Semblance-weighted stack for improved microseismic monitoring

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Summary

Surface microseismic monitoring can be challenging due both strong surface noise and weak signal generated by the hydraulic fractures. Therefore it has become common practice to deploy very large numbers of geophones to allow for the detection of the very small events, primarily through stacking techniques. The cost of acquiring and processing such large datasets, can be prohibitive and, therefore, may not be the most practical design for all monitoring applications. While more sensors theoretically improve the signal-to-noise ratio by $\sqrt{N}$, where, N is the number of measurements, this assumes prior removal of coherent noise sources. Large densely sampled patches remove the coherent surface wave noise through an F-K filter. We demonstrate that semblance-weighted stacking yields similar noise attenuation and improves signal-to-noise of arrivals. We also show that array design impacts signal-to-noise of arrivals and that a hexagonal array provides greater uplift than linear arrays given equal channel count.

Theory

While magnitude is often assumed to govern our detection threshold in microseismic monitoring, in reality, we are constrained by the signal-to-noise ratio (SNR) of a given arrival. This is a function of the moment magnitude of the seismic event, the attenuation of the earth from source to receiver and local noise conditions. As we are limited in our ability to directly alter the signal or the noise, we must use signal processing techniques to increase the SNR. To facilitate this, sampling the wavefield as completely as possible is optimal. Thus to increase the SNR in microseismic monitoring it is common to deploy a large number of sensors. Recently, the “patch” acquisition design (e.g. Schisselé-Rebel and Meunier, 2013, Shuck et. al, 2015) has become a common choice. The patch design consists of a small number (10’s) of sparsely distributed patches each of which is densely sampled. The patch design addresses coherent noise through F-K filtering to attenuated surface noise (Petrochilos and Drew, 2014). The SNR is further increased through stacking the large channel count, which theoretically increases the SNR by $\sqrt{N}$, where, N is the number of measurements (Drew et. al, 2014, Cieslik et. al, 2016). To achieve the full $\sqrt{N}$ increase we require that a given patch is small enough that the signal is the similar within the patch, a moveout correction is applied to account for arrival time differences across the patch, and only random noise remains.

We show that a semblance-weighted stack (Chambers and Booterbaugh, 2018) improves the SNR beyond a simple stack and we increase the SNR beyond √N. The basic idea of semblance-weighted stacking is that a time-varying measure of consistency is used to weight the stack. If all stations recorded the same arrival at the same time then there is high degree of consistency and the stack is up-weighted at this time. This corresponds to an upcoming arrival such as a seismic event. However, if a similar arrival hits each station at a different point in time, such as a surface wave, there is a low degree of consistency and the stack is down-weighted. Chambers (2018) shows that the semblance-weighted stack can significantly increase the SNR over an individual channel. We extend this analysis and demonstrate that the use of semblance-weighted stack provides the same SNR values as significantly more stations simply stacked.

Results

Two surface networks were deployed to monitor a 26 day, three-well hydraulic fracturing program in the Duvernay formation in Alberta, Canada. The primary monitoring network consisted of 25 patches. Each patch recorded 96 channels with each channel comprised of 12 vertical component (1C) geophones for a total of 28800 instruments. Each patch consists of 6 lines with 16 channels per line with inline and crossline sampling of 7.5 and 20m, respectively. Simultaneously, a small pilot network of 8 “super stations” were co-located nearby a subset of the patches to test the efficacy of an alternative acquisition design. Each super station consisted of 6 3C nodal geophones in a hexagonal pattern with intra-station distances of approximately 15m. This design allows for the application of noise filtering techniques on both individual channels and the array. The 3C geophones allow for utilizing S-wave arrivals in the detection and location of seismicity. While we would not advocate an array this small for a full microseismic monitoring program, the objective was to demonstrate the proof of concept and calibrate modeling parameters to estimate the performance of a larger super station array.

To compare the value of the super station acquisition and semblance-weighted stack, we select stations from the 8 patches closest to the super stations. For 20 events detected across both arrays, we calculated the SNR on both the super stations and various sensors within the patch using simple stack and semblance-weighted stack. To extract sensors from the patch, we choose the center point and added stations to the stack by spiraling outward. The only preprocessing we apply to the data are a detrending and despiking algorithm prior to the stacking algorithms. Including a filter or correcting for moveout across the patches would improved SNR.

Figure 1 shows the results of the various stacks. The red points are the individual SNR values for patch-event pairs using the simple stack and the solid red line is the mean.

The box is the interquartile range across all 8 patches and 20 events for the basic stack. The points and line in blue are the semblance-weighted stacks for the same channels. For reference, the dashed black line is the theoretical √N curve normalized to the average SNR using a single station. The orange and green dots show the average SNR for the P-wave arrival on the vertical component at the 8 super stations for the same 20 events using the simple and semblance-weighted stack, respectively. The yellow and green stars are the same as the dots increased by √12 to make the results comparable to the geophone groups in the patch data.

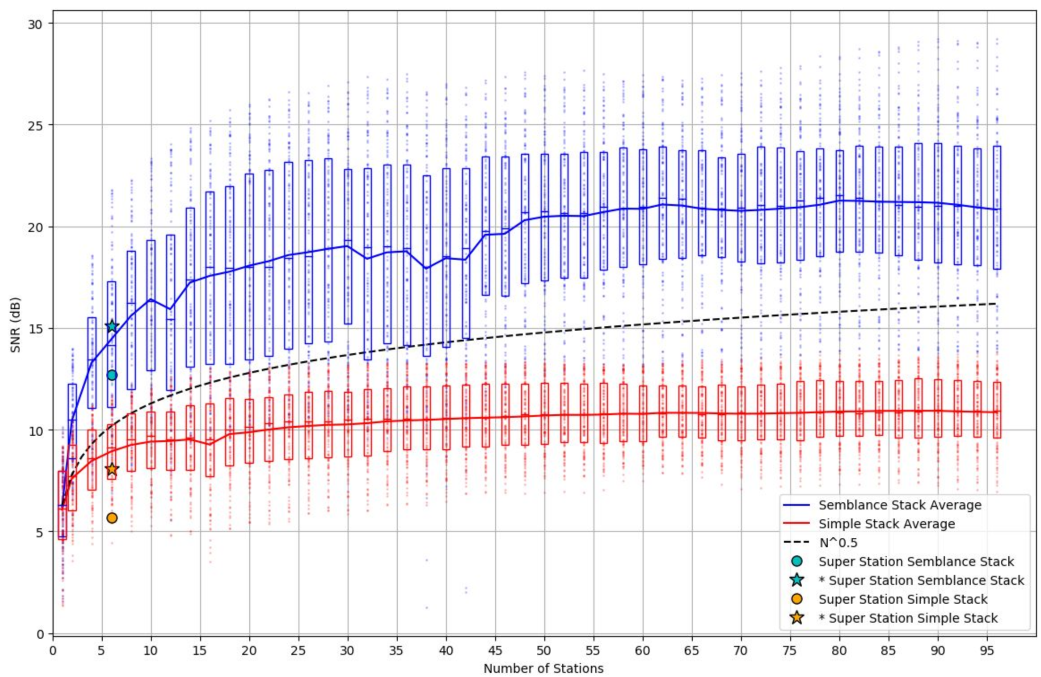

Figure 1: SNR values for 20 events on 8 patches (red and blue) and 8 super stations (yellow and green) using simple and semblance-weighted stack.

Discussion and Conclusions

Similar to Cieslik and Artman (2016), the simple stack result diverges from the theoretical curve at very few stations and there is limited benefit of large numbers of sensors. This is likely due to a number of factors, including failing to remove coherent noise from the data.

By applying the semblance-weighted stack (blue line), we see a bulk shift increase in SNR and now we more closely fit the √N curve. This implies that the semblance-weighted stack has effectively attenuated the coherent noise and the stack is attenuating incoherent noise.

The super station results for the simple stack have a lower SNR than the patch data using the same number of channels (6). We interpret this to be the benefit of using very dense inline station spacing with the patches. In contrast, when applying the semblance-weighted stacking, we see a theoretical increase in SNR over the patch data (assuming a $\sqrt{12}$ to account for the geophone string). This suggests that the hexagonal design provides superior filtering of the data to account for various surface azimuths compared to two lines of 3 stations in the patch. Although not shown, these patterns are consistent across event size.

We suggest that prior to acquisition a careful presurvey modelling is performed that takes into account local noise levels, local geology, and expected event magnitude to design the most cost effective array to meet the projects objectives. Smaller, and potentially more, carefully designed patch geometries, such as the hexagonal super stations shown here, may provide equivalent results to larger rectilinear patches. In addition, one of the main benefits of the large dense patch geometry is the ability to filter surface noise coming from multiple directions. We show that the super station hexagonal geometry provides coherent noise attenuation using a very limited number of sensors. After removing coherent noise, the SNR is a function of channel count. Thus, more small channel count hexagonal, or similar, sub arrays are a potential alternative to the large patch grids.

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