Using real-time microseismic array performance prediction to construct optimal arrays

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Summary

Microseismic monitoring arrays are required to detect the smallest possible event, or to guarantee detection of an event of some minimum size. Diverse geometries and performance metrics have been proposed over the years. Existing methods underestimate or neglect completely the spatial variation of site noise. A simple method is developed for comparing the performance of one array geometry to another which does take the variation of site noise with geography into account. A case study from a recent site survey in Duchesne County, Utah is included to show how such an array metric might work in practice. With such tools in hand for assessing array performance it becomes possible to assess array performance as the sensors are being installed, thus maximizing performance while minimizing installation effort.

Introduction

Past work on array performance has focused on the effect of velocity model errors, timing errors and array geometry on location accuracy and other metrics (Bormann 2002). The variability of site noise, if it is treated at all, is treated in terms of rules to follow when selecting sites. The primary concerns in this regard are geology – hard rock sites are preferred – and cultural noise – to be avoided at all costs.

An alternative approach is to consider the site noise field in a particular area as a variable to be considered like any other in the prediction of array performance. In particular higher levels of ground motion mean lower signal-to-noise ratio. This does not mean that data with low signal-to-noise ratio should be discarded. On the contrary, an accurate measurement can be obtained from many less accurate measurements via averaging.

The performance of arrays used to detect distant events is well-treated, (Bormann, Engdahl and Kind 2009) (Kvaerna 1989) (Mykkeltveit, et al. 1983), and we can take that work and extend it using some basic principles of stochastic data analysis (Bendat and Piersol 2000). With such a tool in hand, rather than attempting to optimize an array before deployment (Rabinowitz and Steinberg 1990) it becomes possible to optimize the array *as* it is being deployed.

Method

There are many factors which need be taken into account in assessing the performance of a seismograph array, but many of them can be summarized as follows:

$$variance = \frac{noise}{signal} = \frac{sensor + site}{event}$$

Where the variance is the expected squared error in a measurement, and the components of the signal and noise are powers, i.e. squared amplitudes.

Each of these quantities varies with frequency, so the result isn't a single value. But if we can plot each of the sensor noise, site noise and event spectra together on one plot, such as that shown in Figure 1, we can assess detection thresholds for various magnitudes of events and choices of site and sensor.

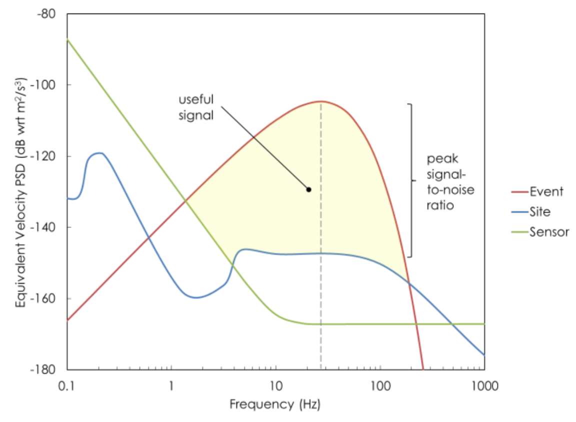

Figure 1: Hypothetical System Detection Limit Study

An event is then detectable if the variance is greater than some threshold determined by the processing algorithm chosen, say 6 dB. It is beyond the scope of this document to determine the exact threshold for a particular algorithm, but consideration must be given to available computing power, and requirements for latency and magnitude and location accuracy. In general, one sensor – or array – will outperform another in the sense of yielding more accurate measurements if the "area" of useful signal is greater.

The remaining problem in assessing the performance of an array is that it is not sufficient to consider each site separately; the array must be considered as a whole. The method proposed here is to find a way to collapse multiple sensors at multiple sites into a single equivalent super-

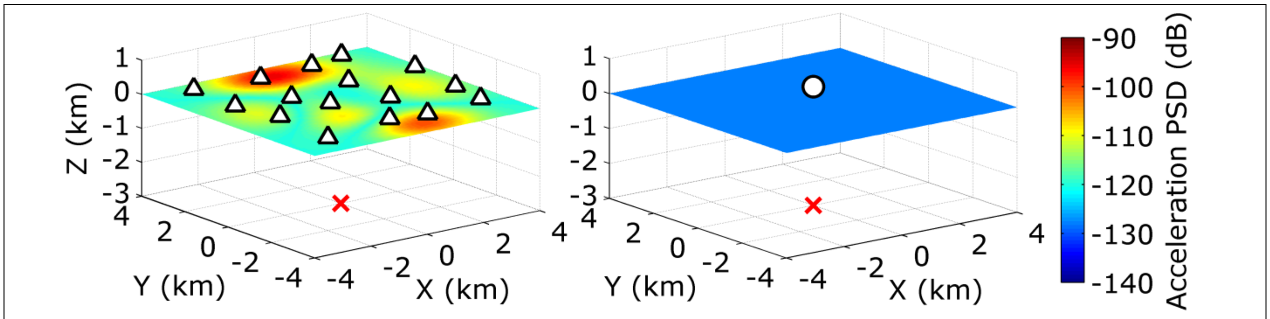

Figure 2: Representing an Array of Sites Δ with a "Super-site" O

sensor at a super-site. This notion of a "super-site" is represented schematically, for a hypothetical ambient noise field, in Figure 2.

It can be shown that the equivalent site noise for arbitrary site noise, coherence and weights, is

$$N_{eq} = \sqrt{\sum_{i=1}^{m}\sum_{j=1}^{m} w_i^* w_j G_{ij}}$$

Taking into account both the variation in the noise field and geometric spreading, we have the following estimate for the variance at each site:

$$\sigma_i^2 = \frac{S_i^2}{N_i^2} = \frac{S_0^2}{N_i^2\sqrt{1+\frac{r_i^2}{d^2}}}$$

Of course the weights then need to be normalized, so the result is

$$w_i = \frac{\dfrac{1}{N_i^2\sqrt{1+\frac{r_i^2}{d^2}}}}{\sum_{i=1}^{m}\dfrac{1}{N_i^2\sqrt{1+\frac{r_i^2}{d^2}}}}$$

The cross-spectral density of propagating noise between two sites can be shown (Mykkeltveit, et al. 1983) to be related to be related to the Bessel-function of zeroth order

$$G_{ij}(f) = P(f)J_0(k_0 r_{ij})$$

Where the wavenumber relates to the frequency as $k_0 = \frac{2\pi f}{v_0}$.

This Bessel function has a first zero at $k_0 r_{ij} = 2.4$ and a first minimum at $k_0 r_{ij} = 3.8$. The correspondence between this model and the measured results at NORESS is shown in Figure 3.

This is a highly frequency-dependent effect. The NORESS array was directed at detecting regional or teleseismic events. Figure 3 in particular was directed at the frequency range 1.6 to 4 Hz. Microseismic monitoring arrays are directed at detecting events for which the peak signal-to-noise ratio is nearer to 30 Hz. For such a hyper-local event the first zero-crossing of the correlation will be closer to 70 m than 700 m.

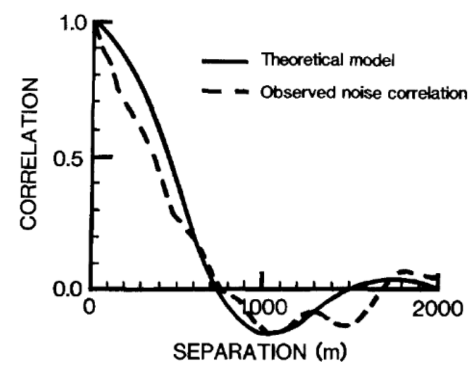

Figure 3: Coherency of propagating noise

There remains the problem of estimating the cross-spectrum G_{ij} from the site noise G_{jj} and G_{jj}. One possibility is that the noisier site is noisier because of localized amplification effects, in which case there is effectively a non-unity transfer function between location i and location j, and by analogy with the definition of coherence

$$G_{ij} = \sqrt{G_{ii}G_{jj}}J_0\left(\frac{2\pi f}{v_0}r_{ij}\right)$$

There are other ways of estimating the cross spectrum, for example, assuming that noisy sites are noisier only because of localized independent noise sources. The above estimate is preferred, however, because it overestimates the cross spectrum and thus is more pessimistic in terms of stacking gain.

Real-time array performance prediction

Putting it All Together

The required inputs for this simple model are:

- the proposed site coordinates x_i and y_i
- an estimate of the noise at each site N_i
- the expected event depth d
- an estimate of the frequency at which peak signal-to-noise occurs f_p

Then the equivalent array site noise is

$$N_{eq}(f) = \sqrt{\sum_{i=1}^{m}\sum_{j=1}^{m} w_i^* w_j |N_i(f)||N_j(f)| J_0\left(\frac{2\pi f}{v_0} r_{ij}\right)}$$

Where the weights are be chosen to be optimal at a particular frequency f_p

$$w_i = \frac{\dfrac{1}{|N_i(f_p)|^2\sqrt{1+\frac{r_i^2}{d^2}}}}{\sum_{i=1}^{m}\dfrac{1}{|N_i(f_p)|^2\sqrt{1+\frac{r_i^2}{d^2}}}}$$

This reduces to the familiar result of $\sqrt{m}$ improvement for a uniform noise field at high frequencies because at high frequencies the Bessel function evaluates to unity for $i = j$ and negligible for $i \neq j$.

This method of computing equivalent site noise attempts to account for the effects of optimally-weighted stacking, geometric spreading and spatial coherence. The result is the noise at a hypothetical super-site located directly above the event. Of course there are many potential difficulties in achieving the performance predicted by such an estimate.

One potential problem is that the noise must be stationary and reasonably Gaussian. Furthermore, both the geomechanics between the source and receiver, and the sensors themselves, must furthermore be reasonably linear.

Perhaps most importantly, however, the implementation of the optimally-weighted stack may be non-trivial. Accounting for time delays is relatively straightforward, but accounting for the radiation pattern may require a computationally expensive grid search of possible source mechanisms. Still the intent here is to assess the relative performance of arrays, not processing algorithms, so the assumption of perfect post-processing seems reasonable.

Case Study

Arrays designed for noise field surveys will in general not be optimal for microseismic monitoring. This being said, it will often make sense to leave the initial survey stations in place as the array is optimized.

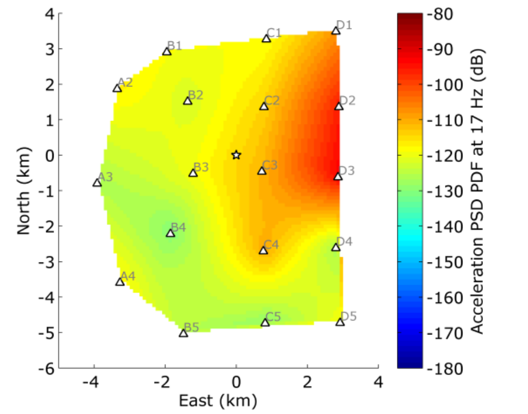

Figure 4: Initial survey array and measured noise field

Figure 4 shows the locations of some Nanometrics Trillium Compact seismometers deployed for a noise field survey, along with the measured and interpolated ground motion acceleration PSD.

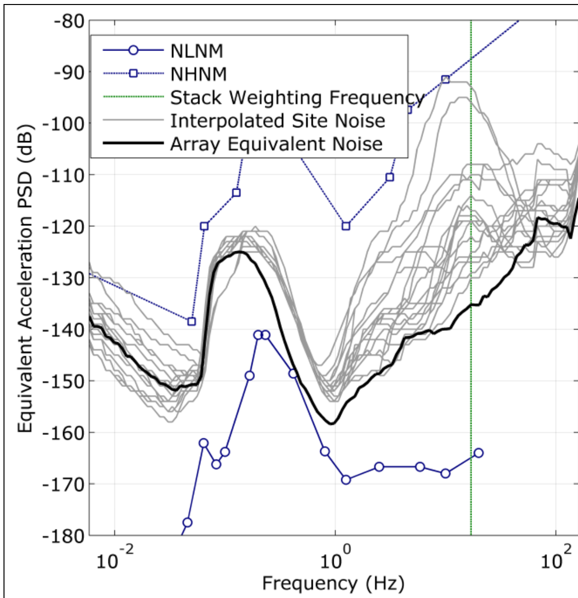

Figure 5: Initial survey site noise spectra

Figure 5 shows the full acceleration PSD noise spectrum for each site, and the equivalent array noise with optimal weighting.

A stack weighting frequency of 17 Hz was chosen as a compromise between the extreme variability of site noise peaking at 10 Hz and event spectra peaking at 30 Hz. By choosing optimal weights at 17 Hz, where the site-to-site noise variation is greatest, better discrimination of good sites vs. bad sites through weighting could be obtainable.

Real-time array performance prediction

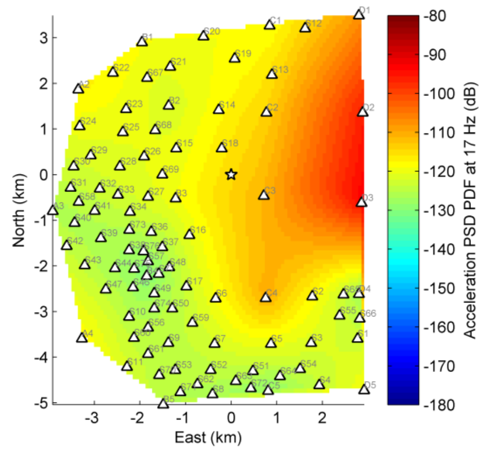

Figure 6: Optimized array locations

Once an initial survey has been performed, with the right tools, it is possible to immediately begin the task of optimizing the array. The general idea is to densify the array in the areas identified as having low site noise, while keeping in mind the need to maintain a wide aperture in order to obtain good location accuracy.

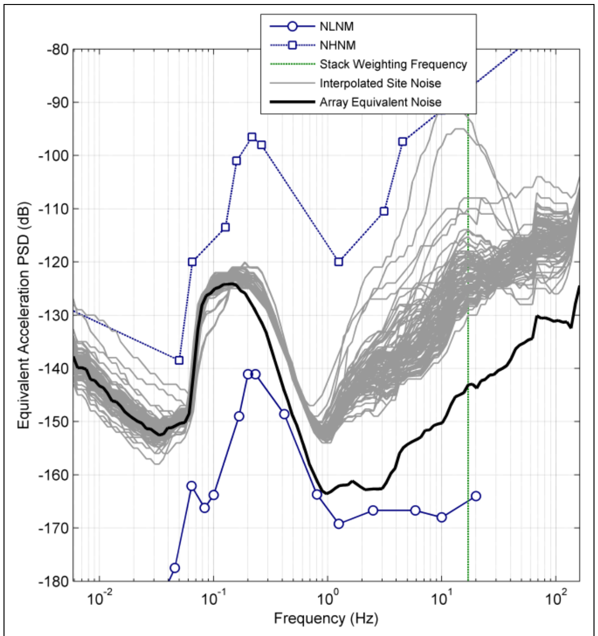

Figure 7: Optimized array site noise spectra

One can envision a process whereby as each sensor or set of sensors is installed, a new updated estimate for the overall array performance is obtained, and this process continues only until the moment when the equivalent array site noise requirements have been met. A possible end result of such a process of array optimization is depicted in Figure 6 and Figure 7.

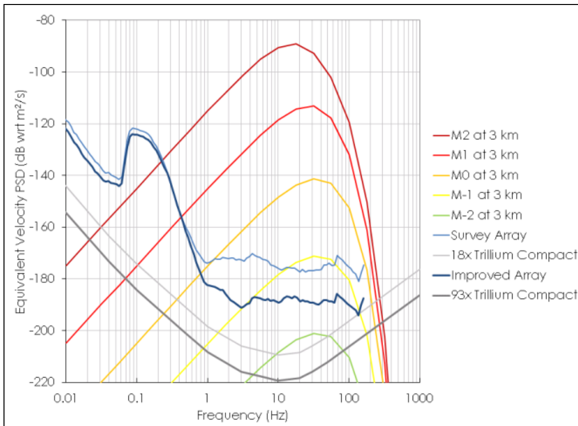

Figure 8: Optimized array detection limit study

Figure 8 is a system detection limit study for the survey and optimized arrays. The preliminary survey array of Trillium Compact seismometers should just barely be able to detect M-1 events, for a required signal-to-noise ratio of 6 dB. The improved array shows a significant improvement in signal-to-noise ratio, with a threshold of detectability of M-1.2, for the same required signal-to-noise ratio.

All of these figures can be generated in the field, providing immediate feedback to the installation crew.

Conclusions

A method has been developed for estimating microseismic array event detection given an estimate of the site noise field. The method is simple enough to be applied in real-time as sensors are being installed, opening up the possibility of optimizing a microseismic array on-the-fly.

A case study from Duchesne county shows how, after an initial survey with 18 sensors, this analysis could be used to guide the placement of an additional 75 sensors, achieving an 8 dB improvement in detection threshold.

Acknowledgements

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