48 traces each (Figure 6). Data were processed in real time using a single, unsigned template approach (Auger et al., 2013). We recently
revisited this data set to assess the gain in both resolution and sensitivity obtained through the use of local signed templates. A single template, local to these stages, has been used for the purpose. We present here the results corresponding to three of the twelve stages, namely stages 6, 7 and 8, that showed the largest microseismic activity at the time of the original processing, to provide a good statistical basis for comparison with the new processing.

Figure 7 shows the map of detected and located microseismic events through the initial processing (i.e., using a remote, unsigned event template, located outside the range of the shown map). Each stage is colour-coded and perforation shots are shown as black-outlined circles (with corresponding stage colour) along the wellbore. The stimulation programme progresses from south to north (from the bottom to the top of the figure), and each stage is composed of four perforation clusters. A total of 649 events have been identified throughout the three stages (see Table 1 for number of events per stage). Although each microseismic cloud is located close to its corresponding perforation cluster, no clear geometrical pattern seems to stand out. Figure 8 shows the same three stages processed with a local, signed template. The location of the template event used to process these three stages is shown as a red star in the cloud of events corresponding to stage 7. A total of 1326 events have been detected and located for the three stages. This represents an increase of more than 42%. Further to this increase, it now appears that the microseismic clouds emanate from their respective perforation clusters; in fact, it is even possible to distinguish which of the clusters is more effective. Such information is vital when considering advanced stimulation design because it is generally assumed that all clusters will take an equal portion of the stimulation (Cipolla and Wallace, 2014).

Figure 9 compares the resulting frequency–size distribution (so-called Gutenberg-Richter plots) obtained through both data sets. The distributions are modelled taking into account the detection capacity of the network (Ringdal, 1975). A microseismic event catalogue (a catalogue being a collection of origin times and location of validated microseismic events) is indeed intrinsically dependent on the network that has been used to build it and the noise level at each station of the network. The basic principles of modelling the detection capacity of a network then amount to characterizing it with a detection function that gives the probability that an earthquake of a given magnitude will be detected. The resulting model provides both the minimum magnitude below which seismic

<table>
<thead>
<tr>
<th>Stage</th>
<th>Remote template</th>
<th>Local template</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 6</td>
<td>179</td>
<td>452</td>
</tr>
<tr>
<td>Stage 7</td>
<td>362</td>
<td>482</td>
</tr>
<tr>
<td>Stage 8</td>
<td>321</td>
<td>392</td>
</tr>
</tbody>
</table>

Table 1 Breakdown of the number of detected and located events per stage and per processing methodology. Note the overall increase when using a local template.
activity is no longer exhaustively recovered (the magnitude of completeness, $m_c$) and the slope of the linear portion of the frequency – size distribution curve (the $b$-value). The lower the magnitude of completeness, the more complete a catalogue will be – within the limits of the physics relating to the rupture size and the stimulated volume. Considering our two data sets, the magnitude of completeness has shifted down from $m_c -2.42$ to $m_c -2.56$, while the $b$-value has changed from 2.0 to 1.97. Note that the resulting fit with the modelled curve is also better at all magnitudes with the reprocessed dataset. Although these changes are only minor, they demonstrate that using a local template increases the overall sensitivity of detection and consequently decreases the magnitude of completeness. This further demonstrates that the use of a local, signed template boosts the S/N of the slant stack, thus dramatically improving the completeness of the catalogue.

**Conclusion**

We have explained how it is possible to increase the signal-to-noise ratio of a microseismic signal recorded during hydraulic stimulation at both the acquisition and processing stages. In the first part of this article, we presented the patch array acquisition design based on simple observations of noise conditions at the surface. This design, coupled with pre-survey scouting and a proper assessment of the noise propagation characteristics, can lead to a significant reduction in the noise (up to 20 dB as reported by Auger et al., 2013). We then introduced our detection and location procedure that uses local information to reduce the bias introduced by the velocity modelling and the unknown geomechanical conditions that may give rise to unexpected focal mechanisms; to do so, we simply use the travel times and phase information of local microseismic events as ‘signed templates’ to locate similar events, based on the observation that earthquakes generated close to each other share similar seismograms. Using several such signed templates to account for the possibly wide variety of sources mechanisms can significantly increase sensitivity to small-magnitude events. Comparing them to perforation shots of known locations helps to assign the microseismic cloud’s barycenter at the correct position.

Lastly, we demonstrated the effectiveness of these combined acquisition and processing techniques on a real dataset recorded in the Woodford formation. We presented the initial results obtained with the use of a single, unsigned template (Rebel et al., 2011) adapted to a patch array design, and compared them to results obtained with the local, signed template. The latter showed a dramatic improvement in both sensitivity and accuracy of the resulting locations.

**Acknowledgements**

The authors would like to thank the E&P company that has anonymously given permission to show these results. Thanks also to Cynthia Gomez, Roger Taylor and Sara Pink-Zerling for reviewing the article.
References


