Ambient Passive Seismic Imaging with Noise Analysis

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SUMMARY

The *ambient passive seismic imaging* technique is capable of imaging repetitive passive seismic events. Here we investigate the effect of noise for this method. These *repetitive* events are the passive seismic sources that emit the seismic energy from a certain subsurface location for a certain amount of time. For example, we assume that drill-bit noise, injection tremors, or long period long duration events occurring during the process of drilling and hydraulic fracturing can be considered to be these kind of the events. Our mathematical analysis provides an understanding of the effectiveness of the imaging in the presence of random and/or coherent noise. We provide synthetic examples to verify our derivation. We conclude first that creating images (averaging) along "long" time windows does not improve the signal-to-noise ratio but does improve the capability to detect repetitive signals by reducing the effects of random noise. Moreover non-random noises such as coherent low velocity surface waves are not reduced by this method, are aliased into the image, and can be misinterpreted as subsurface signal.

INTRODUCTION

Conventional passive seismic imaging is efficiently used in locating induced microseismic events due to hydraulic fracturing that have an impulsive character (Duncan and Eisner, 2010). Most of the energy for these events occurs in a short time window (few tens of milliseconds) in the vicinity of the hydraulic fracturing activity and have a distinct waveform. On the other hand, other passive seismic subsurface events such as drill bit noise, injection tremors, and long period long duration events have a repetitive/continuous nature. To image such events we need a different imaging technique that we investigate here and call ambient passive seismic imaging (APSI). Note that this imaging algorithm is similar to conventional imaging. The key difference is in the size of time window that is utilized for creating an image (Geiser et al., 2006).

We will provide the details of the APSI technique in the theory section. In the presence of white Gaussian noise in the data, we derive a probabilistic solution for each image location and we verify the solution in a numerical (synthetic) simulation. Moreover, we investigate and comment on the effect of a slow velocity surface noise on the imaging technique. Finally, based on the analysis, we suggest the limitation of the technique.

THEORY

Source function and creating an image – In the high-frequency approximation of acoustic wave propagation, the linear inversion operator often called a *Beamformer* (Johnson and Dudgeon, 1993) or *Kirchhoff* (Borcea et al., 2011) operator, if ap-

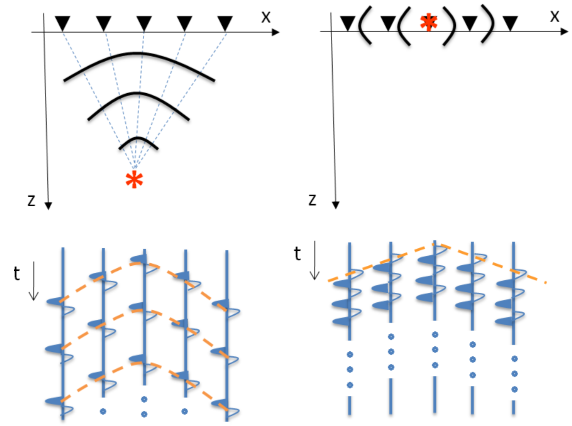

Figure 1: 2D sketch of the synthetic signals: a periodic subsurface repetitive signal (top left) and its corresponding gather at surface receivers (bottom left); and a surface narrow bandwidth noise (top right) and its corresponding gather at surface receivers (bottom right).

plied to passive seismic data $\{d(\mathbf{x_r},t)\}$ may approximate the isotropic seismic source $f(\mathbf{x},t)$. In its simplest form,

$$f(\mathbf{x},t) = \{\mathcal{F}^{*}\mathcal{F}\}^{-1}\mathcal{F}^{*}\{d(\mathbf{x_r},t)\} \approx \frac{1}{R}\sum_{r=1}^{R} d(\mathbf{x_r}, t+\tau(\mathbf{x_r},\mathbf{x})), \tag{1}$$

where R denotes the number of receivers, and $\tau(\mathbf{x_r},\mathbf{x})$ is the travel-time from the receiver location $\mathbf{x_r}$ to a given point in space $\mathbf{x}$.

In addition, once we estimate the source, the seismic image may be created. Here we use an *the average energy* (Mandal and Asif, 2007) of the source $f(\mathbf{x},t)$ over a specific time-range samples $[0, T-1]$

$$\mathbf{i}(\mathbf{x}) = \frac{1}{T}\sum_{t=0}^{T-1} f^2(\mathbf{x},t). \tag{2}$$

Note that T is the number of time samples, so if the duration of time is ΔT, then $T = \frac{\Delta T}{\Delta t}$, where Δt is the sample rate.

Imaging of signal with random noise — Suppose that the broadband *repetitive* seismic signal $w(t)$, with the average energy e_w, arrives from a location $\mathbf{x_s}$ to receiver locations $\mathbf{x_r}$ (Figure 1 left) is contaminated with white Gaussian noise $n(t) \sim \mathcal{N}(\mathbf{0}, \sigma^2\mathbf{I})$, such that

$$d(\mathbf{x_r},t) = s(\mathbf{x_r},t) + n(t),\ \forall r = 1,...,R \tag{3}$$

Using random variables theory together with the Central Limit Theorem (Navidi, 2010), estimating the source function (Equation 1) and creating the image (Equation 2) of such data lead us to the probabilistic solution of any image value, $\mathbf{i}(\mathbf{x})$, and specifically, at source location $\mathbf{x_s}$:

$$\mathbf{i}(\mathbf{x_s}) \sim \mathcal{N}(e_w + \frac{\sigma^2}{R}, \frac{2\sigma^2}{RT}(2e_w + \frac{\sigma^2}{R})), \qquad (4)$$

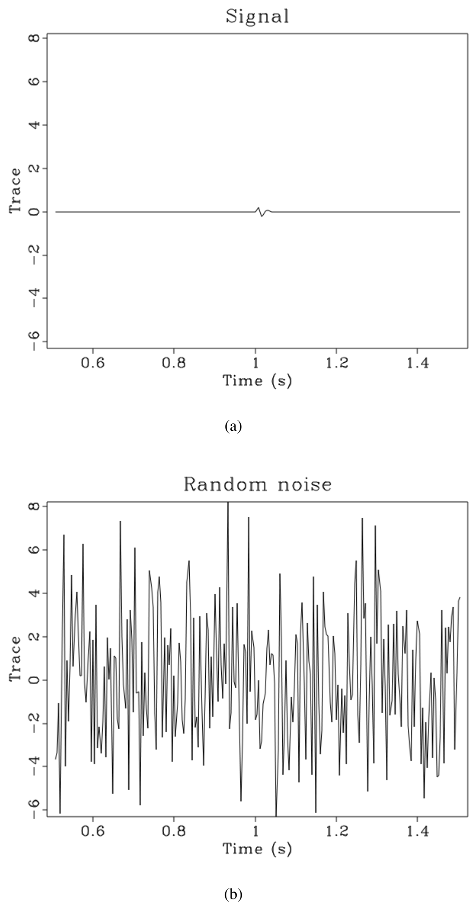

Figure 2: a) Signal with average energy $e_w = 5 \times 10^{-4}$, b) Gaussian noise with the variance $\sigma^2 = 9$

There are a few interesting points we can draw from the equation:

First, to correctly resolve a coherent periodic signal that is contaminated with Gaussian noise, the variance of the image value, $\frac{2\sigma^2}{RT}(2e_w + \frac{\sigma^2}{R})$, should be sufficiently small, so that the image value at the repetitive signal location may be distinguished from the other values. For a given repetitive signal and random noise, the variance can be reduced by increasing the number of receivers, R, or time samples of the data, T. Theoretically, in order to reach a variance of zero, one needs to use an infinite number of receivers and/or averaging along infinite time samples. However, in practice, we aim for a "sufficiently" small variance. Second, the derived mean, $e_w + \frac{\sigma^2}{R}$, of the image values is not a function of T at all. Therefore the averaging over time does not affect signal to noise ratio. To improve the mean or signal-to-noise ratio, we must change the receiver number (R).

In the next section, we show a satisfactory match between numerical and analytical results for Equation 4, which allows us to get quantitative insight into the choice of the number of receivers and the time duration of the data for an effective APSI.

NUMERICAL EXAMPLES

Subsurface repetitive signal and random noise — Here, we apply APSI technique to a synthetic dataset that includes the isotropic repetitive source, Figure 2(a), which is a 1s-periodic minimum-phase Ricker wavelet with 30 Hz central frequency at 3000 meters depth and white Gaussian noise, Figure 2(b). Both the signal and noise are plotted on the same scale in Figure 2, suggesting very low pre-imaging signal-to-noise ratio (SNR=5.5×10^{-5}). For these examples, we use a surface star array consisting of eight arms with 125 receivers on each arm and a 25-meter receiver interval. Without loss of generality we assume that seismic P-wave velocity is constant, $3000\frac{m}{s}$. The time sample rate is 4 ms. The APSI workflow is applied on the dataset and the cumulative images (averages over given time) are created with different time windows ΔT: 1, 100, 200, and 600 seconds, Figure 3. The location of the repetitive signal is identified at time of 200 seconds, although at the cumulative image of 600 seconds, the resolution is improved.

On the same figures, we also plot the predicted probability density functions of the image value at source location ($\mathbf{x_s}$) and of the image value horizontally separated by 1000 m ($\mathbf{x_f}$), based on Equation 4. As previously discussed the mean of the distributions stays the same; only variances decrease by increasing T. Clearly, a one second window is not sufficient to distinguish these two values. For $\Delta T = 100s$, there is still a small overlap between predicted distributions. Finally, in both cases for $\Delta T > 200s$, the "gap" between distribution is sufficient to visually identify the location of the given repetitive signal in the presence of the given noise.

Therefore, based on the average energy of the signal, the variance of the noise, and the number of receivers, using Equation 4, the sufficient time duration of the data to identify the given repetitive signal can be calculated.

Coherent noise — Coherent surface noise is the dominant noise feature of nearly every hydraulic fracture monitoring data (Figure 4) representing more than 70% of recorded energy. Furthermore, it is a constant feature throughout the recorded time and very difficult to reduce through processing. On Figure 4, we plot the spectra of entire array made at three minutes interval for a day. On the figure, we can see that the coherent noise can be very strong and narrow-band: A) it can last for days/months or B) it can have relatively short duration.

In the random noise synthetic example, the variance is reduced and the signal is revealed by time averaging. The technique defines a kind of random noise "threshold" - $\frac{\sigma^2}{R}$, and with sufficient time window *any* subsurface signal can be identified. However, this is not the case if coherent noise is present: just as repetitive signal is enhanced by the reduction of random noise in the time averaging process, *repetitive non-random noise is enhanced*. Nevertheless, we still have the chance to identify

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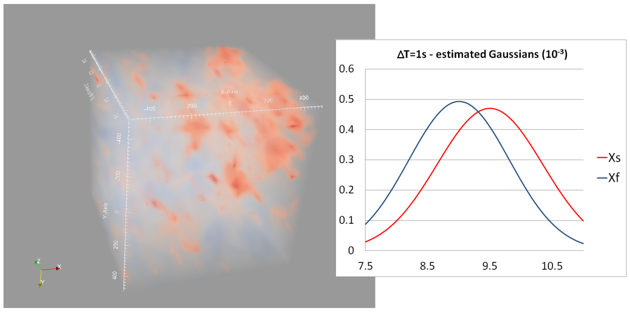
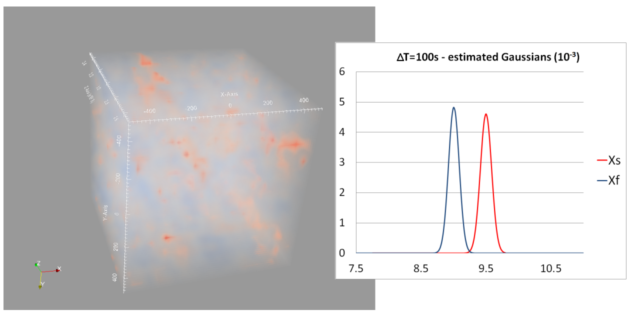
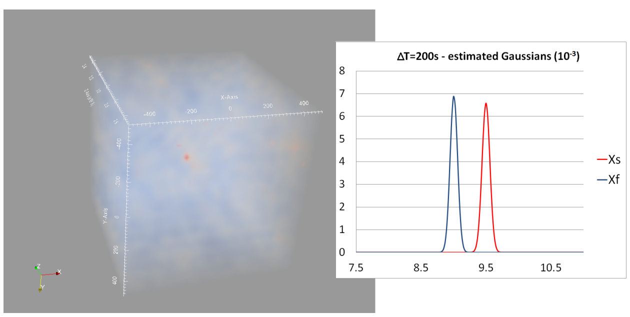


(a)



(b)



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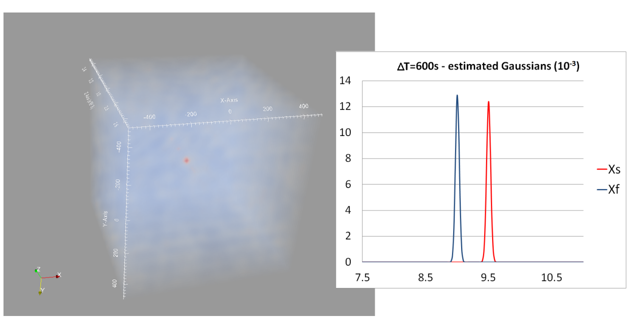

(d)

Figure 3: 3D cumulative images (1000m x 1000m x 1000m) generated by APSI (left) and predicted probability density functions of image values for the source location, $\mathbf{x_s}$, and location 1000 m horizontally separated, $\mathbf{x_f}$ (right). The data includes the signal and noise from Figure 2 after a) 1, b) 100, c) 200, and d) 600 second windows, respectively (dark red - maximum image value; dark blue - minimum image value)

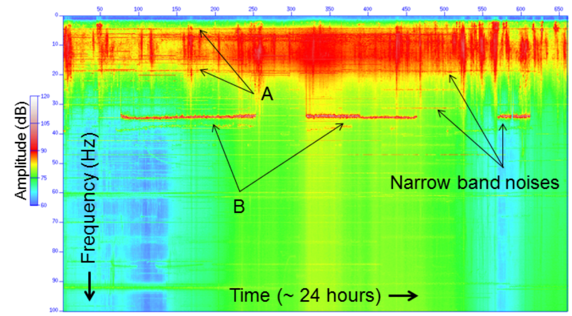

Figure 4: Typical average amplitude spectra over entire array one day interval. Each column represents a spectrum of a three minute interval.

the desired signal, but the threshold for achieving that is not defined by random noise properties, rather both random and coherent noise - $e_c + \frac{\sigma^2}{R}$, where e_c is a coherent noise energy (Figure 5). Therefore, we have two scenarios either the repetitive signal is sufficiently strong to overcome the coherent noise, for example, drill bit source, or it is weaker then coherent noise as in Figure 5.

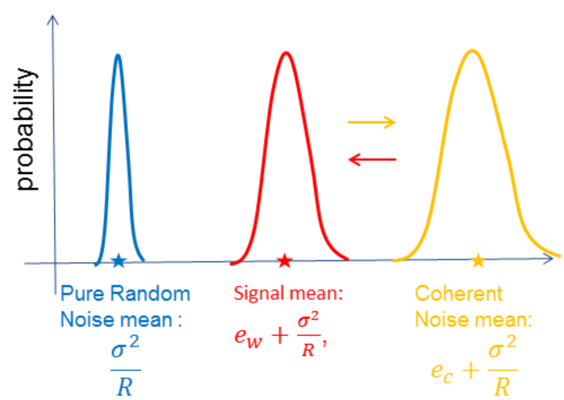

Figure 5: Sketch of possible probability density functions for random noise, subsurface signal, and coherent surface noise energies at certain subsurface locations

In addition, there is another problem with the coherent energy narrow-band type of noise when we use APSI technique: the derived image does not only focus the energy at the location of the noise source but also propagates through lower surface velocity and it manifests itself as an imaging aliasing - having several global maxima.

To prove this point, we made a similar synthetic experiment with the 20 Hz continuous surface wave as we did for random noise (Figure 1 right). Since we did not add random noise the image does not need time averaging and it is stable throughout averaging phase (Figure 6). This form of aliasing is very typical for surface noise, and can be misinterpreted to be several elongated subsurface signals.

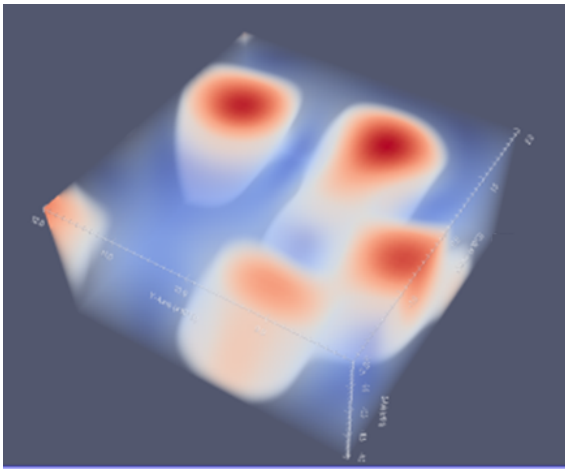

Figure 6: Typical coherent noise signature in the image.

CONCLUSIONS

Here we examine APSI, the technique for imaging repetitive passive seismic signals. Our mathematical analysis and the synthetic examples demonstrate that, in the presence of random noise, APSI is capable of identifying the location of *any* repetitive signal source by creating images along sufficiently long time windows. This time averaging only helps with random noise, but not with coherent noise and depending on the energy, the signal might or might not be resolved.

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