Integration
geoConvention 2013
geoscience
engineering
partnership

Black Box Recording of Passive Seismicity: Pitfalls of not Understanding your Acquisition Instrumentation and its Limitations

Ted Urbancic*, ESG, Kingston, Canada
urbancic@esg.ca

and

Andreas Wuestefeld, Adam Baig, ESG, Kingston, Canada

Summary

We discuss recording system design for effective monitoring of induced seismicity ranging in magnitude from -4 < M < +4. As part of the discussion, we outline frequency and bandwidth limitations, consider different noise and resonance effects on signals, the effects of coupling behaviour, and introduce spectral characteristics typical of signals recorded downhole and at or near the surface. We further provide the basis for which an understanding of how these limitations could affect data collection and interpretation of results (estimates of magnitude, source radii, discrete fracture network) and improve our approach to recording interpretable data. Overall, we emphasize how utilizing the appropriate instruments can be used to avoid some common pitfalls in recording passive seismicity.

Introduction

Seismic events inherently are band-limited due to the nature of the generation process and their source failure mechanisms. The dominant frequencies generated for these events are related to the stopping phase of the rupture, which can then be related to the source dimensions (source radius) and source size (magnitude) of the event. This results in band-limited frequency content that can be considered to be characteristic of the particular event size being generated.

To properly characterize and interpret the behaviour of these events, appropriate instrumentation and sampling rates need to be utilized to maximize the usable bandwidth of the signals. For example, downhole monitoring of microseismic data (M < M0; Figure 1) during hydraulic fracturing and other fluid injection programs typically incorporates 15 Hz elements, which, in theory when shunted, provide a flat response, to within 3 dBs, from about 15 Hz up to about 1000 Hz (Figure 2). However, these elements are not the only part of the overall recording system, which also consists of the sensor pod, a cable (usually wireline) that suspends the pods, a mechanism to couple the pods to the wellbore, the coupling of the wellbore to the earth, and the digitizing/recording units. Each of these components introduces noise into the observed signal that can erode signal quality and thereby result in limiting the usable bandwidth. In the best-case scenario, the overall recording system yields an undistorted picture of ground motion from 15Hz to the Nyquist frequency as imposed by the digitizer or the high-frequency limit of the sensor around 1000Hz. More often, recording conditions translate into resonances ranging from about 350 to 750Hz, which, along with limitations due to the event generation process, results in a limited usable bandwidth. These signals can be further eroded due to attenuation effects and poor signal-to-noise ratios. As a result, only when these recording effects are taken into account can the analysis of recorded signals be considered.

To enhance bandwidth detection limits and increase the size scale recording range, the use of 15 Hz sensors needs to be augmented with low frequency sensors such as Force Balance Accelerometers (FBA's) and the use of low frequency 2 or 4.5Hz sensors which can provide bandwidth coverage from about .5Hz to 100Hz. These sensors generally are used to increase the size scale to include events with M > M0 and typically are installed close to or at the surface. Aside from issues that arise that are similar to downhole acquisition, installation effects such as ground conditions and proximity to surface have a profound effect on the observed signals. Moreover, magnitude saturation, caused by dominant periods longer than the recording system low cut-off, creates limitations on their interpretation.

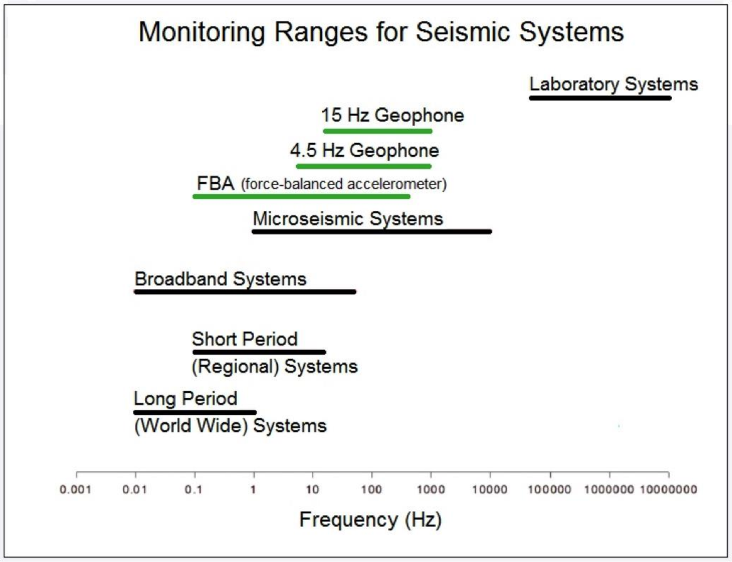


Figure 1. Frequency bandwidth covered by different types of sensors and the range most often monitored in hydraulic fracture and long-term reservoir monitoring.

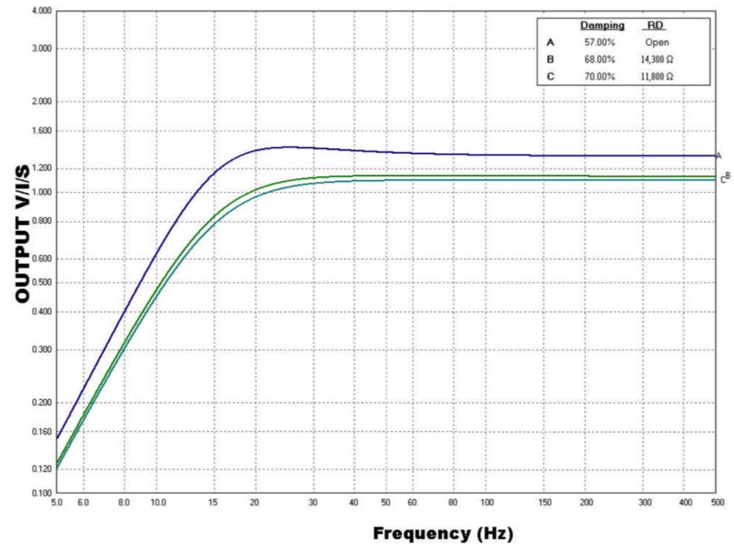
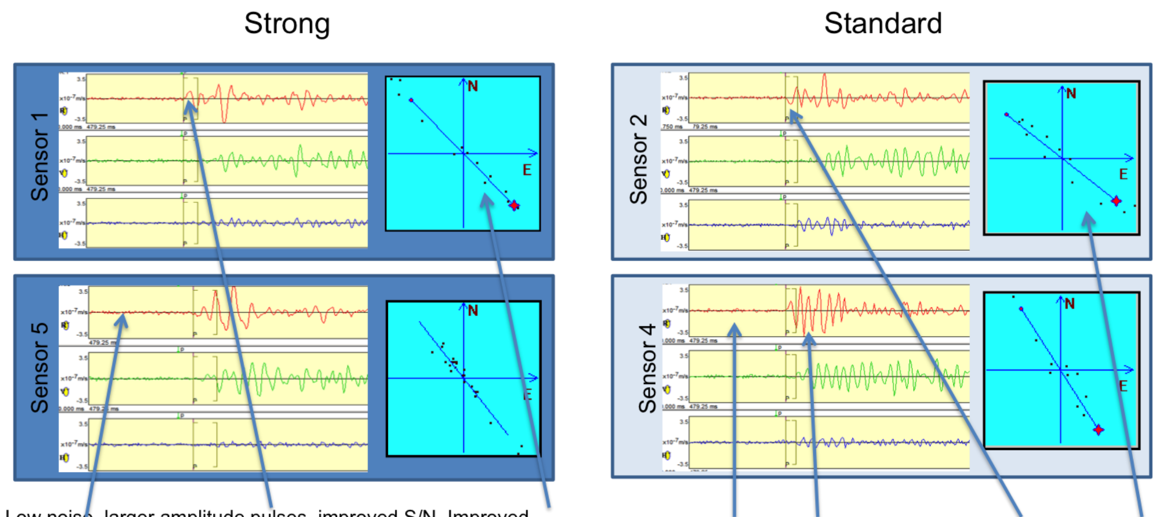


Figure 2. Response curve, un-shunted and shunted for omni-directional 15Hz elements typically deployed in downhole array configurations.

In this paper, we will discuss recording system design for effective monitoring of induced seismicity ranging in magnitude from -4 < M < +4. Based on data recorded using standard downhole approaches for both hydraulic fracture and long term reservoir monitoring we outline frequency and bandwidth limitations, as outlined above, examine resonance effects on interpretation, evaluate coupling effects associated with temporary deployments, and assess how these issues affect the interpretation of passive seismic data. By examining the spectral characteristics typical of signals recorded downhole and at or near the surface, we analyze the role of magnitude saturation and define the need for a hybrid sensor approach to record events over a broad magnitude range and avoid some common pitfalls in recording induced seismicity.

Downhole recording

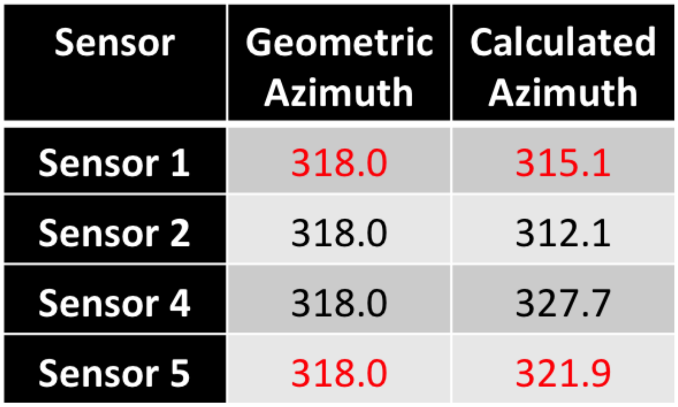
Downhole arrays utilized for hydraulic fracture monitoring are typically clamped arrays employing either magnets, bow springs or clamp arms to provide a good contact with casing. For magnet clamping, arrays are deployed by using weights to drag the arrays into the well. With deployments into the horizontal section of a well, the most commonly deployed approach is to utilize tractors and gravity coupling without any additional clamping devices. The effectiveness of different clamping approaches can be compared and analyzed, however, for the purposes of this discussion, we will focus on magnetic deployment as it is the most commonly used approach. In Figure 3, we provide signals recorded during a hydraulic fracture stimulation using a standard array configuration and off-the-shelf magnets provided by the array supplier. Signals are digitized at the sensors and transmitted through fiber to the surface. Sensors were also deployed within 15m of the standard sensors with stronger magnets, providing approximately 6 times stronger sliding resistance force and 3.25 times stronger pulling force than the standard magnets. Signals for these sensors are also as shown in Figure 3. In general, signals recorded with the stronger magnets had improved signal-to-noise and linearity than the standard magnets (Table 1). The standard signals also appeared to include resonances not observed with the stronger magnets.



Low noise, larger amplitude pulses, improved S/N, Improved linearity

Increased noise, resonance, smaller amplitude pulses,, more Scatter

Figure 3. Signals as recorded with sensors utilizing both standard and strong magnet configurations downhole. Depth of deployment was ~2250m. Signals have been rotated into raypath orientation.



Sensor	Geometric Azimuth	Calculated Azimuth
Sensor 1	318.0	315.1
Sensor 2	318.0	312.1
Sensor 4	318.0	327.7
Sensor 5	318.0	321.9

Table 1. Calculated azimuth based on hodogram analysis of rotated signals for standard magnets (sensors 2 and 4) and for strong magnets (sensors 1 and 5).

In Figure 4, displacement spectra are shown for the P-wave rotated signals in Figure 3. Based on the observed spectra, the usable upper bandwidth limitation for the sensors is ~700Hz. In the standard configuration, there appears to be an enhancement in amplitude at ~300-400Hz, likely the result of resonance in the sensor. Most interestingly, the stronger magnets provide flat spectral level with good signal-to-noise to 15Hz and amplitudes half of an order of magnitude larger than observed with the standard magnets. This translates to a magnitude difference of 0.3, suggesting that current deployments likely underestimate magnitude (see also Abercombie,1995).

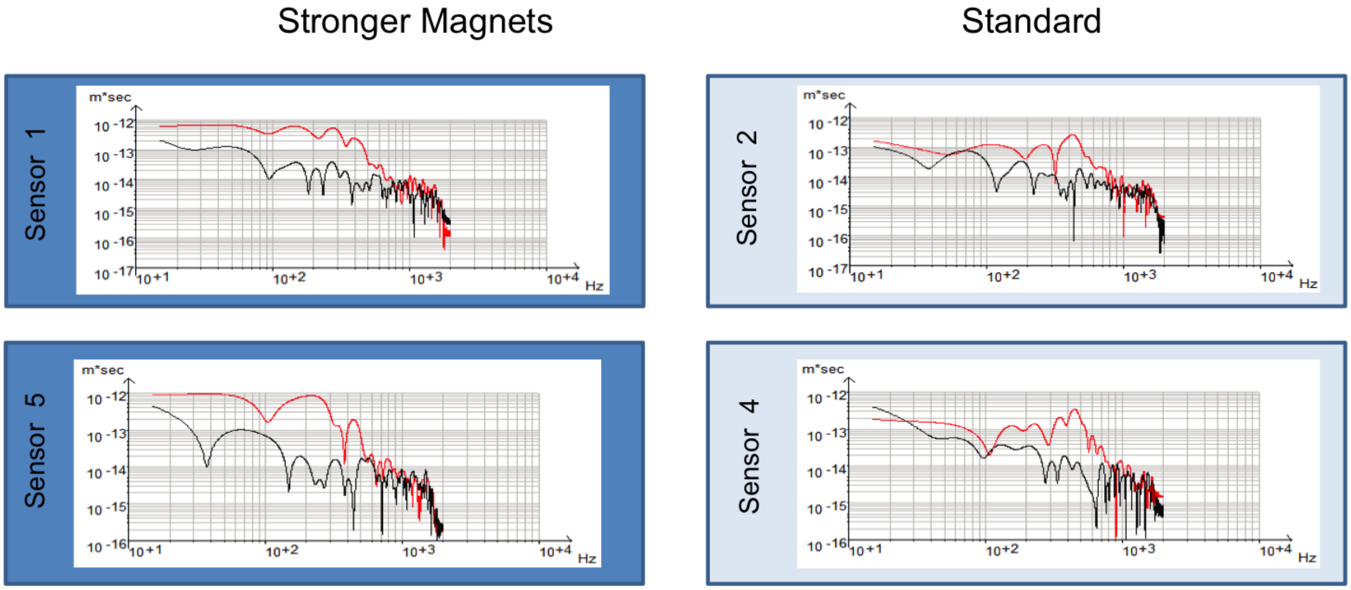


Figure 4. P-wave displacement (red) and noise (black) spectra for sensors with clamping provided by both strong and standard magnets.

Generally, as shown in Figure 3, the background noise is low but slightly elevated for the standard magnets. An examination of the noise floor for a series of 80 downhole shots, generally the background noise level is ~10^{-8}m/s. Over the entire array the vertical components (first channels of a sensor) have slightly higher noise levels for a subset of 80 events (Figure 5). This is likely due to lack of direct coupling in this direction. A similar observation can be made for the stronger magnets. The higher noise of the vertical components can also be observed in the frequency content of the background noise (windowed prior to the P-wave arrival). All sensors exhibit 60Hz noise and many sensors also show high amplitudes around 300Hz the tool resonance frequency

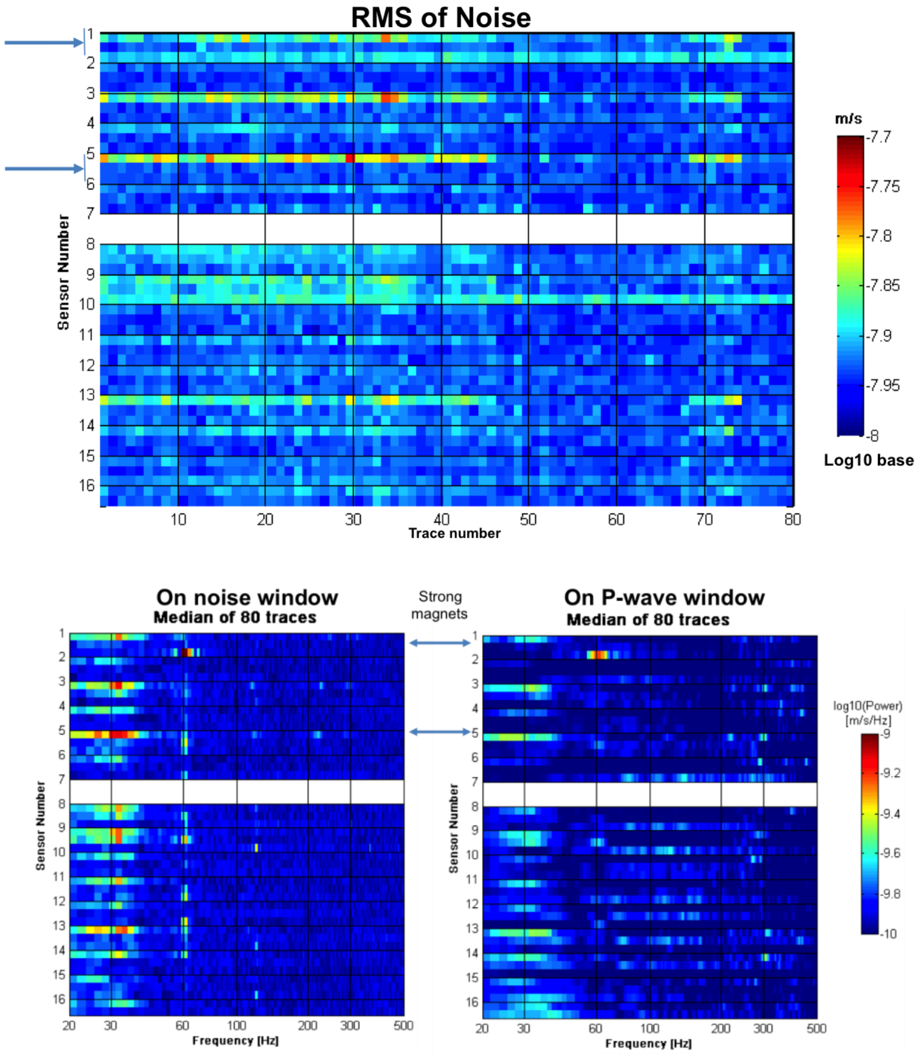


Figure 5. RMS noise (top) for a vertical array of sensors utilizing both standard and strong magnets (arrows) for 80 shots associated with a stimulation program. Sensor 7 was not operational during the survey.

Additionally, an examination of the hodogram data for the 80 known events for each sensor suggests that the sensor orientation does not necessarily remain stable over the duration of a survey (in this case 5 days). In Figure 6, we have plotted the azimuth for each shot point. As observed, for example, sensor 5, even with stronger magnets there appears to be a rotation in orientation over time, suggesting that the magnets are slipping in well. Variability from shot point to shot point is generally within 10 – 15 degrees with an overall rotation upwards of 25 degrees. A second observation, as seen for sensors 3 and 4, show significant swings in orientation upwards of 80 to 90 degrees. All tested magnet clamps consisted of 4 magnets at 90 degrees to each other and theoretically, any two magnets will be in contact with the well casing. The observed swings in orientation therefore can be explained by a flip in these ‘in-contact’ magnets, where one magnet remains in contact with the casing and the second magnet losses contact and is replaced with a third magnet that is now in contact with the casing. These observations strongly suggest that the use of hodogram data with magnetically clamped arrays can be severely compromised if there is no continued evaluation and correction for orientation throughout the survey.

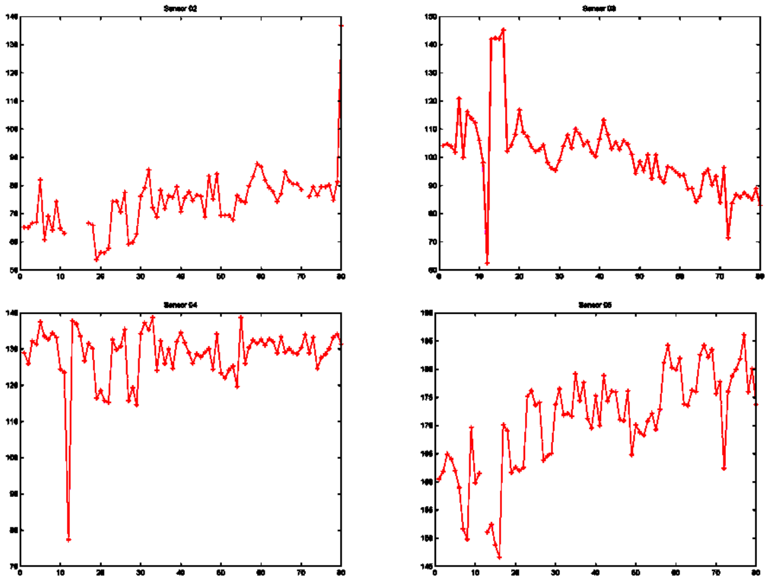


Figure 6. Azimuth from sensors 2,3,4,5 to the shot locations as determined from hodogram analysis for 80 shot locations carried out during the survey.

Near-surface and surface recording

A recent trend in the monitoring of passive seismicity has been to record signals with surface or near-surface based systems. Different types of sensors have been deployed, each with their unique characteristic signals that potentially information on injection based reservoir behaviour. One approach is to install high frequency 10Hz or greater geophones. More recently, near surface installations include low frequency 1Hz, 2Hz and 4.5Hz geophones and Force Balance Accelerometers (FBAs) which can record frequencies down to 0.1Hz or better. Viegas et al. (2012) discuss the advantages of such hybrid surface array.

As discussed earlier, passive seismic signals are band-limited in frequency, which is related to the rupture dimensions. For events with M < M0, the dominant frequency is typically above 100Hz (see Baig and Urbancic, 2010). As the magnitude increases for M > 0, the dominant frequency goes down and can result in magnitude saturation, where the dominant frequency is lower than the cut-off frequency of the flat response of the sensor (Figure 7). In these cases, the recorded signal will only contain a fraction of the overall energy released at the source and give the appearance of the event being smaller (magnitude) than it actually is. This issue can not only occur with typical downhole arrays but utilizing high frequency sensors at or near the surface can exasperate the problem due to attenuation affects on ray propagation.

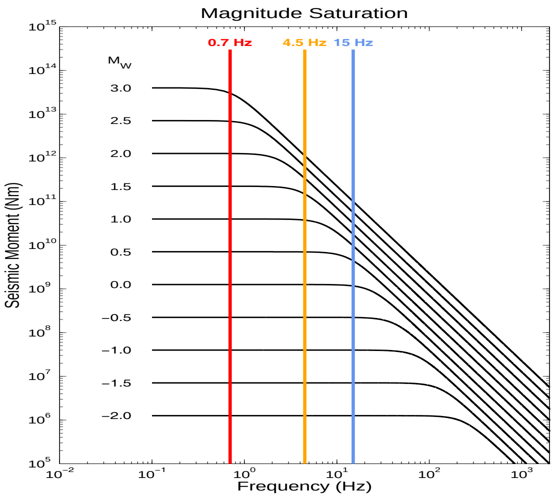


Figure 7. Magnitude saturation as defined for sensors corresponding to FBAs (red), 4.5Hz geophones (yellow) and 15Hz omni-directional geophones.

In Figure 8, we show the P-wave signal as detected at the surface using a triaxial FBA and the equivalent signals on a 15Hz omni-directional triaxial geophone. In both examples the spectra have been corrected for geometrical spreading and Q based on a slope of -2 fall-off in frequency (according to the Brune model). Based on the FBA signals, the event magnitude as determined from the spectral plateau would be M = 2.9. As well, the corner frequency fc = 6 Hz, assuming a Brune-type shear failure, suggests that the event occurrence is related to a structure with a source radius ro = 200m. Whereas, the 15Hz sensor, due to the nature of the sensor, does not see the lower frequency data and therefore would provide a magnitude of M = 1.8 and ro = 60 m based on a fc = 20Hz (see Aki and Richards, 2002). These observations suggest that using high frequency geophones at surface could potentially result in a mis-representation of size scale of events being generated in the reservoir thereby affecting the potential interpretation of magnitude and fracture distribution, and ultimately in the interpretation of the discrete fracture network activated at reservoir depth. Based on these observations we can further suggest that effective monitoring can only be achieved if a full suite of sensors are deployed thereby allowing for the full magnitude range of -4 < M < +4 to be recorded for proper interpretation (Viegas et al., 2012).

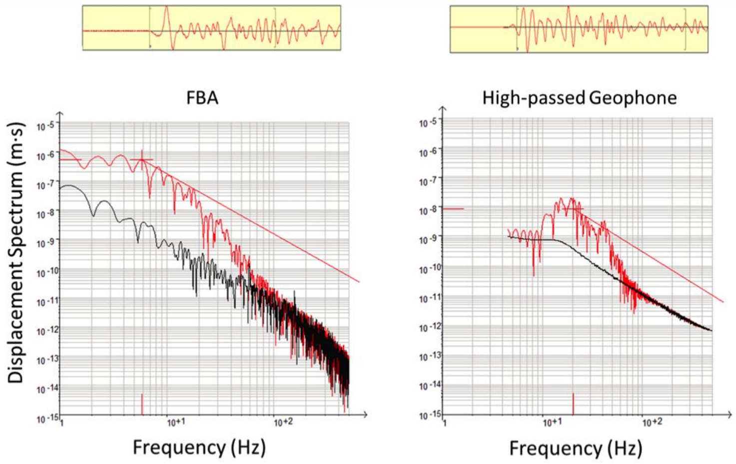


Figure 8. P-wave displacement (red) and noise (black) spectra comparison between a signal recorded on a FBA and equivalently on a 15Hz geophone.

Conclusions

As discussed, most passive seismic monitoring of hydraulic fractures employs either downhole or near-surface high-frequency geophones. In downhole applications these instruments are generally sufficient to accurately characterize events with M < 0. However, limitations or issues in coupling can result in underestimates of event size and poor hodogram quality leading to mis-locations. We also showed how temporary deployments, commonly used in hydraulic fracture stimulations, can result in increased presence of resonance and noise that can lead to further mis-interpretation. In all aspects of recording, the operator needs to understand these potential pit-falls and be able to provide corrections during any monitoring program. We also discussed the need for deploying longer period instrumentation such as Force-Balanced Accelerometers (FBAs), broadband seismometers or 4.5 Hz geophones to effectively monitor for larger-magnitude events (M > 0) that have correspondingly lower dominant frequency signals. We showed that the recording of microseismic events at or near surface utilizing high-frequency sensors also suffers from the fact that higher dominant frequencies associated with events generated in the reservoir are heavily attenuated in the frequency band of interest. In fact, signals observed with near-surface, high-frequency sensors are likely related to larger events (M > 0) occurring in the reservoir that appear to be smaller in magnitude as only a portion of the signals are recorded with currently-installed arrays. Based on observations, by utilizing the appropriate instrumentation, full coverage can be attained for events generated between -4 < M < +4 and a complete image of the reservoir can be attained.

References

Abercombie, R., 1995, Earthquake source scaling relationships from -1 to 5 M L using seismograms recorded at 2.5-km depth, JGR, 100, 24015-24036

Aki, K. Richards, P.G., 2002, Quantitative Seismology, University Science Books

Baig, A. M., and Urbancic , T. I., 2010, Microseismic moment tensors: A path to understanding frac growth, The Leading Edge. 29(3), 320-324

Viegas, G., Baig, A.M., Coulter, W., Urbancic, T.I., 2012, Effective monitoring of reservoir-induced seismicity utilizing integrated surface and downhole seismic networks. First Break, 30, 77-81